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High-Quality Broadband BVRI Photometry of Benchmark Open Clusters

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Doctor of Philosophy

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ABSTRACT

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Photometric techniques are often used to observe stars and it can be demonstrated that fundamental stellar properties can be observationally determined using calibrated sets of photometric data. Many of the most powerful techniques utilized to calibrate stellar photometry employ the use of stars in clusters since the individual stars are believed to have many common properties such as age, composition, and approximate distance. Broadband photometric Johnson/Cousins *BVRI* observations are presented for several nearby open clusters. The new photometry has been tested for consistency relative to archival work and shown to be both accurate and precise.

The careful use of a regular routine when making photometric observations, along with the monitoring of instrumental systems and the use of various quality control techniques when making observations or performing data reductions, will enhance an observer's ability to produce high-quality photometric measurements. This work contains a condensed review of the history of photometry, along with a brief description of several popular photometric systems that are often utilized in the field of stellar astrophysics. Publications written by Taylor or produced during the early Taylor and Joner collaboration are deemed especially relevant to the current work. A synopsis of seven archival publications is offered, along with a review of notable reports of *VRI* photometric observations for the nearby Hyades open star cluster.

The body of this present work consists of four publications that appeared between the years 2005 and 2008, along with a soon to be submitted manuscript for a fifth publication. Each of these papers deals specifically with high-quality broadband photometry of open clusters with new data being presented for the Hyades, Coma, NGC 752, Praesepe, and M67. It is concluded that the *VRI* photometry produced during the Taylor and Joner collaborative investigations forms a high-quality data set that has been: 1) stable for a period of more than 25 years; 2) monitored and tested several times for consistency relative to the broadband Cousins system, and 3) shown to have well-understood transformations to other versions of broadband photometric systems.

Further work is suggested for: 1) the transformation relationships for the reddest stars available for use as standards; 2) the standardization of more fields for use with CCD detectors; 3) a further investigation of transformations of blue color indices for observations done using CCD detectors with enhanced UV sensitivity, and 4) a continuation of work on methods to produce high-quality observations of assorted star clusters (both open and globular) with CCD-based instrumentation and intermediate-band photometric systems.

Keywords: open clusters and associations: individual (Coma, Hyades, M67, NGC 752, Praesepe) – stars: fundamental parameters – techniques: photometric – methods: statistical

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As is often stated, many people have made contributions to this work. I firmly believe and freely declare that the help given in this particular case has been so extensive that I am absolutely convinced it would not have been possible for me to complete this work without continual caring and assistance, dedicated and persistent mentoring, and loving kindness and support from so many individuals who have made a difference in my life during the past 35 years that I have been involved in astrophysical research. I hope that those I remember in these acknowledgments will know with certainty that I will always have a special appreciation for all the efforts they have made on my behalf. I also know that there will be many individuals who are not recognized at this time that have helped move me along throughout my experiences and have nonetheless played an invaluable role as I complete this project. I give a special thanks to all those who have provided these unobserved nudges to me as I have progressed.

As a non-traditional doctoral candidate, I have had the pleasure of seeing many students finish their time at Brigham Young University and move on with their lives and careers. Some of these have worked with me years later and I thank them for all the many life experiences they have freely shared with me and for the many different ways that they have taught me to look at various research projects. I give special thanks at this time to a friend and former student, Dr. Elizabeth J. Jeffery, who was a coauthor on the third publication that is considered in the body of this dissertation. I hope that all of my former students who have moved on with their careers will accept my thanks as I make this move to join them in their current level of academic achievement.

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The research presented throughout this investigation would have a completely different level of quality and scholarship had it not been for the continual guidance, foresight, tenacity, intellectual proficiency, and flair for analysis that have been displayed by Dr. Benjamin J. Taylor since we first became acquainted more than 30 years ago. Ben has been my mentor and example during all of that time. I thank him for allowing me to work with him on many interesting projects over the decades and for introducing me to a degree of scholarly pursuit and presentation that is not often exhibited by others. Ben is among the most completely honest and reliable people I have ever encountered. I have always found that Ben displays an unparalleled command of the astronomical literature. When that knowledge base is coupled with his exceptional intellectual abilities and analytical skills, Ben produces results that are beyond logical challenge. Ben has demonstrated time and again that conservative analysis, along with a complete and candid presentation of the facts, will produce an unassailable set of results. We have seen many times when a reviewer will not agree with a conclusion that we have reached. However, even though I have witnessed numerous occasions when objections were made to the style of a discussion used to present some conclusions that have been reached by Dr. Taylor, I have rarely seen anyone attempt to challenge the conclusions themselves or the data upon which they rest. I thoroughly admire the abilities on display in Dr. Taylor's work and still hope that through continued efforts I will be able to approach the same level of skill that he has displayed for these many years. I also want to thank Ben for being my friend and for taking the time to work with a stubborn charter member of the lumpenproletariat. Finally, I believe that since Ben was always able to provide an extensive analysis of any data set, I was inspired to provide high-quality data for input into all those analysis programs. The result has been that my observational skills and expertise with instrumentation have grown so that I could keep up with Ben’s need to examine and compare high-quality data sets.

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so that I could attend regional star parties. My father worked long and hard every day to make a living for his family, but somehow he still found the time to help a teenager build his first observatory. It is also clear that I would not have attended all of those star parties if my father had not supported the activities. I will be everlastingly thankful to Mom and Dad for placing me on a path that they were not able to travel.

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Chapter 1

Introduction

A determination of fundamental stellar properties is often highly dependent on accurate photometric observations of nearby open star clusters that are used to calibrate empirical relations for stars thought to have similar compositions, ages, or evolutionary histories. Some recent examples of this type of work are discussed later in the present investigation and can be found in VandenBerg and Clem (2003), Pinsonneault et al. (2004, hereafter PTHS), and An et al. (2007). These are each investigations that have relied on broadband photometry of open star clusters such as the Hyades and M67 to establish benchmark values for the color-magnitude diagrams of open and globular clusters. The calibrations established in these papers are often used to make determinations of the age, metallicity, and distance to selected associations and star clusters of various types.

1.1 A Summary of the Present Investigation

The present investigation is centered on four papers that have been published between 2005 and 2008 (Taylor and Joner 2005, Joner et al. 2006, Taylor, Joner and Jeffery 2008, and Joner et al. 2008), along with the manuscript for a fifth paper (Joner et al. 2011, in preparation) that will be submitted for publication. The data table for the fifth paper is presented in preliminary form, since the final group of observations is still incomplete. This table will be finalized in the next few months as soon the last observations are received and analyzed for consistency with previously published results. Each of these five papers is closely tied to broadband (especially $(R\text{-}I)_C$) photometry of nearby open clusters that include the Hyades, Coma, NGC 752, Praesepe, and M67. Of the nearby open clusters, the Hyades and M67 are the most frequently used for calibration work. It is therefore critical that the photometric properties of these clusters are well understood.

1.2 Presentation Outline

The organization of this dissertation will be as follows. In Chapter 2, there is a description of the long-term collaborative efforts in this area of research that have been completed by Benjamin Taylor and this author. The Chapter 3 topics include a narrative on astrophysical measurements, a general discussion of astronomical photometry, and a brief description of several narrowband, intermediate-band, and broadband photometric systems. Chapter 4 discusses techniques and suggestions for making high-quality photometric observations and some of the methods used to reduce the instrumental data to a standard photometric system. Chapter 5 covers the background work done on the original projects that were the motivation for the present investigation, including a section on additional related publications and examples of original sources of red photometry for the Hyades cluster. Chapter 6 gives an account of the motivations for the present investigation. A brief summary of each of the five selected publications, as well as the complete manuscript for each of the five papers that make up the body of this work, are found in chapters 7 through 11. A summary of the conclusions from this work and recommendations for future research are given in Chapter 12. The complete data catalogs for the paper discussed in Chapter

9 were deposited in the Centre de Donnes astronomiques de Strasbourg (CDS) archive at the time of publication and the actual paper only contains short sample tables. The Cousins *VRI* catalogs for the five clusters compared in that paper are presented in the appendix of this dissertation in order to provide additional access to the entire merged dataset of red photometry that has been developed and tested during this investigation.

Chapter 2

Comments on the Taylor and Joner Collaboration

The collaborative research efforts of Taylor and Joner began in the fall of 1981 in the first months after the newly installed 0.61-m telescope became available for observations with the photomultiplier photometer at the West Mountain Observatory. Taylor and Joner (1985; hereafter TJ85) was the first paper to be published from this partnership. Joner et al. (2008) has been the most recent of 21 refereed papers to be published in major astronomical journals as a result of the Taylor and Joner research efforts. Michael Joner has served as first author for nine of the papers where Taylor and Joner both participated and Benjamin Taylor has been the first author for another 10 of these papers.

The Taylor and Joner collaboration was a beneficial partnership for both authors. This was in part due to the nature of projects that were considered, as well as the sharing of responsibility for various portions of the research effort. Both Taylor and Joner share an interest in observational astrophysics. This shared attraction is especially apparent in the area of high-quality measurements made in several different standard photometric systems. It should be noted that the Taylor and Joner team was productive in part due to the ability of each person to work well with the other. During the years that this team actively worked together, each member continued to develop additional skill in their individual areas of expertise.

2.1 Division of Responsibilities

In each of the publications of the Taylor and Joner collaboration, there is a continued emphasis on the rigorous use of statistical inference to establish the quality of different data sets. As was noted, the first publication from this collaboration was TJ85. Those results for the Hyades, Coma, and M67 clusters marked one of the first uses of statistical methods being applied to the analysis and merging of photometric data sets drawn from several diverse populations. The use of statistical methods in data analysis continued to advance with time as Benjamin Taylor moved from error analysis and the use of two-error regressions, to a rigorous measurement of system to system differences through a comparison of zero-points and scale-factors between different data sets and finally, in the later papers, there are frequent references to multiple determinations of transformation error as well as an application of false-discovery rate protocols. The increased use of more and more advanced statistical techniques is the result of the continuous research into new methodology that was undertaken independently by Benjamin Taylor.

For this author, the new observations and subsequent publication of the TJ85 results mark the starting point for many experiences in precision astronomical photometry. The contributions of Michael Joner to this work were concentrated around establishing an astronomical research environment at Brigham Young University during the early 1980s, as well as securing external observing time at the national observatories that could be used to secure data sets of the highest possible quality and consistency.

During the following couple of decades, Michael Joner made continual progress in methods used to better match different instrumental systems and in refined observing techniques that would insure more high-quality results. It is interesting to look back at the information given for the data that contribute to TJ85 and see the array of instrumental systems that are presented. The data for TJ85 were secured using five different telescopes, four types of detectors, and at least seven variations of filters. In addition, a startling variety of standard stars contributed to the various stages of data reduction needed to merge these various sets of observations into one uniform data table. Just a few short years later, the publication of Joner and Taylor (1988; hereafter JT88) listed only two telescopes and two types of detectors along with all filters that were used being made to the same specifications. The standard star values were drawn from Landolt (1983), a few additional stars that were transformed by Taylor (1986), and some of the program stars from TJ85. After this point, the new observations utilized in Taylor and Joner programs typically relied on only one distinct instrumental system or on systems that were as closely matched from observing run to observing run as was possible while working within the national observatory system.

For intermediate-band *uvbyβ* observations, it was common practice to move the BYU set of filters between observatories and telescopes to preserve the instrumental system as much as possible. This was an important step for making high-quality *uvbyβ* observations since they are dependent on a filter-defined system. Michael Joner took charge of the development and purchase of a new set of filters for *uvbyβ* observations after it became clear that some of the original BYU filters were a poor match to the instrumental system and that some of the filters at the national observatories were showing signs of deterioration. Use of the BYU "#1" *uvbyβ* filter set at West Mountain, Kitt Peak, and Cerro Tololo resulted in data that were tied to an instrumental system that was easily transformed to the standard system regardless of where the observations were made.

With the exception of Taylor, Joner, and Jeffery (2008), the papers considered in the main body of this investigation use new observations from a single instrumental system on the

0.5-m telescope at the South African Astronomical Observatory. The results in Taylor, Joner, and Jeffery (2008) are a select case where we have combined both photomultiplier and CCD photometry from many observing runs at different epochs into a combined set of catalogs for the Hyades, Coma, NGC 752, Praesepe, and M67 open clusters.

The data reduction tasks for the collaboration were often shared with Michael Joner doing much of the initial processing of the raw data files for various observing runs and then Benjamin Taylor making the final extinction and transformation determinations to place each night of averaged raw data onto a standard system. For many years it has been common to make these final reductions using BIGPHOT (affectionately known as "the sasquatch of reduction programs" in Taylor and Joner 1996). The BIGPHOT program was written by Benjamin Taylor and has evolved through several iterations since the late 1980s. It allows for a simultaneous solution of extinction, transformation, and a time dependent drift in the instrumental system for photometric observations. In the case of CCD data, Michael Joner has handled the processing of the raw data frames up through the formation of instrumental magnitudes. The CCD processing and magnitude extraction has been done using common IRAF routines. We have used only relatively small numbers of CCD data sets and so the conversion of instrumental magnitudes to a format that can be input into the BIGPHOT program has continued to be done using an *ad hoc* procedure that is usually quite cumbersome.

The writing of the first draft for most of the Taylor and Joner collaborations has been usually done primarily by Benjamin Taylor. The writing process has generally involved the exchange of numerous drafts of the manuscript before converging on a final presentation. It has been common practice for at least the last 20 years to have Lisa Joner read through the final couple of versions for our papers to look for problems with grammar or continuity. We have found these proofreading efforts to be quite useful. The presentation of our results appears to have improved over the years as has our acknowledgment of help and support.

Chapter 3

A Few Comments on Quantitative Stellar Photometry

Stellar photometry forms a subset of the various types of quantitative measurements that are commonly utilized by investigators working on a wide array of astrophysical research. Some of the assorted methods that are commonly used in the field of stellar astrophysics will be briefly noted in the next section. The remainder of this chapter will describe stellar photometry and some of the more popular photometric systems.

3.1 Astrophysical Measurements

Modern measurements secured during investigations intended to elucidate the nature, properties, and distinctiveness of stars and stellar systems are virtually all dependent on an observer sampling various regions of spectral energy distribution (SED) for a select group or population of stellar objects. This sampling procedure is independent of the specific wavelength region being examined, and in virtually all cases involves some type of quantitative spectroscopy or photometry. The major advances made in understanding the intricacies of stellar astrophysics during the last century are primarily due to observers who have made careful applications of these techniques and then applied them to specific problems.

A great deal of time could be spent describing observational techniques that are relevant to different portions of the electromagnetic spectrum. However, the present investigation has been conducted entirely in the optical portion of the spectrum as the well-defined I passbands used for modern red photometry fall just short of the boundary at 1.2 μm that is generally considered the blue edge of the standard near-infrared photometric systems. Thus, this brief commentary will be restricted to descriptions of measurements made in the optical part of the spectrum.

Additionally, it cannot be disputed that spectroscopy is a powerful tool that can be used in many areas of observational stellar astrophysics. The practice of spectroscopy allows an observer to examine large regions of the SED for a star in ever increasing detail, depending on the instrumental dispersion. Thus, spectroscopic studies range all the way from piecewise or very low dispersion spectrophotometric data all the way to a detailed analysis of data from investigations using high dispersion spectroscopy. One must note at this point that high dispersion spectroscopic observations require the use of large aperture telescopes for even the brightest sources. Even with the largest telescopes that are available or currently envisioned, high dispersion spectroscopy is time consuming and dramatically magnitude limited. This study has not utilized the routines of spectroscopy and will therefore not elaborate further on the details of this powerful observational tool. It should be noted that the procedures utilized in photometry can be seen as shortcuts or approximations that are made in order to gather data comparable in content to that which can be observed using spectroscopic methods.

The observational techniques utilized in each of the five papers that form the main body of this dissertation (four published and one to be submitted later this year for publication) are firmly rooted in the art of optical stellar photometry. Thus, the remainder of this section will briefly explain and describe optical photometry as well as some of the standard photometric systems, including the Johnson-Cousins *BVRI* system that has been utilized throughout the course of these investigations. It is hoped that these sections will be an aid to students who require additional background knowledge before reading the main body of this dissertation.

3.2 Astronomical Photometry

As noted above, astronomical photometry is an observational shortcut used to obtain information about different sources without having to sample entire regions of the SED as is typically done when using spectroscopic techniques. It is fair to state that a meaningful data set consists of a set of observations made in selected passbands that can be related back to the fundamental properties of the sources being studied. When using spectroscopy, an observer can select narrow regions of the SED and study various spectral features in great detail. The cost of making these high resolution observations is that the observer is presented with restricted levels of signal due to the narrow portion of the SED that is examined. When using photometry, an observer deliberately uses passbands of moderate or large width in order to increase signal levels. The obvious cost of using photometric methods is that there is a sacrifice in resolution for the various portions of the SED being studied. The positive side of this trade is that the wider photometric passbands allow for the measurement of fainter stars with smaller telescopes. With a well-designed photometric system, an observer can gather information on a large number of stars with far less effort and expense than would be possible for a spectroscopic observer making comparable measurements.

In the case of stellar photometry, the collected observations of different sources are generally made through a well defined set of filters that allow an investigator to determine the brightness for each of the selected stars at each of the effective wavelengths being sampled by each filter. The term brightness is not considered to be a respectable scientific term, but it does have the virtue of having a readily understood meaning. To be more precise, it is common to reduce spectrophotometric observations in terms of flux (with units W m^{-2} Hz^{-1}) being radiated by the star observed through each of the passbands. In filter photometry, it is generally accepted practice to convert the instrumental flux measured through each filter to an apparent magnitude on an inverse logarithmic scale. Another common practice is to form what are known as colors or color indices by taking the differences between two or more of the different apparent magnitudes observed through the various filters that are used to define a specific photometric system. In terms of the observed instrumental flux, f_V, and a convenient additive constant, C, used to scale the result, the instrumental *V* magnitude, m_V, is defined as:

$$m_V = -2.5 \log_{10} (f_V) + C \qquad [1]$$

In the case of *B* and *V* instrumental magnitudes with observed instrumental flux, f_B and f_V, the instrumental color index, $m_B - m_V$, is defined as:

$$m_B - m_V = -2.5 \log_{10} (f_B/f_V) \qquad [2]$$

Depending on the selection and placement of the filter passbands and the degree to which each observation can be related to the exact flux in that passband, it is possible to relate the observed photometric apparent magnitudes through each of the specific filters to fundamental stellar parameters such as photospheric temperature, surface gravity, heavy element abundance, spectral type, and luminosity class. This is often done by convolving the filter passbands with synthetic spectra that are generated from detailed model atmosphere calculations (see Clem et al. 2004).

The number, characteristics, and exact placement of the necessary filter passbands are dependent on the photometric system that is being utilized in order to relate instrumental fluxes to some standard system that has been previously defined. The level to which the observed fluxes match the standard system is subject to both the quality of the observations secured for transformation as well as the precision of the standard system that the data are intended to match.

Over the past century as quantitative photometric observations became ever more popular, there have been a myriad of different systems that have been formally defined. The Asiago Database on Photometric Systems (http://ulisse.pd.astro.it/Astro/ADPS/) contains a catalog of more than 200 different photometric systems that have appeared in the astronomical literature. Optical photometric systems can conveniently be divided into three broad categories that can readily be characterized by the width of the filter passbands that are used to make measurements of specific wavelength intervals in the SED for the objects under investigation. The three distinct groups are usually referred to as being broadband, intermediate-band, and narrow-band photometric systems. The broadband systems are characterized by filters with passband widths of approximately 100-nm, while most of the intermediate-band systems use filters with passband widths of around 30-nm or less. Most of the narrowband photometric systems use filters with passband widths of 5-nm or less and are generally designed to measure the properties of a single spectral feature. A large number of the narrowband systems use custom interference filter sets that are difficult and expensive to duplicate and are therefore not used as often as some of the broadband systems that utilize readily available and inexpensive filters. It should also be noted that in the limit as filters become narrower and more closely spaced, a set of photometric measurements will look more and more like low dispersion spectroscopy.

Within the three categories that are labeled broadband, intermediate-band, and narrowband are numerous photometric systems based on quite specific filter sets and applications to various problems of astrophysical interest. Occasionally, systems are rare or virtually unknown outside of a single observatory where that system is employed. As was stated above, this is frequently true for narrowband systems. These systems are often totally defined by the filters that are used to isolate a specific spectral feature. If the narrowband filters are duplicated for use in another system, it is imperative that they be virtually identical copies. Otherwise, the resulting instrumental systems could be measuring different portions of a spectral feature. The result of such a potential passband mismatch would be two distinct instrumental systems that are quite obviously related but in reality are virtually impossible to reconcile over a broad range of spectral types where variation in the observed color index would be expected.

Since most intermediate and narrowband systems cover a small portion of a given SED where detector and telescope response as well as atmospheric transmission are considered well defined and modeled, it is common practice to refer to these systems as being filter defined systems. Many of the broadband photometric systems use filters that cover a large portion of a SED that may include spectral features that are large and quite variable relative to the amount of flux observed through the passband. The passband may also be wide enough that the telescope and detector response are variable across the range of observed wavelengths. In addition, wide passbands may include atmospheric emission or absorption lines that vary with time and observers can also find that variable atmospheric extinction can dramatically affect instrumental magnitudes within a wide passband. All of these effects can alter the effective wavelength of a broadband filter to the extent that it is not accurate to describe the results as coming from a filter defined system.

Some photometric systems are known and used at virtually all observatories and for almost every type of astrophysical investigation. For all intents and purposes, these systems are universally recognized. These are typically broadband systems where the filters and detectors that were used to define the original photometric system are readily available and easily duplicated. Many of the broadband systems use filters made from several layers of commercially available colored glass that is manufactured in bulk and readily obtained.

Often, the passage of time will cause a given system to undergo a waxing and waning of popularity that is connected to many factors. These certainly include but are not limited to factors such as the types of problems that appear to have astrophysical interest, the state of detector technology, and the size and quality of available instrumentation. A relevant example would include the fact that photometric systems utilizing a set of photographic magnitudes are virtually unknown today except as an historical curiosity. These same systems were still highly regarded well into the time when photoelectric detectors were being utilized because the photographic plates were area detectors that could monitor thousands of objects with a single exposure. It may be surprising, but even into the early years of the CCD revolution in astrophysics photographic magnitudes were often used for large survey projects because a photographic survey plate could cover fields of view that were about 50 times larger than what could be observed with a large CCD of that era. These are some of the reasons why photographic magnitudes and the related systems were able to persist well into a time when more efficient detectors had been developed. Examples of various photometric systems that inhabit the broad and intermediate-band domains can be found in the excellent review article written by

Bessell (2005). A couple of examples from each of these categories will be briefly discussed immediately hereafter.

3.3 Narrowband Photometric Systems

As has been previously mentioned, it is more generally the case that narrowband systems tend to be established to work as instrumental systems that usually do not enjoy great popularity. One notable exception would have to be the β system that was popularized with the introduction of a set of standards by Crawford and Mander (1966) and then followed by a more extensive set of observations on the same system published by Crawford et al. (1966). The system as described by Crawford and Mander (1966) consists of a single color index formed from the magnitude difference between an intermediate-band filter (14.5-nm) and a narrowband filter (3.0-nm), both centered on the H-β Balmer line at 486.1-nm. Since both filters have the same effective wavelength, the resulting color index is independent of atmospheric extinction and interstellar reddening. The β index is extremely useful as a temperature indicator for stars in the B, A, and F spectral classes due to the direct correlation between hydrogen line strength and surface temperature, which is at a maximum for stars of those spectral types. An index like β is also quite useful for locating stars with H-β in emission, as the values of the index are easily seen to be much smaller than is possible for even a late-type star with a weak or even non-existent absorption feature.

There have been a series of studies of a similar index done over the past decade at Brigham Young University (West, Hintz, and Joner, 2010) that have made progress standardizing an instrumental H-α system. This system is directly related to the β system, but it has some added advantages. The most obvious advantage of the H-α system is that it depends on a lower energy transition (the spectral line is located at 656.3-nm) that results in an even easier detection of emission line objects. This can be useful in surveys for objects with circumstellar shells or disks such as Young Stellar Objects, studies of Ae/Be stars, or higher energy sources that possess an accretion disk.

Another example of a specialized narrowband photometric system would be the Wing Eight-Color system developed as a subset of the original photoelectric scanner program of Wing (1967). This system is specifically designed to work on late-type stars and includes a set of filters (between 712.0 and 1097.5-nm) that measure the continuum and several strong spectral features present in the atmospheres of these cool stars. It is interesting to note that narrowband systems generally have a useful range of spectral types that is limited to the strength of the specific spectral features they were designed to measure. Sound advice at this point is to note that there is really no such thing as a “one size fits all” photometric system, and this is especially true for narrow and intermediate-band systems as they are by nature more specialized.

3.4 Intermediate-Band Photometric Systems

The last half of the 20th century saw the development of several intermediate-band photometric systems. Notable among these are the Strömgren or Four-Color *uvby* system, the DDO system, the Geneva system, the Vilnius system, and the Walraven system. It is worth noting that just as the α and β systems were defined by a combination of narrow and intermediate-band filters, the Walraven system uses two filters labeled *B* and *V* that are best described as broadband filters. The other three filters in the Walraven system (*W*, *U*, and *L*) are typical of what is expected in intermediate-band systems. The classic examples of intermediate-band photometric systems are generally designed to be readily calibrated within a specific range of stellar spectra types. The

Strömgren or Four-Color *uvby* system was originally intended to provide a set of color indices that were sensitive indicators of temperature, luminosity class, and metallicity for relatively hot stars of spectral types B through F. In contrast, the passbands of the DDO system were selected so that color indices would measure the same quantities in the much cooler G and K stars. The Strömgren and DDO systems have been among the most popular of the intermediate-band systems. These two systems will be compared and contrasted below since they are designed for use on opposite ends of the stellar temperature scale. Further information on other intermediate-band systems is given in the review by Bessell (2005).

The Strömgren or Four-Color *uvby* system was detailed in the work of Strömgren (1951). The system was originally designed to use four filters labeled as *u*, *v*, *b*, and *y* in order to measure a magnitude and three color indices (y, b-y, c_1, and m_1) that correlate well with the physical properties of B, A, and F stars. The Strömgren system is often combined with the β index as described above since it is a reddening-free temperature indicator for stars of spectral types A and F. The review article by Strömgren (1966) shows how the *uvby* system had been designed to measure the fundamental properties of early-type stars. It is immediately clear that the Strömgren system was well planned and then established as a quantitative photometric system that allows an observer to measure the temperature, gravity, and relative heavy element abundance for early-type stars. When data from the Strömgren system is combined with the reddening-free β temperature index, it is also possible to make a determination of the amount of interstellar reddening in the direction of the stars being observed.

In the Strömgren system, the *y* filter is centered on the same wavelength (550-nm) that is used to measure a visual magnitude in other common photometric systems. The color index defined as b-y is most directly a measure of temperature. The index c_1 uses the *u*, *v*, and *b* filters to measure the size of the Balmer discontinuity in A and F stars and is easily related to the surface gravity or luminosity class of these stars. In B-type stars the c_1 index is an excellent temperature indicator and is considerably more sensitive than the *b-y* index. The index m_1 uses the *v*, *b*, and *y* filters to form an index that measures the size of the depression at 410-nm in the SED of A and F stars that is due to metallicity. By using measurements in the *uvby* and β photometric systems of stars from well studied clusters such as the Hyades, it is possible to construct empirical relationships that relate the observed values of *y, b-y,* c_1, and m_1 to the intrinsic color, absolute magnitude, and metal abundance for a wide variety of program stars. The early work of Crawford (1975, 1978, and 1979) provided just such calibrations based on extensive observations of stars in the nearby Hyades, Pleiades, Praesepe, α Persei, and Coma Berenices clusters, as well as many bright field stars. Similar empirical calibrations have been updated and determined from the more recent work of Schuster and Nissen (1989) and in Nissen and Schuster (1991) for select groups of high-velocity and metal-poor halo and old disk population stars. The conclusion remains that the Strömgren *uvby* system represents a powerful tool for practitioners of quantitative stellar photometry.

Just as Strömgren photometry provided detailed information about the fundamental properties of early-type stars, the six filters of the DDO system provide a set of color indices that are intended as tools to be used to determine the fundamental properties of late-type stars. The six filters utilized in the system-defining publications of McClure (1976) and McClure and Forrester (1981) are labeled as 35, 38, 41, 42, 45, and 48. These filters are used to establish a pseudo-visual magnitude with the 48 filter that is generally labeled as M48. In addition, there are five color indices in the DDO system that are given labels that describe the color differences. These are generally known as C(35-38), C(38-41), C(41-42), C(42-45), and C(45-48). The 35 filter is identical to the Strömgren *u* filter. The index C(35-38) is a measure of the Balmer discontinuity, but is generally only used for stars that are too hot for the C(45-48) index to be a good gravity indicator. The 41 filter is centered on a strong cyanogen absorption feature found in late-type Population I stars. The C(41-42) index is somewhat sensitive to gravity, but is primarily used in the DDO system as an indicator of metal abundance. The 42, 45, and 48 filters serve as a continuum measure for various late-type stars and the indices formed by these three filters are sensitive to both gravity and temperature. The 48 filter is quite similar to the wide filter in the β system. However, the Balmer lines are somewhat weak in the cool late-type stars that are the primary targets for the DDO system and so the 48 filter is a good choice to measure an analog to the visual magnitude. A more detailed description of empirical calibrations for use with the DDO system to determine absolute magnitude, abundance, and reddening for G and K stars can be found in Janes (1975, 1977). It should be clear from this brief summary that the DDO system is another excellent example of an intermediate-band photometric system designed to produce data that can be calibrated to determine the fundamental parameters for stars in a limited range of spectral types.

3.5 Broadband Photometric Systems

The broadband photometric systems are among the earliest standard systems used in modern photometric investigations. The filter bandpasses are wide enough to permit large sections of the SED to be sampled with each measurement. Several broadband systems currently exist and continue to be utilized regularly for a wide variety of large photometric investigations. These systems include several variants of the Johnson system, the Washington system, the Sloan Digital Sky Survey (SDSS) system, the Hipparcos-Tycho system, and the Hubble Space

Telescope (HST) system. A relatively thorough description of each of these systems can be found in the fine review article of Bessell (2005). The research work in this dissertation has all been conducted using broadband filters and a detector that match the well-defined Johnson-Cousins system. The original red passbands of the Johnson system are no longer used, primarily due to the excellent standardization work that was produced by Cousins (1974, 1976) and later expanded on by Menzies et al. (1989). Thus, the only detailed description for a broadband filter set given in this section will be for the standard $UBV(RI)_c$ system. However, it is worth noting that the excellent temperature index from the Washington system, T_1-T_2, has been shown to be a close analog to the standard Cousins *R-I* index (Taylor 1986, Taylor and Joner 2006).

A concern for the future of broadband photometry is that it has become common for large investigations like the SDSS, as well as major space missions like HST and Hipparcos, to establish a new instrumental broadband photometric system. It is anticipated that this trend will continue and that the next generation of massive survey instruments will make use of new and slightly different instrumental systems. These major new projects include, but are not limited to, the Large Synoptic Survey Telescope (LSST), the Panoramic Survey Telescope and Rapid Response System (PanSTARRS), and the James Webb Space Telescope (JWST). It is expected that each of these systems will be similar to previous large projects and operate using an instrumental system that is similar to some existing broadband system but is still different enough that transformations between systems for objects with unusual or extreme SEDs will not be trivial. This is unfortunate, because it can be difficult to compare data for unusual targets that come from different systems and have been secured at different epochs. Since data reductions are already complex for these large projects, adequate transformations for objects with unusual properties may not be available until a relatively lengthy time has passed.

Landolt (2007) has stated a belief that the history and future of all photometric systems are tied closely to a magnitude defined by the *V* filter, which is in turn linked to the human eye. He has stated that this visual magnitude provides an important connection between past work and advances that will be made in the future. Early photometric systems were based on a filtered photographic exposure designed to mimic a visual magnitude and second magnitude that peaked at shorter wavelengths due to the natural response of the early photographic emulsions. Landolt (2007) states the first color index, $m_{pg} - m_{pv}$, was defined by the difference between these photographic and visual magnitudes. The North Polar Sequence was loosely tied to this system of photographic and visual magnitudes, but the sequence was not defined well enough to allow reliable transformations to a repeatable standard system. This system was allowed to slowly slip into historical obscurity.

The use of photomultiplier detectors for research applications during the decade of the 1950s ushered in a new era for modern photometric systems. The *UBV* system was born after the defining work published by Johnson and Morgan (1953). The *UBV* system was formally standardized with the list of 108 standard stars published in Johnson and Harris (1954). Since that time, the astronomical literature has been filled with all manner of studies making use of relatively precise quantitative stellar photometry.

The earliest broadband *UBV* systems were established so that the short wavelength cutoff for the bluest filters was determined by the use of different types of glass in the optical system or by the natural atmospheric cutoff at about 300-nm. Further, the long wavelength cutoff for the red edge of the visual magnitude in the earliest photoelectric systems was set by the response function of the detector that was selected. One of the earliest systems used for photoelectric photometry was the *UBV* system, and as a result of these early choices in system design atmospheric extinction has remained as a major problem involved with the reduction of *U*-band photometry. Despite difficulties that have arisen from time to time when matching observations secured using slight variants of popular broadband photometric systems, the *UBV* filters have remained ubiquitous in the universe of observational choices that are made when a photometric investigation is planned. Part of this continued use is due to a strong sense of tradition that permeates many areas of astrophysical research. Additionally, there are now several catalogs that contain measurements for thousands of stars as well as large collections of *UBV* standard stars that have been observed for many decades. For example, Mermilliod (1987) lists *UBV* entries for collected observations of more than 87,000 stars. This same catalog is also available in an online format in Mermilliod (2006).

Early *UBV* photometric investigators were not always careful when selecting filters and detectors for their different instrumental systems. As a result, it can be difficult to compare some older *UBV* observations that were made using different systems. The observed indices often show major systematic offsets from observer to observer for stars that may be similar in many respects. Two observers can measure a set of program stars of the same temperature and yet arrive at very different results for their color indices that measure temperature.

Experience has shown that a poorly matched instrumental system can introduce significant secondary dependencies to a color index. While it is extremely difficult to design a photometric index that measures a single physical characteristic of a stellar atmosphere, this ideal may be achieved with a well-crafted narrowband index. However, this goal is essentially impossible when using broadband filters. Thus, while a classic color index like *B-V* is primarily sensitive to stellar surface temperature, there are smaller secondary effects in the index due to differences in metal abundance and surface gravity. These are well understood and expected effects within different photometric systems. The real complications arise when there is a significant mismatch between the instrumental system and standard system used to define a specific index. For example, it is likely that an observer using a color index designed to measure photospheric temperature with secondary effects due to luminosity class or metallicity differences among a sample of program stars will find that these secondary effects can be greatly exaggerated or amplified due to instrumental system mismatch. These differences will generally be more pronounced when measuring stars with large differences in temperature, metal abundance, interstellar reddening, or luminosity class. Many different instrumental system mismatches can be attributed to the use of filters made using different brands of colored glass or thicknesses of the glass layers, or to different response functions for the detector that is selected. It is abundantly clear that most of the difficulty in matching *U*-band photometry to a standard system that has been experienced during the era of CCD photometry can be traced directly to the vastly different response functions of CCDs as compared to the 1P21 photomultipliers that were generally used to define photometry in the original *U*-band standards of Johnson and Morgan (1953).

The blue colors such as *U* and *B* both exhibit added problems due to the location of the Balmer jump within the filter passband. The effect is large enough so that the effective wavelength of the *U* filter is a function of the spectral type of the star being observed. This makes it difficult to adequately correct *U* filter measurements even for routine effects such as atmospheric extinction. A thought-provoking discussion of these corrections can be found in Gutiérrez-Moreno et al. (1981). It is stated in Bessell (1990) that small shifts in filter passbands can lead to significant non-linear transformation errors in broadband photometry. An example is given for *U-B* transformation problems, where it is noted that the blue edge of the standard *B*-

band is located close to the Balmer jump. Thus, according to Bessell (1990), a small departure from the standard passbands for an instrumental system will be reflected in the measured indices of early type stars by an added transformation term that is directly related to the size of the Balmer jump.

The *R* and *I* bands in the broadband *UBVRI* system have been modified several times by different groups of users during the years that photomultiplier photometry was widely utilized. The various *RI* systems are of special interest to the main body of work that is presented later in this dissertation and it is therefore relevant to discuss the major changes that have altered the nature of photometry in the red colors.

Kron and Smith (1951) used a red sensitive photocell to measure magnitudes in passbands centered at approximately 680-nm and 825-nm with broadband characteristics similar to the *RI* filters later used in the Cousins photometric system. Kron, White, and Gascoigne (1953) established photometric standard stars for this same *RI* filter combination. The photocell detector used at that time for red photometry had poor gain and relatively high noise. With these limitations the system was only useful for relatively bright stars, and thus general usage was somewhat restricted until red-sensitive detectors improved in quality. This system is considered to be well designed and is usually referred to as the Kron system. The *RI* system that was developed twenty years later by Cousins (1974, 1976) is still considered by many to be a close relative of the Kron system.

The Johnson *UBV* system expanded with the addition of *R* and *I* filter observations added to the large body of work published by Johnson, Mitchell, Iriarte, and Wisniewski (1966). These two additional filter passbands had central wavelengths of approximately 700-nm and 900-nm, respectively. Both of the Johnson filters had widths that were much greater than their counterparts in the Kron system. A major drawback to the early Johnson *UBVRI* system was that the photomultipliers of that time made it necessary to measure *UBV* colors with one type of detector and *VRI* colors with a different detector. In some cases, observers would only observe the *RI* colors with their red sensitive detectors. This technique could lead to difficulties in determining color indices such as *V-R* or *V-I* since there was no direct overlap between the instrumental photometric systems. It has been speculated that the difficulties encountered in transforming the photometry from Eggen (1982) to $(V\text{-}R)_C$ and $(V\text{-}I)_C$ colors were due to the fact that the *V* magnitude and *RI* color observations of Eggen were made during different observing sessions.

This problem disappeared with the development of the higher response S20, S25, and GaAs photocathodes for use in astronomical detectors and also corresponded with the development of the $UBV(RI)_C$ system by Cousins (1974, 1976). This landmark work decisively demonstrated that careful standardization and observing practices could lead to consistent photometric results with rms errors of 3 mmag* or less for comparisons made in all-sky observing programs. There are many examples of work that has been done in this system by a wide variety of observers that achieve photometric precision levels well below a level of 10 mmag. These routine results justify the use of the mmag unit in standard photometric investigations. In contrast, the *VRI* colors of Johnson et al. (1966) are known to have much larger standard errors than is considered acceptable for modern photometric observations. Taylor (1986) has determined a standard error for the Johnson et al. (1966) *VRI* photometry to be 22 mmag.

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* 1 mmag (millimagnitude) = 0.001 mag.

Chapter 4

Standard Photometric Observing Procedures and Data Reductions

The establishment of a routine set of practices for making observations is one of the most important keys to routinely securing high quality data in a photometric observing program. This may seem like obvious advice, but experience has shown me that many of the observational astronomers I have watched working at observatories around the world do not have a regular routine that they follow during an observing run. The advice that I offer in this section is based on words of wisdom given to me almost 30 years ago by Ed Mannery from the University of Washington Department of Astronomy. Ed told me that "[t]he only thing worse than no data is bad data." I have thought about this many times over the years as I've worked on different projects. The reason that bad data is worse than no data is because bad data will waste your time long after you have completed a run at the telescope. Photometric observers are often stuck with making a decision about the quality of a night and whether they should be trying to secure more high-precision data on a project or shift their efforts to a project where spectroscopy or some form of time-series differential photometry would be more productive. Spending telescope time in an effort to secure standardized photometric observations on a non-photometric night is far worse than having no data at all. The low quality data that you mix into your data set will make your high-quality data look bad. If you mix in enough bad data, you will not be able to sort out the results because they will be so thoroughly contaminated. The balance of this chapter will describe some of the general photometric observing practices and data reduction techniques that are utilized to insure that observations produced at various locations are maintained on a consistent standard system.

4.1 Precision Photometric Observing Techniques

The first rule that must be observed when doing high precision photometry is to make sure that observations are made under photometric conditions. Even cirrus clouds that are just barely detectable to the eye can cause variations of several percent in the resulting data. If clouds are actually visible in the sky, photometric conditions are not present. Also, there is no such thing as a partially photometric night. The rule to follow is that conditions are either photometric or non-photometric. It is common to have a night that starts out as actually being photometric and then degrades into being non-photometric as clouds arrive. This is fairly easily detected if regular standard star measurements are a part of the observer's usual observing routine. Of course, it is also possible for a non-photometric night to become photometric over some period of time. This is much more difficult to detect over a short period of time, as the observer is left to make a judgment as to whether the conditions are truly photometric or if the night has become temporarily stable even though the conditions are still decidedly non-photometric. Photomultiplier photometry was always quite difficult because most photometers only allowed for measurements of one star in one filter in a given time period. There is a great advantage to doing observations with a CCD detector, since it is usually the case that dozens or even hundreds of stars can be observed with each program exposure even if the field of view is relatively small. If there are local standards visible in the program field, it is still possible to generate a high-quality differential solution for each frame. However, there is no sound procedure that will allow an observer to standardize multi-color observations from different parts of the sky if they are secured under non-photometric conditions. The power of a full all-sky solution done under photometric conditions is that all of the magnitudes and colors can be used for many different standard stars to determine the properties of the program objects.

Another important part of a high-precision observing routine is to plan to make frequent observations of standard stars. Once again, this was challenging in the photomultiplier era since it would generally take about five minutes to set on each standard star and make a single observation. This was a difficult pace to maintain if the observing routine also included regular measurements of sky background and multiple integrations in each filter. When making photomultiplier observations, an observer would typically center a star in the photometer aperture and then take a palindrome sequence of individual filter integrations, such as *UBVRIIRVBU,* and then offset the telescope to a blank patch of sky and do a *UBVRI* filter sequence to measure the sky brightness. A sequence like this could be completed in just a few minutes, and an experienced observer could tell by looking at the matching integrations on each end of the sequence if the conditions were remaining stable during the time that the observations were made. A quick look at the sky readings would often be another way to look at short term variations in the sky conditions. Even though many stars can be observed simultaneously with a CCD system, it is much more difficult to monitor the quality of a night in real time from a quick look at the last few observations. This is due to the fact that even a quick examination of multiple CCD images is a relatively time-consuming process. One precaution that can be taken is to make a record of each photometric night with consecutive regular images from an all-sky monitoring camera that can be carefully examined at a later time for any signs of clouds or haze.

A low-tech way to monitor conditions would be to make frequent trips outside to visually inspect the sky.

It should be remembered that during the data reduction phase, it is easier to monitor small changes in sky transparency or possible instrumental system drift if frequent observations of standard fields are being made. It is possible to model small changes in the quality of a night and the zero point of the instrumental system if the observer has regular observations of standard stars as a reference. It is also easy to determine the time period when conditions became non-photometric if the observer has a series of standard star observations to serve as a reference.

Unfortunately, these practices are not always followed. It is common to find investigations where the only standard observations secured are in the form of cluster program stars that are used to calibrate all of the CCD data because they have previous photomultiplier observations. An example of this use of secondary standards can be found in Bonifazi et al. (1990). Another questionable practice involves making observations of standard fields on different nights than the program observations. Sagar et al. (2001) present photometry for the star cluster NGC 6631 and state that it was standardized using observations from two Landolt (1992) standard fields. A check of their observation log shows that one of the standard fields was only observed on one night when the program cluster was not observed. It should be remembered that instrumental systems can drift from night to night, and changes in the sky can introduce enough variation so that the transformation equations are unable to account for all the variables. Experienced observers such as Landolt (2007) expect to spend roughly 25% of each night on “overhead” observations. This is the cost of establishing an observing routine. It doesn’t matter what type of detector is being utilized; the results will be more easily standardized if proven experimental methods are used during the observing time. There is no substitute for having an adequate number of reference observations.

A well-designed observing program not only uses frequent observations of standard stars, but also makes use of standard stars that are selected from the system-defining lists that are suitable for work on the project that is being planned. For example, one would not want to concentrate standard star observations on cool red stars at one end of a transformation relation if the targets in the program list were mainly hot O and B-type stars from a young open cluster in a star forming region. Likewise, it is not a good practice to make observations of standard stars in the range $8 < V < 9$ if all of the program objects are in the range $10 < V < 14$. Either case would lead the observer to extrapolate the transformation relations that are constructed when the data are reduced. While it is good practice to make certain that color coverage extends to the red or blue extremes of stellar color, the primary concern when selecting standard stars is that they should be stars that fully bracket the program stars in terms of magnitude and color. In general, there is not a lot of information on the luminosity class, reddening values, or metal abundance for most standard stars, but if possible these factors should be considered when making standard star selections for a given program. The more closely the standard stars match the program objects, the more certain observers can be that they are actually measuring quantities that are directly related to the objects being studied.

Another part of a sound photometric observing routine should be the determination of atmospheric extinction coefficients on each photometric night. It is often assumed by inexperienced observers that 'mean' extinction coefficients are sufficient for use at a quality observing site. In general, this is just not a good assumption to make. My experience with making observations at locations such as Kitt Peak National Observatory, Cerro Tololo Inter-

American Observatory, South African Astronomical Observatory, and West Mountain Observatory are that the extinction coefficients vary all the time from night to night. At some locations an observer may even find that there is an east to west or north to south extinction asymmetry in the sky. For those interested in a supporting opinion of the use of mean extinction coefficients, check the discussion in Landolt (2007, see Table 4) in order to examine a 14-year compilation of extinction coefficients for Cerro Tololo, considered to be one of the premier photometric sites in the world.

An often-overlooked component of a well-designed photometric observing program is the work that goes into matching the instrumental system that will be used to secure the data that are intended to match one of the standard photometric systems. A common source of error is to use filters that are a poor match to the original system filters. Another source of system mismatch would involve using a detector with a response function that is very different from the detector used to define the original system. Results detailed in papers such as Bessell (1990) illustrate the care that is needed to maintain an instrumental system capable of producing results that can be transformed to a standard system.

There are many cases that can be cited to illustrate errors that arise from an instrumental system mismatch. It has already been mentioned that detector response can be an important factor to consider when matching an instrumental system. There are some examples of occasions where even having a similar detector in a system is not good enough. One example of this is related directly to $(R\text{-}I)_C$ photometry. Many of the *I* filters used in Cousins-like systems originally used a single layer of colored glass to define the blue edge of the passband along with the natural cutoff of a typical GaAs photomultiplier to define the red edge of the passband. This combination resulted in sharp filter edges since the GaAs photomultipliers exhibited a rapid drop in sensitivity at about 880-nm. However, there was a potential problem since many observers using this system were not aware of the fact that GaAs photomultipliers, such as the popular RCA 31034-A, had an effective red cutoff that was dependent on operating temperature. Bessell (1979) gives the cutoff wavelength variability for the RCA photomultiplier as a shift to the blue of 0.2-nm/°C. If all observers operated systems cooled with dry-ice (about -78 °C), this would not be a concern. However, different observatories are known to use different set-points on thermoelectric (TE) cooling systems used for photomultipliers in order to maintain a constant temperature on a detector. Thus, while many observers used dry-ice to cool their detectors, other observers such as Cousins (1976) reported maintaining an approximate constant temperature of -10°C on the photomultiplier chamber. (Taylor and Joner also commonly observed using a TE cooling system and a set-point common with Cousins.) This difference in operating temperature could easily result in an effective shift in the red edge of the *I* filter of as much as 14-nm. For many stars this may not make a significant difference, but it is likely that the coolest stars observed could show systematic differences in a color index such as $(R\text{-}I)_C$. Thus, even if identical filters and detectors are used for an instrumental system, it may still be important to consider other factors that could affect one's observations.

Another suggestion to aid observers making precision photometric observations is especially important for users of CCD detectors. The use of a CCD requires that an added block of time be spent doing calibration frames for the detector. These should include bias frames, dark frames, flat field frames, and usually the use of an overscan region on the individual program frames. If a wide-field system is being used, additional illumination corrections may need to be made to the flat field frames in order to get a smooth background across the entire field of view. Also, the use of a back-illuminated CCD may make it necessary to construct special calibration frames to remove interference patterns from the *I*-band frames that are caused by emission lines in the night sky passing through the CCD substrate.

The read noise for a CCD is the major component of variation that is seen in individual bias and dark frames. For this reason, it is important to secure multiple calibration frames. Experience shows that dark frames scale linearly with exposure time for modern CCD detectors that are used for research work. However, it is often the case that the read noise is larger than the dark count for short exposures. An observer can correct for the dark noise during short exposures by using a number of long exposure dark frames that are combined into a master dark frame that is then scaled for the individual program frame exposures. It is important that the individual dark frames are well corrected for the bias level on the detector by using either a master bias frame or an overscan correction on each of the individual dark frames. There is a practical limit to the number of frames that can be secured for calibration purposes during an observing run. A look at any test statistic will clearly show that random events such as noise are better modeled with larger samples. A realistic routine for use with CCD calibrations would be to secure a set of flat and dark frames whenever one has the opportunity to work under the same conditions that will be used during regular observing time. If the observer is using bias frames, a really large number of individual frames might have some minor advantages as the actual bias level is modeled. In reality, it is likely that differences between a master bias derived from 200 frames will be nearly undetectable when compared to a master bias assembled from 20 frames. The 180 frame difference may be about equal to the storage space used by an entire night of program observations with the same CCD. The important thing to remember with calibration frames is that if observations contain less noise, the observer can expect a better determination of photometric values.

CCD detectors are wonderful tools to use at the telescope, but they are also sensitive to small changes in electronic components or to temperature changes within the CCD chamber. Many observers believe that a CCD is a stable detector that never needs to be checked or monitored. This is far from the truth. If the power is cycled on a CCD system, it may take several hours for the system to stabilize once again. A small change in the temperature of the CCD detector can make a large difference in the levels of dark count, which can be quite substantial in some cases. Performance specifications for most CCD detectors that are operated with TE cooling systems show that dark count doubles with every 5-6° C rise in temperature. Some CCD systems are known to have a variable bias level that depends on the temperature of the system chassis. It is a good idea to take calibration frames every night that it is possible to do so, and to monitor the stability of one's instrumental system with time. If changes occur, there is a good chance that the observer will be able to remove them with the calibration frames. If the observer fails to monitor the system for changes, there will be no way to know why the observations do not come out as well as planned.

It is important to remember in connection with observatories, instrumental systems, and precision levels that many of the items discussed in this section are ones that an observer can control. These are factors that are dictated by one's observing routine. A parallel discussion can be found in the recent standardization paper by Landolt (2009). He is careful to list the various components that he considers part of a careful observing routine. Each of these items, such as choice of standards and frequency of standard observations, is under the control of the observer.

There are occasions when one may not be able to adapt one's own routine and instrumental system to an observing program. This is most likely to occur when an observer is using the observing facilities at a remote location. The most obvious example would occur if an observer wanted to use instrumentation that was not available at the observatory being utilized. One cannot make observations on the Strömgren system if there are no *uvby* filters available. Even if the observer provides her own filters, they may not be the correct size or shape to fit into the observatory's equipment. If the observer wanted to use a photomultiplier photometer to reproduce various standard system observations, it would be unlikely that working instrumentation could be located. The 0.5-m telescope at the South African Astronomical Observatory is one of the few photometers in the world that is still kept in operating condition. Even one of the large and well-equipped national observatory facilities may not be able to supply the exact instrumental system that an observer may want to use for a project. It is difficult to adapt many pieces of guest observer equipment to different systems at various observatories. Landolt (2009) has described how he has maintained nearly the same instrumental system at Cerro Tololo Inter-American Observatory for several decades due to his frequent guest observer status, but even in these special cases forced changes occur from time to time. One of the major advantages of having guaranteed continuing access to observing facilities is that it is much easier to maintain a stable instrumental system. For example, the 0.5-m at SAAO has a single instrument mounted all the time that is used for photomultiplier photometry and that instrumental system is continually monitored for stability.

4.2 Photometric Data Reductions

After an observing routine has been followed and high-precision observations have been secured for a photometric study, considerable effort is required to transform those observations from the instrumental system defined by the telescope, detector, and filters into the standardized magnitudes and colors that are based on the standard stars that have been used to define a specific photometric system. The data transformation is a critical step in the process of producing high precision results.

As has been discussed in the previous subsection, it is important to make many observations of standard stars in order to more fully understand the nature and stability of an instrumental system. Also, it is important to make observations of standard stars that are similar in nature to the program objects being observed. These cautions become meaningful once it is realized that after preliminary data processing is done to remove the instrumental signature from a data set (a pulse width correction for photomultipliers or flat field correction for a CCD are good examples), the reduction process is relatively easy to understand. With the instrumental effects removed, it is straightforward to calculate instrumental magnitudes for each filter for each object at the time that the observation was made. If observations were made at a variety of altitudes through the atmosphere, it is then possible to determine the effects of atmospheric extinction for that night and then apply the extinction corrections for each filter to the set of instrumental magnitudes. When the data have been corrected for extinction, the resulting instrumental magnitudes for stars with multiple observations can easily be examined for any sign that the system has registered a small drift in the zero point with time. The resulting zero point corrections can be modeled and applied to the data. The final step consists of calculating a set of transformation equations that are used to relate the observed magnitudes and colors from the instrumental system to the actual quantities in a defined photometric system. The description given above is a bit of a simplification of a more involved process, but it does capture the essential steps that need to be made during the reduction of photometric data.

Once the transformation equations are determined from the standard star observations, the process of data reduction becomes quite mechanical as the only thing left to do is to apply these transformations to the program star observations and then sort them into a database for later analysis and interpretation. This is a process that has become much more complicated with the almost universal usage of CCD detectors in photometric work. During the photomultiplier era, a night of observations using a photoelectric photometer would typically consist of measurements of approximately 100 stars through several filters and the resulting data file would occupy less than 100kB of disk space. Today, it is not uncommon to end a night of observations with a CCD photometer and realize that there are observations for tens of thousands of stars (the majority of which are likely not part of one's list of targets) through several filters, with the resulting data files filling several GB of storage space.

As has been detailed in Chapter 2, the data reductions for this project have been made with the BIGPHOT program written by Benjamin Taylor. For most of the reductions that relate to the work in this dissertation, the data were reduced in groups that were divided into individual observing runs. The transformation and extinction coefficients were carefully monitored within each group of data in order to test for nights where anomalous or significant differences may have been present. Individual data points were collated and averaged for each program star during the reduction process in order to test for nights with a suspicious number of discrepant observations. Groups of observations with significant deviations from previous measurements were often an indicator that a night had started to deteriorate before any problems were noted at the telescope. The ability of BIGPHOT to collect and organize data for a number of observing runs made it easier to monitor the behavior of various instrumental systems from season to season. In cases where data were secured at different observing facilities, BIGPHOT enabled a direct comparison of the data secured at different sites.

Chapter 5

A Brief Summary of Related Research

The appearance of TJ85 serves as a focal point for the new research presented in this dissertation. It is important to recognize that the TJ85 paper that marked the beginning of the Taylor and Joner collaboration was itself inspired by at least two previous publications by Taylor (1978; hereafter T78, and 1980; hereafter T80) intended to determine the differential blanketing between the Hyades, Coma, and M67 open clusters. Thus, it is important to offer a brief summary of these two investigations at the beginning of any review of related research.

T78 presented new photometry that formed the basis for a differential blanketing analysis of the main sequence stars in the Hyades, Coma, and M67 star clusters and concluded that the M67 and Coma clusters have similar main sequence blanketing. It was also concluded that both clusters had lower blanketing than the Hyades. This was a surprising result at the time, since it was thought that the M67 stars had significantly greater than solar metal abundances (Spinrad and Taylor 1969). A secondary result from this investigation was a determination of the interstellar reddening for each cluster. T78 reported a significant non-zero reddening value for the nearby Hyades cluster. This paper also reported the existence of systematic differences between the newly reported photometry and some archival observations.

The primary result reported in the investigation by T80 was that the non-zero reddening value derived in T78 specifically for the Hyades cluster was the result of an error that had been made in the interpretation of the polarimetric observations. T80 secured new polarimetry that was used to correct the previous mistake. T80 concluded by noting that the reddening error did not alter the central conclusion of T78 that indicated a near solar metallicity for the M67 main sequence stars.

5.1 Motivation for the Original Taylor and Joner Cluster Photometry

The primary inspiration for the research publications presented individually in chapters 7 through 11 is the photometric data set presented in TJ85. The papers described at the opening of this chapter are of significant importance to TJ85 due to some of the procedures used and lessons learned from the previous investigations reported in T78 and T80. T78 demonstrated the need for minimizing systematic errors in data sets of color indices, such as *R-I*, due to the fact that those errors are inflated when they are related to indices with a longer color baseline. As noted in TJ85, such errors can easily mask the blanketing differences one is attempting to detect. The uncertainty between previous red photometry and the T78 results was an added concern specifically for this reason.

It was stated in TJ85 that the T78 red photometry had been left on two *ad hoc* systems because available lists of standard stars were insufficient for the standardization process. It is noted in T78 that at that time it was unusual to find data sets that were consistent from observer to observer or location to location (see T78 Table 4). This was especially true for the red colors in the *UBVRI* systems. Different facilities and observers used a variety of filter sets and detectors, and the results were what would be expected for systems operating in a region that is close to the edge of a detector's response limit.

It should be noted at this point that much of the work reported in this investigation involves the red colors that make use of the broadband *VRI* filters. Much of the reason for this choice is due to the fact that T78 was interested in ways to measure differential blanketing. In this type of work, it is necessary to use a photometric temperature index that is insensitive to blanketing as a reference. The atmospheres of stars are much less heavily blanketed in the red portion of the spectrum than in the blue, and this led T78 to make use of "blanketing-unaffected red photometry" as a reference in order to make comparisons between different clusters. Later in Taylor, Johnson, and Joner (1987), a comparison was made for seven different red photometric temperature indices and it was demonstrated that $(R\text{-}I)_C$ and $T_1\text{-}T_2$ were the red colors that were the least sensitive to different levels of blanketing.

An excellent procedure that was followed when possible in T78 was to observe stars in all three clusters on the same nights. This is a difficult task since even the short way around the sky leaves stars in the Hyades cluster separated from stars in the Coma cluster by more than 8 hours of right ascension. Observing run #3 from T78, which is reported again in TJ85, is an excellent example of a valuable technique that can be used when observing groups of stars that are separated by large areas of the sky. The technique of making a direct comparison of clusters located in different parts of the sky in order to minimize zero point errors was pioneered in the work of Sturch (1972, 1973). The results from run #3 presented in TJ85 tie all three of the clusters examined to a common instrumental system and serve as an anchor point for all the data.

It was during this era that Cousins (1973, 1983, 1984) had convincingly demonstrated that an extremely precise copy of the Johnson *UBV* system could be transferred to the southern hemisphere E-regions. The work of Cousins effectively transformed photometric measurements to a realm where it was typical to describe transformation errors in terms of mmag units. About this same time, Cousins (1976) provided a precise set of southern hemisphere standards for his own variant of the red *RI* system. In just one decade, the entire character of the *UBVRI* system had changed so that it could now be used as a well defined system with levels of precision far superior to prior iterations. Around this same time, Landolt (1973) had published an extensive list of equatorial standard stars that were closely matched to the Johnson *UBV* system observations. Landolt (1983) was able to expand a subset of this list to include *RI* observations that were directly related to the set of southern hemisphere standards described by Cousins (1976). In this way, the more precise $UBV(RI)_C$ system utilized in the south by Cousins quickly became available to observers in both hemispheres. It is important to note that this is a brief and incomplete history. It is well known that the *RI* work of Kron, White, and Gascoigne (1953) preceded the work done by Cousins two decades later. However, the detector technology had not caught up with the desire for observations of faint objects and so red systems did not mature until the later time period. The developments and limitations of detectors were summarized earlier near the end of Chapter 3. There were also several attempts to establish large and accurate groups of standard stars at this time, but those did not catch on like the work of Cousins and Landolt. It is not useful to detail all of the various trials of different broadband red photometric systems that were proposed between 1950 and 1990.

At the time the work was being done for TJ85, it was possible to use standard star lists from Landolt (1983) and produce transformed results that matched what were expected from the *VRI* system described by Cousins (1976). Table V in TJ85 contains $(R\text{-}I)_C$ and/or $(V\text{-}R)_C$ entries for 42 Hyades members, 35 M67 members, and 18 members of the Coma cluster, along with conservative accidental errors. TJ85 also discuss the nature of accidental errors, internal errors determined from repeated observations, and attempts to determine the extent to which group transformation error contributes to the final error estimates. Although TJ85 contained a significant number of original observations, the reception of the paper was often somewhat tepid since it relied heavily on data sets that were augmented with observations that had been transformed from other 'Cousins-like' systems. A prime example of this would be the important run #3 data that were originally secured using the Washington system T_1-T_2 index that were then transformed to $(R\text{-}I)_C$. An examination of the TJ85 Table VI shows that there are no statistically significant differences between data sets drawn from various instrumental systems, and thus it is reasonable to assume the various transformations have been applied correctly.

Another possible reason for some initial doubt about the validity of the TJ85 results could be the negative response that many members of the photometric community have toward the use of statistical tests of consistency between data sets. The referee for TJ85 remained skeptical about the value of statistical analysis applied to problems such as zero point consistency even after the paper was accepted for publication. These concerns about the TJ85 results surface again when the recent publications used for this dissertation are presented.

The TJ85 paper was not only the first appearance of data on the 'native' Cousins system for stars in clusters such as the Hyades, but it also marked an early use of the Landolt (1983) set of equatorial Cousins system standards. The Landolt (1983) standards were cited more than 450 times before they were superseded for many with the publication of an expanded set of standard fields in Landolt (1992). The publication of TJ85 marked only the 27th citation of the red standards in Landolt (1983) that were newly available to northern hemisphere observers.

The remainder of TJ85 discusses the suspected differences between the data of Mendoza (1967) and the consensus data set for the Hyades, Coma, and M67. It was found that the differences in $(R\text{-}I)_C$ were significant at greater than a 95% confidence level for both Coma and M67. The same is true for the differences found for the Coma $(V\text{-}R)_C$ values. The TJ85 paper was successful in establishing the first consensus data set for the Hyades, Coma, and M67 star clusters using the modern Cousins *VRI* photometric system.

The results published by JT88 added data for 17 additional and mostly cooler members of the Hyades cluster to the data set presented in TJ85. There are also data for an additional 11 cool giants that are members of the M67 cluster given in JT88 that add to the data published in TJ85. The remainder of the JT88 paper establishes that the new data were reduced to a standard system identical to the one used in TJ85. The JT88 results strongly indicate a slight but easily observable variability in the set of cooler Hyades members that have been observed. Four of the new stars observed in the Hyades appeared to be variable in $(R\text{-}I)_c$ at greater than 97.5% confidence. The observed variation in the $(R\text{-}I)_c$ color apparently has no effect on the $(V\text{-}R)_c$ color, as this index does not appear to exhibit the same level of variation. Also, several of the Hyades stars exhibited *V* magnitude changes during the course of this study that appear to be uncorrelated with any variability in $(R\text{-}I)_c$. The Hyades have been suspected for some time to display greater levels of starspots than stars in similar clusters (Campbell 1984). This is suspected to be the case for dwarfs of spectral type later than F7, but JT88 were not able to conclusively demonstrate that this was a valid explanation for the anomalous $(R\text{-}I)_c$ variability they observed.

The companion paper published as Taylor and Joner (1988; hereafter TJ88) was a data analysis paper to accompany JT88. Because of questions about possible stellar variation on different time scales and the overall reliability of some of the data sets that contributed to a comparison of Hyades stars, it was not possible to draw any firm conclusions about which data sets (if any) could be favored over others. However, a statistical comparison of four different data sets for the Hyades dwarfs did produce evidence of systematic error in the Hyades $(R\text{-}I)_K$ photometry of Eggen (1982) and other photometry by that author (Eggen 1972, 1978, 1983, and 1986). The situation for the observations of M67 giants was much more positive. For a comparison of eight different data sets, it was clear that benchmark values could readily be established for 13 evolved stars that were observed in at least two of the studies and agree without correction. Table II displayed a merged data set with intrinsic Cousins *(V-R)* and *(R-I)* colors for 33 evolved stars in M67 from 10 different sources. The TJ88 paper concludes with comments about the fact that careful transformations of data sets do not necessarily compromise accuracy and that the construction of catalogs using these methods could help to alleviate duplication of effort in many areas of observational astrophysics.

5.2 Other Related Publications

Two additional papers on which the current author has collaborated are directly related to making photometric observations that are both accurate and precise, and are therefore relevant to this dissertation. The first paper presents a list of standard stars in M67 that are useful for observations that have been secured with an area detector such as a CCD. The other paper is a comparison of the equatorial and E-Region standard systems that was conducted over a period of several years from observations made in the southern hemisphere. Both of these papers discuss the Cousins *VRI* system and report tests on a large number of magnitudes and colors from multiple observations with well defined instrumental systems.

There is a portion of the M67 cluster that contains a group of stars known as the "Dipper Asterism." This small area contains at least 20 isolated stars. Two of the stars are red giants and another is a bright blue straggler. The remaining stars have colors that are close to the average of the two extremes. The *V* magnitudes for the stars span a range of more than 4.5 magnitudes. This is an excellent field to use for measuring a number of stars in order to standardize observations made with a CCD detector. Joner and Taylor (1990; hereafter JT90) used many previous observations of stars in M67 in order to establish this field for use as standard stars in the Cousins *VRI* system. JT90 were able to show that new observations from Kitt Peak National Observatory could be combined with existing observations to reproduce the system that was established in TJ85 and JT88.

These new results were also compared with extant data sets to demonstrate that they could be directly compared and used to evaluate the consistency of the TJ85 and JT90 photometry. The resulting paper presented a statistically rigorous discussion of much of the existing M67 photometry and once more showed that the photometry from the Taylor and Joner collaboration was accurate and of reasonably high precision. The merged results for the 19 stars in the "Dipper Asterism" standards given in the data tables for this study all have mean error determinations for the Cousins colors that are decidedly below 10 mmag. Most of this is due to the excellent performance of the instrumental system at Kitt Peak and an average of more than seven observations per star.

It should be noted that JT90 contains an appendix with five brief example exercises that illustrate common statistical errors that are made when comparing or merging two or more sets of data. There are three more appendices that clarify the determination of accidental errors from data differences and give examples for two different methods of wild-point rejection. All of the papers that have been part of the Taylor and Joner Cousins red photometry series have been careful with the use of statistical methods to demonstrate that not only do any new observations match the established standard system, but also that any data transformed and/or merged into that system from other sources also match the standard system.

The last paper to be described and summarized as relevant to the primary dissertation papers is the work of Taylor and Joner (1996; hereafter TJ96). This paper summarizes several years of photomultiplier observations secured by this author from the southern hemisphere as a visiting astronomer at the Cerro Tololo Inter-American Observatory in Chile. The full data set contains a representative sample of *VRI* observations for primary standards from the Landolt equatorial system as well as the southern E-Region standards of Cousins. Additionally, there was deliberate observational overlap with the set of faint E-Region secondary standards that were described in Graham (1982). Originally, these comparisons were intended to be part of a project to establish a set of convenient standard stars to be used when making *VRI* observations with a CCD detector. However, it was quickly realized that another comparison between the different versions of the Cousins red photometric systems would be a valuable support to the photometric claims that Taylor and Joner had been making for the past decade in regards to the northern hemisphere cluster photometry. Thus, the comparisons made in TJ96 provided direct evidence that the selection of Landolt photometric standards and the reduction methods that had been previously used by Taylor and Joner for observations of prominent northern hemisphere star clusters were locked to the native Cousins *VRI* system.

TJ96 comment on the fact that the Cousins *VRI* system is the standard by which high precision photometry is measured, as it is typical to have rms errors quoted that are as small as 3 mmag. The early work of Taylor and Joner was all done in the northern hemisphere and was therefore dependent on the Landolt (1983) standards to anchor their observations to a well defined system. A direct comparison to the Landolt, Cousins, and Graham standards for the Taylor and Joner photometry represented a valuable consistency check for those who doubted the validity of the earlier results such as TJ85.

5.3 A Retrospective on Cluster Photometry Prior to Taylor and Joner (1985)

Star clusters are often studied because, to a first approximation, all of the stars within a cluster can be considered as objects at about the same distance from the Sun, formed out of the same material, at about the same time. If these assumptions are valid, it is readily apparent that star clusters can be considered as laboratories for the study of stellar life cycles due to the fact that stars of different mass are observed to be in a predictable range of evolutionary stages within each star cluster. This is a primary reason why stars that are members of clusters are among the most frequently observed targets in stellar astronomy. It should not be surprising that there are large numbers of photometric observations available for most of the nearby star clusters. The observed luminosities and temperatures for members of benchmark clusters such as the Hyades are used to define standard relations that are then applied to deduce the properties for more distant clusters of stars. It is common practice to make photometric comparisons between various star clusters relative to standard relations for clusters like the Hyades. The empirical relations for *uvbyβ* photometry as derived by Crawford (1975, 1978, and 1979) are excellent examples of the application of this procedure to stellar photometry.

Before moving on to the main body of this investigation, it is important to examine the state of photometry for nearby northern star clusters prior to the appearance of TJ85. It is somewhat surprising that at the time TJ85 was published there were a limited number of values of red photometry for the Hyades stars available in the astronomical literature. A similar situation existed for other interesting star clusters such as M67, Coma, Praesepe, Pleiades, and NGC 752. The existing data sets for each cluster will be reviewed in the papers that make up the body of this dissertation. By way of example, the state of existing red photometry as of 1985 for the Hyades will be reviewed in this section, but the reader should keep in mind that a similar situation prevailed for the other prominent northern star clusters.

The TJ85 results were discussed earlier in this chapter, and it is important to note at this point that the publication of TJ85 marked the first appearance of a study done in the northern hemisphere that presented results on the Cousins *VRI* photometric system for a significant group of principal cluster members. In addition, the errors reported in TJ85 were representative of work that was being done with the Cousins system in the southern hemisphere which had already raised the standards used to judge the quality of a body of photometric observations.

Photometric *UBVRI* measurements on the Johnson system of more than 1000 cluster stars are reported in the work of Mendoza (1967). A minority of these stars also have colors reported for the infrared *JKL* bands in the same paper. Mendoza (1967) notes that some of the observations reported had been previously published in connection with a long-term collaboration with H. L. Johnson. Mendoza (1967) presents *UBVRI* indices for 164 stars in the Hyades, 54 stars in Coma, and 40 stars in M67 that are important to the work presented in this investigation. It should be noted with some caution that many of the bright star measurements for stars in clusters such as the Hyades are identical to measurements that are in the data tables of often cited papers such as Johnson et al. (1966) and Johnson, MacArthur, and Mitchell (1968), and thus do not constitute sets of independent observations. Finally, Carney and Aaronson

(1979) report *UBVRIJHK* values for 10 Hyades dwarfs on the Johnson system used as calibration objects in a study to derive bolometric corrections for subdwarf stars.

Even though the rms errors for transformations to Johnson system photometry (as noted in Taylor 1986) are several times larger than for Cousins photometry, these papers are still being cited frequently in various investigations. A quick check of the Astrophysics Data System shows that in the past five years there are 93 citations of Johnson et al. (1966), 13 citations of Mendoza (1967) and 10 citations of Johnson, MacArthur, and Mitchell (1968). It should be noted in regards to the Johnson et al. (1966) catalog that just the *UBV* portion contains entries of photometry of 4777 bright stars scattered around the sky. This may explain some of the reasons for the continued citations of this source.

The data on the closely related red Kron system for the Hyades is somewhat scattered and can at times be difficult to locate. In general, a similar situation prevailed for northern hemisphere clusters prior to the first step efforts that appeared in TJ85. In regards to the Hyades, Eggen (1982) reports $(R\text{-}I)_K$ photometry for 29 selected main sequence stars out of 72 that were observed in other colors for a study of the Hyades main sequence. The remaining Kron photometry for the Hyades consists of several sets of observations made for a series of surveys to determine the Hyades membership status for stars in the cluster field. The stars that were observed during these surveys were generally drawn from a sample of lower main sequence dwarfs with uncertain membership status. The data are reported in Upgren and Weis (1977), Weis, Delucca, and Upgren (1979), Weis and Upgren (1982), Upgren, Weis, and Hanson (1985), and Weis and Hanson (1988). While these data are instrumental to understanding the membership probabilities for many of the fainter stars in the field of the Hyades, it is important to note that they add little to an understanding of the photometric properties of stars in the Hyades with spectral types earlier than the Sun.

Thus, at the time that TJ85 appeared, there were only limited data sets of red photometry available for studies of the Hyades. The publication of $(R\text{-}I)_C$ values for 41 stars in the Hyades that all have conservative accidental errors of 5.1 mmag or less was a positive first step in order to aid any future investigation requiring precise values for this demonstrably important photometric index. The JT88 data added another 16 stars to the Hyades list with precise values for $(R\text{-}I)_C$ that were secured using an instrumental system and standard stars that were a match to the Cousins system. The accidental errors in JT88 were a little larger than those in TJ85. As explained, this was likely due to the fact that fainter stars were being observed in JT88 and many of the Hyades lower main sequence stars are suspected of having enhanced starspot activity. Still, the accidental errors reported for the Hyades stars in JT88 were all less than 8.5 mmag in $(R\text{-}I)_C$ even with the inclusion of stars that exhibited variability. By contrast, JT88 report accidental errors for the M67 giants with approximately the same range of apparent magnitudes as being 3.2 mmag in $(R\text{-}I)_C$ for observations from either the West Mountain 0.61-m or Kitt Peak 1.3-m telescopes.

Although we have not given a full account of data sets for the Coma and M67 clusters at this time, an examination of the data available in 1988 shows the same lack of precise and homogeneous red data sets for these clusters as well, and thus the TJ85 and JT88 data were useful additions to the library of photometric observations and serve as a starting point for future studies requiring high-quality observations.

Chapter 6

The Motivation for the Dissertation Research

The high-quality photometry presented in TJ85 and JT88 was viewed as the primary source for Cousins *VRI* cluster photometry from the time it was published until approximately 2003. Until that time, these papers were cited once or twice a year in studies dealing with photometric calibration, the establishment of theoretical isochrones, and color-temperature relations for star clusters. Examples of such citations can be seen in VandenBerg and Bell (1985), Bell and VandenBerg (1987), VandenBerg and Poll (1989), Houdashelt, Frogel, and Cohen (1992), Montgomery, Marschall, and Janes (1993), Boyle et al. (1998), and Taylor (2000). The first sign of a problem came with a citation in VandenBerg and Clem (2003). They note agreement with TJ85 and JT88 for the Hyades *V-R* color but note an offset in *V-I* such that $\delta(V\text{-}I) \approx 0.02$ mag. An even greater concern was raised with the publication of Pinsonneault et al. (2004). Those authors included a statement that they were unable to make a transformation between the TJ85 *V-I* photometry for the Hyades and some data from older sources. They made the decision to entirely exclude the TJ85 data from their analysis. This may appear to be a minor disagreement, but when any negative comments are made about a supposed high-quality data set it is common practice in the photometric community to judge all of the measurements associated with that work to be of inferior quality. It is interesting to note that although VandenBerg and Stetson (2004) compared two sets of modern CCD photometry that were ostensibly standardized relative to the M67 standard star observations of JT90, they expressed doubt about the observational data of Sandquist (2004) that matched the Joner and Taylor standards to within a few mmag. They made a statement that "M. D. Joner and B. J. Taylor have made a concerted effort over the years to produce very accurate and precise photoelectric photometry for small samples of stars in M67 and other open clusters" before they noted that the measurements of Montgomery, Marschall, and Janes (1993) fell very close to the relations derived in VandenBerg and Clem (2003). In the view of VandenBerg and Stetson (2004), the extensive compilation of observations by Sandquist (2004) for M67 was suspect even though it was shown to be closely tied to the M67 standards of Joner and Taylor (1990). The related work by Montgomery, Marschall, and Janes (1993) was still considered in the VandenBerg and Stetson (2004) analysis even though it was evident that there were offsets between that work and the Joner and Taylor (1990) standard observations.

Two different investigations were begun in response to the doubts that had been raised about the TJ85 colors. The first new result was derived from a re-analysis of the TJ85 database augmented with subsequently measured stars in both the Hyades and Coma star clusters that had been observed as standard stars for later projects. This study was done at the suggestion of Benjamin Taylor, and the results were published as a set of catalogs in Taylor and Joner (2005). Just prior to this time, Michael Joner suggested a new study of the Hyades be done especially for the purpose of making high-quality observations that are on a stable instrumental system. The 0.5-m telescope and modular photometer at the Sutherland site in South Africa were an ideal choice for the proposed investigation since the transformation coefficients for this system are frequently checked to make sure that the standard Cousins system is reproduced. The results from this second investigation were published as the first large (77 stars) Hyades catalog of homogeneous photometry in the $BV(RI)_C$ system in Joner et al. (2006).

Chapter 7

A Catalog of Temperatures and Red Cousins Photometry for the Hyades

The first publication detailed in this dissertation is "A Catalog of Temperatures and Red Cousins Photometry for the Hyades" by Taylor and Joner (2005), as published in a 17 page paper in volume 159 of the *Astrophysical Journal Supplement Series*. This paper was written primarily as a response to the criticism leveled in Pinsonneault et al. (2004) that Cousins photometry previously published by Taylor and Joner was apparently not on the Cousins system. It is found that this is probably due to a systematic error in one of the Pinsonneault et al. sources, as well as an error in an approximate Johnson to Cousins transformation relation. The Taylor and Joner (2005) results indicate a possible difference in $(V\text{-}R)_C$ of several mmag when the Taylor and Joner results are tested, but that the Taylor and Joner $(R\text{-}I)_C$ values are supported by consistency checks at the 1 mmag level. An $(R\text{-}I)_C$ catalog is assembled for 146 Hyades stars with a spectral type earlier than K5. For the stars that are known to be single that have multiple data sources, the rms errors in the catalog entries are less than 4.4 mmag. Temperatures have been determined on the Di Benedetto (1998) angular-diameter scale for stars in the catalog. The choice to use this temperature scale was made because stars in the Di Benedetto catalog had been calibrated using accurate trigonometric parallaxes observed by the Hipparcos satellite as well as accurate angular diameters determined using modern interferometry techniques. This results in a temperature scale that is firmly established by the best available observational data for absolute calibrations of fundamental stellar parameters. The final result is a relation that is valid for both dwarfs and giants of spectral class A-F-G-K to determine individual temperatures to an estimated accuracy of ± 1%.

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A CATALOG OF TEMPERATURES AND RED COUSINS PHOTOMETRY FOR THE HYADES

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ABSTRACT

Using Hyades photometry published by Mendoza and other authors, Pinsonneault et al. have recently concluded that Cousins $V - I$ photometry published by Taylor & Joner is not on the Cousins system. Extensive tests of the Taylor-Joner photometry and other pertinent results are therefore performed in this paper. It is found that in part, the Pinsonneault et al. conclusion rests on (1) a systematic error in Mendoza's $(R - I)_J$ photometry and (2) a small error in an approximate Johnson-to-Cousins transformation published by Bessell. For the Taylor-Joner values of $(V - R)_C$, it is found that there are possible (though not definite) differences of several mmag with other results. However, the Taylor-Joner values of $(R - I)_C$ data are supported at the 1 mmag level. Using the $(R - I)_C$ data and other published results, an $(R - I)_C$ catalog is assembled for 146 Hyades stars with spectral types earlier than about K5. For single stars with multiple contributing data, the rms errors of the catalog entries are less than 4.4 mmag. Temperatures on the Di Benedetto angular-diameter scale are also given in the catalog and are used to help update published analyses of high-dispersion values of [Fe/H] for the Hyades. The best current mean Hyades value of [Fe/H] is found to be $+0.103 \pm 0.008$ dex and is essentially unchanged from its previous value. In addition to these numerical results, recommendations are made about improving attitudes and practices that are pertinent to issues like those raised by Pinsonneault et al.

Subject headings: Hertzsprung-Russell diagram — open clusters and associations: individual (Hyades) — stars: abundances — stars: fundamental parameters

1. INTRODUCTION

As of this writing, three decades have passed since the establishment of the Cousins *VRI* system (Cousins 1974). That system has displaced a farrago of other *VRI* systems (see § I of Taylor 1986 for a review) and is now in general use. The Cousins system was initially based on the GaAs photocathode, whose sensitivity is decisively higher than that of its older counterparts. Partly for that reason, the new system's standards for acceptable errors were marked improvements on previous work. For standard stars in the E regions, Cousins (1974) enforced an upper limit of about 2 mmag on right-ascension errors in color indices. Later, Cousins (1980) published extensive color-index measurements with implied rms errors of 3 mmag. That error estimate is known to be reliable for $(R - I)_C$ (see Appendix B of Taylor 1996), so it seems reasonable to assume that it is reliable for $(V - R)_C$ as well.

Users of the Cousins system face two challenges: to match (or at least approach) the precision level attained by Cousins and to make that precision meaningful by rigorously controlling systematic errors. To find out whether such error standards are essential, one need look no farther than analyses of the Hyades. For that cluster, one problem of interest is derivation of its reddening value at high precision. Taylor (1980) found that the Hyades value of $E(B - V)$ is 3 ± 2 mmag, and the usefulness of that result has since been demonstrated by its citation in some extensive studies of the Hyades HR diagram (see, e.g., Perryman et al. 1998). From a project designed to update the Taylor (1980) reddening, Taylor & Joner (2002) have obtained a preliminary value of -1 ± 2 mmag for $E(R - I)_C$. Such a result underscores the need for photometry that adheres to the Cousins error standards.

There are other profitable uses for Cousins *VRI* photometry for the Hyades. For one thing, temperatures on an angular-diameter scale may be obtained for the cluster stars. It is very likely that such temperatures are the best available for [Fe/H] analyses, since the spectroscopic temperatures used by some authors can suffer from zero-point offsets (see Tables 2 and 3 of Taylor 2003). In addition, Cousins *VRI* photometry can be used in the construction and analysis of the Hyades color-magnitude diagram. This application is of special importance because the Hyades cluster is used as a benchmark when the color-magnitude diagrams of other galactic clusters and (notably) globular clusters are analyzed (see, e.g., VandenBerg & Clem 2003).

Some time ago, we published Cousins *VRI* Hyades photometry for use in projects like those just described (Taylor & Joner 1985, hereafter TJ85; Joner & Taylor 1988). TJ85 (see its Table VI) report extensive consistency checks of the zero points of contributing data subsets. The mean rms error of the TJ85 data is 3.8 mmag, so the TJ85 errors approach the standard set by Cousins. Since the appearance of the TJ85 data, they have been used by us and also by other authors (see, e.g., Oláh & Petterson 1991 and Taylor 1994a).

However, two problems involving the TJ85 data can be found in the recent literature. VandenBerg & Clem (2003) have compared their isochrones to data for the Hyades and a number of other clusters. For the TJ85 values of $(V - R)_C$, they found that there was no disagreement. For $(V - I)_C$, however, they obtained an offset of about 20 mmag. In addition (and to our surprise), the TJ85 data have been excluded altogether from a recent compilation of Hyades $(V - I)_C$ photometry by Pinsonneault et al. (2004, hereafter PTHS). Despite the fact that the TJ85 results are the only data "native" to the Cousins system that are considered by PTHS, those authors reject the TJ85 data. They note that they could not find a good transformation of those data to the colors they calculate from other sources. As a result, they convey the impression that the TJ85 data disagree with a firmly established consensus of other results.

The rms errors quoted by PTHS for their values of $(V - I)_C$ are also of concern. For bright stars, those errors range from 11 to 16 mmag. As a result, they fall well short of satisfying the rms error standard set by Cousins.

In this first of a series of papers on cluster photometry, we focus attention on the Hyades and the issues raised by PTHS. Detailed scrutiny of the VandenBerg & Clem (2003) zero points is deferred to a subsequent paper in which M67 photometry will be presented. In the present paper, five specific tasks are performed. The first task is an assessment of the TJ85 results and is based on (1) a more extensive database than the one considered by PTHS and (2) a more careful assessment of the data than that performed by PTHS. The second task is a parallel assessment of the PTHS values of $(V-I)_C$. The third task is the compilation of a catalog containing Cousins photometry for the Hyades. Most of the rms errors for the catalog data are much closer to the Cousins standard of accidental error than the errors in the PTHS compilation. The fourth task is the use of the catalog photometry to calculate temperatures on an angular-diameter scale, with those temperatures being included in the catalog. The fifth task is the use of the catalog temperatures to update a published analysis of high-dispersion values of the Hyades metallicity (Taylor 1994c). The results of that analysis will contribute to an updated mean high-dispersion value of [Fe/H] for the Hyades.

The plan for this paper is as follows. In § 2, there is a discussion of the alleged problem with the TJ85 data. In § 3, a procedure for testing those data is described, and a review of data sources considered for those tests is given. Section 4 presents the results of the tests. In § 5, there is a discussion of procedures and data sources for compiling the catalog. In addition, further tests of data quality are discussed. The catalog itself is described in § 6, together with updated mean Hyades metallicities that result from use of the catalog data. In § 7, recommendations are given concerning photometric practice and attitudes toward photometry. Section 8 contains a concluding summary.

2. THE TJ85 DATA: A PRELIMINARY ASSESSMENT OF THE PROBLEM

Though PTHS imply that there is a serious problem with the TJ85 data, they do not say exactly what that problem is. To elucidate this issue, we subtract the TJ85 values of $(V-I)_C$ from those of PTHS and plot the resulting residuals in Figure 1. If $0.30 < (R-I)_C \leq 0.41$, open diamonds appear in the figure; otherwise, open circles are plotted.[1] This procedure is used to highlight the approximate color range in which the residuals differ from zero by the greatest amount. The mean residual for the PTHS data in that color range is -24 ± 4 mmag, and so is unacceptably large when gauged by the error standards of Cousins photometry. Another way to assess the mean residual is to convert it to a temperature offset by using the color-color relations of Cousins (1978) and the Di Benedetto (1998) temperature calibration (see Table 1 of Taylor 2003). The resulting offset is 82 ± 13 K, and especially when it is noted that this offset applies for a temperature range that includes the turnoff points of globular clusters, it is again clear that the offset is unacceptably large.

In the hope of understanding the trend in Figure 1, we begin by reviewing the provenance of the PTHS photometry. For most Hyades stars with $V < 8$ that are considered by PTHS, their adopted source of photometry is on the Johnson system. To convert such photometry to the Cousins system, PTHS apply a

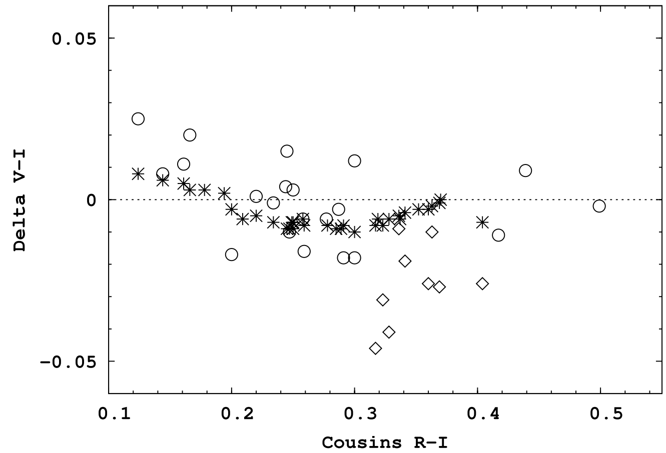

FIG. 1.—$(V-I)_C$ residuals are plotted against values of $(R-I)_C$. Open circles and open diamonds represent differences obtained by subtracting TJ85 data from PTHS data. Asterisks ($*$) depict the offset of the Bessell (1979) transformation from the Taylor (1986) transformations and are calculated by using a procedure described in the text.

transformation given by Bessell (1979) and described by that author as an approximation. Taylor (1986) has since published superseding transformations that are not approximations and that include a rigorous allowance for Paschen-jump effects (see the discussion in Appendix A). To see what role the Bessell transformation may have played in producing the problem, the Taylor transformations are applied to the TJ85 data to produce results on the Johnson system. The Bessell transformation is then applied to those results to recover data on a nominal Cousins system [designated here as $(V-I)'_C$]. Presumably, nonzero residuals of the form $R \equiv (V-I)'_C - (V-I)_C$ reflect offsets produced by the Bessell transformation. Values of R are plotted in Figure 1 as asterisks ($*$), and one notes that they follow the trend of the data residuals, but at a reduced amplitude. Our preliminary conclusion is that the Bessell transformation contributes to the problem, but that problems with photometry (see below) will also have to be considered.

3. THE TJ85 DATA: PREPARING AND PERFORMING FIRST-STAGE TESTS

3.1. *A Sketch of Basic Procedure*

Our next concern is to find out how much of the problem is produced by the TJ85 results themselves. To assess those results, a set of "test data" is assembled from the literature and from our data archives. If necessary, the test data are converted to the Cousins system by using transformations given or cited in Appendix A. Formal zero-point offsets are then obtained by comparing the test data to the TJ85 data. Often (though not always), such an offset is obtained for the entire color range of interest. Offsets may also be calculated for one or more limited color ranges. A common choice of color range is $0.30 < (R-I)_C \leq 0.41$, and stars in this range are referred to below as "solar-type stars."

Offsets with rms errors greater than 3.5 mmag are not reported unless they are of particular interest. Such an error limit is admittedly somewhat arbitrary, but is nonetheless useful because it filters out low-precision results that should contribute little or nothing to the discussion.

Linear regressions of the test data on the TJ85 data are also calculated. This is done to check for possible slope errors in the TJ85 data. To obtain the regressions, a two-error least-squares

[1] Throughout this paper, photometric results stated without units are given in magnitudes.

algorithm given in chapter 7.4.1 of Babu & Feigelson (1996) is employed. Results from the regressions are omitted if the data that would be used to obtain them are clearly sparse. A regression analysis is also omitted if slope information can instead be obtained by comparing zero-point offsets calculated from nonoverlapping color intervals.

3.2. *Archival Data on the Cousins System*

One set of test data used below has not previously been published. Those data are from extensive additional measurements in the Cousins system which we have made since the publication of TJ85. Most of the standard-star data used in those measurements have been drawn from Landolt (1983) and Taylor (1986). However, some of the standard stars have been cluster stars measured by TJ85. For those stars, mean residuals from our reductions to the Cousins system are readily available in our archives. If those residuals are added to the TJ85 data (as is done here), the results amount to an additional, independent set of measurements of the cluster standard stars. Those data are the only test data to be considered here that have been derived from instrumental Cousins systems. For that reason, applications of the new data will receive special attention below.

3.3. *Extending the TJ85 Database*

To compare the TJ85 data to as many test data as possible, one would like to expand the TJ85 database without compromising its quality. For $(R-I)_C$ specifically, this can be done in two ways. TJ85 list data for the Coma star cluster as well as for the Hyades, and we have subsequently used stars in both clusters as standard stars. Moreover, the TJ85 values of $(R-I)_C$ for the two clusters rest on results from a January observing run in which the clusters were compared directly (for more details, see Taylor 1978 and the entry for run 3 in Table I of TJ85). For this reason, new values of $(R-I)_C$ may be derived for the two clusters and then treated as a single data set with a uniform zero point. That procedure has been followed here.

A second way to extend the TJ85 database is to use a relation between $(R-I)_C$ and $B-V$. For the Hyades, a high-precision relation of this sort has been derived by using values of $B-V$ drawn solely from Johnson et al. (1962) (see § 2.2 of Taylor 1994a). Because $B-V$ and $(R-I)_C$ have different wavelength baselines, data for unresolved binaries sometimes stand away from a relation for single stars (see, e.g., Carney 1983). However, data from such binaries have been avoided by using literature sources to be listed below (see § 5.3). One of the tests of the TJ85 data to be described below turns out to be feasible only because the TJ85 database is extended by using values of $B-V$.

An essential step is this second process is derivation of an rms error for the inferred values of $(R-I)_C$. The relation applied here is

$$\sigma(R-I)_C = \sigma(B-V)/S_{BVRI}, \quad (1)$$

with S_{BVRI} being the slope of a color-color relation in which $B-V$ is the dependent variable. The value of $\sigma(B-V)$ may be inferred from the scatter around the relation if the rms errors quoted by TJ85 are used to allow for the contribution to the scatter by the TJ85 data. The inferred rms errors turn out to be 7.7 mmag for $\sigma(B-V)$ and about 3 mmag for $\sigma(R-I)_C$. The second of these errors is quite comparable to the TJ85 measurement errors.

3.4. *Excluded Data*

Some published data that might be considered for this analysis are not included. Values of $V-R$ are set aside if V and R have been measured separately. This procedure responds to the relatively low precision expected for such results. Data for Johnson et al. (1966) are not considered because their rms errors are known to exceed 20 mmag (see Taylor 1986 and references therein). In addition, values of $(V-R)_J$ from Johnson et al. (1968) and photometry from Cousins (1980) are excluded because of insufficient overlap with TJ85 data.

4. THE TJ85 DATA: RESULTS OF FIRST-STAGE TESTS

4.1. *Tests of* $(R-I)_C$

$(V-R)_C$ and $(R-I)_C$ are selected for analysis instead of $(V-I)_C$. It will be shown that analyses of these two color indices yield contrasting results. For $(R-I)_C$, five data sources turn out to be available for initial comparisons. The results of these comparisons are given in Table 1.[2]

A substantial fraction of the data used to construct Table 1 have been obtained by using standard stars from Landolt (1983). To interpret Table 1, one must therefore know whether data from that source are fully on the Cousins system. This question may be addressed by consulting Table 3 of Taylor & Joner (1996). In that table, tests of Landolt's $R-I$ data are given, with $-0.147 \leq R-I \leq 1.997$. Judging from the results of those tests, Landolt (1983) values of $R-I$ require no scale-factor correction and are on the Cousins system to within 1 mmag. It is worth noting that this conclusion follows even if measurements made by Taylor & Joner (1996) themselves are set aside.[3]

The reader will find that in Table 1 and in other tables in this paper, values of the slope S are not quoted directly. Instead, the quantity $s \equiv 100(S-1)$ and its rms error are given. This procedure is followed because the presence of a scale error in the TJ85 data is implied if $S \neq 1$. To decide whether that condition prevails while inspecting values of S, one must mentally difference each value from unity and then decide whether the size of the difference is at least 2 σ. This cumbersome process can be avoided by inspecting values of s while remembering that if $S=1$, $s=0$. To find values of S that may differ from unity, one therefore needs to do no more than find values of s that are at least twice the sizes of their rms errors. This process is especially straightforward if some rescaling is done when s is defined, as is done here.

Looking at the first line of Table 1, one finds that the new data agree well with those of TJ85. Similar agreement appears in the second through fourth lines of the table, where results from three literature sources of comparison data are considered. Note that for all four sets of test data, agreement is obtained for solar-type stars in particular. A discrepant entry does appear for the Mendoza (1967) results (see the boldface entry on the fifth line of the table). However, that problem does not tip the scales against the overall support found for the TJ85 data. This conclusion contrasts markedly with the impression conveyed by PTHS that the TJ85 data stand alone against a phalanx of concordant results.

[2] To avoid burdening the text with excessive detail, Table 1 and most other tables in this paper contain extensive footnotes. Readers are urged to consult those footnotes if they have questions about particular entries in the tables.

[3] We offer no conclusions pro or con about the later data of Landolt (1992), which play no role in this paper's analysis in any case. We also note that an $R-I$ consistency test performed by Bessell (1995) applies for a combination of Landolt's 1983 and 1992 data, and so is likewise not germane to this paper's analysis.

TABLE 1

$R - I$ Tests of TJ85 Data

Source	$100(S-1)$[a]	Overall Correction[b] (mmag)	Solar Stars Correction[b,c] (mmag)
This paper[d]	−1.1 ± 1.4	−0.7 ± 0.9	−1.7 ± 1.2
$(V-K)_J$[e]	−1.2 ± 2.0	−2.0 ± 2.3	−1.5 ± 2.9
Argue 1967[f,g]	. . .	−6.0 ± 3.5	. . .
$(R-I)_K$[g,h]	. . .	−2.4 ± 2.8	−3.1 ± 3.4
Mendoza 1967[i]	. . .	. . .	**−11.8 ± 2.9**

[a] $Y = SX + Z$, with $Y \equiv$ (data from other sources) and $X \equiv$ (TJ85 data).

[b] Corrections are given in the sense (other data) *minus* (TJ85 data).

[c] Unless otherwise stated (see note "i"), $0.30 < (R-I)_C \leq 0.41$ for "solar stars." The boldface entry differs from zero with an overall confidence limit (see Miller et al. 2001) exceeding 0.95.

[d] The quoted rms errors do not include contributions from transformations from instrumental to standard systems.

[e] Entries for this system are derived from residuals from a transformation given by Taylor 1992 (see that paper's Appendix for further information). Literature sources for $(V-K)_J$ are Koornneef (1983) and Carney (1982). Allowance for transformation error has been made by differencing mean residuals from Hyades stars and field stars.

[f] Transformed data from this source are taken from Table 7 of Taylor (1986). Only an overall correction is given for this data source because Taylor (1986) results are available for only five Hyads of interest.

[g] For the quoted offsets, the rms errors include a contribution from the zero-point error of the applied transformation.

[h] Adopted literature data are from Weis & Upgren (1982) and Upgren et al. (1985). Only stars with $(R-I)_C < 0.44$ contribute. The data are transformed using transformations (A6a) and (A6c) from Table 9 (Appendix A) of this paper. Values of $B - V$ have been transformed to $(R-I)_C$ to augment the list of data for Hyades stars. The value of $100(S-1)$ is omitted because its precision is low.

[i] For "solar stars," $0.27 < (R-I)_C < 0.42$. The quoted offset has been normalized by using data for Hyads with $(R-I)_C < 0.27$. The reason for partitioning the data in this way is made clear in Fig. 5 (see § 4.3). Only transformations (A1)–(A4) (see the text of Appendix A in this paper and Table 9) are used.

Formal corrections to the TJ85 data may be obtained from the first four sources listed in Table 1. Those corrections are depicted in Figure 2, and their mean values are given in Table 2. Note that for solar-type stars, the zero point of the TJ85 data is supported at about the 1-mmag level. For the entire color range of interest here, support is offered at the 0.7-mmag level.

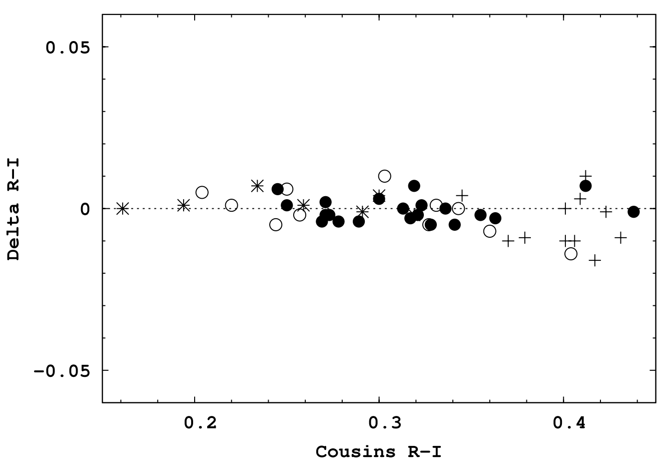

Fig. 2.—Formal $(R-I)_C$ corrections to TJ85 data are plotted against values of $(R-I)_C$. For filled circles, $\sigma < 6$ mmag, and new data contribute. For open circles, $\sigma > 6$ mmag, and new data contribute. For asterisks, $\sigma < 6$ mmag, and new data do not contribute. Pluses apply for data from Weis & Upgren (1982) and Upgren et al. (1985). Information about transformations used to derive the data is given in the footnotes to Table 1.

TABLE 2

Net Formal Corrections to TJ85 Values of $(R-I)_C$

Lower $(R-I)_C$ Limit	Upper $(R-I)_C$ Limit	Formal Correction (mmag)
0.16	0.30	+0.3 ± 1.0
0.30	0.41	−1.7 ± 1.1
0.41	0.44	+0.4 ± 2.4
0.16	0.44	−0.5 ± 0.7

Pending further testing (see § 5), we conclude that the TJ85 zero points are trustworthy.

4.2. *Tests of* $(V-R)_C$

Results for $(V-R)_C$ are summarized in Table 3. For this index, data on the Landolt (1983) system are transformed to the Cousins system when necessary by applying equation (5) of Taylor & Joner (1996). That equation applies if $(V-R)_C < 0.8$, so it covers the color range of interest in this paper.

For $(V-R)_C$, affairs turn out to be more equivocal than they are for $(R-I)_C$. Note first that when the new data are used, it appears that a nonzero value of s is found (see the italicized entry in Table 3, second column, first row of numbers). To help elucidate this problem, two sets of plotted residuals are given in Figure 3. In the upper panel of the figure, residuals for the test data and the data of Mironov et al. (1998) are plotted. The lower panel depicts residuals from two of the transformations from instrumental colors that were used to produce the TJ85 data.

Consider first the plotted points in the upper panel of the figure. Note that the point for vB 183 (*filled triangle*) is not only low, but is farther from the data centroid than the points for other stars with new data (*circles and squares*). This suggests that the data for vB 183 may be "influential" in the sense discussed in chapter 3.12 of Draper & Smith (1981), who review the problem of influential data in some detail. They note that one way to assess such a problem is to delete the suspect data and see how a derived regression relation is changed as a result. If this is done,

TABLE 3

Tests of TJ85 Values of Landolt System $V - R$

Source	$100(S-1)$[a,b]	Zero-Point Correction[b,c]
This paper:		
All stars[d]	*−7.1 ± 2.4*	−3.3 ± 1.7
No vB 183 data[d]	−6.3 ± 4.0	−2.6 ± 1.6
Mendoza 1967	*−5.1 ± 2.2*	. . .
WBVR $V - R$[e]:		
$V < 7.2$ ("blue group")	. . .	+1.5 ± 2.2
$V > 7.2$ ("red group")[b]	. . .	*+7.2 ± 2.3*

[a] $Y = SX + Z$, with $Y \equiv$ (data from other sources) and $X \equiv$ (TJ85 data).

[b] Entries in italics have false-alarm probabilities $p < 0.05$, as judged from t-tests. However, they do not differ from zero with an *overall* confidence level ≥ 0.95, as judged from false-discovery rate (see § 3 and Appendix B of Miller et al. 2001).

[c] Corrections are given in the sense (other data) *minus* (TJ85 data). Units are mmag.

[d] The rms errors quoted for these offsets do not include allowances for errors incurred by transformations from instrumental to standard systems.

[e] Data are from Mironov et al. (1998) and have been converted to $(V-R)_C$ by using transformation (A11) from Table 9 (Appendix A) of this paper. The quoted rms errors include contributions from the zero-point error of the applied transformation. No value of $100(S-1)$ is quoted because the possible color dependence of the residuals can be assessed by comparing results from the "blue group" and the "red group."

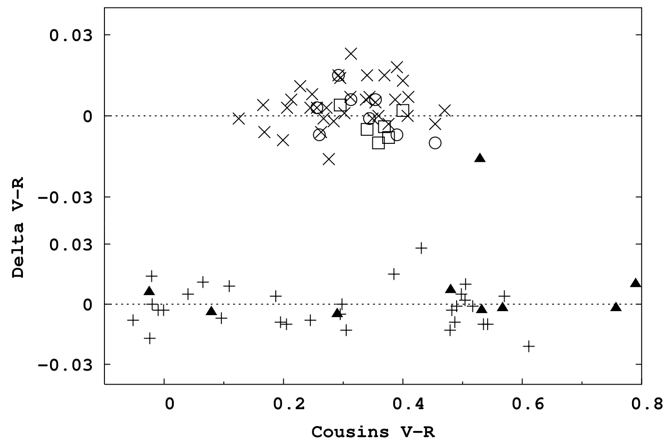

FIG. 3.—$(V-R)_C$ residuals are plotted against values of $(V-R)_C$. Circles and squares depict residuals of new data from TJ85 data, with circles being plotted if $\sigma < 6$ mmag and squares being plotted otherwise. In the upper panel, the filled triangle applies for the data for vB 183. Crosses represent residuals of transformed Mironov et al. (1998) data from TJ85 data. In the lower panel, the depicted residuals are from TJ85 transformations from instrumental to standard systems. Filled triangles and plus signs are plotted for data from observing runs of 1983 October and 1981 October, respectively (see Table I of TJ85).

it is found that the derived value of s no longer differs significantly from zero (see Table 3, second column, second row of numbers). According to Draper & Smith, this means that the original regression line—and hence the original value of s—is questionable.

Looking next at the lower panel of Figure 3, one finds that the apparent slope problem in the upper panel of the figure does not appear in the plotted transformation residuals. In particular, this is true for the instrumental transformation that yielded the TJ85 datum for vB 183 (note the filled triangles in the figure). It therefore appears that the apparent slope problem is caused by variation by vB 183 instead of problems with the instrumental transformations. It should be noted, however, that further measurements will be required for a final verdict on this hypothesis. We are currently involved in a project designed to make such measurements, with vB 183 being part of the primary target list.

Inspection of Table 3 reveals two other possible offsets. Like the vB 183 offset, they are not formally significant at 95% confidence when gauged using false-discovery rate (Miller et al. 2001). However, the appearance of three such offsets in Table 3 is nevertheless deemed to be of some concern. One of the remaining problems appears when the faint-star data of Mironov et al. (1998) are considered (see the last entry in the third column of Table 3 and the crosses plotted in the upper panel of Fig. 3). That problem underscores the need for additional measurements. The other possible discrepancy appears for the Mendoza (1967) results (see Table 3, second column, third row of numbers). Since a similar problem has already been found for the Mendoza values of $(R-I)_J$, it is worthwhile to consider the Mendoza data in more detail.

4.3. *A Close Look at the Mendoza Data*

Residuals for transformed Mendoza data are plotted in Figure 4 [for $(V-R)_C$] and Figure 5 [for $(R-I)_C$]. The transformations used to calculate those residuals are based on Johnson-system photometry from authors other than Mendoza (see the captions of Figs. 4 and 5 for further details). For values of $(R-I)_C < 0.42$ and all plotted values of $(V-R)_C$, the formally negative slopes implied by the least-squares regressions are apparent at once.

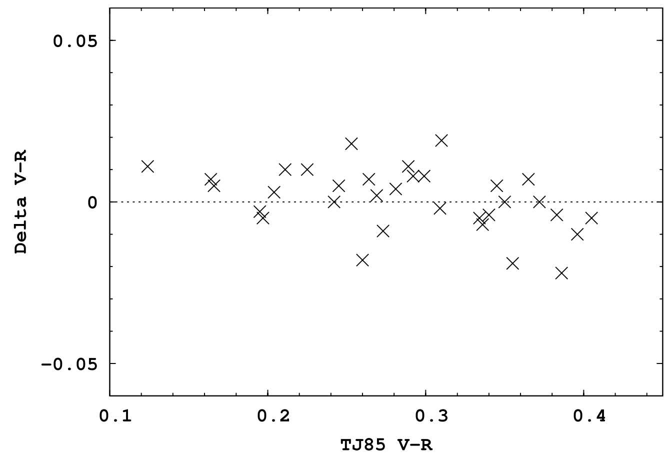

FIG. 4.—$(V-R)_C$ residuals are plotted against values of $(V-R)_C$. The residuals have been generated by subtracting TJ85 values of $(V-R)_C$ from transformed Mendoza (1967) data. Transformation (A10) (Table 9, Appendix A) has been used to transform the Mendoza data.

Recall that through most of the color range of interest, the residuals obtained for the PTHS values of $(V-I)_C$ also have a negative slope (compare Figs. 4 and 5 to Fig. 1). It is therefore natural to ask whether the Mendoza data are the principal contributors to the PTHS residuals.

To answer this question, the residuals of the PTHS $(V-I)_C$ data from the TJ85 data are first represented as a vector $\boldsymbol{P}$. In addition, a vector of residuals $\boldsymbol{P}'$ from the TJ85 data is calculated by using the Mendoza data and the Bessell (1979) transformation. If those two sources are solely responsible for the character of $\boldsymbol{P}$, the difference vector $\boldsymbol{P}'-\boldsymbol{P}$ should be zero. This hypothesis is tested by plotting $\boldsymbol{P}$ and $\boldsymbol{P}'-\boldsymbol{P}$ against $(R-I)_C$ in Figure 6. Note that while $\boldsymbol{P}$ (*plus signs*) is nonzero, $\boldsymbol{P}'-\boldsymbol{P}$ (*filled circles*) adheres closely to the zero line. The mean value of $\boldsymbol{P}'-\boldsymbol{P}$ turns out to be only -0.4 ± 0.7 mmag. It therefore appears that the Mendoza data played a significant role in the rejection of the TJ85 results by PTHS. By analyzing $\boldsymbol{P}'$, we find that about two-thirds of the departure of $\boldsymbol{P}$ from zero is caused by the Mendoza data, with the remaining one-third coming from the Bessell (1979) transformation (recall Fig. 1 and § 2).

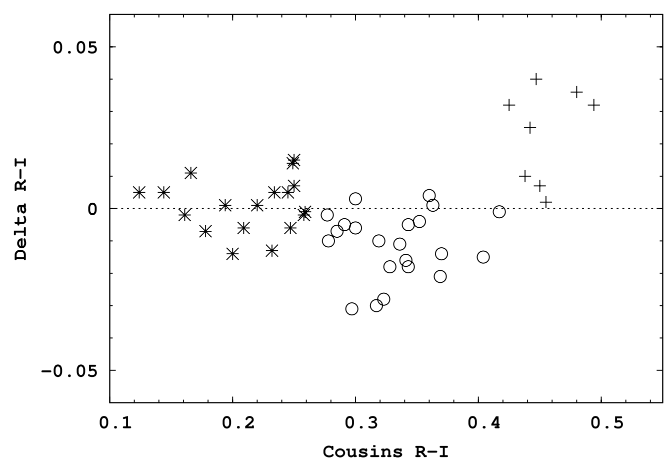

FIG. 5.—$(R-I)_C$ residuals are plotted against values of $(R-I)_C$. The residuals have been generated by subtracting TJ85 values of $(R-I)_C$ from transformed Mendoza (1967) data. Transformations (A1)–(A4) (but not [A5a]–[A5c]) in Appendix A have been applied to the Mendoza data. The residuals have been partitioned at $(R-I)_C = 0.27$ and $(R-I)_C = 0.42$, with asterisks, open circles, and plus signs representing data in the resulting three bins.

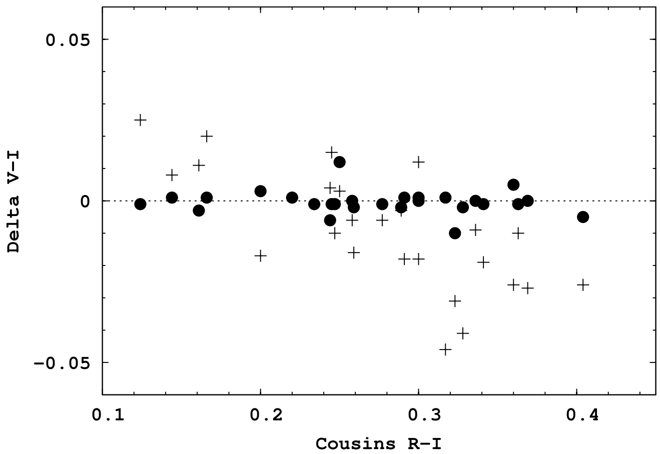

FIG. 6.—$(V-I)_C$ residuals are plotted against values of $(R-I)_C$. Pluses and filled circles are plotted for elements of $\boldsymbol{P}$ and $\boldsymbol{P}' - \boldsymbol{P}$, respectively. For the definitions of the vectors, see § 4 of the text.

An obvious follow-up question is whether the Mendoza data are in error. Given the confused situation for $(V-R)_C$, no conclusion about that color index seems warranted at present. However, an error in the Mendoza values of $(R-I)_C$ is quite firmly indicated by the preceding discussion (recall Tables 1 and 2 in particular). This conclusion will be tested further in a second-stage $(R-I)_C$ analysis to be given below.

5. THE $(R-I)_C$ CATALOG

5.1. *Compiling the Catalog*

The analysis begins with the production of an extended catalog of Hyades photometry. This step increases the number of Hyades stars with data on the TJ85 data point from 41 to 146. In addition, some of the TJ85 data are augmented to yield results with somewhat improved precision. Because of the problems with $(V-R)_C$ depicted above, the catalog is based solely on values of $(R-I)_C$.

When possible, Hyades membership is established for the catalog stars by consulting Table 2 of Perryman et al. (1998). Otherwise, Table IV of Griffin et al. (1988) is consulted. For the stars with entries in the catalog, the range in $(R-I)_C$ is from 0.01 to about 0.61. The corresponding range in spectral types is from A3 to about K5. M-star data are excluded because their rms errors all appear to be at least 7 mmag (see, e.g., Weis & Upgren 1982 and Reid 1993). By enforcing the adopted red-star limit, it is possible to restrict most of the rms errors of the catalog entries to about 4 mmag (see § 6).

Many of the data used to construct the catalog are already on the Cousins system. However, measurements on other systems also prove to be useful. As before, such data are transformed to values of $(R-I)_C$ by employing equations given or cited in Appendix A. For single Hyades stars, this procedure is feasible because Hyades single-star color-color relations have small amounts of scatter whether blanketing-sensitive color indices are used or not (see, e.g., § 2.2 of Taylor 1994a and the tables in Appendix A of Taylor 2003).

As in the case of $B-V$ and $(R-I)_C$, data for unresolved binaries may pose a problem. To identify such stars, the lists of Griffin et al. (1988), Mason et al. (1993), and Patience et al. (1998) are consulted. Possible binaries are also identified by looking for stars for which values of $(R-I)_C$ from long-wavelength photometry appear to be redder than those from short-wavelength photometry. For all stars identified as unresolved binaries, catalog entries for two different wavelength ranges are calculated (see § 6).

Mean catalog values of $(R-I)_C$ and their rms errors are calculated by using weighted averaging. The weights are obtained from the inverse squares of rms errors. In all cases, those errors have been derived from data scatter. For photometry that has been published in the Cousins system, the scatter among repeated measurements has been used to obtain the errors (see, e.g., Table V of TJ85). For photometry published in other systems, the scatter around the applied transformations has been used (see especially Taylor 2003, Appendix A, Tables A.1–A.3, and this paper, Appendix A, Table 9). In this latter case, the straightforward relation

$$\sigma^2_{\rm other} = \sigma^2_{\rm net} - \sigma^2_{\rm C}, \qquad (2)$$

is applied, with σ^2_C being the known variance of the Cousins data used to construct the transformation.

To allow fully for the effects of data scatter, two rms errors are calculated for each averaged value of $(R-I)_C$. One of those rms errors is influenced by the size of the scatter, while the other follows solely from the adopted weights (see eqs. [B11] and [B12], respectively, in Appendix B of Taylor 1991). The larger of the two errors is then adopted.

The data sources used to assemble the catalog are listed in Table 4. Since there are a number of those sources, close attention must be given to their consistency. Conceptually, that consistency may be established in two steps, with the first step concerning data on the Cousins system. Note first that the consistency of the TJ85 results with those of Argue (1967) and the new data is established by entries in Table 1 (recall § 4). The observing runs used to derive the new data are also the sources of Cousins photometry published by Joner & Taylor (1988) and Taylor et al. (1989), so it seems safe to use photometry from the latter sources as well.

Next, consider data published on systems other than the Cousins system. The applied transformations for those data are based on (1) southern-hemisphere measurements reported by Cousins (1980), and (2) the Cousins data of TJ85, Joner & Taylor (1988), and Taylor et al. (1989). The measurements in the second group of papers are based ultimately on use of standard stars from Landolt (1983). Here again, the consistency of data from that source with the Cousins system should be noted (recall § 4.1).

5.2. *Consistency of Contributing Data for Hot Stars*

At this point, it is worthwhile to acknowledge that despite the above discussion, some readers may be skeptical about our extensive use of data transformed from systems other than $(R-I)_C$. That reaction appears to be especially likely for catalog entries that are based on transformed data alone. As one step in allaying such skepticism, we therefore test data consistency for stars with $(R-I)_C < 0.21$ while noting that no data that are "native" to the Cousins system are available if $(R-I)_C < 0.12$.

1. First to be considered are values of $(R-I)_C$ derived from values of β and $b-y$. The mean difference between results from those two sources is found to be 1.0 ± 1.9 mmag.

2. Those data are then averaged and combined with TJ85 results (when available). When the interim averages are compared to transformed values of $(V-R)_W$, the mean difference is found to be 2.2 ± 2.0 mmag.

3. Finally, transformed values of $(V-R)_W$ from the *WBVR* system (Mironov et al. 1998) are included in the averages, and a

TABLE 4

Data Sources for $(R-I)_C$ Catalog

Color Indices	Note	Lower, Upper $(R-I)_C$ Limits	Data Sources
$(R-I)_C$	a	0.12–0.59	Argue (1967), TJ85, Joner & Taylor (1988), new data
$b-y$	b	0.01–0.12	Crawford & Perry (1966)
$b-y$	c	0.12–0.32	Crawford & Perry (1966)
β	...	0.06–0.12	Crawford & Perry (1966)
β	c	0.12–0.32	Crawford & Perry (1966), Taylor (1978)
α	c	0.12–0.27	Taylor (1978)
$B-V$	d	0.16–0.49	Johnson et al. (1962)
Geneva	e	0.35–0.36	Kobi & North (1990)
$(R-I)_J$	f	0.21–0.43	Mendoza (1967)
$(V-R)_W$	g	0.01–0.21	Mironov et al. (1998)
$(R-I)_E$	h	0.44–0.61	Eggen (1982)

[a] For zero-point tests of the Argue (1967) data and the new data, see Table 1.

[b] Am stars are excluded from the catalog because of possible blanketing effects on this index.

[c] The zero point adopted for the transformation equation for this index is known to be appropriate for Hyades data. Values of $(R-I)_C$ used to calculate the transformation are from TJ85. See Appendix A, Tables A1 and A3, of Taylor (2003).

[d] The transformation used for these data has been derived solely from Hyades results. Values of $(R-I)_C$ used to calculate the transformation are from TJ85. See the first entry in Table 10 (Appendix A).

[e] Temperatures have been extracted from data on this system by applying the calibration of Kobi & North (1990). For a successful test of the accuracy of that calibration, see Table 2 of Taylor (2003). For a conversion of the temperatures to values of $(R-I)_C$, see Table 1 of Taylor (2003). That conversion rests ultimately on values of $(R-I)_C$ from Cousins (1980) and TJ85.

[f] Transformations (A1)–(A4) are applied to these data to yield preliminary values of $(R-I)_C$. Those results are then corrected by applying transformations (A5a)–(A5c), which are based on values of $(R-I)_C$ from TJ85. See the text of Appendix A for transformations (A1)–(A3) and Table 9 (in Appendix A) for the other equations cited.

[g] These data are transformed to values of $(V-R)_C$ by using transformation (A11) in Table 9 (see Appendix A). The accuracy of the results is established by the entry in the next-to-last row and third column of Table 3. The data are then transformed to values of $(R-I)_C$ by using transformations (A8) and (A9) from Table 9 (see Appendix A). Those transformations are based on Cousins data from Cousins (1980).

[h] Data from this source are adopted only for Hyades stars without other values of $(R-I)_C$. The adopted transformations are transformations (A6b), (A6d), and (A6e) (see Table 9, Appendix A), which are based on Cousins data from Cousins (1980), TJ85, Joner & Taylor (1988), and Taylor et al. (1989).

net formal correction to these updated averages is inferred from 2MASS values of $V-K$. The value of the correction is found to be -1.1 ± 2.3 mmag.

In sum, it is found that four independent data sources yield results for hot stars that agree to within a few mmag. It therefore appears to be quite reasonable to trust the catalog averages for those stars.

5.3. *Further Consistency Tests: The Data of Eggen (1982)*

Because the catalog data are more extensive than those of TJ85, it is also possible to test the catalog data by performing additional data comparisons. Results of those comparisons are reported in Table 5. One notes that a second offset appears for the Mendoza (1967) results (see the boldface entry in the fourth column of Table 5). However, the most conspicuous entry in Table 5 is for the data of Eggen (1982) (note the boldface entry in the second column of the table). The problem is displayed more fully in the upper panel of Figure 7. To help assess the extent of the problem, residuals from the field-star data of Eggen (1986) are plotted in the lower panel of the figure.

The slope problem depicted in Table 5 appears clearly in the upper panel of Figure 7. To understand the problem, note that it is unlikely to be a property of the catalog data because it appears for field stars (*filled circles*) as well as Hyades stars (*open circles*). This property of the data is verified by statistical testing (see § A2 of Appendix A of this paper). Note further that the slope problem does not appear in the lower panel of the figure.[4]

[4] The slightly nonzero slope that appears in the lower panel does not turn out to be significant at 95% confidence. However, there is an offset that requires the zero point in the transformation for the Eggen (1986) data to be revised (see the Appendix in Taylor & Joner 1988 and also transformation [A6g], Table 9, Appendix A of this paper).

For this reason, it is unlikely to be an artifact of the applied transformation. The only remaining explanation is that the slope problem is a property of Eggen's results. This conclusion is of particular interest because those results made at least some contribution to the PTHS averages.

Eggen's field-star data may be used to apply a correction to his Hyades data (see transformation [A6f] in Table 9, Appendix A). When this is done, the result is encouraging agreement between Eggen's data and the catalog results (see the fourth line of numbers in Table 5). In addition to this test of accuracy, a test of precision may be made by noting that the residuals of the Eggen data from the catalog data have an rms error per datum of only 5.6 mmag. Since Eggen's data cannot be infinitely precise, this result implies that the rms errors of 3–5 mmag that are obtained for the catalog data are realistic. All told, the agreement finally obtained between the catalog data and Eggen's data (from Tables 1 and 3 of Eggen 1982 specifically) is encouraging.

5.4. *Further Consistency Tests: The 2MASS $V-K$ Results*

In addition to the Mendoza and Eggen results, 2MASS $V-K$ data that are quoted by PTHS pose a possible problem. To assess that problem, a plot of residuals is given in Figure 8. If attention is restricted to stars with $(V-K)_J < 2.1$, the plotted points are encouraging. In particular, no offset is noted at $(R-I)_C = 0.21$ (compare the plotted plus signs and open circles). For stars with $(V-K)_J > 2.1$, however, an offset does appear (compare the open circles and asterisks).

Using a transformation given by Taylor (2003), it is found that the boundary quoted just above corresponds to $(R-I)_C = 0.44$. Looking back at the upper panel of Figure 7, one then notes that at that color, there is no corresponding offset in the plotted points for the Eggen (1982) data. Since such an offset would appear if there were some difficulty with the catalog data,

TABLE 5

Tests of Catalog Values of $(R-I)_C$

Source	$100(S-1)$[a]	Overall Correction[b] (mmag)	Solar-Stars Correction[b,c] (mmag)
Carney & Aaronson (1979)[d,e]	-0.8 ± 3.2	...	...
Eggen (1979)[f,g]	$+4.4 \pm 2.7$	$+6.2 \pm 3.2$	...
Eggen (1982)[f,h]:			
Without correction	**+12.1 ± 1.3**	...	...
With field-star correction	-3.2 ± 2.3	$+0.2 \pm 2.2$	-2.7 ± 2.9
Johnson et al. (1968)[d,g]	-3.7 ± 2.3	-5.1 ± 2.6	...
Mendoza (1967)[d,i]	...	...	**−36.0 ± 5.7**
$V-K$[j]:			
$(R-I)_C < 0.44$	$+1.0 \pm 0.7$	$+1.1 \pm 1.6$	-2.9 ± 1.9
$(R-I)_C < 0.21$	...	-1.1 ± 2.3	...

[a] $Y = SX + Z$, with $Y \equiv$ (data from other sources) and $X \equiv$ (catalog data).

[b] Corrections are given in the sense (other data) *minus* (TJ85 data). Quoted rms errors include contributions from the zero-point errors of photometric transformations.

[c] Unless otherwise stated (see note "i"), $0.30 < (R-I)_C \leq 0.41$ for "solar stars."

[d] Only transformations (A1)–(A3) (see the text of Appendix A of this paper) and transformation (A4) (see Table 9 of Appendix A) have been used to transform these data.

[e] No zero-point tests are reported because of the effects of group transformation error (see § IV of TJ85).

[f] Transformations (A6b) and (A6d) (see Table 9, Appendix A of this paper) have been used to transform these data.

[g] A zero-point test for solar-type stars is not reported because its rms error exceeds 3.5 mmag.

[h] Only data from Eggen's Tables 1 and 3 are used. The comparison values of $(R-I)_C$ do not include transformed Eggen data that appear in the final catalog. The boldface entry differs from zero with an overall confidence level (see Miller et al. 2001) exceeding 0.95.

[i] For "solar stars," $0.27 < (R-I)_C < 0.42$. The quoted offset has been normalized by using data for Hyads with $(R-I)_C > 0.42$. The boldface entry differs from zero with an overall confidence level (see Miller et al. 2001) exceeding 0.95.

[j] This is the 2MASS version of $V-K$. Values of that color index are from Table 1 of Pinsonneault et al. 2004. Transformations (A13) and (A14) (see Table 9, Appendix A) and a transformation from $(V-K)_J$ to $(R-I)_C$ (see Table 10, Appendix A) have been applied to these data.

it appears that those data are not the source of the problem. A possibility worth considering instead is that a revised transformation is required at $(V-K)_J > 2.1$. For a firm decision about this possibility, further measurements will be required.

5.5. *An Overall Assessment of the Accuracy of the Catalog Data*

Returning to Table 5, we note that the catalog data (like the TJ85 data) do not stand over against a consensus of other results. Instead, if the entry for the uncorrected Eggen (1982) data is set aside, the remaining entries convey the same encouraging impression as the entries in Table 1. To quantify that impression, one may note that the most precise zero-point offsets in Table 5 are from the Eggen (1982) and 2MASS results. If those data are combined, the resulting formal zero-point correction to the catalog data is $+0.4 \pm 1.4$ mmag. We therefore conclude that the catalog zero point is trustworthy and that the PTHS rejection of the TJ85 data was caused (at least in part) by a color-dependent

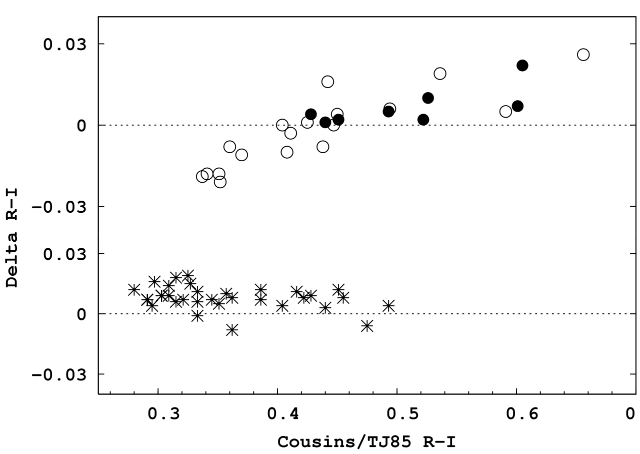

Fig. 7.—$(R-I)_C$ residuals are plotted against values of $(R-I)_C$. In the upper panel, residuals from catalog data are plotted. The residuals are for transformed data from Tables 1 and 3 of Eggen (1982), with open and filled circles representing residuals for Eggen's Hyades and field-star data, respectively. In the lower panel, residuals from Cousins (1980) results are plotted. The residuals are for transformed data from Table XVI of Eggen (1986). For residuals plotted in both panels, the transformations applied to Eggen data are transformations (A6b) and (A6d) in Table 9, Appendix A.

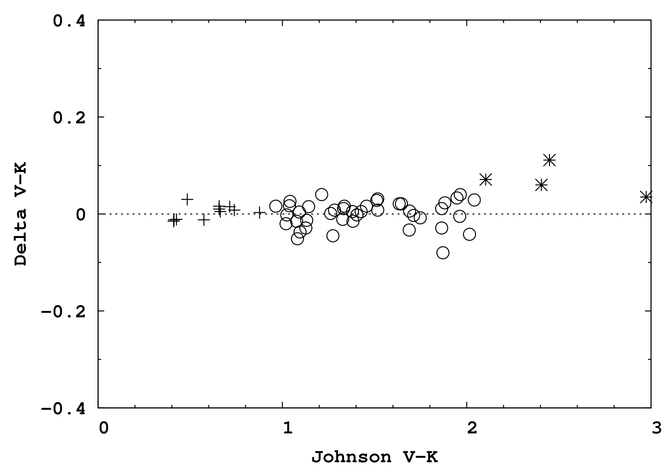

Fig. 8.—$(V-K)_J$ residuals are plotted against values of $(V-K)_J$. The data used to plot the abscissa are transformed values of $(R-I)_C$. The transformation applied here is from Table A.4 of Taylor (2003). Residuals from those data are obtained from 2MASS results (see Table 1 of PTHS). To transform those results to the Johnson system, transformations (A13) and (A14) from Table 9 (Appendix A) of this paper are applied. The data are partitioned at $(R-I)_C = 0.21$ and $(R-I)_C = 0.44$, with plus signs, open circles, and asterisks representing residuals in the resulting three bins.

term in the Mendoza data. The appearance of a second offset for those data in Table 5 reinforces the latter conclusion.

6. DESCRIPTION OF THE CATALOG

Three types of data are reported in the catalog. "Type 3" results are reported for binaries that have been identified in the ways described in § 5. All other stars (including some binaries) are regarded as "effectively single" in this context. If such stars have only one contributing datum or if $\sigma > 4.3$ mmag for their mean values of $(R - I)_C$, their entries are classifed as "type 2." Otherwise, they are classified as "type 1." The latter category also includes entries for the Hyades giants, with the source data for those stars being taken from Appendix B of Taylor (1996).

Type 1 entries are thought to be more reliable than those of type 2 because the type 1 source data permit consistency checks. In all cases without exception, such checks include inspection of the contributing values of $(R - I)_C$. If those data include a published value of $(R - I)_C$ with $\sigma \leq 4.3$ mmag, that datum alone is used. Otherwise, the contributing data are averaged (recall § 5).

Temperatures on an angular-diameter scale are also included in the catalog. The temperature scale is that of Di Benedetto (1998). When possible, values of $\theta \equiv 5040/T_{\rm eff}$ are obtained from the photometry by using a relation given in Table 1 of Taylor (2003). For stars that are too hot for that relation to apply, a relation from Table 4 of Di Benedetto (1998) is used instead. Type 3 catalog entries consist of two "color-equivalent" values of θ, with one applying at $\lambda < 5500$ Å and the other at $\lambda \sim 7000$ Å.

Entries for type 1, type 2, and type 3 data appear in Tables 6, 7, and 8, respectively (see also SIMBAD). It should be noted that a published analysis of archival values of [Fe/H] for the Hyades (Taylor 1994c) is rendered formally obsolete by the new Hyades temperatures. Using those temperatures, the updated mean value of [Fe/H] for the Hyades is found to be $\leq +0.105 \pm 0.005$ dex from the results of Paulson et al. (2003) and $+0.103 \pm 0.008$ dex from other sources, with the latter value being preferred because it is not an upper limit. Details about the updated analysis are given in Appendix B.

7. PERSPECTIVES

To understand fully the problems with the PTHS data noted above, one must relate those problems to both attitudes and practice in the photometric discipline. To do this, we begin by noting a common attitude toward "old" data. Too often, it is believed that such data are always suspect or worthless and that only "recent" or "new" results are worth considering. In photometry, this conclusion may be supported by arguing that the error limits of "old" data are not better than 10 mmag. Reasons that may be urged for such a limit include low precision of individual measurements and problems with standardization.

The salient problem with such judgments is the fact that they are not answerable to conclusions drawn from the data themselves. Though it is true that "old" results must sometimes be replaced in toto, the Hyades offer an instructive counterexample. Instead of being dominated by a single outdated database, published Hyades photometry turns out to be a patchwork of databases with diverse degrees of quality. For most of those databases, the 10-mmag limit does not exist, with this fact being underscored by the entries in Tables 1, 3, and 5. In such circumstances, the sensible procedure is to use the data in two ways displayed above: (1) in assembling a database that meets contemporary standards of quality, and (2) in consistency tests that help to establish the reliability of that database. Once those steps have been taken, new data can be secured with the aim of complementing (not replacing) such reliable results as already exist. It is worth stressing that whenever the usefulness of "old" data is underrated, the resulting alternative to programs like the one just described is needless (and likely extensive) duplication of effort. We believe that the force of this latter perception should be more widely acknowledged than it is at present.

Another issue worth noting in this context is the fact that photomultipliers have been generally displaced by CCDs in photometric practice. This change does not imply that there has been an automatic, technology-driven improvement in the quality of published photometry. As a counterweight to their improved sensitivity, CCDs require careful attention to data-preparation steps such as flat-fielding. Moreover, if a CCD is used to measure isolated standard stars, the judgment that this practice is a waste of the CCD's capabilities may result in measurement of an inadequate number of such stars. We think these are good reasons for avoiding a blanket assumption that CCD data are always superior to "old" photomultiplier results.

Of course, it is true that one can also be incautious in the use of published data by failing to apply adequate quality control to them. Here the question at issue is what must be done to ensure that quality control is in fact adequate. A partial answer to that question is furnished by the results given above for the Eggen (1982) and Mendoza data. Judging from those results, it is not adequate to test published photometry for zero-point offsets alone, as both TJ85 and PTHS have done. It seems clear that testing for color-dependent errors should be performed as well, using statistical analysis supplemented by examination of vectors of residuals. We strongly suggest that this procedure be made standard practice.

When data quality is assessed, accidental errors should receive close attention. Unfortunately, a gratuitous barrier to this perception is a widespread belief that accidental errors are inevitably the losers in a purely imaginary contest with systematic errors, with only the latter being genuinely important. One way to counter that impression is to note that while data may be corrected for systematic errors, their accidental errors are inherent properties and must be accepted as such. This point is especially pertinent if a database suitable for projects requiring high-precision photometry is to be assembled (recall § 1). In this case, one must (1) give preference to high-precision data (whether "old" or not) and (2) weight all contributing data according to their precision. Besides recommending respect for the Cousins standards of accidental error, we therefore urge that the importance of accidental errors per se be generally acknowledged.

Another issue of interest is the proper choice of Cousins photometric indices. PTHS follow a widespread practice by emphasizing $(V - I)_C$ while de-emphasizing the Cousins R passband. However, Taylor & Joner (1996) showed some time ago that it is sometimes useful to work with $(R - I)_C$ instead of $(V - I)_C$. The analysis given above reinforces this point. We therefore suggest that in the future, choices of Cousins photometric indices should be made explicitly to ensure that the indices that are most useful for each photometric project are in fact adopted for that project.

Finally, the use and credibility of color transformations should receive ongoing attention. One of two pertinent problems encountered here is a belief that transformations inevitably corrupt data quality. In fact, this is not true if properly calculated transformations are used without extrapolation. A review of ways of gauging transformations for reliability is given in Appendix A of Taylor (2003). Readers who are skeptical about transformations per se are invited to consult that discussion and

TABLE 6

$(R-I)_C$ and θ: Best Hyades Data (Type 1)

vB	Catalog	Number	Type[a]	$(R-I)_C$	σ[b]	θ[c]	σ[b]
1	Hic	15304	N	0.308	2.3	0.843	2.5
2	Hic	15310	N	0.325	2.8	0.862	3.0
4	Hic	16529	N	0.426	2.8	0.989	3.6
6	Hic	18170	N	0.200	4.3	0.733	4.2
7	Hic	18327	N	0.431	2.7	0.995	3.4
8	Hic	18658	N	0.239	2.5	0.771	2.4
10	Hic	19148	N	0.315	1.9	0.851	2.1
11	HR	1279A	N	0.220	3.3	0.752	3.2
12	HR	1279B	N	0.444	3.3	1.012	4.2
13	Hic	19504	N	0.240	2.6	0.772	2.5
14	Hic	19554	S	0.209	4.3	0.742	4.2
15	Hic	19793	N	0.336	2.2	0.873	2.4
16	Hic	19789	N	0.238	3.6	0.770	3.5
17	Hic	19781	S	0.359	3.1	0.903	3.9
18	Hic	19786	N	0.337	4.2	0.875	5.3
19	Hic	19796	N	0.276	2.3	0.809	2.5
20	Hic	19877	N	0.221	4.2	0.753	4.1
21	Hic	19934	N	0.400	3.9	0.955	5.0
23	Hic	20056	S	0.347	2.7	0.887	3.5
25	Hic	20082	N	0.455	3.7	1.026	4.7
26	Hic	20130	N	0.373	3.1	0.921	4.0
27	Hic	20146	N	0.361	2.0	0.905	2.5
28	Hic	20205	G	0.441	6.0	1.016	6.0
30	Hic	20219	N	0.160	3.1	0.703	3.6
31	Hic	20237	N	0.301	2.4	0.835	2.6
32	Hic	20255	S	0.215	2.7	0.748	2.6
33	Hic	20261	N	0.124	3.1	0.669	3.5
34	Hic	20284	S	0.258	2.5	0.789	2.4
35	Hic	20349	N	0.248	2.1	0.780	2.1
36	Hic	20350	N	0.251	2.7	0.783	2.7
37	Hic	20357	N	0.234	3.0	0.766	2.9
39	Hic	20441	S	0.351	3.4	0.892	4.4
41	Hic	20455	GS	0.435	4.0	1.012	4.0
42	Hic	20480	N	0.379	2.7	0.929	3.4
44	Hic	20491	N	0.258	3.0	0.790	2.9
46	Hic	20492	N	0.417	3.4	0.977	4.4
47	Hic	20542	N	0.082	2.8	0.628	3.1
48	Hic	20557	N	0.287	2.0	0.820	2.2
49	HD	27835	N	0.320	2.9	0.856	3.1
51	Hic	20567	N	0.250	2.9	0.782	2.8
53	Hic	20614	N	0.215	2.7	0.747	2.6
54	Hic	20635	N	0.069	2.8	0.614	3.2
55	Hic	20641	N	0.145	2.8	0.689	3.1
56	Hic	20648	N	0.011	3.7	0.546	4.7
59	HD	28034	S	0.294	2.4	0.828	2.6
60	Hic	20711	N	0.160	2.8	0.703	3.2
62	Hic	20712	N	0.292	2.4	0.826	2.6
64	Hic	20741	N	0.337	1.7	0.875	2.1
65	Hic	20815	N	0.291	3.0	0.825	3.2
66	Hic	20826	N	0.302	2.4	0.836	2.5
68	Hic	20873	N	0.194	2.6	0.727	2.7
69	Hic	20890	S	0.374	3.1	0.922	3.9
70	Hic	20889	G	0.432	4.0	1.009	4.0
71	Hic	20885	GS	0.424	4.0	1.006	4.0
72	Hic	20894	S	0.100	2.8	0.646	3.1
73	Hic	20899	N	0.320	2.8	0.856	3.0
74	Hic	20901	N	0.111	2.8	0.656	3.1
75	Hic	20916	S	0.289	2.5	0.823	2.6
76	Hic	20949	N	0.378	2.7	0.928	3.4
77	Hic	20935	S	0.279	2.4	0.812	2.6
78	Hic	20948	N	0.259	3.0	0.791	2.9
79	Hic	20951	N	0.403	3.0	0.959	3.8
80	Hic	20995	S	0.186	2.8	0.720	2.9
82	Hic	21029	N	0.085	2.8	0.631	3.1
84	Hic	21036	N	0.146	2.8	0.691	3.1
86	Hic	21066	N	0.261	2.5	0.793	2.7

TABLE 6—*Continued*

vB	Catalog	Number	Type[a]	$(R-I)_C$	σ[b]	θ[c]	σ[b]
87	Hic	21099	N	0.369	3.0	0.916	3.8
88	Hic	21112	N	0.300	3.0	0.835	3.2
89	Hic	21137	S	0.197	2.8	0.730	2.9
90	Hic	21152	N	0.239	2.7	0.771	2.6
92	HD	28805	N	0.370	3.9	0.917	5.0
93	HD	28878	N	0.424	2.7	0.986	3.4
94	Hic	21267	N	0.247	3.0	0.779	2.9
95	Hic	21273	S	0.138	2.8	0.683	3.1
97	Hic	21317	N	0.325	2.0	0.862	2.2
99	HD	29159	N	0.413	2.7	0.972	3.4
101	Hic	21474	S	0.249	3.0	0.781	2.9
104	Hic	21589	S	0.061	2.8	0.606	3.2
105	Hic	21637	N	0.311	2.7	0.846	2.9
106	Hic	21654	S	0.344	3.3	0.884	4.2
107	Hic	21670	N	0.136	2.8	0.681	3.1
108	Hic	21683	N	0.085	2.8	0.631	3.1
109	Hic	21741	N	0.400	3.9	0.955	5.0
110	Hic	21788	N	0.353	2.9	0.896	3.7
111	Hic	22044	N	0.145	2.8	0.689	3.1
113	Hic	22221	S	0.302	3.4	0.837	3.6
116	Hic	22380	N	0.401	2.7	0.957	3.4
118	Hic	22422	N	0.310	2.3	0.846	2.5
119	Hic	22496	S	0.304	3.0	0.839	3.2
123	Hic	22565	N	0.123	2.8	0.668	3.1
124	Hic	22607	S	0.276	2.5	0.809	2.7
126	Hic	22850	N	0.166	3.1	0.709	3.6
129	Hic	23497	N	0.081	2.8	0.627	3.1
142	Hic	22203	S	0.346	2.7	0.886	3.5
143	Hic	22566	N	0.289	3.0	0.823	3.3
153	Hic	13806	N	0.418	4.0	0.978	5.1
154	Hic	13834	N	0.235	3.3	0.767	3.2
174	Hic	20563	N	0.494	3.2	1.076	4.1
175	HD	285742	N	0.479	4.3	1.057	5.5
176	Hic	20679	S	0.447	2.6	1.016	3.3
179	Hic	20827	N	0.441	2.5	1.008	3.2
183	HD	28977	N	0.437	1.8	1.002	2.4
187	Hic	23498	N	0.378	3.0	0.927	3.8
311	Hic	21723	N	0.502	4.3	1.086	5.1

[a] "G" = giant; "N" = dwarf nonbinary; "S" = dwarf binary treated as single star.
[b] Values of σ are quoted in mmag.
[c] $\theta \equiv 5040/T_{\mathrm{eff}}$.

TABLE 7
$(R-I)_C$ and θ: Single-Data Hyades Stars (Type 2)

vB	Catalog	Number	Type[a]	$(R-I)_C$	σ[b]	θ[c]	σ[b]
115	Hic	22350	S	0.411	6.4	0.970	8.2
127	Hic	23069	N	0.369	4.7	0.915	6.0
140	Hic	20601	S	0.379	2.9	0.929	3.7
162	Hic	19870	S	0.358	5.7	0.902	7.3
173	Hic	20485	K	0.614	4.3	1.188	2.7
177	HD	285828	KS	0.553	4.3	1.140	4.0
180	Hic	20978	N	0.414	5.2	0.974	6.7
181	HD	285805	K	0.569	4.3	1.154	3.7
228	Hic	19098	N	0.427	2.9	0.990	3.7
229	Hic	19263	N	0.468	5.6	1.042	7.1
253	Hic	20086	K	0.591	5.2	1.172	3.9
271	Hic	20751	S	0.480	3.0	1.058	3.8
319	HD	29896	S	0.469	3.0	1.043	3.8
324	HD	284785	N	0.492	3.1	1.073	3.9
328	Hic	22224	S	0.457	2.9	1.029	3.7
−	Hic	19098	N	0.427	2.9	0.990	3.7

[a] "K" = late K dwarf; "N" = dwarf nonbinary; "S" = dwarf binary treated as single star.
[b] Values of σ are quoted in mmag.
[c] $\theta \equiv 5040/T_{\mathrm{eff}}$.

TABLE 8
VALUES OF θ FOR HYADES BINARIES (TYPE 3)

vB	Catalog	Number	Type[a]	θ_S[b]	σ[c]	θ_L[b]	σ[c]
5	Hic	16908	B	1.005	3.7	1.023	9.9
22	Hic	20019	B	0.933	3.7	0.965	5.5
29	Hic	20215	B	0.836	2.6	0.846	10.3
40	Hic	20440	B	0.837	2.6	0.881	5.6
43	Hic	20482	B	1.000	3.7	1.050	9.9
50	Hic	20553	B	0.858	3.9	0.882	3.6
52	Hic	20577	B	0.859	4.2	0.882	3.8
57	Hic	20661	B	0.805	2.7	0.792	10.3
58	Hic	20686	B	0.890	3.7	0.894	4.4
63	Hic	20719	B	0.867	3.2	0.894	5.0
81	Hic	21008	B	0.796	2.7	0.809	2.8
85	Hic	21053	B	0.775	3.1	0.782	5.2
91	HD	28783	B	0.985	3.7	1.019	6.1
96	Hic	21280	B	0.967	3.6	0.982	6.1
100	Hic	21459	B	0.750	3.1	0.761	5.2
102	Hic	21543	B	0.856	2.6	0.873	8.3
114	Hic	22265	B	0.910	3.7	0.912	9.9
120	Hic	22505	B	0.919	3.7	0.902	9.9
121	Hic	22524	B	0.811	2.7	0.813	10.3
122	Hic	22550	B	0.832	4.0	0.845	7.8
128	Hic	23214	B	0.786	2.6	0.831	3.4
151	Hic	23701	B	1.019	3.7	1.063	9.9
178	Hic	20850	B	0.967	3.6	0.987	6.1
182	HD	28545	B	0.967	3.6	1.009	4.6
285	Hic	21123	B	1.029	3.7	1.066	8.3
	Hic	19263	B	1.038	3.8	1.057	5.5

[a] "B" = a combined-light dwarf binary.
[b] $\theta \equiv 5040/T_{\rm eff}$. "S": use at $\lambda < 5500$ Å; "L": use at $\lambda \sim 7000$ Å.
[c] Value of σ are quoted in mmag.

then to review again the successful use made above of transformations that satisfy Taylor's criteria.

A second problem is that some users of photometry recognize only Bessell's transformations as the photometric discipline's standard (see, e.g., PTHS and Alonso et al. 1996). A prominent difficulty with this judgment (though not the only one) is that Bessell's transformations do not include a rigorous allowance for the effect of the Paschen jump on relations between Johnson and Cousins colors (recall § 2, and see also note 6 of Taylor 2003). We urge readers who accept only the Bessell transformations to consult Taylor (1986) and Appendix A of this paper. Taylor (1986) addresses the Paschen-jump difficulty and some other issues raised by Bessell's work (Bessell 1979, 1983).

8. SUMMARY

When differences between PTHS and TJ85 values of $(V-I)_{\rm C}$ are plotted against color, an approximately parabolic relation emerges. To see whether this problem is caused by the TJ85 data, those data are tested by using both new and previously published results. For $(R-I)_{\rm C}$, no zero-point errors are found at about the 1-mmag level. This result holds for the complete color range of interest and also for stars with $0.30 < (R-I)_{\rm C} \leq 0.41$, where the difference between the PTHS and TJ85 data is greatest.

When the TJ85 values of $(V-R)_{\rm C}$ are compared to other results, some possible differences are found. One of those differences is between the new data and the TJ85 results. However, it appears that variation of a cool star (vB 183) is the cause of the problem. Further measurements will be required to test this hypothesis and to clarify the status of the other possible data differences.

The tests yield firm evidence for color-dependent errors in (1) Mendoza's Hyades values of $(R-I)_{\rm J}$ and (2) the data in Tables 1 and 3 of Eggen (1982). A fair conclusion is that the first of these errors causes part of the difference between the PTHS and TJ85 data. In addition, part of that difference may be attributed to a small slope error in the approximate Bessell (1979) transformation between $(V-I)_{\rm J}$ and $(V-R)_{\rm C}$. Conclusions about the remaining difference must await the additional $(V-R)_{\rm C}$ measurements.

Using the TJ85 data plus new and transformed results, a photometric catalog is assembled for 146 Hyades stars. For stars other than unresolved binaries that do not have single-star colors, the catalog contains values of $(R-I)_{\rm C}$. Tests of these data that parallel the tests of the TJ85 data are made, and the results are found to be satisfactory at about the 1.5-mmag level. Besides photometry, the catalog contains values of $\theta \equiv 5040/T_{\rm eff}$, with $T_{\rm eff}$ being on the angular-diameter scale of Di Benedetto (1998). Using the catalog entries, it is found that for the Hyades, the current best mean high-dispersion value of [Fe/H] is $+0.103 \pm 0.008$ dex.

The problems with the PTHS data are put in perspective by reviewing pertinent attitudes and practice in the photometric discipline. Recommendations are made concerning (1) the use and testing of published data, (2) the use and significance of accidental errors, (3) choosing appropriate Cousins photometric indices, and (4) the use and credibility of color transformations.

In the research reported in this paper, extensive use has been made of the SIMBAD database (operated at CDS, Strasbourg, France) and the Lausanne photometric database (Mermilliod et al. 1997). We thank Lisa Joner for carefully proofreading this paper and Ben Rose for producing the figures. Page charges for the paper have been generously underwritten by the College of Physical and Mathematical Sciences and the Physics and Astronomy Department of Brigham Young University.

APPENDIX A

TRANSFORMATIONS

In this Appendix, literature citations are given for some of the transformations used in this paper. The remaining transformations are stated. For the Johnson system, the nature of a "first-stage" $R - I$ transformation is described, and the accuracy of that transformation and its $V - R$ counterpart is assessed. For transformations of $(R - I)_{\rm K}$, a detailed review of the derivation process is given.

A1. THE JOHNSON *VRI* SYSTEM

If Johnson *VRI* photometry is to be transformed accurately to the Cousins system, an adequate allowance must be made for the effects of the Paschen jump. This is the principal issue of concern if M stars are not considered (as is the case in this paper). As of 1985, the Paschen jump had been approached by using line-segment approximations and plotted correction curves (Bessell 1979, 1983). However, neither approach yielded the multivalued transformations required by the variation of the Paschen jump with luminosity class (Bessell 1983). Using a device introduced by Gutiérrez-Moreno (1975), Taylor (1986) approached this problem by using the photometrically accessible Balmer jump as a proxy for the Paschen jump. Taylor defines a Balmer-jump parameter in the following way:

$$\delta_{BJ}(U - B) \equiv (U - B)_0 - 1.378(B - V)_0 + 0.709, \quad \text{(A1)}$$

with the subscript "0" designating indices corrected to zero reddening.

Instead of transforming $V - I$ directly, Taylor (1986) found it preferable to transform $V - R$ and $R - I$ separately and then add the results if values of $V - I$ are desired. $\delta_{BJ}(U - B)$ appears in a number of Taylor's $(R - I)_{\rm J}$ transformations (see the first page of Table 4 of Taylor 1986). One of those transformations is used here:

$$(R - I)_{\rm C} = 0.762(R - I)_{\rm J} - 0.073\delta_{BJ}(U - B) + 0.074. \quad \text{(A2)}$$

This version of the equation omits a right-ascension term that is zero for the Hyades. For dwarfs, the equation applies over the following color range:

$$0.096\delta_{BJ}(U - B) + 0.005 \leq (R - I)_{\rm J} \leq 0.397. \quad \text{(A3)}$$

Equations (A1)–(A3) make up one of the Johnson *VRI* transformations used here. Further information about this transformation (including its data sources) is given in the notes to Table 4 of Taylor (1986). Five other transformations for Johnson *VRI* data are given in Table 9 (see the first four lines of that table and its transformation [A10]). Two of those transformations, like equations (A1)–(A3), may be described as first-stage transformations. The other three are supplementary relations that are to be applied to Mendoza (1967) values of $R - I$ after the first-stage transformations have been used (see transformations [A5a]–[A5c]). The documentation of all five transformations (and the others listed in Table 9) is explained below.

For the first-stage transformations, residuals are plotted in Figure 9. That figure should be consulted to gauge the color limits of the transformations and the color distribution of the data used to derive them.

A2. THE KRON SYSTEM

To transform Kron photometry to the Cousins system, PTHS employ a relation given by Bessell & Weis (1987). At $(R - I)_{\rm C} < 0.35$, the Bessell-Weis relations that were presumably used by PTHS are defined by only five scattered data pairs (M. S. Bessell 2005, private communication). In addition, it is possible that there are differences between transformed Kron photometry from Weis and coauthors and from Eggen. Especially for the color range noted above, Bessell & Weis do not rule out the possibility that such differences exist at about the 10-mmag level.

An alternative set of transformations for $(R - I)_{\rm K}$ was given by Taylor (1986) and is employed in this paper. Supplementary transformations for Eggen data are given in Table 9, with one of those relations being used in § 5.3. Because some questions have been raised about the derivation of those relations, a step-by-step review of their derivation and testing is given here.

Data sources.—To strengthen the derivation, data from Eggen and from Kron and his collaborators are considered together when possible. Sources for both kinds of data are given in the footnotes to Table 9 and in similar notes following Table 4 of Taylor (1986).

Order of adopted polynomial.—Bessell (1986) has pointed out that a cubic transformation is to be expected in this problem. As variable-star observers are aware, however, there can be little to choose in practice between polynomial fits (such as cubics) and piecewise linear regressions. The latter are chosen here because they offer definite tactical advantages, as will become apparent at once.

Use of a two-error least-squares algorithm.—Because we are seeking linear fits, it is possible to apply a least-squares algorithm given in § 7.4.1 of Babu & Feigelson (1996). That algorithm applies in the so-called "two-error" case, with the rms errors of both the

TABLE 9

Transformation Equations of the Form $Y = SX + Z$

Number	Y (mag)	X (mag)	S	Z	Centroid σ (mmag)	σ(other)[a] (mmag)	X Limits (mag)
(A4)[b]	$(R-I)_C$	$(R-I)_J$	0.978 ± 0.006	−0.012 ± 0.007	2.8	17	+0.397, 2.06
(A5a)[c]	$(R-I)_C$	$(R-I)_{CM}$	1.000	0.000 ± 0.002	2.0	7.2	+0.13, 0.26
(A5b)[c]	$(R-I)_C$	$(R-I)_{CM}$	1.276	0.072	–	–	+0.26, 0.30
(A5c)[c]	$(R-I)_C$	$(R-I)_{CM}$	1.000	0.011 ± 0.003	2.6	9.7	+0.30, 0.42
(A6a)[d]	$(R-I)_C$	$(R-I)_K$	1.040 ± 0.008	0.110 ± 0.002	1.8	15	−0.28, 0.395
(A6b)[d]	$(R-I)_C$	$(R-I)_E$	1.040 ± 0.008	0.115 ± 0.002	2.2	>4.3	−0.19, 0.42
(A6c)[d]	$(R-I)_C$	$(R-I)_K$	1.250 ± 0.006	0.027 ± 0.005	1.9	22	+0.395, 1.224
(A6d)[d]	$(R-I)_C$	$(R-I)_E$	1.250 ± 0.006	0.027 ± 0.005	1.9	11	+0.42, 1.224
(A6e)[e]	$(R-I)_C$	$(R-I)_{CE}$	0.894 ± 0.010	0.048 ± 0.005	1.1	4.3	+0.33, 0.78
(A6f)[f]	$(R-I)_C$	$(R-I)_{CE}$	0.913 ± 0.017	0.038 ± 0.009	1.8	4.3	+0.33, 0.78
(A6g)[g]	$(R-I)_C$	$(R-I)_E$	1.040 ± 0.008	0.107 ± 0.001	1.5	4.9	+0.17, 0.37
(A7)[h, i]	$(R-I)_C$	$b-y$	1.021 ± 0.037	−0.003 ± 0.002	1.7	6.7	−0.04, 0.137
(A8)[h]	$(R-I)_C$	$(V-R)_C$	1.000	0.000 ± 0.001	1.3	3	+0.06, 0.14
(A9)[h]	$(R-I)_C$	$(V-R)_C$	0.907 ± 0.042	0.013	2.0	3	+0.14, 0.206
(A10)[d]	$(V-R)_C$	$(V-R)_J$	0.717 ± 0.002	−0.030 ± 0.002	0.7	24	+0.025, 0.619
(A11)[h, j, k]	$(V-R)_C$	$(V-R)_W$	0.713 ± 0.003	−0.004 ± 0.002	0.9	10	0.00, 1.22
(A12)[h, j, l]	$(V-R)_C$	$(V-R)_W$	0.713 ± 0.002	−0.005 ± 0.001	0.6	12	0.00, 1.28
(A13)[m]	$(V-K)_2$	$(V-K)_J$	0.991 ± 0.005	0.047 ± 0.006	–	–	. . ., 1.018
(A14)[m]	$(V-K)_2$	$(V-K)_J$	0.989 ± 0.005	0.049 ± 0.006	–	–	1.018, . . .

[a] For transformations (A8) and (A9), σ(other) applies to both $(V-R)_C$ and $(R-I)_C$. When quoted for other relations, σ(other) applies to the color index that is not on the Cousins system.

[b] From Table 4 (p. 582) of Taylor (1986).

[c] "$(R-I)_{CM}$" designates Mendoza (1967) Hyades data after transformations (A2) and/or (A4) have been applied. Values of $(R-I)_C$ used to derive the transformations are from TJ85.

[d] From Table 4 (p. 583) of Taylor (1986). For hotter stars, the sources for Eggen data are Eggen (1978) and Tables 6 and 18 of Eggen (1982). Other data sources are those given by Taylor (1986).

[e] "CE" designates data from Tables 1 and 3 (Eggen 1982) after transformations (A6b) and/or (A6d) have been applied. Required values of $(R-I)_C$ are from sources listed by Mermilliod et al. (1997).

[f] "CE" designates field-star data (Table 3, Eggen 1982) after transformations (A6b) and/or (A6d) have been applied. Required values of $(R-I)_C$ are from sources listed by Mermilliod et al. 1997.

[g] This relation applies for Eggen data published after 1982. See Taylor (2003), Appendix A, Table A.4.

[h] Values of $(R-I)_C$ used to derive this transformation are from Cousins (1980) measurements of field stars with luminosity classes II–V.

[i] Values of $b-y$ are from Crawford & Barnes (1970). For a complementary relation for redder stars, see Taylor (2003), Appendix A, Tables A.1–A.3.

[j] This transformation is based on Kornilov et al. (1991) data for field stars with luminosity classes II–V.

[k] The right ascension range used to derive this relation is from 0 to 8 hr (epoch 2000).

[l] The right ascension range used to derive this relation is from 0 to 24 hr (epoch 2000).

[m] "$(V-K)_2$" is the 2MASS version of $V-K$. This transformation has been derived by using a relation from Carpenter (2001) and data from Koornneef (1983).

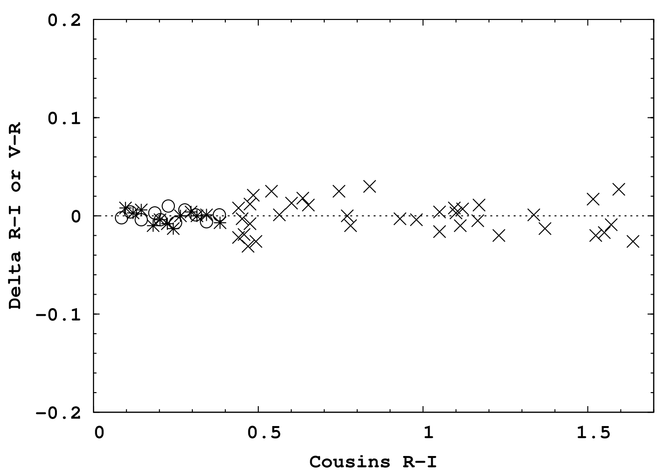

Fig. 9.—Transformation residuals for $(V-R)_C$ and $(R-I)_C$ are plotted against values of $(R-I)_C$. Asterisks represent binned residuals from eqs. (A1)–(A3). Crosses represent residuals from transformation (A4), while circles represent residuals from transformation (A10) (see Table 9).

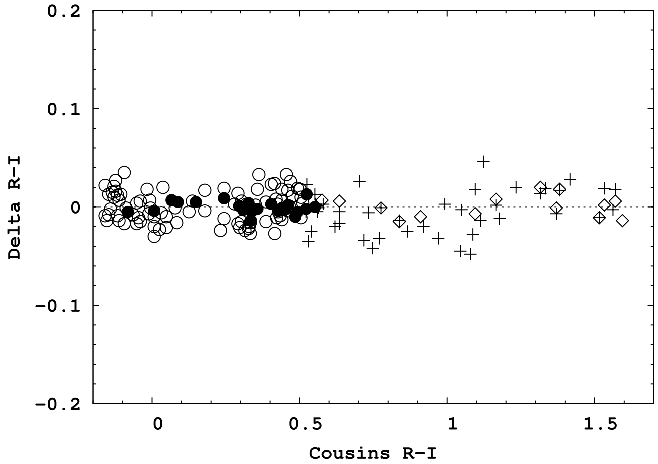

FIG. 10.—Transformation residuals for $(R-I)_C$ are plotted against values of $(R-I)_C$. Filled circles and open diamonds apply for Kron photometry from Eggen's papers and are from transformations (A6b) and (A6d) of Table 9. Open circles and plus signs apply for Kron data from sources other than Eggen and are from transformations (A6a) and (A6c) of Table 9. For the sutures between hot-star and cool-star relations, the values of $(R-I)_C$ are 0.52 for Kron data and 0.55 for Eggen data.

dependent and independent variables being nonzero. It is worth noting that many least-squares codes apply only to the "one-error" case, in which the rms errors of the independent variable are assumed to be zero. That approximation can be adequate if the errors for the dependent variable are much larger than those for the independent variable, and it has in fact been used to derive the relations for the Johnson system discussed above. For Cousins and Kron photometry, however, rms errors can be comparable, so two-error analysis is required.

Standard deviations for coefficients.—The adopted algorithm yields rms errors for calculated regression coefficients. Such errors are required if the coefficients are to be tested statistically, as is done below.

Statistical testing and conventions.—Primary statistical testing is carried out by using three varieties of the Student's t-test. To evaluate possible wild points, the Thompson (1935) version is used (see § 6.2 of Taylor 2000). Straightforward t-testing is applied to decide whether coefficients are decisively nonzero, while unequal-variance t-testing is used when data are to be compared to each other (see the notes to Table 3 of Taylor 1992 for a worked example of unequal-variance testing). False-discovery rate (Miller et al. 2001) is used to evaluate the results of the testing. If those results are positive, they are reported here with values of p, with $p \equiv 1 - C$ and C being the derived confidence level.

Use of plotted residuals.—The rule of procedure applied here is that plotted residuals may be used to infer null conclusions, but not positive results. If the latter are suspected, they are accepted only if they are confirmed by statistical testing. This rule is based on experience with tests of conclusions drawn from plotted data (e.g., see § 6.1 and Appendix A of Taylor 2001).

First-stage analysis: results for hotter stars.—For separate regressions of Kron and Eggen data on Cousins results, slopes are obtained that do not differ at 95% confidence. The Kron relation is therefore retained, and Eggen data are used to obtain an offset from that relation. The statistical significance of the offset turns out to be marginal ($p = 0.03$). For safety's sake, however, the offset is used to obtain a relation for Eggen data whose slope is identical to that for Kron data, but whose intercept is slightly different. One contributing data pair (for HR 875) is rejected by using the Thompson test.

First-stage analysis: results for cooler stars.—Here the coefficients of separate relations for Kron and Eggen data do not turn out to differ at 95% confidence.[5] Moreover, in this case (unlike that for hotter stars), the slope of the Kron relation is not deemed to be sufficiently precise to stand by itself. Accordingly, inverse-variance weighting is used to obtain averaged coefficients from the two relations. As expected from Bessell's results, the slope of the averaged relation differs from the slope of the relation for hotter stars at the 20 σ level ($p < 10^{-6}$).

First-stage analysis: critiquing a plot of residuals.—This plot is given in Figure 10. When the plot is inspected, it is found that the $(R-I)_C$ region in which a departure from the zero line is most likely extends from about 0.80 to about 0.98. However, the mean residual in that region is not significant at 95% confidence ($p > 0.2$). No apparent departures in other regions are larger, so we conclude that the plot is adequately linear. In addition, we inspect the data at sutures between the relations for hotter and cooler stars. For data from Kron and collaborators, the suture is at $(R-I)_C = 0.52$; for Eggen data, the suture is at $(R-I)_C = 0.55$. No signs of an offset appear at these sutures. Judging from these null results, the first-stage relations are satisfactory.

Second-stage analysis: calculations.—As Figure 7 shows, there is reason to suspect that after a first-stage transformation is applied to the Eggen (1982) Hyades data, a further correction is required. To evaluate that possibility, separate regressions are obtained for Hyades stars (Eggen's Table 1) and field stars (Eggen's Table 3). For the Hyades relation, the slope turns out to differ from unity with $p < 10^{-6}$. Despite the fact that data from only eight field stars are available, it is found that the slope for those stars also differs from unity, with $p = 0.002$. Neither the slopes nor the intercepts for the two relations are found to differ at 95% confidence. The combined data are therefore used to obtain an overall relation for both field stars and Hyades stars.

[5] We have been informed that Eggen used a different instrumental setup from Kron and his collaborators. However, it is worth stressing that that fact is irrelevant in this context. What counts is that statistically indistinguishable coefficients are in fact obtained from the two data sources.

TABLE 10

Literature Sources for Other Transformations

Color Index	Color Index	Paper	Location
$B-V$	$(R-I)_C$	Taylor (2003)	Table A4
β	$(R-I)_C$	Taylor (2003)	Tables A1, A3
α	$(R-I)_C$	Taylor (2003)	Tables A1, A3
$b-y$	$(R-I)_C$	Taylor (2003)	Tables A1, A3
$(V-K)_J$	$(R-I)_C$	Taylor (2003)	Table A4
β	$b-y$	Crawford (1979)	§ II
$(V-R)_L$ [a]	$(V-R)_C$	Taylor & Joner (1996)	§ 6

[a] This is the Landolt (1983) version of $(V-R)_C$.

Second-stage analysis: evaluating residuals.—When the Hyades residuals from the overall relation are examined, the Eggen datum for vB 40 (the bluest star considered) appears to be excessively negative. The Thompson *t*-test confirms this impression, with the value of p from false-discovery rate being 0.011. After deletion of the data for vB 40, a plot of the remaining residuals suggests that for the four remaining hottest stars, residuals are also excessively negative (see Fig. 7). However, if the net offset for those residuals is evaluated, it is found to be significant at only the 1.7 σ level, with the resulting value of p being 0.1. This result is not strong enough to reject a null hypothesis stating that Eggen's data for blue stars are offset only if $(R-I)_C < 0.3$. As a result, the data for the four remaining bluest stars are retained.

Presenting the results in tabular form.—The relations derived from the analysis are given in Table 9, which is intended to serve as an example of what we regard as adequate documentation of transformations. Note first that for Kron-system transformations, coefficients are given with rms errors. This practice is followed for most coefficients given in the table, though exceptions are made for assumed slopes of unity and for coefficients that are adopted to enforce piecewise continuity between neighboring relations. If the source data for a given relation are fully available for analysis and the relation is not based solely on adopted coefficients, values are also given for the rms error of the centroid of the relation (σ_c) and for the rms error of the non-Cousins source data being considered (σ_s). The second of these rms errors is obtained by calculating the net scatter around the relation while allowing for a known contribution from Cousins data (for the latter, see Appendix B of Taylor 1996; for the applied equation, see eq. [2] of the text). Note that the net rms error $\sigma_{\rm net}$ for a transformed datum is given by the following equation:

$$\sigma_{\rm net}^2 = S^2\sigma_s^2 + \sigma_c^2.$$

In particular, this equation may be used with the Johnson-system transformation given above, with $S = 0.762$ and σ_c being set to 0.002 to allow for contributions from both the centroid error and from rms errors in *UBV* photometry.

Further assessment of the results.—Table 9 also contains color limits for the listed transformations (when available). For the Kron-system transformations, the pertinence of those limits may be assessed by looking again at Figure 10. That figure shows that the data used to derive the transformations are reasonably well distributed throughout the color range considered.

Kron-system transformations given in Table 9.—These transformations appear in lines 5 through 11 of the table. They do not include a relation for Hyades stars alone, but they do include the relation for field stars alone because that relation is used in § 5.3. The last of the listed transformations is not used in this paper, but is given for the sake of completeness, and is from Appendix A (Table A4) of Taylor (2003). The analysis used to derive that transformation is described in the Appendix of Taylor & Joner (1988).

Upgrading standards of analysis.—We draw attention again to the issue of one-error and two-error analysis. When photometric transformations are derived in the future, two-error analysis should be applied when necessary, and the adopted analysis mode (one-error or two-error) should be stated explicitly. In addition, publication of rms errors with least-squares coefficients should be mandatory. In part, this practice may be caused by use of least-squares programs that do not report the required errors. We suggest that the use of such programs be avoided.

A3. ADDITIONAL TRANSFORMATIONS

In addition to transformations for the Johnson *VRI* and Kron $R-I$ systems, Table 9 contains new transformations that are given as transformations (A7)–(A9) and (A11)–(A14). Those transformations have been obtained from the two-error least-squares algorithm cited above. Some transformations used in this paper have been published previously and are not used to transform either Johnson *VRI* photometry or values of $(R-I)_K$. Literature sources for those transformations are given in Table 10. We note that unless there is good reason to conclude that the transformations cited in Table 10 apply generally, they apply specifically for the Hyades.

APPENDIX B

MEAN HYADES VALUES OF [Fe/H]

Revised mean Hyades metallicities are given here for results from three papers. Analyses by Paulson et al. (2003) are considered because their spectroscopic temperatures are not on the Di Benedetto (1998) scale (see Fig. 11). In addition, data reviews

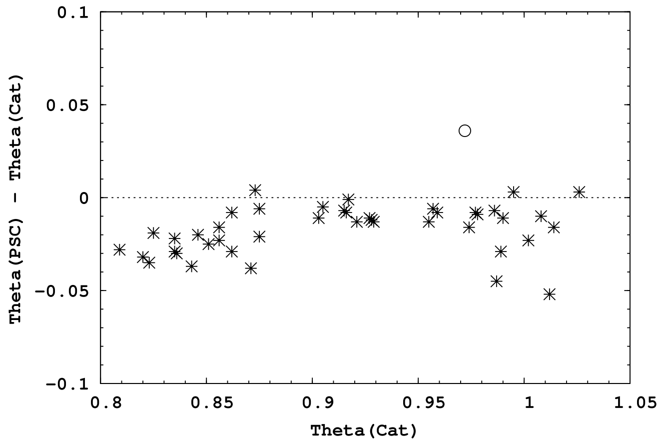

FIG. 11.—Residuals in $\theta \equiv 5040/T_{\rm eff}$ are plotted against values of θ on the Di Benedetto (1998) scale. The residuals are formed by subtracting catalog values of θ from Paulson et al. (2003) values of θ. The open circle applies for vB 99, and the asterisks apply for data from other Hyades stars.

by Taylor (1994c) and Taylor (1998) are updated. Before averaging, the data given by Paulson et al. and adopted by Taylor (1994c) have been corrected to the temperature scale used in this paper. Pertinent mean values of [Fe/H] are summarized in Table 11.

It has been suggested that the Hyades metallicity is formally higher than the corrected and adjusted means quoted in Table 11 (Grenon 2002). Mean Hyades values of [Fe/H] that are formally $\geq$0.13 dex have appeared in the literature for some years. One of those means (from Perryman et al. 1998) is based on a fallacious inference from available high-dispersion results (see Appendix B of Taylor 2000). Another (given by Gratton 2000) includes an assumed error bar and is based on literature sources that do not appear to be fully specified. There is some uncertainty about two other published means, however, because they are based on lists of metallicities for individual stars that have not (yet) appeared in print (see Boesgaard et al. 2002 and Yong et al. 2004). The second of those means is of particular interest because it is from an updated version of Paulson et al. (2003). Though the weight of evidence behind the mean metallicities given in Table 11 is now very strong, it must also be acknowledged that further reviews of the Hyades metallicity will be required as additional information becomes available.

TABLE 11
UPDATED HYADES MEAN METALLICITIES

Entry Number	Source	[Fe/H] (dex)
1.................................	Paulson et al. (2003):	
	Uncorrected	0.132 ± 0.007[a]
	Corrected	≤0.105 ± 0.005[b]
2.................................	Giants:	
	Taylor (1998) analysis	0.102 ± 0.023[c]
	Updated	0.108 ± 0.022[d]
3.................................	Dwarfs:	
	Taylor (1994b) analysis	0.107 ± 0.010
	Updated	0.102 ± 0.009[e]
4.................................	Updated overall mean	0.103 ± 0.008[f]

[a] The datum for Hic 10672 has been excluded by using a Thompson t-test. Data for vB 1 and vB 2 are retained because they are not excluded when such a test is applied.

[b] The value of $D \equiv -d[\mathrm{Fe/H}]/d\theta$ adopted to derive this estimate is 1.5. This number is an approximate average from Fig. 1 of Taylor (1994b). No meaningful average value of D is available for the Paulson et al. data, but $D = 1.5$ is less than the scattered values they quote. Larger values of D would yield lower averages. (In accordance with standard notation, $\theta \equiv 5040/T_{\rm eff}$.)

[c] So-called "indirect" data contribute to this average. See § 7 of Taylor (1998).

[d] Data from Boyarchuk et al. (2000) are included.

[e] Results from King & Hiltgen (1996) are included, and temperatures from Tables 6–8 have been adopted.

[f] This average is from entries 2 and 3 and is based on inverse-variance weighting.

REFERENCES

Alonso, A., Arribas, S., & Martinez Roger, C. 1996, A&A, 313, 873
Argue, A. N. 1967, MNRAS, 135, 23
Babu, G. J., & Feigelson, E. D. 1996, Astrostatistics (London: Chapman & Hall)
Bessell, M. S. 1979, PASP, 91, 589
———. 1983, PASP, 95, 480
———. 1986, PASP, 98, 1303
———. 1995, PASP, 107, 672
Bessell, M. S., & Weis, E. W. 1987, PASP, 99, 642
Boesgaard, A. M., Beard, J. L., & King, J. R. 2002, BAAS, 201, 4401
Boyarchuk, A. A., Antipova, L. I., Boyarchuk, M. E., & Savanov, I. S. 2000, Astron. Rep., 44, 76
Carney, B. W. 1982, AJ, 87, 1527
———. 1983, AJ, 88, 623
Carney, B. W., & Aaronson, M. 1979, AJ, 84, 867
Carpenter, J. M. 2001, AJ, 121, 2851
Cousins, A. W. J. 1974, Mon. Notes Astron. Soc. South Africa, 33, 149
———. 1978, Mon. Notes Astron. Soc. South Africa, 37, 62
———. 1980, South African Astron. Obs. Circ., 1, 234
Crawford, D. L. 1979, AJ, 84, 1858
Crawford, D. L., & Barnes, J. V. 1970, AJ, 75, 978
Crawford, D. L., & Perry, C. L. 1966, AJ, 71, 206
Di Benedetto, G. P. 1998, A&A, 339, 858
Draper, N. R., & Smith, H. 1981, Applied Regression Analysis (New York: Wiley)
Eggen, O. J. 1978, ApJS, 37, 251
———. 1979, ApJ, 234, 168
———. 1982, ApJS, 50, 221
———. 1986, AJ, 92, 910
Gratton, R. 2000, in ASP Conf. 198, Stellar Clusters and Associations: Convection, Rotation, and Dynamos, ed. R. Pallavicini, G. Micela, & S. Sciortino (San Francisco: ASP), 225
Grenon, M. 2002, Highlights Astron., 12, 680
Griffin, R. F., Gunn, J. E., Zimmerman, B. A., & Griffin, R. E. M. 1988, AJ, 96, 172
Gutiérrez-Moreno, A. 1975, PASP, 87, 805
Johnson, H. L., MacArthur, J. W., & Mitchell, R. I. 1968, ApJ, 152, 465
Johnson, H. L., Mitchell, R. I., & Iriarte, B. 1962, ApJ, 136, 75
Johnson, H. L., Mitchell, R. I., Iriarte, B., & Wiśniewski, W. Z. 1966, Comm. Lunar Planet. Lab., 4, 99
Joner, M. D., & Taylor, B. J. 1988, AJ, 96, 218
King, J. R., & Hiltgen, D. D. 1996, AJ, 112, 2650
Kobi, D., & North, P. 1990, A&AS, 85, 999
Kornilov, V. G., et al. 1991, Trudy Gosud. Astron. Inst. Shternberga, 63, 4
Koornneef, J. 1983, A&AS, 51, 489
Landolt, A. U. 1983, AJ, 88, 439
———. 1992, AJ, 104, 340
Mason, B. D., McAlister, H. A., Hartkopf, W. I., & Bagnuolo, W. G., Jr. 1993, AJ, 105, 220
Mendoza, V. E. E. 1967, Bol. Obs. Tonantzintla Tacubaya, 4, 149
Mermilliod, J.-C., Mermilliod, M., & Hauck, B. 1997, A&AS, 124, 349
Miller, C. J., et al. 2001, AJ, 122, 3492
Mironov, M. V., Moshkalev, V. G., & Kharitonov, A. V. 1998, Astron. Rep., 42, 799
Oláh, K., & Petterson, B. R. 1991, A&A, 242, 4430
Patience, J., Ghez, A. M., Reid, I. N., Weinberger, A. J., & Matthews, K. 1998, AJ, 115, 1972
Paulson, D. B., Sneden, C., & Cochran, W. D. 2003, AJ, 125, 3185
Perryman, M. A. C., et al. 1998, A&A, 331, 81
Pinsonneault, M. H., Terndrup, D. M., Hanson, R. B., & Stauffer, J. R. 2004, ApJ, 600, 946 (PTHS)
Reid, N. 1993, MNRAS, 265, 785
Taylor, B. J. 1978, ApJS, 36, 173
———. 1980, AJ, 85, 242
———. 1986, ApJS, 60, 577
———. 1991, ApJS, 76, 715
———. 1992, PASP, 104, 500
———. 1994a, PASP, 106, 444
———. 1994b, PASP, 106, 590
———. 1994c, PASP, 106, 600
———. 1996, ApJS, 102, 105
———. 1998, PASP, 110, 708
———. 2000, A&A, 362, 563
———. 2001, A&A, 377, 473
———. 2003, A&A, 398, 721
Taylor, B. J., & Joner, M. D. 1985, AJ, 90, 479 (TJ85)
———. 1988, AJ, 96, 211
———. 1996, AJ, 111, 1338
———. 2002, BAAS, 200, 902
Taylor, B. J., Joner, M. D., & Johnson, S. B. 1989, AJ, 97, 1798
Thompson, W. R. 1935, Ann. Math. Stat., 6, 1935
Upgren, A. R., Weis, E. W., & Hanson, R. B. 1985, AJ, 90, 2039
VandenBerg, D. A., & Clem, J. L. 2003, AJ, 126, 778
Weis, E. W., & Upgren, A. R. 1982, PASP, 94, 475
Yong, D., Lambert, D. L., Allende Prieto, C., & Paulson, D. B. 2004, ApJ, 603, 697

Chapter 8

Homogeneous Photometry for the Hyades: Scale-Factor and Zero-Point Tests of Previously Published *BV(RI)*$_c$ Photometry

The next publication is "Homogeneous Photometry for the Hyades: Scale-Factor and Zero-Point Tests of Previously Published *BV(RI)*$_c$ Photometry" by Joner et al. (2006), available in print as a six page paper in volume 132 of the *Astronomical Journal*. This paper was written as a second response to the claims made in Pinsonneault et al. (2004). However, the results in Taylor and Joner (2005) were so convincing that the emphasis of Joner et al. (2006) was directed toward the presentation of a catalog with new homogeneous *BV(RI)*$_C$ photoelectric photometry for 77 members of the Hyades. This paper was also notable as it was the first Taylor and Joner paper to contain observations using the color index *B-V*. These data were secured on the 0.5-m telescope at SAAO that had been used to establish and monitor the Cousins system at the Sutherland site in South Africa. The consistency tests reveal no detectable scale factor errors between the new photometry and previous Taylor and Joner measurements. The tests also show that any zero-point corrections in the new data can be no larger than a few mmag. The *B-V* colors in the new data set indicate an offset of about 8 mmag in the SAAO system that is unresolved by these measurements.

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HOMOGENEOUS PHOTOMETRY FOR THE HYADES: SCALE-FACTOR AND ZERO-POINT TESTS OF PREVIOUSLY PUBLISHED $BV(RI)_C$ PHOTOMETRY

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ABSTRACT

New $BV(RI)_C$ observations of 77 stars in the Hyades are reported and discussed. The new observations are used to test published magnitudes and color indices for that cluster. For values of $(V - R)_C$ and $(R - I)_C$ published previously by Taylor & Joner, the tests reveal no detectable scale-factor problems. In addition, the tests show that possible zero-point corrections to the published data can be no larger than a few millimagnitudes. These test results indicate that future studies requiring precision photometry for Hyades stars would be well served by selecting data samples from sources as close as possible to the native Cousins system. Tests of $B - V$ photometry published by Johnson & Knuckles reveal a zero-point ambiguity of approximately 8 mmag in the new data that will require further measurements to resolve.

Key words: methods: statistical — open clusters and associations: individual (Hyades) — stars: fundamental parameters — techniques: photometric

Online material: machine-readable table

1. INTRODUCTION

Observations of the Hyades open star cluster have provided a basis for practically all calibrations in stellar astrophysics, as well as serving as the foundation for determinations of the overall distance scale and age of the universe. It is of the utmost importance to ensure that data contributing to the establishment of these fundamental relations be of the highest precision. With the absolute importance of the Hyades being without question, it is somewhat surprising to learn that until recently there did not exist even one large and homogeneous photometric data set for the Cousins *VRI* color indices for single stars that are considered to be high-probability cluster members.

Two decades ago, Taylor & Joner (1985, hereafter TJ85) published measurements of $(V - R)_C$ and $(R - I)_C$ for 41 Hyades stars. Taylor & Joner (2005, hereafter TJ05) have since tested the TJ85 photometry extensively for possible systematic errors and have combined it with other published results to derive temperatures for 146 Hyades stars. The TJ85 values of $(R - I)_C$ are a major contributor to those temperatures. Tests of those data proved to be numerically satisfactory, but private correspondence with other astronomers has since made it clear that the results of those tests are not universally accepted because of the character of the color transformations used to construct them. In addition, tests of the TJ85 $(V - R)_C$ data left open the possibility that they might require corrections of several millimagnitudes. In an attempt to resolve both of these problems, we have made an additional set of Hyades measurements using a system generally recognized as an authoritative source of photometry on the Cousins system. The resulting data and the outcomes of tests that can be performed by applying those data are reported in this paper.

2. NEW MEASUREMENTS: SITE AND OBSERVING PROCEDURE

The new measurements were made with the 0.5 m telescope and modular photometer at the Sutherland site of the South African Astronomical Observatory (SAAO). The observing and reduction procedures for this system have been described quite extensively in § 2 of Koen et al. (2002) and in the Appendix of Kilkenny et al. (1998). For this reason, only some essential information about these procedures supplied to us by D. Kilkenny (2005, private communication) will be given here. The adopted paired-pulse correction was 20 ns and was established by analyzing transformation residuals in *V* from a large number of nights. Standard extinction coefficients were used but were regularly tested by comparing measurements of E-region standards made near the zenith with measurements made at air masses of 1.5 or more. Adjustments to these coefficients are made only if the tests show they are necessary. Such adjustments are required in only a minority of cases.

The transformation coefficients applied to measurements made at Sutherland are determined at intervals of several months. Each set of coefficients is derived by devoting an entire night to measurements of standard stars, with about 100 such measurements being made. On each subsequent night when program stars are measured, zero points are then determined for the transformation coefficients by making about 15–20 measurements of standard stars.

The $V - R$ and $V - I$ scale factors used to transform the new measurements to the standard system are listed in the first row of Table 1. Note that those scale factors are well within 10% of unity, thereby implying that the instrumental match to the standard system is good. The coefficients were determined in 2004 August but are effectively identical to counterparts determined in 2002 June and 2004 February. Evidently, the long-term stability in the Sutherland system noted by Kilkenny et al. (1998) continues to prevail.

For measurements made at Sutherland, it is standard procedure to superpose piecewise linear corrections on the straight lines represented by the coefficients. However, those corrections are not listed in Table 1 because they are never larger than 2 mmag for the Hyades stars considered here and are, in fact, usually zero.

TABLE 1
SCALE FACTORS IN *VRI* TRANSFORMATIONS

Observatory	$S-1$[a] $(V-R)$	σ $(V-R)$	$S-1$[a] $(R-I)$	σ $(R-I)$	$S-1$[a] $(V-I)$	σ $(V-I)$
SAAO[b]	+0.047	0.003	...	...	0.015	0.003
WMO[c]	+0.100	0.007	−0.028	0.005	...	...
KPNO[d]	+0.078	0.008	+0.001	0.008	...	...
CTIO[e]	−0.043	0.006	−0.022	0.004	...	...

[a] S is the slope in the equation $Y = SX + Z$, with Y being Cousins-system data and X being data on instrumental systems.
[b] Typical coefficients for the 0.5 m telescope of the SAAO.
[c] Typical coefficients for the 0.6 m telescope of the West Mountain Observatory of Brigham Young University.
[d] Typical coefficients for the 1.3 m telescope of Kitt Peak National Observatory.
[e] Typical coefficients for the 1.0 m telescope of Cerro Tololo Inter-American Observatory.

The corrections tend to be at their most important for very blue and very red stars, but the colors of the program stars avoid both of these extremes.

3. NEW MEASUREMENTS: RESULTS

The new data obtained from the measurements described above are reported in Table 2. The results for each individual data set have been used to calculate the standard deviations reported (in millimagnitudes) with each mean value. For the *i*th line of data, somewhat more precise standard deviations can be obtained from the expression $\sigma_0 n_1^{-0.5}$. The number of measurements n_i is given for each entry, and the standard deviation per datum σ_0 appears at the bottom of the table.

The quoted values of σ_0 have been calculated by obtaining a variance from the raw data for each star and then averaging the results with $(n_i - 1)$ weighting (see eq. [5.11.14] of Keeping 1962). Encouragingly, the values of σ_0 we obtain for color indices agree well with counterpart values reported by Cousins (1980) based on measurements at the SAAO Cape Town site.

For two stars (vB 64 and vB 66), excessive scatter in the raw V measurements is detected at better than 95% confidence. This inference is made by using variance-ratio tests to compare the data scatter for those stars with the scatter prevailing generally. The results are then interpreted by applying false-discovery rate (Miller et al. 2001). No values of V are reported for the two stars in question.

It may be noted that chromospheric activity is a possible explanation for the scattered V measurements of vB 64 and vB 66. The first of these stars is noted as a possible BY Draconis variable in SIMBAD, and detectable chromospheric activity in the Hyades extends up into the F star range (see Fig. 3 of Duncan et al. 1984). It is in fact likely that photometric precision for stars in a cluster such as the Hyades may ultimately depend on intrinsic factors such as chromospheric activity because of the care taken in establishing and maintaining the Cousins system.

4. TESTS OF THE TJ05 RESULTS

4.1. *Transformation Protocols and Additional Data*

With the SAAO results in hand, we now consider additional data that can be used to test the accuracy of the TJ05 results. First, however, a limit is imposed on the character of the transformations used to obtain those data. TJ05 used transformations that bridge substantial wavelength intervals. Because this practice is still controversial, we transform color indices from one system to another only if the wavelength baselines of the two systems overlap substantially.

As in TJ05, we use results from the archives of photomultiplier measurements made by B. J. Taylor & M. D. Joner. All of those data have been obtained by using GaAs tubes and Bessell (1979) filters. For all resulting transformations to the Cousins system, the absolute value of the scale factor is once again within about 10% of unity (see the second through fourth rows of Table 1).

One other transformation is required by the fact that there is a slight scale-factor difference between the Landolt and SAAO versions of $(V-R)_C$. Taylor & Joner (1996) have reviewed results from an extensive set of measurements that bear on this problem. They find that the following relation is adequate:

$$(V-R)_C = 0.989(V-R)_L, \tag{1}$$

with $(V-R)_L$ being the Landolt version of Cousins $V-R$. Equation (1) applies if $(V-R)_C < 0.8$ mag. Before data from Table 2 are compared to the Landolt-system values of $V-R$ given by TJ85, equation (1) is applied to the TJ85 results.

4.2. *Results for Taylor-Joner Data*

We now determine formal corrections to the data of TJ85 and TJ05. This is done by applying a two-step statistical analysis. In the first step, the program data are tested for scale-factor corrections. If it is found that such corrections are not statistically significant, a second step is taken to determine zero-point corrections. A detailed description of this procedure is given in the Appendix, and the results of the analysis appear in Table 3.

Considering $(R-I)_C$ first, we find that no scale-factor correction is required for either the TJ85 or TJ05 data (see the fourth column of Table 3). These results agree very well with those obtained by TJ05. The subsequent zero-point tests yield formal corrections to the Cousins system that are quite comparable to those obtained by TJ05 (see the fifth column of Table 3). Using the results of those tests, it is possible to determine the minimum correction to the TJ05 data that could have been detected by our procedure. The size of that correction turns out to be 3.0 mmag, so we conclude that no correction as large as this is required.

We consider $(V-R)_C$ next. Here, in contrast to $(R-I)_C$, the TJ05 analysis left open the possibility that the TJ85 data would have to be either rezeroed or rescaled. Fortunately, the additional tests that can now be made show that neither procedure is in fact required. The minimum zero-point correction that could have been detected turns out to be 4.8 mmag, with no correction as large as this or larger being required.

It should be noted that for the Hyades stars with photometry and temperatures listed by TJ05, $0.07 \leq (R-I)_C < 0.62$. For

TABLE 2
NEW SAAO $BV(RI)_C$ DATA FOR THE HYADES

vB[a]	HIP	GSC[b]	V[c]	$B-V$[c]	$V-R$[c]	$R-I$[c]	$V-I$[c]	n[d]
1	15304	00649−00766	7.373 (5.0)	0.585 (2.0)	0.323 (1.6)	0.311 (3.3)	0.634 (4.0)	6
2	15310	00649−01241	7.747 (4.4)	0.629 (2.1)	0.345 (1.8)	0.316 (2.3)	0.662 (2.8)	6
6	18170	01253−00716	5.946 (5.5)[e]	0.348 (4.5)	0.201 (1.1)	0.200 (2.3)	0.401 (2.6)	4
7	18327	01253−00868	8.964 (3.8)	0.906 (3.4)	0.492 (3.0)	0.423 (1.2)	0.915 (3.1)	5
8	18658	00662−00633	6.340 (0.5)	0.422 (0.5)	0.243 (5.0)	0.237 (1.0)	0.480 (4.0)	2
10	19148	01250−00686	7.811 (1.4)	0.605 (2.2)	0.327 (2.3)	0.315 (1.3)	0.642 (3.0)	5
13	19504	01255−00312	6.576 (4.3)	0.429 (2.7)	0.247 (2.3)	0.234 (2.0)	0.481 (2.9)	4
14	19554	00080−01093	5.699 (6.6)[e]	0.358 (2.5)	0.212 (1.9)	0.202 (3.3)	0.415 (1.7)	4
15	19793	01815−00517	8.047 (8.2)	0.664 (4.5)	0.356 (2.4)	0.335 (0.7)	0.691 (3.9)	4
17	19781	00679−00597	8.419 (3.4)[e]	0.706 (2.9)	0.380 (1.9)	0.356 (2.7)	0.737 (3.8)	7
18	19786	00675−00351	8.030 (3.0)[e]	0.652 (3.1)	0.357 (0.8)	0.333 (2.3)	0.689 (2.0)	6
19	19796	00671−00211	7.080 (2.4)	0.526 (1.0)	0.289 (1.7)	0.280 (3.4)	0.569 (2.4)	6
20	19877	01251−00128	6.300 (1.8)[e]	0.405 (3.2)	0.230 (3.4)	0.223 (2.1)	0.453 (4.9)	4
23	20056	01268−00327	7.514 (7.5)	0.688 (2.6)	0.375 (2.0)	0.343 (4.7)	0.718 (3.5)	3
25	20082	01264−00498	9.548 (5.4)	0.984 (2.4)	0.533 (5.6)	0.458 (3.5)	0.991 (3.3)	3
26	20130	01272−00325	8.597 (5.3)	0.748 (5.4)	0.405 (1.3)	0.362 (4.1)	0.768 (2.9)	3
27	20146	01268−00352	8.427 (5.5)	0.730 (3.0)	0.393 (2.9)	0.359 (6.2)	0.752 (6.1)	4
30	20219	00679−00750	5.568 (2.2)[e]	0.288 (3.7)	0.161 (5.1)	0.157 (2.7)	0.318 (4.8)	4
31	20237	01272−00439	7.444 (2.8)	0.572 (2.7)	0.313 (3.4)	0.305 (1.9)	0.618 (4.6)	4
32	20255	01268−01268	6.094 (4.5)	0.384 (8.5)	0.220 (4.5)	0.220 (1.0)	0.441 (3.5)	2
33	20261	01264−01010	5.242 (3.8)[e]	0.233 (3.5)	0.116 (4.4)	0.126 (4.7)	0.243 (4.6)	4
34	20284	00680−00027	6.141 (3.5)	0.462 (4.5)	0.265 (2.7)	0.246 (2.4)	0.511 (2.5)	3
35	20349	01276−00251	6.779 (4.7)	0.436 (1.6)	0.248 (4.0)	0.248 (4.5)	0.496 (4.4)	4
36	20350	01268−00295	6.787 (3.2)	0.447 (3.9)	0.255 (2.2)	0.253 (2.8)	0.508 (4.8)	4
37	20357	00680−00994	6.578 (4.3)	0.421 (5.8)	0.240 (2.6)	0.239 (1.9)	0.479 (4.2)	4
39	20441	01264−00758	7.821 (6.5)	0.674 (8.7)	0.365 (1.9)	0.352 (3.5)	0.717 (2.6)	3
44	20491	01820−01157	7.159 (5.0)	0.466 (3.3)	0.254 (3.3)	0.262 (2.8)	0.516 (2.5)	4
46	20492	00680−00194	9.097 (5.2)	0.866 (3.1)	0.466 (2.4)	0.409 (1.9)	0.875 (3.8)	6
48	20557	01277−00747	7.125 (3.5)	0.521 (2.0)	0.295 (5.1)	0.280 (1.3)	0.575 (4.3)	4
49	. . .	01265−00569	8.203 (2.2)	0.605 (4.3)	0.333 (2.8)	0.310 (2.7)	0.643 (1.4)	4
51	20567	01269−00806	6.947 (2.5)	0.458 (1.3)	0.249 (2.3)	0.253 (3.1)	0.502 (1.1)	4
53	20614	01273−01106	5.965 (5.0)	0.389 (6.0)	0.229 (1.0)	0.230 (9.9)	0.459 (9.4)	2
59	. . .	01265−00224	7.472 (2.4)	0.555 (4.4)	0.311 (1.0)	0.303 (3.7)	0.614 (2.7)	3
64	20741	01265−00241	. . .	0.673 (4.5)	0.358 (5.1)	0.340 (4.1)	0.698 (5.2)	4
65	20815	01265−01048	7.404 (5.0)	0.545 (4.7)	0.302 (3.3)	0.297 (2.6)	0.599 (1.5)	4
66	20826	00676−00062	. . .	0.560 (3.3)	0.316 (1.7)	0.299 (3.8)	0.615 (4.6)	4
67	20842	01277−01628	5.711 (0.9)	0.285 (1.2)	0.158 (2.7)	0.147 (1.2)	0.305 (1.8)	3
68	20873	00681−01152	5.892 (5.0)	0.335 (3.3)	0.198 (3.0)	0.193 (1.7)	0.391 (4.1)	3
69	20890	01273−00711	8.580 (4.6)	0.736 (2.2)	0.398 (2.3)	0.366 (0.8)	0.764 (2.6)	4
73	20899	01269−00022	7.837 (6.4)	0.619 (2.2)	0.339 (1.1)	0.318 (1.7)	0.657 (2.1)	4
74	20901	00677−01116	5.014 (2.5)	0.212 (3.5)	0.107 (3.5)	0.112 (1.8)	0.219 (2.0)	3
75	20916	01265−00791	6.565 (3.9)	0.536 (6.7)	0.307 (2.9)	0.291 (2.4)	0.599 (1.8)	3
77	20935	01269−00294	7.007 (1.5)	0.505 (2.7)	0.283 (2.1)	0.290 (6.1)	0.573 (8.1)	3
78	20948	01269−00557	6.890 (1.3)	0.462 (2.4)	0.259 (1.1)	0.258 (1.6)	0.517 (2.1)	4
79	20951	01269−00697	8.934 (3.5)	0.827 (2.8)	0.448 (2.8)	0.393 (3.0)	0.841 (3.3)	4
80	20995	01265−01175	5.552 (1.5)	0.335 (2.8)	0.194 (2.6)	0.197 (3.5)	0.391 (3.8)	3
84	21036	00681−01153	5.395 (3.1)	0.260 (5.4)	0.150 (2.2)	0.152 (1.2)	0.302 (1.2)	3
86	21066	00673−00700	7.015 (3.0)	0.476 (3.4)	0.274 (2.4)	0.262 (2.6)	0.536 (1.0)	4
87	21099	01273−00428	8.572 (6.3)	0.755 (2.8)	0.403 (1.9)	0.367 (2.3)	0.771 (0.5)	4
88	21112	00681−00829	7.746 (2.9)	0.554 (3.9)	0.301 (3.3)	0.297 (1.4)	0.599 (3.3)	5
89	21137	01265−01173	5.998 (3.0)	0.344 (2.2)	0.199 (2.9)	0.196 (2.0)	0.394 (3.0)	3
90	21152	00090−00033	6.352 (2.1)	0.431 (1.2)	0.248 (1.5)	0.230 (2.4)	0.478 (2.7)	3
92	. . .	01266−01286	8.641 (3.7)	0.755 (2.3)	0.406 (2.2)	0.368 (1.2)	0.774 (1.4)	4
93	. . .	01266−00149	9.357 (4.9)	0.897 (2.9)	0.483 (0.9)	0.418 (2.7)	0.901 (3.5)	3
94	21267	00681−00651	6.597 (3.4)	0.434 (5.3)	0.246 (4.0)	0.244 (2.3)	0.489 (4.2)	5
97	21317	01266−00278	7.898 (4.6)	0.632 (4.2)	0.342 (3.7)	0.331 (5.2)	0.672 (4.8)	4
99	. . .	01266−01175	9.345 (4.6)	0.867 (8.5)	0.467 (3.6)	0.419 (2.2)	0.886 (2.9)	3
101	21474	01266−01214	6.619 (2.7)	0.455 (2.0)	0.248 (4.9)	0.255 (1.9)	0.504 (6.1)	4
106	21654	00694−00225	7.945 (2.3)	0.648 (4.3)	0.360 (1.9)	0.332 (2.3)	0.692 (2.7)	3
107	21670	00682−01726	5.365 (1.5)	0.258 (4.0)	0.139 (3.4)	0.133 (2.5)	0.272 (4.9)	3
111	22044	00687−01627	5.379 (2.9)	0.259 (1.0)	0.149 (0.9)	0.149 (1.5)	0.297 (1.3)	3
113	22221	00683−00688	7.228 (3.0)	0.571 (2.2)	0.322 (2.4)	0.316 (0.9)	0.638 (1.7)	5
116	22380	01284−01397	8.947 (5.6)	0.842 (6.4)	0.455 (3.5)	0.403 (5.3)	0.858 (2.3)	3
118	22422	01280−00485	7.739 (2.2)	0.585 (2.1)	0.327 (1.8)	0.301 (3.2)	0.628 (1.5)	3
119	22496	01284−00332	7.095 (3.9)	0.578 (4.2)	0.327 (2.8)	0.318 (5.9)	0.645 (3.4)	4

TABLE 2—*Continued*

vB[a]	HIP	GSC[b]	V[c]	$B-V$[c]	$V-R$[c]	$R-I$[c]	$V-I$[c]	n[d]
123	22565	01288−01706	5.085 (6.4)	0.217 (2.1)	0.121 (3.5)	0.134 (2.2)	0.255 (1.7)	3
124	22607	00696−01789	6.250 (3.7)	0.501 (1.3)	0.297 (4.3)	0.279 (4.1)	0.576 (0.4)	3
126	22850	01288−01591	6.347 (3.3)[e]	0.293 (5.6)	0.175 (6.6)	0.167 (5.2)	0.342 (3.5)	4
142	22203	01267−01102	8.280 (3.2)	0.674 (0.4)	0.366 (5.1)	0.345 (4.7)	0.711 (0.7)	3
143	22566	01280−01110	7.886 (2.3)	0.532 (2.7)	0.295 (0.7)	0.289 (1.7)	0.584 (1.9)	3
174	20563	01269−01212	9.966 (9.3)	1.069 (4.2)	0.602 (4.0)	0.500 (4.0)	1.102 (5.3)	3
175	...	01269−00128	10.248 (5.8)	1.028 (9.7)	0.583 (4.3)	0.488 (1.2)	1.070 (5.4)	3
176	20679	...	8.989 (3.3)	0.939 (8.6)	0.520 (1.5)	0.458 (0.7)	0.978 (1.5)	3
179	20827	00680−00104	9.475 (9.9)	0.927 (6.0)	0.509 (3.1)	0.440 (1.9)	0.949 (4.3)	4
183	...	01266−00944	9.644 (6.9)[f]	0.921 (3.2)	0.505 (3.9)	0.437 (1.7)	0.942 (3.6)	4
187	23498	00697−01892	8.596 (3.7)	0.776 (6.5)	0.414 (2.3)	0.372 (5.6)	0.786 (4.4)	3
311	21723	00690−00945	9.992 (6.9)	1.085 (1.2)	0.624 (2.0)	0.511 (3.1)	1.135 (1.8)	3
σ_0[g]	...	...	0.008	0.007	0.006	0.006	0.007	...

Note.—Table 2 is also available in machine-readable form in the electronic edition of the *Astronomical Journal*.
[a] This is the van Bueren (1952) number.
[b] This is the number from the Hubble Guide Star Catalog.
[c] Entries in parentheses are standard deviations in millimagnitudes derived from the scatter for each individual set of measurements.
[d] Number of measurements.
[e] For this datum (but not for the color indices), subtract 1 from the listed value of n (see footnote c).
[f] The SAAO V magnitude for this star is 0.024 ± 0.0083 brighter than a V magnitude measured by the authors at Kitt Peak National Observatory.
[g] If $V > 9.0$ mag, $\sigma_0 \sim 0.0155$ for V and 0.011 for $B-V$. For $(V-I) \equiv (V-R)+(R-I)$, $\sigma_0 = 0.007$. If $\sigma_0 < 0.010$, the centered 68% confidence interval for σ_0 has a width of ± 0.0004 (for V) or ± 0.0003 (for the color indices).

the stars listed in Table 2 of this paper, the color range is somewhat narrower: $0.11 \le (R-I)_C < 0.51$. For blue stars, the difference between these color ranges is likely insignificant. To be prudent, however, it should be assumed that the results just given do not apply for stars with $(R-I)_C > 0.51$.

4.3. *Results for Johnson-Knuckles Values of B − V*

Because the new measurements include values of $B-V$, it is of interest to add a comparison of those data to previously published results. Archival photometry of Johnson & Knuckles (1955) and Mendoza (1967) contain similar results for $B-V$, so it seems reasonable to select only one of those data sets for analysis. The Johnson & Knuckles data are chosen because they include numbers of measurements per datum, thus allowing us to consider various levels of data quality in our analysis.

The results of the analysis (given in the last row of Table 3) show no detectable scale-factor difference between the SAAO and Johnson & Knuckles results. However, the latter require a formal correction of about $+8.1 \pm 1.3$ mmag to reduce them to the SAAO zero point. At first glance, such a correction is quite conceivable, since it is only about 1.3 times the rms error of the zero point of the Johnson & Knuckles data (see their Table 1*a*). Before accepting the correction, however, it is worthwhile to compare it with results from two other sources. One is Table 1 of Sturch (1973), who has compared the Hyades to standards from Johnson (1963). The other is Taylor & Joner (1992), who have made Strömgren measurements of both Hyades stars and field stars with values of $B-V$ given by Johnson et al. (1966).

The Strömgren data may be used to calculate values of $B-V$. The transformation applied here is from Cousins (1987), but with a zero point adjusted to yield the same $B-V$ values in the mean as those given by Johnson et al. (1966) for the field stars. The adjusted transformation may then be used to derive Strömgren-based values of $B-V$ for the Hyades, and those values in turn may be compared to Johnson & Knuckles (1955) data. The resulting formal correction to the latter is then found

TABLE 3
Results of Statistical Tests

Color Index	Data Tested	Source Data	$s \equiv 100(S-1)$[a]	Zero-Point Correction[b]	FDR Applied?[c]	Minimum Correction[d]
$(R-I)_C$	TJ85[e]	JT reductions[f]	-1.1 ± 1.4	-0.7 ± 0.9	...	...
	TJ85[e]	This paper	-2.1 ± 1.0	-0.9 ± 1.0	Y	...
	TJ05[g]	This paper	-0.9 ± 0.8	$+0.1 \pm 1.0$	Y	3.0
$(V-R)_C$	TJ85[e]	JT reductions[h]	-6.3 ± 4.0	-2.6 ± 1.6	...	...
	TJ85[e]	This paper	-0.4 ± 1.5	-4.2 ± 1.4	Y	...
	TJ85[e]	Combined[i]	0.0 ± 1.4	-3.5 ± 1.3	Y	4.8
$B-V$	JK55[j]	This paper	-0.3 ± 0.5	$+8.1 \pm 1.3$	Y	...

[a] S is the slope in the equation $Y = SX + Z$, with Y being source data (see the third column) and X being tested data (see the second column).
[b] This is the formal zero-point correction (in millimagnitudes) required to put the tested data on the zero point of the source data.
[c] "FDR" refers to the dependent version of false-discovery rate (see § 3.1 of Miller et al. 2001).
[d] This is the minimum correction to the tested data (in millmagnitudes) that could have been detected at 95% confidence.
[e] Data are from Taylor & Joner (1985), Table V.
[f] Data are from Taylor & Joner (2005), Table 1, line 1.
[g] Data are from Taylor & Joner (2005), Tables 6–7.
[h] Data are from Taylor & Joner (2005), Table 3, line 2. Results for the presumed variable star vB 183 (see footnote f of Table 2 of this paper) are excluded.
[i] The source data are from this paper and from all pertinent photometric reductions by Joner & Taylor.
[j] Data are from Tables 2a–2c of Johnson & Knuckles (1955).

to be -5.8 ± 2.8 mmag. A counterpart correction may be obtained by averaging entries in Sturch's Table 1, with mean numbers of measurements being used as weights. That result is -5.0 ± 2.3 mmag. Plainly the two corrections agree, so they can be averaged using inverse-variance weights, yielding -5.3 ± 1.8 mmag. It is then found, however, that this formal correction differs from the one implied by the SAAO data with a false-alarm probability of about 10^{-5}. Further judgment about this problem should probably be reserved until additional measurements have been made.

5. SUMMARY

The new and archival measurements considered in this paper do not reveal scale-factor errors in either the TJ85 color indices or the $(R-I)_{\rm C}$ data of TJ05. In addition, there is no indication that the TJ05 data require a zero-point correction even as large as 3.0 mmag. For the $(V-R)_{\rm C}$ results of TJ85, the corresponding limit is found to be 4.8 mmag. It is clear from these results that any future investigators requiring reliable $(V-R)_{\rm C}$, $(R-I)_{\rm C}$, or $(V-I)_{\rm C}$ indices for the Hyades stars as a basis for establishing or calibrating fundamental relations would be well served by selecting data samples from TJ85, TJ05, or the homogeneous data set presented in this investigation (with allowances made for the transformation between the Landolt and Cousins $V-R$ systems). A zero-point ambiguity is found for the Johnson & Knuckles (1955) values of $B-V$, which should be resolved by obtaining further measurements.

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APPENDIX

THE STATISTICAL ANALYSIS: DETAILED DESCRIPTION

Each analysis is performed in two stages. In the first stage, tests for scale-factor differences are performed, with the first applied equation being

$$R_3 = SR_2 + Z. \quad \text{(A1)}$$

Here R represents either $V-R$ or $R-I$. Subscripts "2" and "3" refer to data sources listed in the second and third columns of Table 3, respectively. Each version of equation (A1) is calculated using a two-error least-squares algorithm (see Babu & Feigelson 1996, § 7.4.1).

Having obtained a value of S, the following equations are used:

$$s \equiv 100(S-1), \quad \text{(A2)}$$

$$s \equiv s_c \pm \sigma_s, \quad \text{(A3)}$$

$$t = |s_c|(\sigma_s)^{-1}, \quad \text{(A4)}$$

and

$$\nu = N - 1, \quad \text{(A5)}$$

with N being the number of data pairs (in other words, the number of stars for which data are available). If s is considered instead of S, one may treat $s = 0$ instead of its equivalent $S = 1$ as the null hypothesis H_0. In turn, this change of variables permits the use of a simple test: one inspects Table 3 to see which of its listed values of s satisfies the condition $t < 1.96$ (or, equivalently, $|s_c| < 1.96\sigma_s$). This test is based on the fact that if $t < 1.96$, two-tailed t tables show that H_0 is not rejected for any value of the number of degrees of freedom ν.

Regardless, it is found that $t < 1.96$ for six of the seven values of s listed in Table 3. For the second listed value of s, however, $t = 2.1$, and with $\nu = 32$, the probability p of Type I error is found to be 0.043. However, when false-discovery rate is applied to this result (see below), H_0 is ultimately maintained. Since H_0 is therefore maintained for all listed values of s, the analysis proceeds to a second stage on the assumption that no scale-factor differences have been detected. (For the use of the term "maintained" instead of "accepted" for H_0, see footnote 7 of Miller et al. [2001]).

The second-stage analysis is based on a vector $\Delta\boldsymbol{R}$ of data differences and an associated vector $\boldsymbol{w}$ of weights. The elements in these vectors are given by the equations

$$\Delta R_i = R_{3i} - R_{2i} \quad \text{(A6)}$$

and

$$w_i^{-1} = \sigma_{3i}^2 + \sigma_{2i}^2 + \sigma_0^2, \quad \text{(A7)}$$

with i ranging from 1 to N and equation (A7) being based on equation (10.12) of Kendall & Stuart 1977. The values of σ_{2i} and σ_{3i} are both derived from scatter in contributing measurements. For the SAAO data specifically, $\sigma(\text{SAAO})_i$ can be inferred from the entries in Table 2; for $\sigma(\text{TJ})_i$, data are given by TJ85 and TJ05. The parameter σ_0 represents "extra" scatter (possibly from stellar variation) and is initially unknown.

Using $\Delta\boldsymbol{R}$ and $\boldsymbol{w}$, a mean offset A and its rms error σ_A are derived as follows:

$$A = \left[\sum w_i(\Delta R_i)\right]\left[\sum w_i\right]^{-1}, \quad \text{(A8)}$$

$$\sigma_A^{-2} = \sum w_i, \quad \text{(A9)}$$

and

$$Q = \sum w_i(\Delta R_i - A)^2, \quad \text{(A10)}$$

with all sums running from $i = 1$ to N. The basis for equation (A8) is given in equations (B11), (B12), (C4), and (C5) of Taylor 1991 (see Appendices B and C of that paper). The key to this part of the analysis is the statistic Q, which is χ^2 distributed with $N-1$ degrees of freedom (see Kshirsagar 1983, p. 341). Using Q, the χ^2 distribution, and repeated trial values of σ_0, a centered confidence interval (often a 68% confidence interval) is established for σ_0. If the 95% confidence interval for σ_0 includes zero, σ_0 is set to zero; otherwise, its value at the midpoint of the 68% confidence interval is adopted. The initial value of the formal correction to the TJ data is then $A \pm \sigma_A$.

Allowances must now be made for the error contributions by all transformations used to obtain values of R. For SAAO color indices, the transformations from instrumental to standard systems contribute rms errors. For $V-R$, allowance must also be made for the rms error of equation (1) in the text. To allow for these contributions, the rms errors of the pertinent transformation centroids are added in quadrature to values of σ_A to obtain augmented values σ'_A. Then H_0 is identified as the hypothesis that $A \pm \sigma'_A$ is zero. The subsequent procedure is the same as that applied to values of s.

In a final step, values of p derived from values of A or s that do not appear in TJ05 are assembled. Results for the TJ05 data are excluded because they are effectively superseded by the entries in the third and sixth rows of Table 3. The dependent version of false-discovery rate (see § 3 of Miller et al. 2001) is then applied. As noted in the text, this test does not designate any values of p for which H_0 is rejected with an overall confidence level of 95% or greater.

REFERENCES

Babu, G. J., & Feigelson, E. D. 1996, Astrostatistics (London: Chapman & Hall)

Bessell, M. S. 1979, PASP, 91, 589

Cousins, A. W. J. 1980, S. African Astron. Obs. Circ., 1, 234

———. 1987, Observatory, 107, 80

Duncan, D. K., Baliunas, S. L., Noyes, R. W., Vaughan, A. H., Frazer, J., & Lanning, H. H. 1984, PASP, 96, 707

Johnson, H. L. 1963, in Basic Astronomical Data, ed. K. Aa. Strand (Chicago: Univ. Chicago Press), 204

Johnson, H. L., & Knuckles, C. F. 1955, ApJ, 122, 209

Johnson, H. L., Mitchell, R. I., Iriarte, B., & Wiśniewski, W. K. 1966, Comm. Lunar Planet. Lab., 4, 99

Keeping, E. S. 1962, Introduction to Statistical Inference (Princeton: van Nostrand)

Kendall, M., & Stuart, A. 1977, The Advanced Theory of Statistics (4th ed.; London: Griffin)

Kilkenny, D., van Wyk, F., Roberts, G., Marang, F., & Cooper, D. 1998, MNRAS, 294, 93

Koen, C., Kilkenny, D., van Wyk, F., Cooper, D., & Marang, F. 2002, MNRAS, 334, 20

Kshirsagar, A. M. 1983, A Course in Linear Models (New York: Dekker)

Mendoza, E. E. V. 1967, Bol. Obs. Tonantzintla & Tacubaya, 4, 149

Miller, C. J., et al. 2001, AJ, 122, 3492

Sturch, C. 1973, PASP, 85, 724

Taylor, B. J. 1991, ApJS, 76, 715

Taylor, B. J., & Joner, M. D. 1985, AJ, 90, 479 (TJ85)

———. 1992, PASP, 104, 911

———. 1996, AJ, 111, 1338

———. 2005, ApJS, 159, 100 (TJ05)

van Bueren, H. G. 1952, Bull. Astron. Inst. Netherlands, 11, 432

Chapter 9

Cousins Photometry and Temperatures for the Hyades, Coma, NGC 752, Praesepe, and M67

The third paper is "Cousins Photometry and Temperatures for the Hyades, Coma, NGC 752, Praesepe, and M67" as published by Taylor, Joner, and Jeffery (2008) in a 14 page paper that appeared in volume 176 of the *Astrophysical Journal Supplement Series*. This paper presents new Cousins *VRI* data for Praesepe and NGC 752. Previously unpublished CCD and photomultiplier data are used with existing data to form an augmented database for M67. The database for the Coma cluster is expanded using previously unpublished photomultiplier data. The extant Hyades catalogs are updated with the new data that appeared in Joner et al. (2006). There is a discussion of gradient corrections to magnitudes that have been applied as positional corrections to CCD photometry for M67. These corrections can be applied to the *V* magnitudes of Sandquist (2004). The corrected *V* magnitudes are combined with the $(V\text{-}I)_C$ values from Sandquist (2004) to produce a supplemental M67 catalog. Numerous comparisons are performed on the catalog data and they are all found to be satisfactory in terms of zero-point and scale-factor. In contrast, the data of Montgomery, Marschall, and Janes (1993) for M67 is found to have a likely scale-factor error, as well as a zero-point error of 27 ± 3 mmag in the $(V\text{-}I)_C$ color index. Once again, it is found that careful photometry at the level of a few mmag has been possible for some decades and is not a recent achievement. The often described ‘cosmic scatter’ of about 10 mmag or the presence of an inescapable lower limit of 10 to 20 mmag in data scatter is also addressed in this paper in connection with the results of multiple consistency tests that satisfy the previously defined FM (for “few millimag”) standard of data quality. The updated and new catalog values are illustrated in the published paper with several examples of “stub” tables. The complete catalogs have been deposited in the Centre de Donnes astronomiques de Strasbourg (CDS) archive. The full VRI data tables from this paper are presented in the Appendix of this dissertation for the Coma, M67, Praesepe, and NGC 752 star clusters.

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COUSINS PHOTOMETRY AND TEMPERATURES FOR THE HYADES, COMA, NGC 752, PRAESEPE, AND M67

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ABSTRACT

In this paper, new Cousins *VRI* data are presented for NGC 752 and Praesepe, and new and extant data are combined into an augmented database for M67. For those three clusters, catalogs containing Cousins *VRI* photometry, reddening-corrected values of $(V-K)_J$, and temperatures are produced. The same is done for Coma by using both previously published and newly derived Cousins photometry. An extant set of catalogs for the Hyades is updated to include *V* magnitudes and values of $(R-I)_C$ that were published after the original catalogs appeared. Finally, M67 *V* magnitudes published previously by Sandquist are corrected for an effect that depends on location on the face of the cluster. The corrected data and values of $(V-I)_C$ given by Sandquist are then set out in a supplementary catalog. Data files containing all of these catalogs are deposited in the CDS archives. To assess the quality of the data in the catalogs, the consistency of extant Cousins *VRI* databases is tested by performing analyses with the following features: (1) quantities as small as a few millimags are regarded as meaningful; (2) statistical analysis is applied; (3) no use is made of data other than *VRI* measurements and comparable results; (4) no inferences are drawn from color-magnitude comparisons; (5) pertinent data that have not been included previously are analyzed; and (6) results based on direct comparisons of stellar groups at the telescope are featured. In this way, it is found that our updated M67 color data and those of Sandquist are on the E region zero point. In contrast, values of $(V-I)_C$ from Montgomery and collaborators are found to be too red by 27 ± 3 mmag, with an even larger offset being likely for unpublished data from Richer and his collaborators. Zero-point tests of our Cousins *VRI* colors for Coma, Praesepe, and NGC 752 are also satisfactory. Scale factor tests of the M67 colors are performed, and a likely scale factor error in the Montgomery et al. colors is found. However, it appears at present that the scale factors of our M67 colors and those of Sandquist are satisfactory. For the most part, zero-point tests of the assembled *V* magnitudes are also satisfactory, although it is found that further work on the *V* magnitudes for Praesepe and M67 would be useful. To put these results in perspective, it is pointed out that photometric tests that are satisfactory at the few-millimag level have been published for some two decades and so are not appearing for the first time in this paper.

Subject headings: Hertzsprung-Russell diagram — open clusters and associations: individual (Coma, Hyades, M67, NGC 752, Praesepe) — stars: fundamental parameters

1. INTRODUCTION

Two years ago, Taylor & Joner (2005, hereafter TJ05) published three catalogs containing temperatures and values of $(R-I)_C$ for the Hyades. In this followup paper, those catalogs are updated and counterparts are given for four additional clusters: Coma, NGC 752, Praesepe, and M67. Reliable reddening values are available for all five clusters, and precise values of [Fe/H] are known for all of them except NGC 752 (Taylor 2006, 2007a, 2007b).[2] One major aim of this paper is to fulfill the remaining requirements for high-quality color-magnitude analyses of these clusters.

For NGC 752 and Praesepe, new Cousins *VRI* photometry is presented here. For M67, previously published photometry is combined with new results to form an expanded Cousins *VRI* database (to be called the "augmented" M67 database below). Statistical tests of zero-point accuracy are then performed on the data for all three clusters. In addition, such tests are applied to previously published *VRI* photometry for Coma and M67. Particular attention is given to the M67 tests because there appear to be zero-point differences among some extant M67 *VRI* photometry. Zero points that are deemed to be fully reliable will be established in response.

The plan for this paper is as follows. In § 2 a description of the sources and reduction techniques for the new data is given. The M67 zero-point problem is stated in full in § 3, and the first basic steps toward its solution are taken. In § 4 the adopted zero-point analysis technique is set out in detail. Results of the analysis are given for M67 in §§ 5–7 and for Coma, Praesepe, and NGC 752 in § 8. The augmented M67 data also include *V* magnitudes, so the results of zero-point tests of those data are reported in § 9. For both the four clusters just mentioned and the Hyades, the new and revised catalogs and the procedure used to construct them are described in § 10. In § 11 essential perspectives on literature practice are given and recommendations for future improvements are made. The paper concludes with a summary in § 12.

2. NEW DATABASES: SOURCES AND REDUCTIONS

The new photometry can be grouped into three databases. One of them includes photomultiplier data measured from 1972

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[2] After first citations, papers by Taylor & Joner and Joner & Taylor will be cited as "TJ" and "JT," respectively, with the last two digits of the publication year added. "T" followed by two digits represents a paper published by Taylor. All of these abbreviations are given in the reference list.

TABLE 1
M67 Photometry: Formal Positional Corrections

Source	Color Index[a]	C_α [b]	C_δ [b]	C_0 [c]
CTIO (this paper)	$(R-I)_C$	−0.6 ± 1.0	2.9 ± 0.8	0
KPNO (this paper)	$(V-R)_L$	1.5 ± 0.2	1.7 ± 0.3	0
Laugalys et al. (2004)[d]	$(V-I)_C$	−0.8 ± 0.2	0	2.6 ± 0.9
Laugalys et al. (2004)[e]	V	−0.5 ± 0.2	−0.6 ± 0.2	24 ± 1
Montgomery et al. (1993)	V	2.8 ± 0.6	0.3 ± 0.6	−12.9 ± 2.6
Sandquist (2004)	V	2.4 ± 0.3	−2.8 ± 0.4	0

[a] Subscript "L" designates the Landolt (1983) version of $(V-R)_C$ (see § 6 of Taylor & Joner 1996).
[b] Units are mmag arcminute^{-1}. If a quantity is zero by assumption, no standard error is quoted.
[c] Units are mmag. If a quantity is zero by assumption, no standard error is quoted.
[d] Because $C_\alpha \neq 0$ at the 4 σ level, results of I_C and $(V-I)_C$ positional tests of extrinsic data given by Laugalys et al. are deemed to be superseded.
[e] False-discovery rate (see Miller et al. 2001) shows that neither C_α nor C_δ differs from zero at an overall confidence rate of 0.95.

through 1992. The telescopes used include the 1.3 m and Number 2 0.9 m telescopes at Kitt Peak National Observatory (KPNO). Measurements were also made at the 1 m telescope of Cerro Tololo Inter-American Observatory (CTIO) and the 0.6 m telescope of the West Mountain Observatory of Brigham Young University. The observing techniques used at these telescopes and the reduction procedures applied to the data have been described in § 2.1 of Joner & Taylor (1990). Some (although not all) of those data have been published in Joner & Taylor (1988, 1990) and Taylor & Joner (1985, 1988).

A second database is taken from M67 frames taken in 1993 December and 1995 January at the 0.9 m telescope of CTIO. The detector used at that telescope was a Tek1024 Number 2 CCD. The third database is taken from M67 frames obtained in 1992 February at the 0.6 m Burrell-Schmidt telescope at KPNO. At that telescope, the detector was an S2KA CCD mounted at the Newtonian focus. In this case, only data from a subframe of 601×601 pixels were used.

At each telescope where CCD photometry was performed, only data from nights deemed to be photometric were retained. We stress the fact that both the photomultiplier and CCD data are solely from measurements made on such nights. When CCD cameras were used, an average of 20 bias frames was obtained on each night. Flat frames were taken through each of the adopted filters at twilight. Both cameras were cooled using liquid nitrogen, so no dark frames were required in the reductions. After initial processing was done using the bias and flat frames, aperture photometry was performed to extract raw magnitudes. Intermediate processing then yielded instrumental values of V, $(V-R)_C$, and $(R-I)_C$. Those data were reduced with the BIGPHOT program, which was also used to reduce the photomultiplier data (see § 2.1 of JT90).

The standard stars used in this program are in M67 or are listed by Landolt (1992). However, no standard star data were adopted from the latter source. As in TJ05, all of our adopted standard star data are from photomultiplier measurements reduced to the system of Landolt (1983). For M67 stars in particular, the standard-star data were taken from TJ85 and JT90.

After initial reductions of the CCD data were complete, the data were tested in two ways. In both sets of tests, the CCD data and the photomultiplier data were differenced. The first test consisted of a search of the resulting residuals for gradients across the face of the cluster. These tests were prompted by an illuminating discussion by Laugalys et al. (2004), who used photomultiplier data to deduce that there are gradient errors in a number of published CCD data sets for M67. Because no flat-fielding procedure is required in photomultiplier photometry, the assumption that such photometry is less likely to suffer from gradient errors than CCD data seemed plausible to us. We therefore applied the same basic procedure that Laugalys et al. did. However, we used least-squares analysis in place of the graphical technique used by those authors. The adopted regression equation has the form

$$\Delta(\mathrm{Index}) = C_\alpha \Delta\alpha + C_\delta \Delta\delta + C_0, \tag{1}$$

with "Index" designating V, $(V-R)_C$, and $(R-I)_C$ in turn. The quantity $\Delta\alpha$ is an offset in right ascension, while $\Delta\delta$ is the corresponding declination offset. In both cases, the offsets are from the center of M67 given in SIMBAD.

To decide whether gradient errors had been found, it was necessary to test the regression coefficients (C_α, C_δ, and C_0) for statistical significance. This was done by using t-tests and false-discovery rate (see § 4.2 of Taylor & Joner 2006 and § 3 of Miller et al. 2001, respectively). In two cases, it was found that at least one of the derived coefficients is significant at an overall confidence level of 95% or better. These coefficients (see the first two lines of Table 1) were then used to make the required corrections.

When these tests and corrections were complete, the zero points of the photomultiplier and CCD data were compared. If statistically significant offsets were found, the CCD data were corrected to the zero points of the photomultiplier data. For the CTIO results, the mean remaining offsets from the photomultiplier zero points are

$$[\Delta V,\ \Delta(V-R)_C,\ \Delta(R-I)_C] = [3 \pm 2,\ -1 \pm 1,\ 1 \pm 1]\ \mathrm{mmag}. \tag{2}$$

For the KPNO data, the corresponding equation is

$$[\Delta V,\ \Delta(V-R)_C,\ \Delta(R-I)_C] = [3 \pm 2,\ 0 \pm 2,\ -2 \pm 1]\ \mathrm{mmag}. \tag{3}$$

As one can see from inspection, none of these offsets have absolute values that exceed twice their standard errors, so none of the offsets are statistically significant.

3. ASSESSING M67 COLOR INDICES: FIRST STEPS TOWARD A SOLUTION

With the augmented M67 database in hand, we consider the M67 zero-point problem described in § 1. A number of M67 *VRI* data sets have been published (see § 5), but not all of them have played an active role in the problem. The databases that have been featured fall naturally into a "blue group" and a "red group." The blue group contains the JT90 data and a data set from Sandquist (2004), while the red group contains data sets from Montgomery et al. (1993) and Richer et al. (1998). According to VandenBerg & Stetson (2004, hereafter VdBS) the zero-point separation between these groups is about 0.02 mag. Those authors conclude that the zero point of the red group is probably correct.

To approach this problem, we begin by adopting two protocols. One is the so-called FM (for "few millimag") standard of data precision and accuracy (see § 2 of T06). According to this standard, photometric quantities can be meaningful if they range down to a few millimags. For averages specifically, errors as small as about 1 mmag are deemed to be acceptable. Readers who are unfamiliar with the FM standard are invited to consult § 7.3 of TJ06 and § 11 of this paper.

The second adopted protocol is statistical analysis. Before now, it appears that statistical procedures have not been applied to the zero-point problem. The procedure that has been used most often has been graphical fitting of isochrones to plotted color magnitude data (see, e.g., Figs. 4–6 of VdBS). Judging by statistical standards, the salient weakness of that procedure is its inability to yield rigorous confidence limits for deduced quantities (see § 4.1 of Taylor 2001a). We therefore conclude that graphical color magnitude inference is not genuinely trustworthy and suggest that it be displaced by statistical analysis in the future.

The statistical procedures adopted here include two least-squares algorithms (see § 2.1 of TJ06). Their output residuals are tested for wild points by using the Thompson *t*-test (see the second tool described in § 6.2 of Taylor 2000). The statistical significance of the coefficients they yield is evaluated by using ordinary *t*-tests. In addition, an algorithm for analyzing differences between data vectors is applied. Each application of the algorithm yields a mean difference between the vectors and an estimated rms error for the data in one of them. A detailed derivation of this algorithm is given in Part 2 of Appendix C of Taylor (1991). However, interested readers should probably consult a summary description of the algorithm instead (see Appendix C of JT90 or § 6.2 of T00).

4. ASSESSING M67 COLOR INDICES: DETAILED PROCEDURE

4.1. *Analysis Tactics*

Our next step is to select a specific way of performing the analysis. To begin, we set aside two procedures used by VdBS. Those authors use plots of $B - V$ against $(V - I)_C$ for cluster and field stars. The problem with this technique is that the use of $B - V$ leads to ambiguities that have nothing to do with the accuracy of the $(V - I)_C$ data that are being tested. This is true partly because $B - V$ data sets can have their own zero-point offsets and partly because $B - V$ is sensitive to blanketing. As a result, $B - V$ is sensitive to both metallicity and to inherent scatter in the relation between metallicity and blanketing (for a brief discussion of such scatter, see § 5.3 of T06).

VdBS also gauge data accuracy by comparing $[M_V, (V - I)_C]$ main-sequence loci for M67 and NGC 188 (see especially their Fig. 5). To do this, they must obviously adopt data for NGC 188, and they also require reddening values for both that cluster and M67. At the moment, their adopted reddening value for M67 is supported by a reasonably comprehensive analysis (see § 9 of T07a), but their reddening value for NGC 188 is not. In this case, ambiguity is therefore introduced by their choice of a reddening value for NGC 188 and also their choices of photometry for that cluster. One notes that Stetson et al. (2004), who use the same approach as VdBS, concede (at least pro forma) that their deduced results could be influenced by a "pernicious conspiracy" among systematic errors in contributing quantities. All told, eliminating any possibility for such a conspiracy would be worthwhile.

The alternative approach we adopt consists of a series of comparisons between data vectors. When $(V - R)_C$ is analyzed, for instance, the vectors contain values of $(V - R)_C$ that are drawn from diverse sources, but apply for the same selection of stars. Equivalent procedures are used for $(R - I)_C$ and $(V - I)_C$. We stress the fact that in this procedure, the only participating quantity besides the data sets being tested is the M67 reddening (see § 4.4). As a result, ambiguities like those noted above are minimized.

In most cases, the results derived from the two vectors are formal zero-point differences. For M67 data, however, some tests for differing scale factors are performed as well. In these cases, linear regression relations between vectors are calculated. The result of each test is then stated as a value of

$$s \equiv 100(S - 1), \tag{4}$$

where S is the slope of the calculated relation. If $s \neq 0$ at 95% confidence or better, it is concluded that a scale factor difference between the vectors has been found.

4.2. *Groups of Comparisons*

Three groups of comparisons between the augmented M67 database and other data sets are performed. One group is inspired by the choice of standard star data by Montgomery et al. (1993). Those authors note that some of those data are from JT90. If the JT90 data are in error while those of Montgomery et al. are not, the Montgomery et al. reductions must have yielded a zero-point error that largely or entirely compensates for the one affecting the JT90 data. VdBS do not note this point, so they do not acknowledge that such a coincidence seems unlikely prima facie. A pertinent way to gauge this possibility is to find out whether other observers who have used the JT90 standards (either directly or indirectly) have derived results on the Montgomery et al. zero point. Tests are performed to see whether this has in fact happened.

A second group of comparisons focuses on data based on sets of standard stars that are completely disjointed from the set we have used. In this case, both zero-point and scale factor comparisons are performed. Note that if agreement is found in these cases, it cannot be dismissed as a simple artifact of the use of common standard stars. In addition, tests of this sort can now include comparisons between the augmented M67 database and a data set based directly on the E region standards (for a collection of E region standard star data, see, e.g., Menzies et al. 1989). For both reasons, this set of comparisons is deemed to be important.

A third group of comparisons is a response to the problem of reducing photometry to a standard system. It has been known for some time that if measurements of two or more groups of stars are transformed *independently* to a standard system, zero-point differences can result (see, e.g., § 2 of Strom et al. 1971 and Table 3 of Stetson et al. 2004). Such differences are much less likely, however, if photometric nights are used to perform direct comparisons of the groups at the telescope. Sturch (1972, 1973) appears to have been the first to publish fully documented exercises of this sort. We follow Sturch's procedure here and refer to it with the phrases "Sturch comparison" and "Sturch exercise."

4.3. *Sturch Comparisons: A Two-Step Process*

We use Sturch comparisons as part of a two-step exercise in which an indirect link is established between M67 and the E region standards. This is done by treating the Hyades as a northern

TABLE 2

Reddening Ratios

Ratio	Value	Source
$A_V/E(B-V)$	3.28	Buser (1978), Table 6[a]
$A_V/E(b-y)$	4.27	Crawford & Mandwewala (1976), Table X[a]
$E(b-y)/E(B-V)$	0.77	... [b]
$E(V-R)_C/E(B-V)$	0.58	Taylor (1986), Table 3[c]
$E(R-I)_C/E(B-V)$	0.70	Taylor (1986), Table 3[c]
$E(V-K)/E(B-V)$	2.63	Cardelli et al. (1989)[d]

[a] The quoted ratio is based on the Whitford (1958) reddening law and applies at spectral type F0.
[b] The quoted ratio follows from the two entries just above.
[c] See Table 2 of this source for a review of ratios from diverse reddening laws.
[d] The quoted ratio is based on an averaged reddening law derived by Cardelli et al.

TABLE 3

Hyades and Landolt (1983) Data: Scale and Zero-Point Tests

Source of Tested Data	Index	s [a]	Offset[b] (mmag)	Reddest Color (mag)
Landolt (1983)[c]	$(V-R)_C$	... [d]	0 ± 3	0.80
Landolt (1983)[e]	$(R-I)_C$	0.1 ± 0.2	0.1 ± 0.5	1.45
Hyades (TJ85)[f]	$(V-R)_C$	0.0 ± 1.4	-3.5 ± 1.3[g]	0.51
Hyades (TJ85)[f]	$(R-I)_C$	-2.1 ± 1.0[g]	-0.9 ± 1.0	0.51
Hyades (TJ05)[f]	$(R-I)_C$	-0.9 ± 0.8	0.1 ± 1.0	0.51

[a] $s \equiv 100(S-1)$.
[b] This quantity is the formal correction to be *added* to the data being tested.
[c] The quoted results are from § 6 of TJ96. The confidence interval is not a $\pm 2\,\sigma$ interval but instead includes the maximum corrections required if eq. (5) of TJ96 (which is a compromise relation) is adopted.
[d] The scale factor difference obtained here appears in eq. (5).
[e] The quoted results are from Table 3 of TJ96.
[f] The quoted results are from Table 3 of Joner et al. (2006).
[g] Although $t > 2$ for this datum, it does not differ from zero at 95% overall confidence when tested using false-discovery rate (see Miller et al. 2001).

hemisphere proxy for those standards. Extensive Cousins *VRI* photometry of the Hyades has been published, so a review of the scale factor and zero-point status of those data is the first of the two steps.

In the second step, Hyades measurements are used to establish zero points for M67 data. The data sets adopted for the indirect comparison include data for both clusters. Some of those data are from Sturch comparisons, while the remainder are from data sources that appear likely to have uniform zero points. The M67 data in the adopted data sets are more extensive than those available for the direct comparison to the E region standards. In addition, the indirect comparison is based partly on measurements of stars on and near the M67 main sequence. This condition does not hold for the direct comparison, which is limited to data for giants and blue stragglers in M67 because those data have been secured with a photomultiplier and a 0.5 m telescope. For these reasons, the direct and indirect comparisons yield complementary links to the E region standards.

4.4. *Use of Transformations*

The data used in the Sturch comparisons are not on the Cousins system, although they are on comparable systems. To deal with this problem, color-color transformations are applied. Those transformations have been derived rigorously by using procedures given in a tutorial by TJ06. In addition, they are based partially or wholly on Hyades data, as required by the procedure adopted here. Allowances for the errors introduced by the transformations are made by using a discussion in § 7.1 of TJ06.

We acknowledge that to a number of readers, the use of transformations is likely to appear to be self-defeating. Skepticism about the accuracy of transformed data has been fairly common for some time (for a recent example, see § 2 of Ramírez & Meléndez 2005). A concise response to this issue is given below (see § 11). Readers with fundamental questions about transformations are invited to consult TJ06 as well. That paper contains an extended discussion of the derivation and use of accurate transformations.

For some data, the original wavelength baselines are quite different from those of the Cousins system. In those cases, the transformations have some reddening dependence. The reddening ratios required here are given in Table 2 together with their sources. The required values of $E(B-V)$ are adopted from a series of detailed analyses by T06, T07a, and T07b. Readers with questions about the accuracy of the adopted reddening values are invited to consult those papers. To assess the effects of reddening uncertainties on the data comparisons, we note that the largest quoted standard error for an adopted value of $E(B-V)$ is 4 mmag. Numerical tests show that in the worst case considered [conversion of $V-K_2$ to $(R-I)_C$], the effect of an error of that size is scaled down by a factor of 5. In the best case [conversion of $(R-I)_J$ to $(R-I)_C$], the induced error is even closer to 0. We therefore conclude that even in the context of the FM standard, the effects of reddening uncertainties can be neglected.

5. ASSESSING M67 COLOR INDICES: FIRST TESTS AND RESULTS

5.1. *Testing Hyades Data*

To apply the procedure just described, we begin by reviewing the status of Cousins *VRI* Hyades photometry given by TJ85 and TJ05. Since all of that photometry is on the standard system of Landolt (1983) the status of Landolt's data is reviewed as well. To test the Landolt data, extrinsic results from sources given by Taylor & Joner (1996) are used. To test the Hyades data, extrinsic results given by Joner et al. (2006) are used.[3] All tests refer the tested data to the E region standards, and all are made using measurements for more than 35 stars. In addition, all data used in the tests have rms errors ranging from 2 to 6 mmag.

For $(V-R)_C$, a scale factor difference between the Landolt and E region data is found:

$$(V-R)_L = 1.011(V-R)_C, \; (V-R)_C < 0.8 \text{ mag}, \quad (5)$$

with the subscript "L" referring to the Landolt system (see eq. [5] of TJ96). As a result, all other $V-R$ tests refer the tested data to a fictitious database produced by applying equation (5) to E region values of $(V-R)_C$. In Table 3, results from both comparisons of this kind and $(R-I)_C$ comparisons are given. The first two entries in the table show that if data for M stars are excluded (as they are throughout this paper), it has been possible to secure accurate Hyades data by using the Landolt (1983) standard stars. The last three entries show that there are no detectable differences between the Hyades data of TJ85 and TJ05 and Hyades data standardized by using E region standards. We conclude that combined data from all those sources are on the E region system at the level required by the FM standard.

[3] For clarity of reference, we say that "extrinsic" data are used to establish the status of "tested" data.

5.2. *Assembling M67 Data*

To establish the link from the Hyades to M67, the databases listed in Table 4 are used. The databases labeled R_1, I_1, and I_2 in the table are from Sturch comparisons. For database I_3, that condition does not hold. However, the data in that database are from an all-sky survey that appears likely to have a uniform zero point (see Cutri et al. 2003). (The footnotes to Table 4 give further information, including references to Appendix A for discussions of some required color-color transformations.)

To identify other extrinsic databases that can be considered here, the WEBDA database has been consulted. Extrinsic Cousins data published before 1990 are not used here because they have been discussed by JT90. Measurements made by Stassun et al. (2002) are excluded because they have not been fully reduced to a standard system. All other published Cousins *VRI* data sets listed by WEBDA are included along with data from Laugalys et al. (2004). Extrinsic data based directly from E region standards are from a forthcoming paper (see M. D. Joner et al. 2008, in preparation).

TABLE 4
HYADES, COMA, M67: DATA SETS FOR ZERO-POINT TESTS

Data Set	Index	Hyades	Coma	M67	Sources
R_1	$(V-R)_J$	Y	...	Y	Mendoza (1967)[a,b]
I_1	$b-y$	Y	Y	Y	TJ92, JT97[c]
I_2	$(R-I)_J$	Y	...	Y	Mendoza (1967)[a,d]
I_3	$V-K_2$	Y	Y	Y	Cutri et al. (2003)[e]

[a] V. E. E. Mendoza (1977, private communication) affirms the zero-point uniformity of these data. See § IV of TJ85 for the reason Coma data from this source are omitted.
[b] See item 1 of Appendix A for a review of transformations for these data.
[c] For a transformation from $b-y$ to $(R-I)_C$, see Table 4 of TJ06.
[d] For the required transformations from $(R-I)_J$ to $(R-I)_C$, see eqs. (A1)–(A5c) in Appendix A of TJ05. These transformations allow for a problem with the Mendoza data discussed in § 4.3 of TJ05.
[e] For a review of transformations for these data, see item 2 of Appendix A.

5.3. *Testing M67 Data*

The results of the M67 data tests are given in Table 5. In this case, the tested data have rms errors ranging from 3 to 8 mmag, and this range also holds for extrinsic data for which no rms errors are listed. The fourth through sixth columns of the table contain numbers of data pairs, calculated formal offsets, and derived rms errors for extrinsic data, respectively. By comparing entries in those three columns, one can see how the standard errors listed for the offsets follow from the number and precision of the contributing data.

For the first five data sources listed in Table 5, the label "M" is used. These are the tests designed to see whether authors who have used the JT90 standards have recovered results like those of Montgomery et al. (1993; see our § 4.2). For one of the five labeled tests, the result must be set aside because a positional gradient is detected (see the entry for Laugalys et al. 2004). Note, however, that three other tests do not recover the Montgomery et al. offset (which is given in the uppermost boldface entry in the "Difference" column). Statistical testing underscores this conclusion: the offset for the Montgomery et al. data differs from zero at a very high confidence level ($P > 4.7$), while $P < 0$ for the other three entries.[4] Even before the remaining results are reviewed, one must suspect that the Montgomery et al. data suffer from a zero-point error that they alone possess.

Just after the Table 5 entries for Montgomery et al. data are entries for Sandquist (2004) data. The latter are given out of sequence so that they may be compared at once to their counterparts for Montgomery et al. Note that the rms error derived for the Sandquist data is quite a bit smaller than its counterpart for the Montgomery et al. data (look at the second line with boldface entries in Table 5). In addition, the Sandquist data have an offset that is smaller in absolute value. The implications of this second result will be considered shortly.

The next three offsets listed in Table 5 describe test results for $(V-R)_L$. None of them differ from zero with $P > 0$. From the Mendoza (1967) data, one finds that the 2 σ limit of the formal zero-point adjustment is 10.8 mmag. This means that the data do not rule out a zero-point adjustment of that size with $P > 0$. In the context of the FM standard, this is a relatively large uncertainty. Fortunately, the entries based on the Gilliland et al. and SAAO data yield 2 σ limits of 3.6 and 3.2 mmag, respectively. Those limits are quite satisfactory.

The last five entries in Table 5 apply for $(R-I)_C$. In this case, it appears at first that a result comparable to the one for $(V-R)_L$ will be obtained at once. For the first four entries, P is found to be <0. Here again, the Mendoza (1967) data yield a fairly large 2 σ limit (9.4 mmag). However, the other two Sturch comparisons suggest that that limit may be as small as 1.6 mmag (see the entry for data set I_3). A separate test for giants yields consistency with a consensus of independent data (see the second entry from the bottom of Table 5). However, the entry for the SAAO data yields an offset of -6 ± 1.6 mmag (see the boldface entry on the last line of the table). In this case, the value of P is 1.33.

Fortunately, this result does not imply that one must make a choice between the zero points implied by the direct and indirect methods. Instead, the Table 5 offsets are reassessed after a 2 mmag correction has been subtracted from the $(R-I)_C$ data in the augmented M67 database. It is assumed that if the JT90 data had included this correction, M67 data based on JT90 standards would also have included it, leaving the resulting formal zero-point differences unaltered. For this reason, Table 5 entries for data sets flagged with an "M" are not adjusted. For entries flagged with a double asterisk, however, 2 mmag are added to the quoted offsets. The entire list of revised offsets (which does not appear in Table 5) is then retested by using false-discovery rate (Miller et al. 2001) and Student's *t*-tests.

When this procedure is carried out, it is found that the revised $(R-I)_C$ zero point does not differ from either the direct or indirect zero points with $P > 0$. The only offsets that continue to be statistically significant are those for the Sandquist and Montgomery et al. data. Note that since the 2 mmag adjustment is made in response to statistical testing and yields superior results from such testing, it cannot be fairly regarded as an ad hoc device.

6. ASSESSING M67 COLOR INDICES: FURTHER RESULTS FOR TWO IMPORTANT PAPERS

The test results given above for the Montgomery et al. and Sandquist data sets warrant further development. We therefore compare the zero points of those data sets to the zero points of the E region standards. Fortunately, the augmented M67 database can be used as proxies for those standards if one allows for

[4] If the confidence level C is very close to unity, it must be expressed with a row of nines that can make the number hard to grasp. A more accessible alternative is to let $p \equiv 1 - C$ be the probability of Type I error for an isolated test and then define P as $-\log_{10}(20p)$, as is done here. It is useful to remember that $P = 0$ if $C = 0.95$ and $P = 1$ if $C = 0.995$, with the latter value leading to decisive rejection of a null hypothesis in almost all cases.

TABLE 5
M67 *VRI* COLORS: OFFSETS AND ACCIDENTAL ERRORS

Extrinsic Source	Extrinsic Color[a]	Tested Color[a]	n[b]	Difference[c] (mmag)	σ[d] (mmag)
M: Anupama et al. (1994)[e]	$(V-I)_C$	$(V-I)_C$	30	2 ± 4.7	24
M: Chevalier & Ilovaisky (1991)[e]	$(V-R)_L$	$(V-R)_L$	29	2 ± 1.5	7
M: Chevalier & Ilovaisky (1991)[e,f]	$(R-I)_C$	$(R-I)_C$	29	6 ± 2.7	14
M: Laugalys et al. (2004)[e,g]	$(V-I)_C$	$(V-I)_C$	202	...	10
M: Montgomery et al. (1993)[e]	$(V-I)_C$	$(V-I)_C$	172	25 ± 1.3	16
**Sandquist (2004)	$(V-I)_C$	$(V-I)_C$	78	−6 ± 1.0	6
R_1: Mendoza (1967)[h]	$(V-R)_J$	$(V-R)_L$	37	6 ± 5.4	33
Gilliland et al. (1991)[f]	$(V-R)_L$	$(V-R)_L$	63	−4 ± 1.8	13
SAAO[i]	$(V-R)_L$	$(V-R)_L$	11	0 ± 1.6	...
**I_1: JT97[j]	$b-y$	$(R-I)_C$	35	−2 ± 1.5	...
**I_2: Mendoza (1967)[h]	$(R-I)_J$	$(R-I)_C$	39	−6 ± 4.7	15
**I_3: Cutri et al. (2003)[k]	$V-K_2$	$(R-I)_C$	242	0 ± 0.8	...
**1988 consensus, giants[l]	...	$(R-I)_C$	12	−2 ± 1.3	...
**SAAO[i, m]	$(R-I)_C$	$(R-I)_C$	11	−6 ± 1.6	...

[a] Subscript "L" designates the Landolt (1983) version of $(V-R)_C$ (see § 6 of TJ96).
[b] The quantity n is the number of stars for which data are compared.
[c] Differences are in the sense "extrinsic source minus this paper" and are expressed as values of the tested color index.
[d] The quantity σ is the rms error per data entry for data from the extrinsic source. No value of σ is given if accidental errors for the extrinsic data are already known independently.
[e] Data from this source have been derived (directly or indirectly) using standard-star data from JT90.
[f] The zero point of the data used to standardize the Gilliland et al. results is known to be consistent with the zero point of the augmented M67 database (see § 5 of JT90).
[g] No difference is given here because a positional correction is required instead (see Table 1).
[h] Data for giants are used in the $(V-R)_L$ test, but not in the $(R-I)_C$ test.
[i] The extrinsic data used here are given by M. D. Joner et al. (2008, in preparation).
[j] Applied luminosity corrections are from Fig. 6 of Crawford & Barnes (1970) and the δc_1 term in the Crawford (1975) calibration. Data for giants are excluded from the analysis.
[k] The V data required for this index are taken from this paper. Data for giants are excluded from the analysis.
[l] The extrinsic data for this test are averaged from the following sources: $(R-I)_K$ (Brooke 1969), T_1-T_2 (Canterna 1976), CTIO/CIT $V-K$ (Cohen et al. 1978), and $(R-I)_J$ (Mendoza 1967). For further information, see Table 1 of TJ88.
[m] The quoted offset is statistically significant before (but not after) the zero-point correction described in the text is applied.

the uncertainties in the zero-point relationship between the augmented M67 data and the E region data. The zero-point differences found in this way are as follows:

1. $\Delta(V-I)_C = 27 \pm 2.9$ mmag ("Montgomery et al. minus E region");
2. $\Delta(V-I)_C = -4 \pm 2.7$ mmag ("Sandquist minus E region").

Note that the zero point of the Montgomery et al. data differs decisively from that of the E region standards, while the E region and Sandquist zero points are indistinguishable. (The calculation required to obtain these results is given in Appendix B.)

One would like to know whether scale factor differences can also be found. If the Gilliland et al. and Sandquist data are each compared to the augmented M67 data in turn, one finds that $s = 0.4 \pm 0.7$ and $s = 2.1 \pm 1.4$, respectively. (Recall that the method used to obtain these results and the definition of s are described in § 4.) Evidently, the augmented database shares a common $(V-R)_L$ scale factor with the Gilliland et al. data and a common $(V-I)_C$ scale factor with the Sandquist data. On the other hand, if the augmented database and the Montgomery et al. data are compared, one finds that $s = 2.7 \pm 1.1$ and $P = 0.55$. In addition, Sandquist's Figure 5 suggests that there is a corresponding scale factor difference between his data and those of Montgomery et al. Prima facie, it therefore appears that the zero-point offset of the Montgomery et al. data is accompanied by a scale factor offset. Although that assessment should be checked by using additional databases, it is accepted here on an interim basis.

These results have a consequence worth noting. An et al. (2007) have derived M67 distance moduli from color-magnitude analyses of both the Montgomery et al. and Sandquist data. Pending an updated analysis, their distance modulus based on the Sandquist data should be used (see their Table 7).

7. SOME COMMENTS ABOUT THE VdBS ANALYSIS

Recall at this point that the VdBS analysis favors the zero point of the Montgomery et al. data. Although general questions have been raised about the VdBS analysis techniques (recall § 4.1), obviously it would ultimately be best to rely on pertinent specifics. If this is done, does one find that the results of the two analyses are implacably opposed to each other? Fortunately, we can show that this is not the case.

The issue of interest here is a problem first discussed by VandenBerg & Clem (2003, see §§ 3.2 and 3.6 of their paper). For stars with solar metallicity, those authors use the data of Montgomery et al. to calibrate their $(V-I)_C$ isochrones. Subsequently, they fit isochrones to color-magnitude diagrams for the Hyades (see their Figs. 22–24). For $(V-I)_C$, they find that the plotted data are about 0.02 mag bluer than the isochrone, with the offset being almost independent of color. In contrast, no comparable problem appears for $B-V$ or $V-R$ (compare Fig. 24 of VandenBerg & Clem to their Figs. 22 and 23).[5]

One way to explain this problem is to attribute it to the $(V-I)_C$ data of Montgomery et al. Both VandenBerg & Clem and VdBS consider this hypothesis, although they do not ultimately accept it. Now that we have shown that it is very likely to be

[5] For the sake of clarity, it should be noted that the designation $(V-R)_0$ used by VandenBerg & Clem corresponds to $(V-R)_L$ in the notation of this paper. This identification applies for both M67 and the Hyades.

TABLE 6
HYADES, NGC 752, PRAESEPE: DATA SETS FOR ZERO-POINT TESTS

Data Set	Index	Hyades	NGC 752	Praesepe	Sources
R_2	$(V-R)_J$	Y	...	Y	Mendoza (1967)[a]
I_2	$b-y$	Y	Y	...	TJ92, JT95 [b]
I_3	$(R-I)_J$	Y	...	Y	Mendoza (1967)[c]
I_4	$V-K_2$	Y	Y	Y	Cutri et al. (2003)[d]
I_5	$V-i*$	...	Y	...	Jennens & Helfer (1975a, 1975b)[e]

[a] See item 1 of Appendix A for a review of transformations for these data.
[b] Praesepe is omitted for a reason given in § 9.1 of T06. For a transformation from $b-y$ to $(R-I)_C$, see Table 4 of TJ06.
[c] For the required transformations from $(R-I)_J$ to $(R-I)_C$, see eqs. (A1)–(A5c) in Appendix A of TJ05. These transformations allow for a problem with the Mendoza data discussed in § 4.3 of TJ05.
[d] See item 2 of Appendix A for a review of transformations for these data.
[e] A transformation for these data is derived in Appendix C.1 of T07b. That transformation links data for NGC 752 to field-star data (see Taylor 1986) instead of Hyades data.

correct, it is worthwhile to explore its consequences. To do this, let the $(V-I)_C$ isochrones of VandenBerg & Clem be moved 27 mmag to the blue, and let this be done for both the Hyades and M67. Now the M67 isochrone fits the augmented M67 database, while the shift of the Hyades isochrone has at least approximately absorbed the Hyades offset of 0.02 mag. As a result, it appears that both isochrones now fit data that we have found to be on the same zero point. Moreover, this appraisal probably does not require revision if the M67 value of $E(B-V)$ adopted by VandenBerg & Clem is replaced by the reddening value deduced by T07a. By happenstance, the two reddening values differ by only 3 mmag.

For $(V-R)_L$, VandenBerg & Clem obtain an acceptable fit to the Hyades data of TJ85 (see their Fig. 23). Those data share a zero point with the augmented M67 results and hence with the data of Gilliland et al. (1991; see our Table 5). One therefore expects the M67 isochrone of VandenBerg & Clem to be an adequate fit to the Gilliland et al. results as well. For stars with $M_V < 8$ mag, that turns out to be the case. This test is not very definitive because the plotted Gilliland et al. data are quite scattered (see Fig. 14 in VandenBerg & Clem). However, it does appear that consistency has again been achieved.

This reasoning is not carried further here because it quickly leads beyond the scope of our paper. However, it is persuasive enough to suggest that the results of a complete analysis using recalibrated VandenBerg & Clem isochrones might be fully consistent with our data. Acting on a recommendation made in § 3, we suggest that such an analysis be carried out statistically.

8. ASSESSING COLORS FOR COMA, PRAESEPE, AND NGC 752

We now return to our own analysis and, with solutions for two program clusters in hand, consider results for the other three. For Coma, some further preparation is required before an analysis can be done. As Table 4 shows, tests of $(R-I)_C$ for Coma can be carried out using data sets I_1 and I_3. However, no data sets listed there can be used to test Coma values of $(V-R)_L$. In this case, extrinsic data from measurements described in § 3.2 of TJ05 are adopted.

Further preparation is also required before the new data for Praesepe and NGC 752 are tested. By and large, measurements for those clusters were made on the same nights, so their $(V-R)_C$ and $(R-I)_C$ data may each be tested as a unit. However, those units include only scattered measurements of stars in the other three clusters. To test the new data, a second set of measurements from Sturch comparisons is therefore required. Data sets adopted for this purpose are listed in Table 6.

Results of zero-point tests for Coma, Praesepe, and NGC 752 are listed in Table 7. This time (in contrast to Table 5), rms errors are not given for extrinsic data sets. Instead, we note that the errors are once again derived or are known in advance and that they tend to be smaller than the errors for M67 because brighter clusters are now being considered. This point should be kept in mind as the formal offsets and numbers of contributing data pairs are inspected (see the last two columns of Table 7).

Note that the first offset listed in Table 7 for Coma applies for $(V-R)_L$, while the other two apply for $(R-I)_C$. One can see at once that all three offsets imply that no adjustment of the Coma zero points is required. Moreover, the 2 σ uncertainties in the offsets are ≤ 3.0 mmag and so are quite satisfactory.

For Coma, no fully independent data that could be used to perform adequate scale factor tests are known to exist. For this reason, no results from such tests are reported here. Instead, it is assumed that the results of the scale factor tests for M67 apply to Coma as well. That assumption is based on the fact that the Coma data and the photomultiplier data for M67 can be considered as part of a single unit (see, e.g., Table I of TJ85). We recommend that the Coma data be used in further color-magnitude analyses of that cluster to see whether problems posed by previous $V-I$ results recur (see § 3.6 of Pinsonneault et al. 1998).

On the fourth line of Table 7, results are reported from a test of the combined $(V-R)_L$ data for Praesepe and NGC 752. That test appears to be the only one of its kind that is feasible at present. Here again, it is found that a derived offset does not differ from zero with $P > 0$. If the Mendoza (1967) data used for the zero-point test are also used for a scale factor test, the resulting value of s is 4.5 ± 2.2. This result is accepted here as evidence of scale factor consistency. However, it should be remembered that the derived standard error for s is relatively large (recall the counterpart errors quoted in § 6).

The last two entries for Praesepe and the first two listed for NGC 752 display formal $(R-I)_C$ offsets for those clusters. Data for giants are excluded from all four tests. Here a discrepant result with $P = 2.4$ appears (see the upper boldface entry in the last column). Judging from the balance of evidence, however, the common $(R-I)_C$ zero point for the two clusters is correct. If the discrepant result is set aside, the 2 σ limit on this inference is 3.0 mmag (see the entry for data set I_3).

If the procedure developed above were to be applied here, a value of s applying to $(R-I)_C$ would now be calculated. The procedure adopted instead at this point is to test the color zero point for NGC 752 giants. Since those stars are redder than those cluster stars that are on and near the main sequence, separate zero-point tests for the bluer and redder stars can accomplish

TABLE 7
COMA, PRAESEPE, NGC 752: COLOR OFFSETS

Cluster	Extrinsic Source	Extrinsic Color[a]	Tested Color[a]	n[b]	Difference[c] (mmag)
Coma	TJ05[d]	$(V-R)_L$	$(V-R)_L$	16	2 ± 1.5
Coma	I_1: Crawford & Barnes (1969), TJ92[e]	$b-y$	$(R-I)_C$	17	−1 ± 1.5
Coma	I_3: Cutri et al. (2003)[f]	$V-K_2$	$(R-I)_C$	18	2 ± 1.4
Praesepe	R_1: Mendoza (1967)	$(V-R)_J$	$(V-R)_L$	39	3 ± 2.3
Praesepe	I_2: Mendoza (1967)	$(R-I)_J$	$(R-I)_C$	36	3 ± 3.0
Praesepe	I_3: Cutri et al. (2003)[f]	$V-K_2$	$(R-I)_C$	38	2 ± 1.5
NGC 752	I_1: Crawford & Barnes (1970), JT95[g]	$b-y$	$(R-I)_C$	19	−2 ± 2.2
NGC 752	I_3: Cutri et al. (2003)[f]	$V-K_2$	$(R-I)_C$	29	6 ± 1.4
NGC 752	**I_4: Jennens & Helfer (1975a, 1975b)[h]	$V-i^*$	$(R-I)_C$	7	9 ± 2.7
NGC 752	**M67 data, this paper[i]	$(R-I)_C$	$(R-I)_C$	8	−5 ± 2.9

NOTE.—No $b-y$ test is performed for Praesepe because of the color-color offset found for that cluster (see § 9 of T06).
[a] Subscript "L" designates the Landolt (1983) version of $(V-R)_C$ (see § 6 of TJ96).
[b] The quantity n is the number of stars for which data are compared.
[c] Differences are in the sense "extrinsic source minus this paper" and are expressed as values of the tested color index.
[d] These data have been standardized by using Landolt (1983) standards (see § 3.2 of TJ05).
[e] The first abbreviation stands for Crawford & Barnes (1969). The zero-point consistency of data from the two papers is established by TJ92.
[f] The values of V required for this index are taken from this paper.
[g] The first abbreviation stands for Crawford & Barnes (1970). The zero-point consistency of data from the two cited papers is established by JT95.
[h] This offset is from eq. (C2) of T07b, and applies solely for giants. The adopted value of $E(B-V)$ is from T07b.
[i] This result is the difference between the formal $(R-I)_C$ corrections derived for M67 and NGC 752 giants by using values of $V-K_2$. Allowance is made for the offset listed two entries above this one.

much the same thing as a derivation of s. Two tests are performed for the giants (see the entries in Table 7 flagged with double asterisks). Unfortunately, they yield formal zero-point corrections that disagree with $P = 1.9$ (compare the lower boldface entry in the last column of the table with the entry just below it). Note, however, that the last result listed in Table 7 is a null correction that is based partly on an M67 zero point that seems to be quite secure (recall § 5.3). As a result, the interim judgment adopted here is that no convincing case currently exists for adopting the boldface correction for the giants. The $(R-I)_C$ data for the giants are therefore adopted, although with an acknowledgment that further tests of their zero point should ultimately be made.

9. V MAGNITUDES: ESTABLISHING ZERO POINTS

Since all of our cluster databases contain V magnitudes as well as colors, zero-point tests for the magnitudes are included. Here the aim of the adopted procedure is to establish all the V magnitudes on the zero point for the Johnson et al. (1966, hereafter JMIW) measurements of field stars. In one case, cluster data that have been standardized directly to the JMIW system are used (see Table I of Dickens et al. 1968). Otherwise, cluster measurements are linked to that system by using data sets that contain measurements of both cluster stars and JMIW stars. Note that such data sets can be regarded as products of Sturch exercises.

For all the program clusters except M67, the results of the zero-point tests for V magnitudes are given in Table 8. The first five lines of the table apply for the Hyades and Coma. The first two lines show that for those clusters, there are differences between the adopted zero points and those of Johnson & Knuckles (1955). The third line shows that the zero point of southern hemisphere Hyades measurements by Joner et al. (2006) is consistent with the zero points of adopted northern hemisphere measurements.[6] In the fourth and fifth lines, the results of two satisfactory tests of the northern hemisphere measurements are reported. Using the most precise of the five tests (see line 3 of the table), one concludes that the zero point of the V magnitudes for the Hyades and Coma is established at a 2 σ level of 4 mmag.

The fifth through eighth lines of the table apply for Praesepe. This case turns out to be another one in which zero-point control does not yield a consistent set of tests. Like the color data for Praesepe and NGC 752, the V data for the two clusters are on a common zero point, so it is somewhat reassuring to find that a zero-point test for NGC 752 yields satisfactory results (see the penultimate line of Table 8). However, the balance of evidence is invoked here only as a stopgap measure. Future Sturch exercises in which Praesepe is compared to nearby clusters are planned.

In Table 9, results of zero-point tests of the augmented M67 V magnitudes are listed. Extrinsic data sets from photomultipliers are used for this purpose only if a substantial fraction of the data are from more than one measurement per datum. We adopt this policy because, in our experience, photomultiplier magnitudes from a single night of observing are less likely to be reliable than photomultiplier colors obtained in the same way.

The first line of entries in Table 9 is for a data set that, like ours, has been corrected for a gradient error (see Fig. 6 of Laugalys et al. 2004). No dependence on position in the cluster is detected in the differences between the two data sets (see the fourth entry of Table 1). However, such a dependence is found for the measurements of both Sandquist and Montgomery et al. (see the second and third lines in Table 9 and the fifth and sixth lines in Table 1). This deduction confirms results obtained graphically by Laugalys et al. (see their Figs. 6 and 9). Here as in the case of $(V-I)_C$, a small rms error is found for the Sandquist data, while a relatively large one is found for the data of Montgomery et al. (see the upper boldface entries in Table 9). With these results and the results of the $(V-I)_C$ analysis in hand, the dubious quality of the Montgomery et al. VI_C data becomes fully evident.

The fourth and fifth lines of Table 9 show that two consistency tests of our V magnitudes are satisfactory. All of the remaining

[6] Determining the consistency of V zero points for the northern and southern hemispheres has been a concern for some time (see, e.g., § 4 of Taylor & Joner 1996). For the sake of caution, the result quoted here should probably not be regarded as a definitive resolution of the overall problem. Further work on the problem is planned.

TABLE 8

HYADES, COMA, PRAESEPE, NGC 752: V OFFSETS

Cluster	Extrinsic Source[a]	Tested Data[b]	n[c]	ΔV[d] (mmag)
Hyades	Johnson & Knuckles (1955)[e]	1,2,3	77	24 ± 6
Coma	Johnson & Knuckles (1955)[e]	1,2	18	41 ± 8
Hyades	Joner et al. (2006)[f]	1,2	29	−5 ± 2
Hyades, Coma	JMIW (TJ92)	2	29	2 ± 3
Coma	JMIW (Stetson 1991)	1,2	12	−6 ± 4
Praesepe	JMIW (TJ92, JT95)[g]	4	15	−20 ± 4
Praesepe	JMIW (Dickens et al. 1968)[h]	4	18	0 ± 4
Praesepe	JMIW (Stetson 1991)	4	7	−16 ± 4
Praesepe	Johnson (1952)[h]	4	26	−2 ± 9
NGC 752	JMIW (TJ92, JT95)[g]	4	14	−3 ± 3
NGC 752	Johnson (1953)[h]	4	37	−21 ± 15

[a] JMIW is Johnson et al. (1966).

[b] Data are from following sources: (1) Table 4 of TJ92; (2) reductions described in § 3.3 of TJ05; (3) Table 2 of Joner et al. (2006); (4)measurements described in § 2.

[c] The quantity n is the number of stars for which data are compared.

[d] The quantity ΔV is in the sense "extrinsic source minus this paper."

[e] This result supersedes a counterpart stated in § 2.2 of JT90. The standard error given here includes a contribution from a zero-point error given by Johnson & Knuckles.

[f] Although this is a 2.5 σ result, it is not significant at 95% confidence when gauged by false-discovery rate using all entries in the table (see Miller et al. 2001).

[g] The comparison between the JMIW data and those in this paper is made by using data from the second source listed.

[h] The standard error given here includes a contribution from a zero-point error in the cited paper by Johnson.

entries except the one on the last line display zero-point offsets of a sort that has been well known for decades (for an early precedent, see Eggen 1963). However, the entry on the last line (see the formal offset in boldface) suggests that the V zero point for the new data is modestly satisfactory. Note that the 2 σ limit is relatively large (12 mmag) in this case.

TABLE 9

M67 V MAGNITUDES: OFFSETS AND ACCIDENTAL ERRORS

Extrinsic Source	Detector[a]	n[b]	ΔV[c] (mmag)	σ[d] (mmag)
Laugalys et al. (2004)	CCD	202	24 ± 1	12
Sandquist (2004)[e]	CCD	73	. . .	**9**
C: Montgomery et al. (1993)[e]	CCD	175	. . .	**30**
C: Anupama et al. (1994)[f]	CCD	30	−2 ± 3	16
C: Chevalier & Ilovaisky (1991)[f]	CCD	29	−1 ± 1	5
Gilliland et al. (1991)[g]	CCD	63	17 ± 2	11
Coleman (1982)	PM	13	12 ± 3	8
Eggen & Sandage (1964)	PM	56	22 ± 3	26
Sanders (1989)	PM	25	3 ± 3	18
JMIW (TJ92, JT97)[h]	PM	10	4 ± 6	. . .

[a] PM = photomultiplier data. For these data sets, only data for stars with $V < 13$ are analyzed.

[b] The quantity n is the number of stars for which data are compared.

[c] The quantity ΔV is in the sense "extrinsic source minus this paper."

[d] If numbers of measurements are given in the extrinsic source, σ is the rms error per measurement. Otherwise, σ is the rms error per data entry. No value of σ is given if accidental errors are known independently for data from the extrinsic source.

[e] The quantity ΔV is not given because a positional correction is required instead (see Table 1).

[f] Results in this paper have been derived (directly or indirectly) using JT90 standard-star data.

[g] We do not confirm the Laugalys et al. deduction that a positional error exists for these data.

[h] JMIW is Johnson et al. (1966). The comparison is made by using data on a uniform zero point from the other two cited papers.

10. THE CONTENTS OF THE CATALOGS

10.1. *The Catalogs and Their Photometric Sources*

With tests of data consistency complete, we describe the data files produced here and deposited in the CDS archives. As noted in § 1, those files include updated color and temperature listings for the Hyades. In § 6 of their paper, TJ05 present two catalogs for "effectively single" stars and one for binaries. Corresponding catalogs are produced here (for a sample, see Table 10).

When TJ05 appeared, Hyades values of $(R-I)_C$ from Joner et al. (2006) were not yet available. Those data have now been added to the source data for the three catalogs. In addition, the catalogs for effectively single stars now include both values of $(V-K)_J$ and V magnitudes. The colors are included because they are the arguments for the temperature calibration used to derive the temperatures listed in the catalogs (see below). Users can now compare isochrones to temperatures, values of $(V-K)_J$, and values of $(R-I)_C$ and see whether they obtain consistent results. As for the V magnitudes, they are secured (if possible) from the measurements whose zero points are tested in § 9. Otherwise, data from Johnson & Knuckles (1955) are used after the correction for the V offset given in Table 8 has been applied.

The new catalogs also include two data files each for Coma, Praesepe, and NGC 752. For each cluster, one file includes either Cousins *VRI* photometry from TJ85 (for Coma) or the new Cousins *VRI* data (for the other two clusters). A sample of one of those files is given in Table 11. The remaining files include temperature data and values of V and $(V-K)_J$. A sample of one of those files appears in Table 12.

For Coma, as for the Hyades, the adopted sources of V data have been described in § 9. For the other two clusters, new V measurements (except as noted in Table 12) are reported. The reported $(V-K)_J$ results have been transformed from values of $b-y$, $(R-I)_C$, and $V-K_2$, using transformations given by TJ06. An allowance is made for the $V-K_2$ offset implied by the entry for data set I_4 in Table 7. The temperatures yielded by this selection

TABLE 10
$(R - I)_C$ and Temperatures: Single Hyades Stars

vB	Cat.	Number	Kind[a]	$(R - I)_C$	σ[b]	$(V - K)_J$	σ[b]	θ[c]	σ[b]	V	σ[b]
1	Hic	15304	N	0.311	4.0	1.350	21.	0.846	4.5	7.376	3.2
2	Hic	15310	N	0.316	4.0	1.376	21.	0.851	4.5	7.750	3.2
4	Hic	16529	N	0.426	4.3	2.000	26.	0.990	5.7	8.856	9.6

[a] (G) a giant; (N) a dwarf nonbinary; (S) a binary treated as a single star.
[b] The value of σ has been multiplied by 1000.
[c] $\theta \equiv 5040/T_{\rm eff}$.

of input data have standard errors that satisfy the FM standard quite adequately.

For M67, the augmented database occupies one file, while temperatures are included in another. The augmented data supersede the Joner & Taylor (1990) V magnitude for I-51, which appears to be in error. In addition, the augmented data supersede the extant data for I-198 and I-199. In this case, the data being replaced are for stars that are a little too faint for precise measurements with the system used by Joner & Taylor. Concerning the temperature data, we note that they are based partly on values of $(V - R)_C$ from Sandquist (2004) instead of values of $b - y$. The latter are relatively sparse for M67, so the high precision of the Sandquist colors (see Table 5) recommends them as an obvious replacement. A transformation of the Sandquist data to values of $(R - I)_C$ is given in item 3 of Appendix A.

In the M67 temperature file, the V data are averages from the augmented M67 data and those of Sandquist. Here also, the Sandquist data are adopted because their precision is high (see Table 9). Before use, they are corrected for the positional gradient noted in § 9. Those corrections are applied by using equation (1) and appropriate entries in Table 1. Besides Cousins *VRI* and temperature catalogs, the M67 files include one containing corrected Sandquist V data. The file also includes Sandquist $(V - I)_C$ measurements. They require no adjustment (recall § 6) and hence have not been changed. A sample of this file is given in Table 13.

For clusters other than the Hyades, no versions of the new catalogs have been published before, and complete versions of the new catalogs are not being presented in this paper. It is therefore worthwhile to include some numerical information about the catalogs. The number of stars with Cousins photometry ranges from 17 for the sparse cluster Coma to 241 for M67. The number of stars with temperatures ranges from 27 for Coma to 347 for M67. The ranges in V for stars with temperatures are about 3 mag for NGC 752, 4 mag for Coma and Praesepe, and 8 mag for M67. For values of θ ($\equiv 5040/T_{\rm eff}$), most of the M67 rms errors range from 0.005 to 0.010. For Coma, Praesepe, and NGC 752, the errors are somewhat smaller because the clusters are brighter. In these cases, the rms error range is from 0.001 to 0.007.

10.2. *The Adopted Temperature Calibration*

Here, as in TJ05, temperatures are derived using the Di Benedetto (1998) calibration. Although more recent calibrations have been published (see, e.g., Ramírez & Meléndez 2005), the Di Benedetto calibration is supported by an analysis performed by Taylor (2001b). The only modification made to that calibration is a response to the publication of temperatures for giants based on angular diameters (see Mozurkewich et al. 2003). When those data are compared to relation 3 in Table 4 of Di Benedetto (1998) the following zero-point correction is obtained:

$$10^3(\Delta \log_{10} T) = 2.1 \pm 0.9. \quad (6)$$

This correction is applied to the tested relation.

10.3. *Binaries*

Since the catalog data are to be used in color-magnitude analysis, policies dealing with inclusion and exclusion of binaries are required. For the Hyades, the adopted procedure is still that given in § 5 of TJ05. For Coma and Praesepe, binaries are initially identified from radial velocity and speckle measurements. The papers consulted for those data include Mason et al. (1993), Abt & Willmarth (1999), Mermilliod & Mayor (1999), and Bouvier et al. (2001). Data for binaries identified from those papers are retained in the temperature catalogs for Coma and Praesepe only if the binaries fall within the main sequence scatter in the color-magnitude diagrams of those clusters. Photometry for binaries has not been excluded from the Cousins *VRI* catalogs.

M67 and NGC 752 have vertical subgiant branches, so it is difficult to use their color-magnitude diagrams to test for binary status. Fortunately, reasonably comprehensive lists of known binaries are readily available for both clusters (see Table 3 of Sandquist 2004 and Table 1 of Daniel et al. 1994, respectively). Using those lists, data for double-lined spectroscopic binaries and RS CVn stars have been excluded from the temperature catalogs. Data for single-lined binaries have been retained in those catalogs and are flagged there. Here also photometry for binaries has not been excluded from the Cousins *VRI* catalogs.

10.4. *Effects of Reddening Uncertainties*

It should be noted that the errors quoted for the catalog values of θ do not include the effects of the standard errors of the reddening values for the clusters. If $\delta\theta$ is defined as the error induced by the standard error of $E(B - V)$, then $|10^3\delta\theta|$ is ≤ 2.4 for M67 and Praesepe, ≤ 2.0 for NGC 752, and zero for the other clusters. At worst, these errors are comparable to the errors listed for the catalog values of θ. If necessary, allowances should be made for the values of $\delta\theta$ just quoted when color-magnitude analyses are performed.

TABLE 11
Praesepe: Cousins *VRI* Photometry

WEBDA No.	Cat.	No.	V	σ[a]	$(V - R)_C$	σ[a]	$(R - I)_C$	σ[a]
31	KW	31	9.726	8.0	0.305	6.2	0.282	7.4
34	KW	34	9.457	4.6	0.242	3.9	0.253	4.2
40	KW	40	7.767	5.3	0.099	3.7	0.091	4.3

[a] The value of σ has been multiplied by 1000.

11. PERSPECTIVES

If we could be confident that the results in Tables 3–9 are credible prima facie, this paper could now be ended with a summary. In fact, VdBS present evidence to the contrary that cannot be overlooked. In their § 2.2, those authors refer to formal

TABLE 12

PRAESEPE: V, $(V-K)_J$, TEMPERATURES

WEBDA No.	Cat.	No.	V [a]	σ [b]	$(V-K)_J$ [c]	σ [b]	θ [d]	σ [b]
31	KW	31	9.642	8.0	1.169	8.	0.806	1.6
34	KW	34	9.373	4.6	0.925	6.	0.752	1.4
38	KW	38	8.616	9.0	0.673	15.	0.696	3.2

[a] These data have been corrected for absorption.
[b] The value of σ has been multiplied by 1000. For giants, values of V are from Johnson (1952).
[c] These data have been corrected for reddening. For the Praesepe giants, values of $(R-I)_C$ are averages from Canterna (1976), Mendoza (1967), and Eggen (1985). Transformations required to convert those data to $(R-I)_C$ are from Table 4 of Taylor (1986) and Appendix B of Taylor (1996). For all giants, values of $(V-K)_J$ are derived from $(R-I)_C$ by applying the third transformation in Table IV of Taylor et al. (1987).
[d] $\theta \equiv 5040/T_{\rm eff}$. These data have been corrected for reddening.

TABLE 13

SANDQUIST (2004): $(V-I)_C$ AND CORRECTED V

WEBDA No.	V [a]	$(V-I)_C$ [b]
6	12.796	0.653
12	13.080	0.649
13	14.115	0.682

[a] These data have been corrected for positional effect.
[b] These data are as given by Sandquist (2004).

zero-point offsets presented by TJ96 that are fully as small as those derived in this paper (see especially Table 3 of TJ96). The smallest offset quoted by TJ96 is 0.1 ± 0.5 mmag, and it is featured prominently in §§ 7–8 of their paper (see also the second line in Table 3 of this paper). Note that in this case, the implied 2 σ limit is 1.0 mmag. According to VdBS, however, TJ96 found no such limit that was better than about 0.01 mag (or 10 mmag).

A misrepresentation of a published result by an order of magnitude is difficult to excuse. However, we leave such issues to a subsequent paper (Taylor 2008) and focus instead on a likely reason for the problem. In a paper published at the same time as VdBS, Stetson et al. (2004) argue that for *UBVRI* photometry, there is a lower limit on data scatter of about 0.01–0.02 mag (see § 3 of Stetson et al.). Although that view has since been modified by one of the participating authors (see Catalan et al. 2006), Stetson et al. deem the limit to be inescapable. It seems plausible that VdBS extended the limit (called here the "10 mmag limit") to zero-point coherence and then projected it onto the results of TJ96 because they expected to see it there.

Thanks to unpublished dialog with other photometrists, we are aware of other instances in which results that satisfy the FM standard have not been accepted. Although the credibility of that standard has been addressed in print (see § 7.3 of TJ06), we offer here some additional comments in the hope of clarifying the issue further.

11.1. *Zero-Point Jitter: A Published Illustration*

We first direct the attention of readers to Table 14, which is drawn from Table 1 of TJ88. That table contains $(R-I)_C$ data vectors from measurements of M67 giants. Three available vectors of this sort have been set aside because their zero points disagree with those of the remaining data (see § IV of TJ88). Those data comprise the seven data vectors given in the table. Note that four of the vectors contain data that have been transformed from photometric systems other than $(R-I)_C$.

The 10 mmag limit yields a definite prediction about the transformed data in particular. Since transformations of results from diverse instrumental systems to a standard system must allegedly respect the limit, the same outcome must hold a fortiori when data from one standard system are transformed to another. Note that the same conclusion is reached if one starts with the adverse judgment about transformations noted in § 4. That prediction may be tested by looking first at the last two lines of Table 14, in which mean residuals and their standard errors are listed. The means are calculated relative to the data of Cohen et al. (1978).

Note that the means do not display the predicted jitter. In addition, if the individual contributing data listed above the means are consulted, no support is found for any suspicion that the means are simply misleading representations of offsets that are actually $\geq$10 mmag. We point out that counterpart data vectors with a similar lack of zero-point jitter are the sources of the null mean offsets quoted in §§ 5–6 and § 8.

The history from which Table 14 is drawn offers two other insights of interest. The table is part of a series of discussions that all present similar results (see Table VI of TJ85, Table 4 of Taylor 1986, Table 3 of T96, Tables 1–3 and 5 of TJ05, § 7.3 of TJ06, and Table 6 of T07b). There is therefore no basis for any suspicion that the examples of adherence to the FM standard given in §§ 5–6 and § 8 are a dubious latter-day innovation. In addition, we note that the FM standard can apply to transformations from instrumental to standard systems, as one would expect if the standard is genuine (see Table VI of TJ85). All told, there is clearly no basis for rejecting the FM standard in favor of a universal 10 mmag limit.

11.2. *Corrective Measures: An Illustration*

We also point out that when data do not satisfy the FM standard, corrective measures may be feasible. This point may be illustrated by considering *UBVRI* magnitudes for NGC 188 assembled by Stetson et al. (2004). Those authors show that zero-point differences among those data are as large as 86 mmag.

Stetson et al. (2004) analyze a total of 13 data sets. However, they do not include $B-V$ measurements by Jennens & Helfer (1975b). The significance of the Jennens & Helfer (hereafter JH) data becomes clear when one notes that Jennens & Helfer (1975b) also measured NGC 752 and that Jennens & Helfer (1975a) report measurements of field stars. The accounts in the two papers suggest that all three sets of measurements can be regarded as the product of a de facto Sturch exercise.

Acting on this hint, we apply the JH data in the same way that comparable databases are used in § 9. The JH data are compared to three data sets, with one including values of $B-V$ for NGC 188 that have been reduced by Stetson et al. (2004) to a compromise zero point. A second comparison is made to published $B-V$ measurements for NGC 752, and it reveals that the zero points of published data for that cluster cohere at the FM level (again see Table 6 of T07b). A third comparison is made to values of $B-V$ measured for field stars by JMIW. The resulting formal zero-point difference is found to be 0.6 ± 1.4 mmag.

Since the zero points of the JMIW and JH data are found to be closely identical, one can regard the JH data as a proxy for the JMIW data. A comparison of the JH and Stetson et al. data then yields a formal correction required to put the $B-V$ data of Stetson et al. (2004) on the JMIW zero point. That correction turns out to be -11 ± 9 mmag. The reliability of this result might be questioned because almost all of the adopted JH data for NGC 188 are from a single measurement per star. The same is true for

TABLE 14
M67: An $(R - I)_C$ Consistency Test

Star	B[a] $(R - I)_K$[b]	C[c] $T_1 - T_2$[b]	CFP[d] $V - K$[b]	WMO[e] $(R - I)_C$[b]	KPNO[f] $(R - I)_C$[b]	Me[g] $(R - I)_J$[b]	TJ85[h] $(R - I)_J$[bh]
F 84	...	475	478	485	477	471	475
F 105	544	548	541	554	...	524	...
F 108	617	606	609	...	602	560	608
F 141	470	468	476	475	...	471	...
F 151	460	465	465	476	...	471	466
F 164	...	486	486	482	...	486	...
F 170	596	...	596	594	...	597	589
F 193	460	...	445	...	...	448	...
F 223	...	478	487	455	487	479	...
F 224	491	486	481	489	...	479	...
F 244	376	419	424	421	422	433	...
F 266	...	485	...	475	...	494	...
S 488[i]	...	800	...	785	...	...	...
$\delta(R - I)_C$[j]	2.9	1.8	...	0.3	2.5	6.3	2.5
$\sigma(\delta)$[k]	7.0	1.8	...	4.5	1.5	4.8	6.1

[a] Brooke (1969). When these data are inspected, allowance should be made for the scatter introduced by their rms error of 19 mmag.
[b] The quoted data originally appeared as values of this color index. The Cohen et al. (1978) data appeared as values of $V - K$ on the CTIO/CIT system.
[c] Canterna (1976).
[d] Cohen et al. (1978).
[e] See entries for West Mountain Observatory data in Table IV of JT88.
[f] See Table V of TJ85 and entries for KPNO data in Table IV of JT88.
[g] Mendoza (1967).
[h] See Table IV of the cited source.
[i] S = Sanders (1977).
[j] This is the absolute value of the mean residual from the data of Cohen et al. (1978). An error in the mean residual published originally for the WMO data has been corrected.
[k] This is the standard error of the mean residual given just above.

the JH data for NGC 752, however, and the basic quality of those data does not appear to have been compromised as a result.

For $U - B$, this procedure is not useful because the rms error of the derived formal correction turns out to be 22 mmag. In addition, the derived 2 σ limit for the $B - V$ offset is 18 mmag, which is admittedly rather large when gauged by FM standards. Nevertheless, the size of the $B - V$ correction underscores two key points: (1) the correction process is feasible, and (2) adoption of a rigid 10 mmag limit is undesirable partly because it is likely to discourage derivation and use of such corrections. If further Sturch comparisons are made (between NGC 188 and M67, for example), it may be quite possible to obtain even more promising correction procedures.

12. SUMMARY

In this paper, new Cousins *VRI* data are presented for NGC 752 and Praesepe, and new and extant data are combined into an augmented database for M67. For those three clusters, a set of catalogs is produced containing Cousins *VRI* photometry, reddening-corrected values of $(V - K)_J$, and temperatures. The same is done for Coma by using both previously published and newly derived Cousins photometry. An extant set of catalogs for the Hyades is updated to include *V* magnitudes and values of $(R - I)_C$ published since the original catalogs appeared. Finally, a catalog containing Sandquist (2004) $(V - I)_C$ and *V* data is produced after a gradient across the face of the cluster in those *V* data has been corrected.

In a parallel effort, the consistency of $(V - I)_C$ databases for M67 is tested by performing an analysis with the following features:

1. the FM standard is adopted,
2. statistical analysis is applied,
3. no use of $B - V$ measurements is made,
4. no color-magnitude comparisons between M67 and NGC 188 are performed,
5. no assumption is made that independent systematic errors have canceled,
6. data reduced ultimately to the system of JT90 are included,
7. data based on standardization that is independent of ours are included,
8. results of Sturch exercises are used.

(see § 3 for the first two features and § 4 for the others). It is found that the new M67 data and those of Sandquist (2004) are on the E region zero point. In contrast, $(V - I)_C$ measurements by Montgomery et al. (1993) (and very likely those of Richer et al. [1998] as well) are found to be too red by 27 ± 1 mmag or more. Zero-point tests of the Cousins *VRI* colors presented here for Coma, Praesepe, and NGC 752 yield satisfactory results. A likely scale factor error in the Montgomery et al. colors is found, but tests that can be performed at present suggest that the scale factors of the Sandquist colors and those presented in this paper are satisfactory. For the most part, zero-point tests of *V* magnitudes are also satisfactory, although it is found that further work on Praesepe and M67 *V* magnitudes would be useful.

The proper context for the results in this paper is reviewed, and it is pointed out that they follow onto a fairly extensive set of fully comparable counterparts. The need to avoid blocking the road of inquiry by arguing against the FM standard is also noted.

In the research reported in this paper, extensive use has been made of the SIMBAD database (operated at CDS, Strasbourg, France), the WEBDA database (operated at the Institute for

Astronomy at the University of Vienna), and the Smithsonian/NASA ADS listings. We return sincere thanks to the operators of those Web sites. Page charges for this paper have been generously underwritten by the College of Physical and Mathematical Sciences and the Physics and Astronomy Department of Brigham Young University.

APPENDIX A

NOTES ON TRANSFORMATIONS

1. $(V-R)_\mathrm{J}$.—To transform these data to values of $(V-R)_\mathrm{L}$, the equations required initially are equation (5) of this paper and the equation at the top of the second page of Table 4 in Taylor (1986). In the form required here, that equation is

$$(V-R)_\mathrm{J} = 1.394(V-R)_\mathrm{C} + 0.042 \qquad \text{(A1)}$$

and applies if 0.012 mag $\leq (V-R)_\mathrm{C} \leq$ 0.414 mag. When the two relations just mentioned have been applied, it is found that an auxiliary equation is also required. Let

$$Y = SX + Z, \qquad \text{(A2)}$$

with X being interim transformed values of $(V-R)_\mathrm{J}$ and Y being $(V-R)_\mathrm{L}$. From least-squares analysis, it is found that $S = 1.022 \pm 0.010$ and $Z = -0.009 \pm 0.003$ mag, respectively. Combining this equation with the two cited already yields the following result:

$$(V-R)_\mathrm{L} = 0.741(V-R)_\mathrm{J} - 0.040. \qquad \text{(A3)}$$

It should be remembered that equation (A2) applies for the $(V-R)_\mathrm{J}$ data of Mendoza (1967) specifically.

2. $V-K_2$.—To transform these data to values of $(V-K)_\mathrm{J}$, equations (A13) and (A14) from Table 9 of TJ05 are revised so that $V-K_2$ is the independent variable and are then applied. To determine the color range for which those equations are applicable, values of $(R-I)_\mathrm{C}$ are transformed to $V-K_2$ by using the equations just noted and entries 6–8 in Table 4 of TJ06. A least-squares analysis is then applied. If Y in equation (A2) represents direct values of $V-K_2$ and X represents values of $V-K_2$ from transformations, it is found that $S = 1.008 \pm 0.005$ and $Z = -0.015 \pm 0.008$ mag. Since neither $S-1$ nor Z differs from zero at the 2 σ level, it is concluded that equations (A13) and (A14) of TJ05 are correct over the color range of the transformed data: 0.18 mag $\leq V-K_2 \leq$ 2.97 mag. For $(R-I)_\mathrm{C}$, the corresponding range runs from 0.011 to 0.614 mag.

3. *Sandquist values of* $(V-I)_\mathrm{C}$.—The basic equations applied to the data of Sandquist (2004) are entries 3–5 in Table 4 of TJ06. Allowance is made for the zero-point offset listed for the Sandquist data in Table 5. When this has been done, three equations of the form

$$(R-I)_\mathrm{C} = S_S(V-I)_\mathrm{S} + Z_S \qquad \text{(A4)}$$

result. The derived numerical values of S_S and Z_S are as follows:

1. If $-0.008 \leq (V-I)_\mathrm{S} \leq 0.210$, $S_S = 0.497$ and $Z_S = 0.004$.
2. If $0.210 \leq (V-I)_\mathrm{S} \leq 0.624$, $S_S = 0.479$ and $Z_S = 0.011$.
3. If $0.624 \leq (V-I)_\mathrm{S} \leq 0.988$, $S_S = 0.412$ and $Z_S = 0.053$.

All values of Z_S and all range limits are in magnitudes.

APPENDIX B

COMPARISONS TO THE E REGION ZERO POINT

The entries for the Sandquist (2004) and Montgomery et al. (1993) data in Table 5 refer those data to the zero point of the augmented database. If they are referred instead to the E region zero point, this must be done by reversing the discussion of § 5 and proceeding back through the augmented M67 data and the Hyades. Here it is useful to assume that the zero-point uncertainty introduced at each of these steps is from the best of the pertinent zero-point tests in Tables 5 and 3, respectively. We also make the conservative assumption that $(V-I)_\mathrm{C}$ errors may be obtained by adding $(V-R)_\mathrm{C}$ and $(R-I)_\mathrm{C}$ errors in quadrature. Adding standard errors of 1.8 and 0.8 mmag from Table 5 and 1.3 and 1.0 mmag from Table 3 in quadrature, we find that the net "transfer error" is 2.5 mmag.

For the Montgomery et al. data, adding the transfer error in quadrature to the error quoted in Table 5 yields the following result:

$$\Delta(V-I)_\mathrm{C} = 27 \pm 2.8 \text{ mmag}. \qquad \text{(B1)}$$

Here unlike § 5.3, $\Delta(V-I)_\mathrm{C}$ represents the actual difference between the Montgomery et al. data and the augmented M67 database after the 2 mmag correction discussed in § 5.3 has been applied. A t-test shows that $\Delta(V-I)_\mathrm{C}$ differs from zero with $P > 4.7$. No testing of this result in company with other values of $\Delta(V-I)_\mathrm{C}$ is required to conclude that it is highly statistically significant.

For the Sandquist data,

$$\Delta(V - I)_C = -4 \pm 2.7 \text{ mmag}. \tag{B2}$$

Here also allowance has been made for the 2 mmag correction just mentioned. In this case, $P < 0$, so we conclude that the zero points of the Sandquist and E region data are indistinguishable.

REFERENCES

Abt, H., & Willmarth, D. W. 1999, ApJ, 521, 682
An, D., Terndrup, D. M., Pinsonneault, M. H., Paulson, D. B., Hanson, R. B., & Stauffer, J. R. 2007, ApJ, 655, 233
Anupama, G. C., Kembhavi, A, K., Prabhu, T. P., Singh, K. P., & Bhat, P. N. 1994, A&AS, 103, 315
Bouvier, J., Duchêne, G., Mermilliod, J.-C., & Simon, T. 2001, A&A, 375, 989
Brooke, A. L. 1969, Ph.D. thesis, Australian National Univ.
Buser, R. 1978, A&A, 62, 411
Canterna, R. 1976, AJ, 81, 228
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Catalan, M., et al. 2006, ApJ, 651, L133
Chevalier, C., & Ilovaisky, S. A. 1991, A&AS, 90, 225
Cohen, J. G., Frogel, J. A., & Persson, S. E. 1978, ApJ, 222, 165
Coleman, L. A. 1982, AJ, 87, 369
Crawford, D. L. 1975, AJ, 80, 955
Crawford, D. L., & Barnes, J. V. 1969, AJ, 74, 407
———. 1970, AJ, 75, 946
Crawford, D. L., & Mandwewala, N. 1976, PASP, 88, 917
Cutri, R. M., et al. 2003, 2MASS All-Sky Catalog of Point Sources (Pasadena: IPAC)
Daniel, S. A., Latham, D. W., Mathieu, R. D., & Twarog, B. A. 1994, PASP, 106, 281
Di Benedetto, G. P. 1998, A&A, 339, 858
Dickens, R. J., Kraft, R. P., & Krzeminski, W. 1968, AJ, 73, 6
Eggen, O. J. 1963, ApJ, 138, 356
———. 1985, AJ, 90, 333
Eggen, O. J., & Sandage, A. R. 1964, ApJ, 140, 130
Gilliland, R. L., et al. 1991, AJ, 101, 541
Jennens, P. A., & Helfer, H. L. 1975a, MNRAS, 172, 667
———. 1975b, MNRAS, 172, 681
Johnson, H. L. 1952, ApJ, 166, 640
———. 1953, ApJ, 117, 356
Johnson, H. L., & Knuckles, C. F. 1955, ApJ, 122, 209
Johnson, H. L., Mitchell, R. I., Iriarte, B., & Wiśniewski, W. Z. 1966, Commun. Lunar Planet. Lab., 4, 99 (JMIW)
Joner, M. D., & Taylor, B. J. 1988, AJ, 96, 218
———. 1990, PASP, 102, 655 (JT90)
———. 1995, PASP, 107, 351 (JT95)
———. 1997, PASP, 109, 1122 (JT97)
Joner, M. D., Taylor, B. J., Laney, C. D., & van Wyk, F. 2006, AJ, 132, 111
Landolt, A. U. 1983, AJ, 88, 439
———. 1992, AJ, 104, 340
Laugalys, V., Kazlauskas, A., Boyle, R. P., Vrba, F. J., Davis Philip, A. G., & Straižys, V. 2004, Baltic Astron., 13, 1
Mason, B. D., Hartkopf, W. I., McAlister, H. A., & Sowell, J. 1993, AJ, 106, 637
Mendoza, V. E. E. 1967, Bol. Obs. Tonantzintla Tacubaya, 4, 149
Mermilliod, J.-C., & Mayor, M. 1999, A&A, 352, 479
Menzies, J. W., Cousins, A. W. J., Banfield, R. M., & Laing, J. D. 1989, South African Astron. Obs. Circ., 13, 1
Miller, C. J., et al. 2001, AJ, 122, 3492
Montgomery, K. A., Marshall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Mozurkewich, D., et al. 2003, AJ, 126, 2502
Pinsonneault, M. H., Stauffer, J., Soderblom, D. R., King, J. R., & Hanson, R. B. 1998, ApJ, 504, 170
Ramírez, I., & Meléndez, J. 2005, ApJ, 626, 465
Richer, H., Fahlman, G. G., Rosvick, J., & Ibata, R. 1998, ApJ, 504, L91
Sanders, W. L. 1977, A&AS, 27, 89
———. 1989, Rev. Mex. AA, 17, 31
Sandquist, E. L. 2004, MNRAS, 347, 101
Stassun, K. G., van den Berg, M., Mathieu, R. D., & Verbunt, F. 2002, A&A, 382, 899
Stetson, P. B. 1991, AJ, 102, 589
Stetson, P. B., McClure, R. D., & VandenBerg, D. A. 2004, PASP, 116, 1012
Strom, S. E., Strom, K. M., & Bregman, J. N. 1971, PASP, 83, 768
Sturch, C. 1972, PASP, 84, 666
———. 1973, PASP, 85, 724
Taylor, B. J. 1986, ApJS, 60, 577
———. 1991, ApJS, 76, 715
———. 1996, ApJS, 102, 105 (T96)
———. 2000, A&A, 362, 563 (T00)
———. 2001a, A&A, 377, 473
———. 2001b, A&A, 398, 721
———. 2006, AJ, 132, 2453 (T06)
———. 2007a, AJ, 133, 370 (T07a)
———. 2007b, AJ, 134, 934 (T07b)
———. 2008, ApJ, submitted
Taylor, B. J., & Joner, M. D. 1985, AJ, 90, 479 (TJ85)
———. 1988, AJ, 96, 211 (TJ88)
———. 1992, PASP, 107, 351 (TJ92)
———. 1996, AJ, 111, 1338 (TJ96)
———. 2005, ApJS, 159, 100 (TJ05)
———. 2006, PASP, 118, 1716 (TJ06)
Taylor, B. J., Johnson, S. B., & Joner, M. D. 1987, AJ, 93, 1253
VandenBerg, D. A., & Clem, J. L. 2003, AJ, 126, 778
VandenBerg, D. A., & Stetson, P. B. 2004, PASP, 116, 997 (VdBS)
Whitford, A. E. 1958, AJ, 63, 201

Chapter 10

Tests of Broadband Photometric Consistency for Standard Stars, the Hyades, and M67

Paper 4 is the publication titled "Tests of Broadband Photometric Consistency for Standard Stars, the Hyades, and M67" by Joner et al. (2008) and is presented in an 11 page article in volume 136 of the *Astronomical Journal*. This paper reports new photoelectric $BV(RI)_C$ photometry for 19 Hyades stars and 11 M67 stars that was secured during another observing season at SAAO using the 0.5-m telescope at Sutherland. The zero-points for these data compare closely to the previous SAAO photometry published in Joner et al. (2006). The new M67 measurements are compared to the data published in the catalogs of Taylor, Joner, and Jeffery (2008) and are found to be consistent with those data. These results confirm the scale-factor problem derived for the data of Montgomery, Marschall, and Janes (1993). Numerous tests are made on the *B-V* colors and it is found that previously suspected problems can be resolved. The Sandquist (2004) *B-V* data appear to be satisfactory. However, the Montgomery, Marschall, and Janes (1993) data for M67 are apparently not on a single zero-point in *B-V*. The previous conclusion about the zero-point of the E region *B-V* zero-point needing a correction of about -9 mmag is apparently well-supported. Further testing is suggested in order to strengthen this conclusion.

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TESTS OF BROADBAND PHOTOMETRIC CONSISTENCY FOR STANDARD STARS, THE HYADES, AND M67

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ABSTRACT

New South African Astronomical Observatory (SAAO) $BV(RI)_C$ measurements of 19 Hyades stars and 11 M67 stars are reported. The zero points of the new color indices conform closely to those of SAAO data reported in a previous paper. In addition, the new M67 measurements of $(V - R)_C$ and $(R - I)_C$ are compared to data published previously by Taylor, Joner, and Jeffery. The results support conclusions drawn by those authors that the scale factors of their data are correct and that a scale factor problem exists in measurements published by Montgomery, Marshall, and Janes. The new values of $B - V$ are used with *Tycho* data in tests of extant Hyades and M67 measurements and of the accuracy of the SAAO $B - V$ system. A problem encountered previously with the Hyades $B - V$ zero point is resolved, and an extant Hyades relation between $B - V$ and $(R - I)_C$ is re-zeroed. A satisfactory zero point is also obtained for M67, and published photomultiplier values of $B - V$ are reduced to that zero point, averaged, and tabulated. It is found that the zero point of $B - V$ data published by Sandquist is satisfactory. However, tests of $B - V$ measurements made by Montgomery et al. suggest that those data are not on a single zero point. Finally, the scale factor of the E region $B - V$ system is found to be satisfactory, but a well-supported interim conclusion is drawn that E region values of $B - V$ should be corrected by about −9 mmag. It is suggested that this conclusion be tested by using instrumental systems that have not yet contributed to the testing process.

Key words: methods: statistical – open clusters and associations: individual (M67, Hyades) – stars: fundamental parameters – techniques: photometric

1. INTRODUCTION

It has been known for some time that when published bodies of broadband photometry are compared, disturbing inconsistencies can be found. This problem has appeared repeatedly when systems of standard stars are tested (see for example, Oja 1994; Menzies & Marang 1996). In addition, it has appeared when measurements of cluster stars are collected from diverse sources (see especially Table 3 of Stetson et al. 2004). As a result, theorists who wish to analyze cluster data may be constrained to discuss their accuracy at length before making even tentative choices among them (see for example, Section 2.2 of VandenBerg & Stetson 2004).

Partly because they are so persistent, problems like these are arguably the most significant challenges that photometrists face. Fortunately, it is possible to overcome them in at least three ways. For *BV* photometry specifically, one may appeal to the *Tycho* B_T, V_T system (Perryman et al. 1997). This system is likely to be uniform over the entire sky, and it can be transformed with confidence to a useful version of *BV* photometry (see Section 4). By applying this system, one can escape obstacles such as azimuthal extinction variation and photomultiplier flexure that can hamper ground-based photometry.

A second possibility is to compare groups of stars by measuring them on the same nights with a single instrumental system. As far as we know, the earliest published examples of this procedure appear in Sturch (1972, 1973). Useful results may be obtained from either straightforward "Sturch exercises" or from overlapping sets of such exercises.

A third possibility is to apply measurements made with an unusually stable instrumental system. This procedure is suitable for both *BV* data and Cousins *RI* photometry. In particular, it has been adopted recently in the first paper in this series (Joner et al. 2006, hereafter Paper I). Using a dedicated *BVRI* system at the South African Astronomical Observatory (SAAO), the authors made new measurements of the Hyades and then compared them to previously published photometry.

In this paper, we follow up on the analysis performed in Paper I. Using further SAAO photometry of the Hyades and new SAAO photometry of M67, we investigate four problems. One of these concerns the character of extant $V(RI)_C$ photometry for M67. In this case, we augment a discussion given recently by Taylor et al. (2008). A second problem concerns the zero point of Hyades $B - V$ photometry, and it was discussed but not solved in Paper I. The third problem concerns the zero point of M67 $B - V$ photometry, and the fourth is the overall relationship of the SAAO and Johnson $B - V$ systems.

The structure of this paper is as follows. A brief description of reduction procedures appears in Section 2, and the new data are also presented there. Statistical procedures and photometric transformations are described briefly in Sections 3 and 4, respectively. In Section 5, the M67 and Hyades *VRI* measurements are compared with previously published data. $B - V$ analyses appear in Section 6 (for field stars and the Hyades) and Section 8 (for M67). Section 7 resolves a problem posed by the zero-point status of photometry by Johnson and his collaborators, while Section 9 explores a problem posed by the conclusions drawn in Section 6. The paper concludes in Section 10 with a review of results.

2. REDUCTION PROCEDURES AND RESULTS

As in Paper I, measurements were made with the 0.5 m telescope and modular photometer at the SAAO Sutherland station. The Hyades were observed from 2006 October through 2007 January, while M67 was observed from 2006 January through 2007 April. The adopted reduction procedures have been described in Section 2 of Paper I, so only a few comments about them will be made here. We first note that substantial non-linear corrections were not applied to the data because very blue

Table 1
New SAAO $BV(RI)_C$ Data for the Hyades

vB[a]	HIP	GSC[b]	V[c]	$B-V$[c]	$V-R$[c]	$R-I$[c]	$V-I$[c]	n[d]
7[e]	18327	01253–00868	8.996(3.2)[f]	0.906(3.7)	0.490(2.0)	0.426(2.0)	0.916(2.8)	6
64[g]	20741	01265–00241	8.106(6.6)	0.677(4.7)	0.362(2.5)	0.341(4.2)	0.703(2.8)	4
66[g]	20826	00676–00062	7.503(2.3)	0.562(6.6)	0.315(2.0)	0.295(4.1)	0.608(4.5)	3
89[g]	21137	01265–01173	6.008(2.5)	0.333(3.4)	0.199(1.8)	0.192(2.1)	0.391(1.3)	4
109	21741	01830–01358	9.390(5.5)	0.823(5.3)	0.431(6.1)	0.395(3.3)	0.825(7.8)	4
173	20485	01264–00902	10.464(4.3)	1.242(2.8)	0.735(3.0)	0.622(1.7)	1.357(3.0)	6
174[g]	20563	01269–01212	9.980(5.0)	1.069(3.3)	0.598(2.5)	0.504(1.9)	1.101(2.3)	4
175[g]	...	01269–00128	10.275(2.5)	1.035(2.3)	0.584(2.0)	0.487(1.5)	1.071(2.7)	3
176[g]	20679	...	9.015(1.5)	0.946(3.0)	0.526(1.9)	0.455(2.0)	0.981(0.3)	3
181[h]	...	...	10.318(9.0)	1.168(2.5)	0.676(2.8)	0.575(2.4)	1.252(3.0)	3
183[g]	...	01266–00944	9.649(1.8)	0.928(5.0)	0.503(2.0)	0.437(4.9)	0.940(3.5)	5
229	19263	01250–00414	9.907(4.4)	1.034(1.8)	0.575(1.9)	0.485(2.9)	1.060(4.2)	6
231	19207	01250–00004	10.465(3.5)	1.192(3.3)[i]	0.695(3.3)	0.583(3.0)	1.278(1.3)	5
253	20086	01268–00707	9.989(4.7)	1.119(1.7)	0.655(1.9)	0.612(1.0)	1.267(2.1)	4
262	20527	00680–00889	10.872(4.5)	1.299(8.4)[i]	0.774(2.2)	0.665(5.5)	1.439(3.3)	4
291	21261	01274–01346	10.687(5.2)	1.233(8.4)[i]	0.721(3.1)	0.596(2.7)	1.317(4.9)	5
311	21723	00690–00945	10.020(10.0)	1.092(8.5)	0.621(8.0)	0.516(3.0)	1.137(5.0)	2
324	...	01279–02259	9.823(4.5)	1.071(3.6)	0.602(3.2)	0.508(1.5)	1.110(4.6)	5
...	19808[j]	00675–00186	10.675(2.7)	1.239(9.2)[i]	0.733(2.3)	0.637(2.9)	1.370(2.1)	4
σ_0[k]	...	...	0.009	0.008	0.006	0.006	0.008	...

Notes.
[a] This is the van Beuren (1952) number.
[b] This is the number from the *Hubble Guide Star Catalog.*
[c] Entries in parentheses are standard deviations in millimags derived from the scatter for each individual set of measurements. The $B-V$ data are on the SAAO (not the Johnson et al. 1966) zero point. Values of V and $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see Equation (5) of Taylor & Joner 1996).
[d] Number of measurements.
[e] Judging from the new V datum and its counterpart in Table 2 of Paper I, this star is variable in V with a range of about 32 mmag.
[f] This datum has been derived from five measurements.
[g] Measurements in Paper I and/or this paper suggest that this star may vary in V.
[h] This star is HD 285805.
[i] For these measurements, $\sigma_0 = 15.8$ mmag.
[j] This star is vA 68.
[k] The quoted values of σ_0 are rms errors in millimags. Each value has been derived from at least 79 measurements.

and very red stars were avoided. In the SAAO reduction procedure, the largest of these corrections range from 20 to 60 mmag (in absolute value). For the G and K dwarfs considered in Paper I, however, such corrections did not exceed 2 mmag. Here, despite the fact that measurements of the B star F 81 (see Johnson & Sandage 1955) are included, the corresponding upper limit to the corrections is only 6 mmag.

It should also be noted that (as in Paper I) the adopted extinction coefficients for each night were tested by comparing measurements of standard stars made near the zenith with measurements made at air masses of at least 1.5. That practice was deemed to be adequate for observing M67 and the Hyades because at Sutherland both clusters culminate at about 1.4 air masses. Finally, there was continued reliance on the stability of derived transformation coefficients during intervals of several months. Encouraging support for the success of these policies is offered by the close agreement between the zero points of the new data and those of the Paper I data (see Section 5 and entry 1 of Section 6).

The new data (for 19 Hyades stars and 11 M67 stars) are given in Tables 1 and 2, respectively. The M67 data are limited to stars with $V < 11.5$ because of the size of the telescope used.[3] It should be noted that Table 2 includes measurements of S1082 = ES Cnc, a triple system and eclipsing binary (see Van den Berg et al. 2001 and Sandquist et al. 2003) whose status was noted only after it had been included in our list of program stars. Results of individual measurements of ES Cnc are given in Table 3.

3. STATISTICAL PROCEDURES

Two statistical procedures used in Paper I are also applied here. One (a χ^2 differencing algorithm) is used to compare the zero points of data vectors. The other is a two-error least-squares algorithm that is used to derive linear relations between photometric data vectors. This algorithm yields values of $s \equiv 100(S-1)$, with S being a slope.

Most of the pertinent details about these procedures are given in the Appendix to Paper I. However, that source does not include an algorithm for identifying wild points that can appear when either of the two adopted procedures is applied. Wild points are detected by applying Thompson t tests, and the results are then interpreted by using false-discovery rate (FDR). The Thompson t test is the second statistical tool described in Section 6.2 of Taylor (2000). A convenient summary of FDR appears in Section 3 of Miller et al. (2001).

Other statistical procedures applied here include (1) the basic Student's t test, (2) the F (variance-ratio) test, (3) a

[3] Here and below, data quoted in magnitudes are stated without units. If millimags are used instead, that unit is always stated.

Table 2
New SAAO $BV(RI)_C$ Data for M67

F[a]	Sanders[b]	V[c]	$B-V$[c]	$V-R$[c]	$R-I$[c]	$V-I$[c]	n[d]
55	752	11.316(3.9)	0.299(2.6)	0.165(1.8)	0.170(3.5)[e]	0.332(5.7)	17
81	977	10.017(3.2)	−0.071(1.9)	−0.030(1.1)	−0.031(2.7)	−0.067(2.1)	18
105	1016	10.282(5.6)	1.262(3.1)	0.645(1.1)	0.572(3.0)	1.217(4.4)	15
131[f]	1082	...[f]	0.426(3.3)	0.250(2.2)	0.256(3.7)	0.505(5.3)	5
136	1072	11.284(2.6)	0.645(4.1)	0.359(1.7)	0.344(2.6)	0.702(3.5)	16
141	1010	10.459(6.9)	1.117(4.7)	0.559(2.6)	0.501(3.2)	1.060(3.8)	4
151	1084	10.481(5.0)	1.103(2.0)	0.552(1.5)	0.498(2.1)	1.050(2.9)	15
153	968	11.265(2.9)	0.124(2.3)	0.052(1.9)	0.054(6.1)	0.106(6.8)	16
170	1250	9.645(4.0)	1.350(2.4)[g]	0.693(1.2)	0.611(2.5)	1.304(2.3)	15
223	1316	10.522(4.6)	1.116(2.2)[e]	0.563(1.4)	0.504(2.9)	1.068(3.8)	13
266	1479	10.491(4.6)	1.112(2.5)[e]	0.553(2.6)	0.499(2.5)	1.052(4.1)	14

Notes. None of the tabulated data have been corrected for reddening.
[a] This is the Fagerholm (1906) number and also the WEBDA number.
[b] This is the Sanders (1977) number.
[c] Entries in parentheses are standard deviations in millimags derived from the scatter for each individual set of measurements. The $B-V$ data are on the SAAO (not the Johnson et al. 1966) zero point. Values of $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see Equation (5) of Taylor & Joner 1996.)
[d] Number of measurements.
[e] One wild point has been deleted, leaving $n-1$ contributing data.
[f] This star is ES Cnc (Sandquist et al. 2003). See Appendix for individual measurements.
[g] Two wild points have been deleted, leaving 13 contributing data.

Table 3
New SAAO $BV(RI)_C$ Data for ES Cnc

HJD[a]	Phase[b]	V	$B-V$	$V-R$[c]	$R-I$	$V-I$
120.04922	0.094	11.206	0.421	0.255	0.269	0.524
128.51353	0.021	11.253	0.416	0.250	0.255	0.505
129.51890	0.962	11.237	0.428	0.249	0.247	0.496
154.38413	0.249	11.157	0.429	0.252	0.255	0.507
212.27027	0.459	11.185	0.435	0.242	0.252	0.494

Notes. None of the tabulated data have been corrected for reddening.
[a] Add 2,454,000 to the listed dates.
[b] Phases have been calculated from the ephemeris of van den Berg et al. (2001).
[c] Values of $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see Equation (5) of Taylor & Joner 1996.)

data-comparison algorithm, and (4) the unequal-variance t test. The first and second of these procedures are basic algorithms described in numerous statistics texts. The third procedure is the third statistical tool described in Section 6.2 of Taylor (2000). The fourth procedure is illustrated in the notes to Table 3 of Taylor (1992).

To grasp the results from the tests, it is useful to take note of some definitions. For an isolated test, let C be the derived confidence level and $p \equiv 1 - C$ be the false-alarm probability (or, to be more exact, the probability of Type I error). Because the meaning of C can be hard to visualize if it differs from zero by a small amount, values of $P \equiv -\log_{10}(20p)$ are stated instead. Note that $P = 0$ if C is exactly 95% and that positive values of P imply that $C > 95\%$.

For each test performed in this paper, a value of P is calculated. Each calculation includes an allowance for the number N of contributing data, so values of P based on small values of N are not less reliable than those based on large values of N. The results of the tests are stated in ways that depend on their outcomes. If $P < 0$, its value is not given, and a note is instead made that a null result has been obtained. This outcome is often stated by noting that a statistic that does not differ from zero at the 2σ level has been obtained. If $P > 0$, its meaning must be assessed by applying FDR because multiple tests are performed (see Section 2 of Miller et al. 2001). The only values of P given below are those that turn out to be significant with an *overall* confidence level of at least 95%.

4. PHOTOMETRIC TRANSFORMATIONS

Turning to photometric transformations, we note that two of them are applied below. One is the following relation between Strömgren photometry and $B-V$:

$$B - V = 1.520(b-y) + 0.604m_1 - 0.105 + 0.005E(B-V). \quad (1)$$

This relation is applied to photometry from overlapping Sturch exercises (Taylor & Joner 1992; Joner & Taylor 1997). All quantities in the relation are stated in magnitudes, and $B-V$, $b-y$, and m_1 are not corrected for reddening. The relation is valid if $0.05 \leqslant B-V \leqslant 0.70$. Its original version is from Cousins (1987), but its zero point has been rederived by using $B-V$ values from Johnson et al. (1966, hereafter JMIW). In addition, the reddening term has been included by using reddening coefficients from the Asiago database.[4]

Especially because an m_1 term is included in Equation (1), values of $B-V$ derived by using that equation may be sensitive to metallicity differences. However, metallicity corrections are neglected here because the metallicities of the program stars are very similar. For field stars, the mean value of [Fe/H] is -0.041 ± 0.013 dex (Taylor & Croxall 2005). For the Hyades and M67, the values of [Fe/H] are 0.103 ± 0.008 dex and -0.009 ± 0.009 dex, respectively (see Table 11 of Taylor & Joner 2005 and Table 8 of Taylor 2007, respectively).

The other relation applied here is used to transform *Tycho* photometry to values of $B-V$. One way to do this is to adopt a

[4] See http://ulisse.pd.astro.it/Astro/ADPS

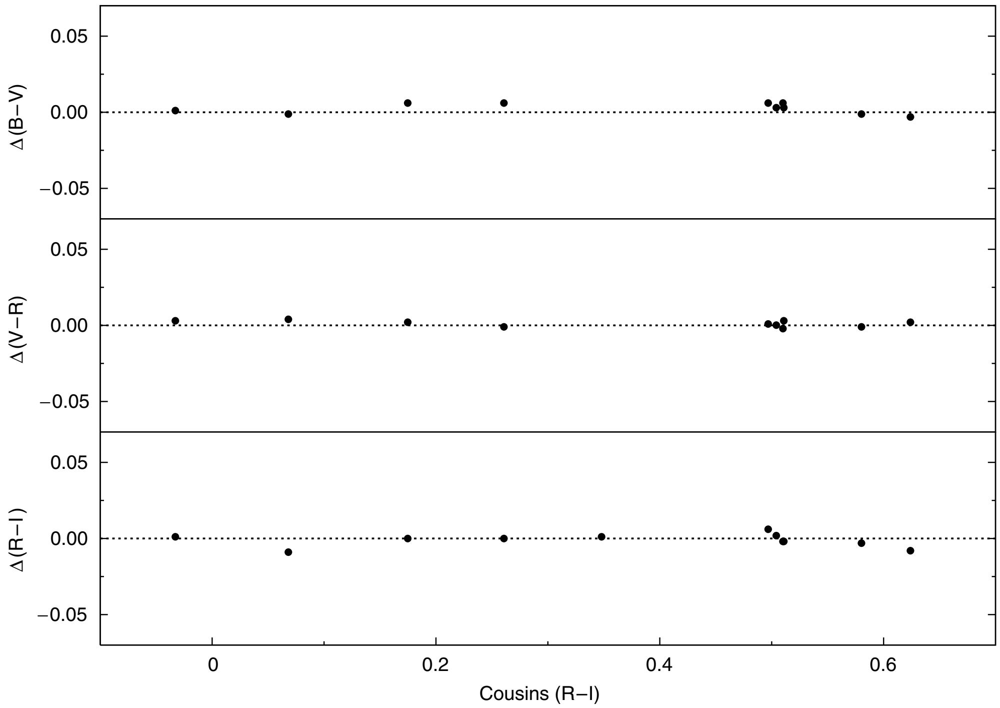

Figure 1. In the upper panel, M67 $B - V$ residuals (in the sense "SAAO minus interim consensus") are plotted against $(R - I)_C$. In the middle and lower panels, M67 $(V - R)_C$ and $(R - I)_C$ residuals (in the sense "SAAO minus Taylor et al. 2008") are plotted against $(R - I)_C$.

linear transformation given by Perryman et al. (1997). However, we instead adopt a nonlinear transformation to the SAAO system given in Table 2 of Bessell (2000). That algorithm is based on data for more than 600 stars, and its shape appears to be quite adequate over a wide color range (see Figure 4 in Bessell's paper). Its zero point will be tested as the analysis proceeds.

In accordance with a recommendation by Taylor & Joner (2006), we briefly review some possible systematic effects on output data from these transformations. Bessell's relation is applied only to stars that are unlikely to be reddened, while Equation (1) is applied only to stars with $E(B - V) < 0.05$. The effects of Balmer-line variation on results from Equation (1) are limited by applying the equation only to data for AF V stars. CN effects on results from Bessell's transformation are limited by applying the transformation to data for G and K giants, but not to data for dwarfs later than G2 (which appear to be missing from the *Tycho* catalog in any event). No corrections for the effects of binarity are made because the passbands of the original and the transformed data are reasonably close to each other in wavelength space (see notably Figure 5 in Bessell's paper). No corrections for rotational effects are made because they appear to be negligible (see Sections 4.2 and 4.3 of Taylor 2008).

5. ANALYSIS OF THE $(V - R)_C$ AND $(R - I)_C$ MEASUREMENTS

The first data to be considered here are *VRI* results for the Hyades. Those data can be used to improve on an existing transformation between $(V - K)_J$ and $(R - I)_C$ (see the Appendix). In addition, the 19 Hyades stars measured include eight with measurements reported in Paper I, so a consistency check between the new data and those of Paper I can be performed. The formal $(V - R)_C$ and $(R - I)_C$ corrections required to put the new data on the Paper I zero points turn out to be 0.0 ± 1.6 and 0.2 ± 1.6 mmag, respectively. Clearly, the zero points for the two data sets agree closely.

The M67 measurements are considered next. Here, the topic of interest is the relationship between the new SAAO data and a set of databases considered by Taylor et al. (2008). In Sections 5.3 and 6 of their paper, those authors discussed the relationship between a new M67 database they had presented, extant results from Montgomery et al. (1993) and other sources, and the SAAO data given in this paper. Using those results, Taylor et al. showed that the zero points of their newly presented data are acceptably close to the zero points of the E region standards. However, they also performed a scale factor analysis that did not include a comparison between their new data and the SAAO measurements. That omission is significant because for all results they considered except those of Montgomery et al., s could not be distinguished from zero at 95% confidence. When the Montgomery et al. data were compared to their own data set, s was found to be 2.7 ± 1.1, and the hypothesis that $s = 0$ was rejected with $P = 0.55$. Clearly, one would like to be as certain as possible about the source of this problem.

The procedure adopted here is to compare the scale factors of the SAAO data with those of the data presented by Taylor et al. Residuals derived from that comparison are plotted against values of $(R - I)_C$ in the lower two panels of Figure 1. Note that for both $(V - R)_C$ (middle panel) and $(R - I)_C$ (lower panel), the lines of residuals are essentially flat and display only small amounts of scatter. Small and precise values of s are therefore expected, and in fact s is found to be -0.37 ± 0.23 for $(V - R)_C$ and 0.0 ± 0.65 for $(R - I)_C$. Since neither value of s differs from zero by at least twice its standard error, we conclude with some confidence that the measurements published by Taylor et al. (2008) have the same scale factor as the SAAO data. Presumably that scale factor is correct, and the scale factor problem described above can be attributed to the Montgomery et al. (1993) data.

Table 4
$B - V$ Tests: Hyades and Field Stars

Entry	Stars	Extrinsic Source	Extrinsic Index	Tested Source	Tested Index	$\Delta(B-V)$ (mmag)	P[a]
1	Hyades	SAAO (Paper I)	$B-V$	SAAO (Table 1)	$B-V$	-1.5 ± 2.2	...
2	Hyades	SAAO (Paper I)	$B-V$	JK55[b]	$B-V$	8.1 ± 1.3	>4.7
3	Hyades	SAAO (*Tycho*)	$B_T - V_T$	SAAO (Paper I)	$B-V$	0.2 ± 1.6	...
4	Field	$JMIW_1$[c,d]	$B-V$	SAAO (*Tycho*)	$B_T - V_T$	-9.4 ± 1.5	>4.7
5	Field	$JMIW_2$[c,e]	$B-V$	SAAO (*Tycho*)	$B_T - V_T$	-8.4 ± 1.6	>4.7
6	Field	$JMIW_2$[c,f]	$B-V$	SAAO (*Tycho*)	$B_T - V_T$	-10.1 ± 2.6	2.0
7[g]	Both	$JMIW_1$[c]	$B-V$	JK55[b]	$B-V$	$*-1.3 \pm 2.0*$	...
8	Hyades	TJ92[h]	$b-y, m_1$	JK55[b]	$B-V$	$*-5.8 \pm 2.8*$	...
9	Hyades	J63, S73[i]	$B-V$	JK55[b]	$B-V$	$*-4.9 \pm 2.3*$	...
10	Both	...[j]	...	JK55[b]	$B-V$	-3.5 ± 1.3	0.7

Notes. The entries in the penultimate column are differences in the sense (extrinsic source minus tested source). The standard errors quoted in that column include allowances for accidental errors introduced by reduction and transformation relations when such allowances are required.
[a] Values of P are quoted if the overall significance level (see Miller et al. 2001) is >95%.
[b] The source paper is Johnson & Knuckles (1955).
[c] The source paper is JMIW (Johnson et al. 1966).
[d] This sample is drawn from AF V and GK III stars with $V > 2$ and 9 or more measurements by JMIW. Johnson & Harris (1954) standards make up 69% of the sample.
[e] This sample is drawn from AF V and GK III stars with $V > 2$ and 6 or more measurements by Johnson et al. Johnson & Harris (1954) standards make up 31% of the sample.
[f] This sample is drawn from the list of unreddened B III–V stars in Table 10 of Taylor (2008) with $V > 2$. Johnson & Harris (1954) standards make up 29% of the sample.
[g] In this entry, the sum of entries 2 and 4 is given.
[h] The source paper is Taylor & Joner (1992).
[i] Standards given by Johnson (1963) are compared to the Hyades by Sturch (1973).
[j] This entry is a weighted average of the three entries just above it.

6. A $B - V$ ANALYSIS FOR FIELD STARS AND THE HYADES

We now direct our attention to $B - V$ measurements of field standard stars and Hyades stars. A numerical result for each step in the resulting analysis is given in Table 4. Supplementary details (including some not discussed below) appear in the table's footnotes. The steps in the analysis are as follows.

Entry 1. This entry is included to show that the SAAO instrumental system is as stable in $B - V$ as it is in $(V - R)_C$ and $(R - I)_C$.

Entry 2. In Section 4.3 of Paper I, the Hyades measurements reported in that paper are compared with the data of Johnson & Knuckles (1955). A disquieting offset found through this comparison is shown in Table 4.

Entry 3. Because the Hyades lie well to the north of the E region standards, the offset might be produced by an effect in the SAAO instrumental system that varies with declination. To test this possibility, the Paper I Hyades data are compared with transformed *Tycho* photometry. Both of these data sets have been reduced to the E region system, but this was done using ground-based photometry for the first data set and satellite photometry for the second. As a result, a comparison of the two data sets yields a consistency test.

Note that according to entry 3, no detectable zero-point offset is found. This test is reasonably stringent: the 2σ limit obtained from entry 3 is 3.2 mmag, so an offset with an absolute value larger than this would have been detected with $P \geqslant 0$. Unless coincidence is at work (see Section 9), it appears that systematic effects do not influence either the Bessell calibration or SAAO photometry at the few-millimag level.

Entries 4–6. Another possible explanation of entry 2 is a zero-point offset in the SAAO system itself. This hypothesis is tested by comparing JMIW values of $B - V$ to transformed *Tycho* data for field standard stars. The samples for entries 4 and 5 include data for AF V and GK III stars, with the number of JMIW measurements being $\geqslant 9$ for entry 4 and $\geqslant 6$ for entry 5. In contrast to those entries, entry 6 is derived from luminosity class IV–V stars with $B - V < 0.04$. Note that despite their diverse sources, the three entries are all decisively nonzero and agree well with each other.

Given this result, one naturally asks whether a scale factor difference or a nonlinear relation between the SAAO and JMIW standards can be found. The first step in testing for such problems is to plot differences between these two data sets against $B - V$ (see Figure 2). Note that if data that produce positive residuals for two red stars are omitted, the resulting line of residuals is nearly horizontal and has little or no perceptible curvature. This result is reassuring because possible curvature has previously appeared in a corresponding set of residuals (see Figure 2b of Menzies & Marang 1996). Calculated values of s turn out to be 0.0 ± 0.2 with data for the two red stars included and -0.3 ± 0.2 if those data are excluded. We therefore conclude that no scale factor difference is detected.

Entry 7. Entry 4 is now selected for further use because it is based on data for a higher percentage of original *UBV* standards than entries 5 and 6 (see footnote "b" of Table 4). Assume, for the sake of argument, that entry 4 is applied to all values of $B - V$ for SAAO standards. This procedure leaves entries 1 and 3 unaffected because in each case both sets of contributing data are adjusted by the same amount. However, entry 2 is altered because in this case SAAO data comprise only one of the two sets of contributing photometry. By adding entry 4 to entry 2, one obtains the revised formal correction to the Johnson & Knuckles (1955) data that is listed as entry 7 of Table 4.

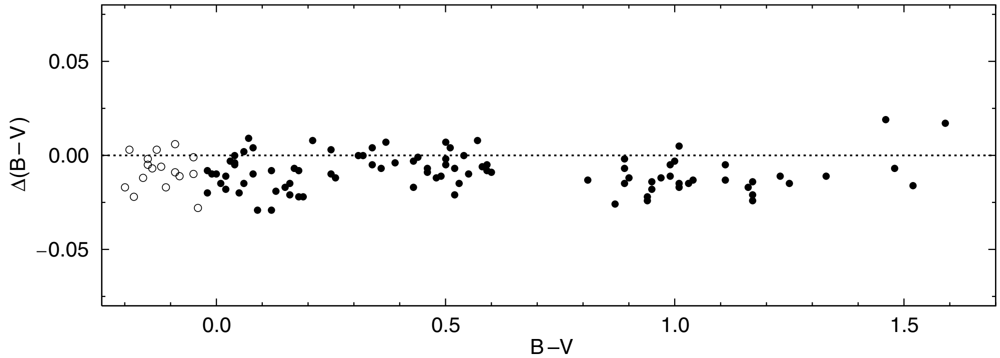

Figure 2. For field stars, $B - V$ residuals (in the sense "JMIW minus transformed *Tycho* data") are plotted against values of $B - V$. Data that contribute to entries 5 and 6 in Table 4 are represented by the filled and open circles, respectively. The two lines of residuals have been adjusted to reflect their average zero point.

Entries 8 and 9. These entries are counterparts to entry 7, but are not based on SAAO and *Tycho* data. Entry 8 is derived from Strömgren photometry, while entry 9 is based on measurements of Hyades stars and Johnson standards made on the same nights with a single *UBV* instrumental system (see Sturch 1973).[5] Note that these two entries disagree with entry 2; this problem was noted in Paper I, but no explanation was advanced there. Now, with entry 2 replaced by entry 7, one has three offsets that appear to agree despite being from independent sources (compare the three entries flagged with asterisks in the last column of Table 4). This assessment is confirmed by applying the χ^2 algorithm mentioned in Section 3.

Entry 10. The weighted mean of entries 7–9 turns out to differ from zero with $P = 0.66$. Using that mean value, an extant relation between $B - V$ and $(R - I)_C$ for single Hyades dwarfs may be re-zeroed (see Equation 1 of Taylor 1994). Let

$$B - V = \sum_{i=0}^{3} C_i r^i, \tag{2}$$

with $r \equiv (R - I)_C$. For the re-zeroed relation,

$$[C_0, C_1] = [(0.244 \pm 0.001), (-1.13 \pm 0.41)] \tag{3}$$

and

$$[C_2, C_3] = [(9.53 \pm 1.45), (-7.89 \pm 1.61)]. \tag{4}$$

This relation holds if $0.11 \leqslant (R - I)_C \leqslant 0.50$. It is recommended for use in color–magnitude analysis of the Hyades when values of $B - V$ are considered.

7. A COMMENT ON JOHNSON PHOTOMETRY

Since data published by Johnson and his collaborators define the *UBV* system, readers may wonder whether applying the entry 10 correction to some of that photometry is a meaningful operation. This issue can be resolved by noting that in the 1950s *UBV* cluster photometry was commonly performed in two steps: (1) cluster measurements were referred to one or more local standards and (2) those standards were then tied into the standard system. This procedure was adopted by Johnson & Knuckles (1955) in particular. Because some zero-point uncertainty is inevitably incurred in the second of these steps, cluster photometry from sources such as Johnson & Knuckles does not have the definitive zero points of field star photometry from sources such as JMIW.

When local standards were used, probable errors were stated for the zero points determined in the second step. By adopting a probable error from Table 1a of Johnson & Knuckles (1955) and converting it to a $\pm 2\sigma$ interval, one finds that interval is about ± 12 mmag for Hyades values of $B - V$.[6] This result shows at once that an adjustment of the Johnson & Knuckles data by -3.5 mmag is well within the expected range of possibilities. Especially because Menzies & Marang (1996) have also made use of data based on 1950s zero-point procedure, we suggest that zero-point practice as described in source papers be checked before data from that epoch are used. This procedure is easy to apply if probable errors for zero points are given in separate tables in the source papers. Johnson & Knuckles adopt that practice, and it appears to have been used consistently in cluster papers by Johnson and his collaborators.

8. A $B - V$ ANALYSIS FOR M67

Numerical results for an M67 analysis are given in Table 5, with supplementary details again appearing in footnotes. The steps in this analysis are as follows.

Entries 1–4. These entries concern a "consensus" database for M67 giants assembled by Taylor (2007) and cited in Table 11 of that paper. The contributing data are initially from Eggen & Sandage (1964), Coleman (1982), Janes & Smith (1984), and Sanders (1989), and are solely from photomultiplier measurements.

Entry 1. Attention is focused first on the Sturch (1973) data. That author measured stars in M67 as well as the Hyades stars and field standard stars noted above. Entry 1 shows that the Sturch and Coleman (hereafter S–C) data have indistinguishable zero points.[7]

Entries 2 and 3. Entry 2 is an offset between the S–C data and the Sanders (1989) measurements, while entry 3 is a corresponding offset for the data of Eggen & Sandage (1964). The offsets are applied before data from the two sources tested are included in the consensus database.

Entry 4. For measurements published by Janes & Smith (1984), the offset from the Sanders (1989) data is

[5] Data from Sturch (1972) are not used because at least some of those data are superseded in Sturch (1973).

[6] Because it is no longer standard practice to quote probable errors, we note that they can be converted to standard errors by dividing them by a factor of 0.68. This factor can be obtained readily from tables of integrals under the Gaussian.

[7] Though the Sturch data are used to establish a zero point for the consensus database, they are not ultimately included in that database because most of them are derived from a single measurement per star.

Table 5
$B-V$ Tests: M67

Entry	$B-V$ Range[a]	Extrinsic Source	Extrinsic Index	Tested Source	Tested Index	$\Delta(B-V)$ (mmag)	P[b]
1	>0.85	Coleman (1982)	$B-V$	Sturch (1973)	$B-V$	−3.3 ± 4.5	...
2	>0.62	SC[c]	$B-V$	Sanders (1989)[d]	$B-V$	−14.9 ± 4.3	1.3
3	>0.55	SC[c]	$B-V$	ES64[e]	$B-V$	−10.8 ± 2.8	1.9
4	>0.90	JS84[f]	$B-V$	Sanders (1989)[d]	$B-V$	−19.6 ± 6.4	0.7
5	−0.1, 1.1	Corrected SAAO[g]	$B-V$	Consensus[h]	$B-V$	+2.3 ± 2.4	...
6	>0.85	Consensus[h]	$B-V$	MMJ[i]	$B-V$	−4.2 ± 2.2	...
7	>0.94	Consensus[h]	$B-V$	MMJ[j]	$B-V$	−25.4 ± 7.0	1.3
8	>0.60	SC[c]	$B-V$	Sandquist (2004)	$B-V$	+3.6 ± 3.5	...
9	0.5, 0.7	NTC, JT97[k]	$b-y, m_1$	Sandquist (2004)	$B-V$	−4.7 ± 3.6	...
10	⩾0.4	...[l]	...	Sandquist (2004)	$B-V$	+2.3 ± 2.4	...

Notes. The entries in the last column are differences in the sense (extrinsic source minus tested source). The standard errors quoted in that column include allowances for accidental errors introduced by reduction and transformation relations.
[a] Entries in this column are in magnitudes.
[b] Values of P are quoted if the overall significance level (see Miller et al. 2001) is >95%.
[c] "SC" refers to data from Sturch (1973) and Coleman (1982) that are combined without a zero-point adjustment.
[d] For the range $B-V < 0.62$, the formal correction to the Sanders data calculated using data from Eggen & Sandage (1964) and Sturch (1973) is +8.0 ± 4.2 mmag. That correction and the one listed in the table above differ with $P = 1.2$.
[e] "ES64" refers to Eggen & Sandage (1964). For stars with $0.4 \leqslant B-V \leqslant 0.75$, the formal correction to the ES64 data calculated using Strömgren photometry is −20.3 ± 2.9 mmag. That correction and the one listed in the table differ with $P = 0.4$.
[f] "JS84" refers to Janes & Smith (1984).
[g] This entry is based on data from Table 2 that have been corrected by −9 mmag (see entry 4 of Table 4).
[h] This entry refers to combined data from Janes & Smith (1984), Coleman (1982), Eggen & Sandage (1964), and Sanders (1989). The adopted zero-point adjustments to these data are (in order) 0, 0, −11, and −15 mmag, with the last correction applying only at $B-V > 0.6$ mag. Sanders data from outside this range are not used. After entry 5, corrected SAAO data are added to the database.
[i] "MMJ" refers to data from Montgomery et al. (1993) for sample 1 stars (listed in Table 1 of Eggen & Sandage 1964).
[j] "MMJ" refers to data from Montgomery et al. (1993) for sample 2 stars (not listed in Table 1 of Eggen & Sandage 1964).
[k] "NTC" refers to transformed Strömgren data from Table I of Nissen et al. (1987). "JT97" refers to transformed Strömgren data from Table 3 of Joner & Taylor (1997). Both sets of data are on a zero point established by Taylor & Joner (1992). The transformation applied to these data is Equation (1). The assumed value of $E(B-V)$ for M67 is 41 ± 4 mmag (see Taylor 2007).
[l] This entry results from averaging entries 8 and 9.

indistinguishable from the offset obtained for the S–C data (compare entries 4 and 2). Judging from this result, the zero point of the Janes & Smith data and that of the S–C data are effectively identical. The Janes & Smith data are therefore included in the consensus database without a zero-point adjustment.

Entry 5. The consensus database is now compared with SAAO data from Table 2. The latter are adopted after a zero-point adjustment derived above (see entry 3 of Table 4) is applied. The resulting null offset implies that the zero points of the adjusted SAAO data and the S–C data are indistinguishable. Judging from a flat row of residuals in the uppermost panel of Figure 1, it appears that the scale factors are also indistinguishable. The latter deduction is confirmed by a calculated value of s (0.06 ± 0.23).

Entries 6 and 7. The re-zeroed SAAO data are included in the consensus database, and the resulting data (for G and K giants only) are given in Table 6. Those data are then differenced from the measurements of Montgomery et al. (1993), and the residuals are used to test the zero points of the Montgomery et al. data. Before being tested, the residuals are divided into two groups. For a group that will be called "sample 1" here, the parent stars are listed in Table 1 of Eggen & Sandage (1964). For "sample 2," the parent stars are not listed in that table.

This exercise does not separate the parent stars into two groups with mutually exclusive locations in the color–magnitude array of M67. For that reason, the adopted partitioning may appear at first to be ad hoc. Nevertheless, one finds that the two samples yield contrasting results. Both their net scatter and their mean offset from zero appear to differ (compare the filled circles plotted for sample 1 in Figure 3 with the open circles plotted there for sample 2). Statistical testing supports both of these

Table 6
Consensus Photomultiplier $B-V$ Values for M67

WEBDA	Sanders	$B-V$ (mag)[a]	WEBDA	Sanders	$B-V$ (mag)[a]
37	794	0.969(9.6)	231	1254	1.045(4.1)
84	1074	1.099(5.6)	244	1237	0.935(4.1)
105	1016	1.253(2.5)	266	1479	1.102(2.2)
108	978	1.365(4.1)	286	1592	1.080(9.6)
135	989	1.052(5.1)	305	721	1.058(9.6)
141	1010	1.107(3.5)	2152	1402	1.122(7.9)
143	1040	0.868(4.8)	3035	1293	1.019(6.1)
151	1084	1.093(2.8)	4169	494	1.068(6.8)
164	1279	1.109(4.8)	4202	488	1.532(5.1)
170	1250	1.342(2.1)	6470	364	1.293(5.6)
193	1305	1.004(9.6)	6474	676	1.200(7.9)
217	1288	1.069(6.1)	6495	1135	1.440(9.6)
218	1277	1.045(6.1)	6513	1533	1.233(7.9)
223	1316	1.107(2.0)	6514	1553	1.625(7.9)
224	1221	1.115(4.3)	6515	1557	1.265(7.9)

Notes. None of the listed data have been corrected for reddening.
[a] The data in parentheses are standard errors in millimags.

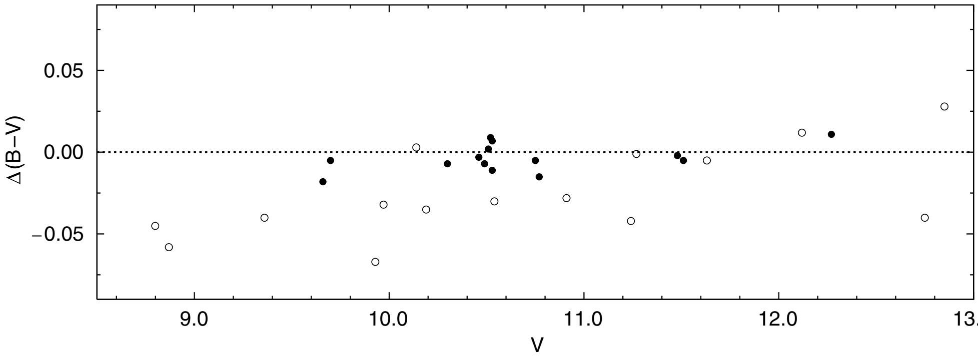

Figure 3. For M67, $B - V$ residuals are plotted against V for the data of Montgomery et al. (1993). The adopted values of V are from Eggen & Sandage (1964), Janes & Smith (1984), Sandquist (2004), and Taylor et al. (2008). The filled and open circles represent data for sample 1 and sample 2 stars, respectively.

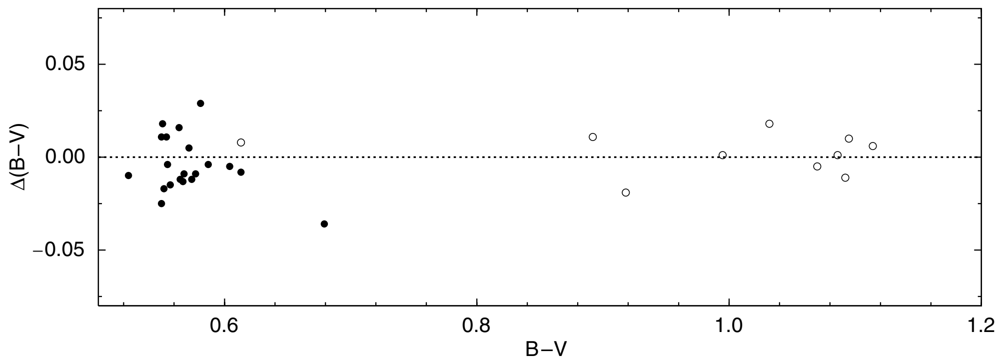

Figure 4. For M67, $B - V$ residuals are plotted against $B - V$ for the data of Sandquist (2004). The open circles are plotted if the comparison data are from Sturch (1973) and Coleman (1982; see Table 5 and the discussion of its entry 8 in Section 8). The filled circles are plotted if the comparison data are from Nissen et al. (1987) and Joner & Taylor (1997; see Table 5 and the discussion of its entries 9 and 10 in Section 8).

assessments. For sample 1, the mean residual does not differ detectably from zero (see entry 6 in Table 5). For sample 2, a firmly significant difference is found (see entry 7 in Table 5). In addition, the root mean square (rms) scatter of the residuals is found to be 7 mmag for sample 1 and 25 mmag for sample 2. Using a variance-ratio test, one finds that these two results differ with $P > 2.7$.[8]

These are some of the more unusual statistical results we have seen. Partly because those results appear to be reasonably decisive as well, we perform no further tests of the Montgomery et al. (1993) data. Instead, we suggest that those data, like the V and $(V - I)_C$ measurements of Montgomery et al., should not be used in color–magnitude or color–color analysis. Additional support for this suggestion is offered by the data of Sandquist (2004), which will be considered below. Sandquist finds that there is an overall offset of about 8 ± 1 mmag between his values of $B - V$ and those of Montgomery et al.[9] (The character of the $(V - I)_C$ data of Montgomery et al. is discussed in Sections 5 and 6 of Taylor et al. 2008. A detection of a positional effect in the V data of Montgomery et al. is documented in Table 1 of Taylor et al.)

Entry 8. Attention is now directed to the Sandquist (2004) data. First, a comparison is made between those data and the S–C results, which can now be regarded as a proxy for the re-zeroed SAAO data (recall entry 5). The resulting residuals are plotted as open circles in Figure 4. Judging from that figure, the mean residual is effectively zero. This initial estimate is supported by the result of the statistical test reported for entry 8.

Entry 9. Here, the zero point of the Sandquist (2004) results is compared with that of transformed Strömgren data for stars on and near the vertical subgiant branch in M67. Once again, no nonzero mean offset is detected in either Figure 4 (note the filled circles) or by a statistical test.

Entry 10. Note that the mean residuals given in entries 8 and 9 agree. This is especially encouraging because the two means have been derived for color intervals that are largely complementary (see the appropriate entries in the second column of Table 5). Entry 10 includes an overall mean residual that has been derived from the two accordant means by using inverse-variance weighting. To interpret that mean value, we adopt a 2σ limit as before and conclude that no offset as large as 4.8 mmag is detected in the Sandquist (2004) data. Those data (and the entries in Table 6) are therefore recommended for use in color–magnitude and color–color analysis as a substitute for the measurements of Montgomery et al. (1993).

9. THE SAAO $B - V$ OFFSET: A KNOTTY PROBLEM CONSIDERED

So far, the $B - V$ analysis has not revealed any serious problems. In particular, the results of adopting the zero-point offset derived for the SAAO system in Section 6 have been satisfactory. Now, however, we acknowledge that our analysis

[8] It should be noted that the apparent contrast between the residuals plotted in Figure 3 is not completely sustained by statistical testing. Despite appearances, the slopes of the two sets of residuals cannot be distinguished at 95% confidence.

[9] In his Figure 5, Sandquist presents a graphical comparison of his M67 $B - V$ data with those of Montgomery et al. We assume that an rms error is included in the offset quoted in the figure by Sandquist (-8 ± 11 mmag). The required standard error of the mean follows from the appearance in Sandquist's plot of data for an estimated 100 stars or more.

does not include the results of two previous comparisons between the Johnson and SAAO systems. Cousins (1984) performs such a comparison by measuring a number of the Johnson & Harris (1954) standard stars. Menzies & Marang (1996) report data on the SAAO system for stars in IC 4665 that have been measured by Johnson (1954) and other authors.[10]

Before zero-point offsets from measurements by Cousins (1984) and Menzies & Marang (1996) are calculated, the photometric literature for IC 4665 is examined. This is done to identify published data sets that (1) have reasonably high precision, (2) include at least 10 stars, and (3) have been standardized using Johnson standards. It is found that only measurements made by Hogg & Kron (1955) and Johnson (1954) satisfy these conditions. For a reason that will become clear shortly, only Johnson's data are used.

When a value of $\Delta(B-V)$ like those in Tables 4 and 5 is calculated for Johnson's (1954) data, the result is as follows:

$$\Delta(B-V) = 1 \pm 6\,\mathrm{mmag}. \tag{5}$$

The standard error in this equation is dominated by zero-point uncertainty of the sort described in Section 7. Adopting measurements from Hogg & Kron (1955) would not improve Equation (5) because their data have been reduced to the Johnson (1954) zero point. Apparently, the measurements of Menzies & Marang (1996) cannot be used to perform a satisfactory zero-point test.

When the Cousins (1984) data are considered instead, one finds that

$$\Delta(B-V) = -0.8 \pm 1.2\,\mathrm{mmag}. \tag{6}$$

A useful way to evaluate this result is to compare it to the corresponding entries in Table 4 with the highest available precision. On this basis, entries 4 and 5 in Table 4 are selected. Using an unequal-variance t test (see Section 3), it is found that Equation (6) differs from those entries with $P > 2.70$. This high level of significance underscores an important contrast: the analysis in Section 6 yields a nonzero correction to the SAAO standards, but the Cousins (1984) data do not.

This is a problem that is not to be solved by making any merely facile choice. Given the care with which Cousins established the *UBV* system for the E region standards (see for example, Cousins 1973), Equation (6) would be accepted without hesitation if additional pertinent data were not available. Since such data are available, however, we shall try to make the best decision about the problem that the evidence permits.

An essential starting point is the deduction that at least one SAAO photometer suffers from a declination effect in $B-V$. Admittedly, this is not a welcome idea. Although declination effects in V are quite conceivable (see Section 3.1 of Menzies & Marang 1996), a declination effect in a color index is both new to our experience and a troubling hint of possible problems in other photometric venues.[11] Nevertheless, we accept the verdict and try to decide which of the SAAO photometers is more likely to be the source of the problem.

For the sake of argument, we begin by assuming that the declination effect is in the photometer that is currently being used at SAAO. The results of this assumption are as follows.

1. Given the null offset in entry 3 of Table 4, there must also be a declination effect in the *Tycho* photometry. Note that it is difficult to imagine how such an effect could be produced. In particular, instrument flexure is ruled out by the fact that the *Tycho* measurements were made in free fall.
2. The declination effects in the *Tycho* photometry and SAAO photometry of the present epoch must be very similar despite the fact that the *Tycho* and SAAO instrumental systems are completely independent. Such a coincidence, though conceivable, seems unlikely.

Next, we assume instead that the declination effect is in the photometer used by Cousins (1984). Now the results are as follows.

1. There is no need to suppose that the *Tycho* photometry harbors systematic effects.
2. In addition, there is no need to conclude that such effects are produced by the current SAAO photometer. For this reason, the agreement displayed in entry 3 of Table 4 receives a natural explanation.
3. Cousins (1984) notes that the photometer he used to test the E region photometry is the one used to establish *UBV* photometry for the E region standards. One therefore concludes that the declination effect was not detected because it appears in both sets of measurements. Note that as a result there is no need to attribute any problem to the careful observing and reduction procedures that Cousins employed.

Since the second option is clearly the more palatable of the two, we adopt it. However, it seems unwise to regard it as definitive, so we instead describe it as a well-supported interim choice that should be tested further. This should be done by taking note of point 3, which is a useful reminder that accuracy tests should be based on data from at least two independent instrumental systems. Pertinent measurements that include Johnson standards with a photometer that has not contributed to the discussion so far would be especially welcome.

10. SUMMARY

New SAAO $BV(RI)_C$ measurements of cluster stars are presented, with data being reported for 11 stars in M67 and 19 Hyades stars. Because measurements for eight of those stars were reported in Paper I, it is possible to test the zero-point consistency of the new and previously published data. It is found that the zero points of the new color indices conform closely to those obtained in Paper I. In addition, the new M67 measurements of $(V-R)_C$ and $(R-I)_C$ are compared to data published by Taylor et al. (2008). The accuracy of the scale factor of those data is supported by the new results. For this reason, the new data reinforce a conclusion drawn by Taylor et al. that a scale factor problem is present in the $(V-I)_C$ measurements of Montgomery et al. (1993).

The new values of $B-V$ participate in an analysis of Hyades and M67 data and the accuracy of the SAAO $B-V$ system. A problem with the Hyades $B-V$ zero point posed in Paper I is resolved, and an extant Hyades relation between $B-V$ and $(R-I)_C$ is re-zeroed. A satisfactory zero point is also obtained

[10] Taken at face value, a third comparison (see Section 4 of Koen et al. 2002) suggests that the SAAO zero point should be corrected by about +22 mag. However, this comparison is based solely on M dwarfs, and it appears that extant $B-V$ photometry of such stars has a zero-point jitter of about 10 mmag (see Section 3 of Koen et al. 2002). In addition, the cited comparison depends partly on *Tycho* photometry and partly on ground-based photometry (again see Section 4 of Koen et al. 2002). We therefore suggest that (1) $B-V$ photometry of M dwarfs should not be used to test the SAAO zero point and (2) the correct zero point for such photometry should ultimately be the subject of further discussion.

[11] Fortunately, there is good reason to conclude that such problems do not affect commonly used sets of Cousins *VRI* colors (see Table 3 and Sections 5–7 of Taylor & Joner 1996).

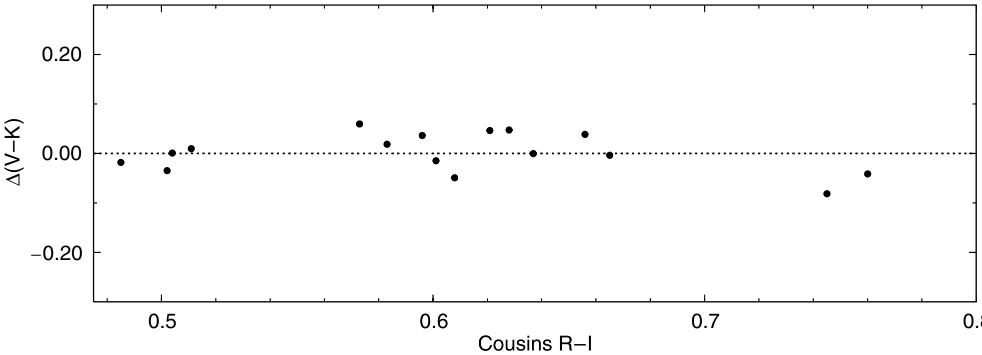

Figure 5. $(V-K)_J$ residuals from equations (A1) and (A2) are plotted against $(R-I)_C$.

for M67, and photomultiplier values of $B-V$ for evolved M67 stars are reduced to that zero point (if necessary), averaged, and tabulated. The zero point of $B-V$ data published by Sandquist (2004) turns out to be satisfactory. However, tests of $B-V$ measurements made by Montgomery et al. suggest that those data are not on a single zero point. Finally, the scale factor of the E region system is found to be satisfactory, but a well-supported interim conclusion is drawn that E region values of $B-V$ should be corrected by about −9 mmag. It is suggested that this conclusion be tested by measuring Johnson standards and by using instrumental systems that have not yet contributed to the testing process.

As in Paper I, we gratefully acknowledge SAAO for granting telescope time on such a well-established observing system. We also thank Lisa Joner for reading the manuscript carefully and Dr. D. Kilkenny for providing data reductions for the paper and a careful evaluation of its reasoning. The WEBDA database (operated at the Institute for Astronomy at the University of Vienna), the SIMBAD database (operated at Centre de Données Astronomiques de Strasbourg, Strasbourg, France), the General Catalogue of Photometric Data (Mermilliod et al. 1997), the Asiago Database of Photometric Systems (Moro & Munari 2000), and the Smithsonian/NASA ADS listings have all contributed to this investigation, and we thank the operators of these Web sites with alacrity. Finally, we note with thanks that page charges for both Paper I and this paper have been generously underwritten by the College of Physical and Mathematical Sciences and the Physics and Astronomy Department of Brigham Young University.

APPENDIX

AN UPDATED TRANSFORMATION BETWEEN $(V-K)_J$ AND $(R-I)_C$

Taylor & Joner (2006) have published a transformation between $(V-K)_J$ and $(R-I)_C$. The transformation consists of three relations that apply in disjoint intervals in $(R-I)_C$. Taylor & Joner note that the reddest of these relations is based on data that fall well short of being uniformly distributed in color. This problem can be partially solved by adding data for vA 68 and vB 229, 231, 262, 291, and 324 to the original data set and then recalculating the relation. The result may be expressed as follows: if

$$(V-K)_J = C_0 + C_1(R-I)_C, \quad \text{(A1)}$$

then

$$[C_0, C_1] = [(0.551 \pm 0.077), (3.80 \pm 0.13)] \quad \text{if} \quad (R-I)_C \geqslant 0.495. \quad \text{(A2)}$$

A plot of $(V-K)_J$ residuals against $(R-I)_C$ is given in Figure 5. While the color coverage of the revised relation has been improved, one can see that further data will ultimately be required at $(R-I)_C \sim 0.55$ and $(R-I)_C \sim 0.70$. Meanwhile, readers who want to use the full relation are invited to consult Table 4 of Taylor & Joner (2006) while substituting the above relation for entry 8 in that table.

REFERENCES

Bessell, M. S. 2000, PASP, 112, 961
Coleman, L. A. 1982, AJ, 87, 369
Cousins, A. W. J. 1973, Mem. R. Astron. Soc., 77, 223
Cousins, A. W. J. 1984, South Afr. Astron. Obs. Circ., 8, 69
Cousins, A. W. J. 1987, Observatory, 107, 80
Eggen, O. J., & Sandage, A. R. 1964, ApJ, 140, 130
Fagerholm, E. 1906, PhD thesis, Uppsala Univ.
Hogg, A. R., & Kron, G. E. 1955, AJ, 60, 365
Janes, K. A., & Smith, G. H. 1984, AJ, 89, 487
Johnson, H. L. 1954, ApJ, 119, 181
Johnson, H. L. 1963, in Basic Astronomical Data, ed. K. Aa. Strand (Chicago, IL: Univ. Chicago Press), 204
Johnson, H. L., & Harris, D. L. 1954, ApJ, 120, 196
Johnson, H. L., & Knuckles, C. F. 1955, ApJ, 122, 209
Johnson, H. L., Mitchell, R. I., Iriarte, B., & Wiśnewski, W. Z. 1966, Commun. Lunar Planet. Lab., 4, 99
Johnson, H. L., & Sandage, A. R. 1955, ApJ, 121, 616
Joner, M. D., & Taylor, B. J. 1997, PASP, 109, 1122
Joner, M. D., Taylor, B. J., Laney, C. D., & van Wyk, F. 2006, AJ, 132, 111
Koen, C., Kilkenny, D., van Wyk, F., Cooper, D., & Marang, F. 2002, MNRAS, 334, 20
Menzies, J. W., & Marang, F. 1996, MNRAS, 282, 313
Mermilliod, J.-C., Mermilliod, M., & Hauck, B. 1997, A&AS, 124, 349
Miller, C. J., et al. 2001, AJ, 122, 3492
Montgomery, K. A., Marshall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Moro, D., & Munari, U. 2000, A&AS, 147, 361
Nissen, P. E., Twarog, B. A., & Crawford, D. L. 1987, AJ, 93, 634
Oja, T. 1994, A&A, 286, 1006
Perryman, M. A. C., et al. 1997, The *Hipparcos* and *Tycho* Catalogues (SP-1200) (Noordwijk: ESA)
Sanders, W. L. 1977, A&AS, 27, 89
Sanders, W. L. 1989, RevMexAA, 17, 31
Sandquist, E. L. 2004, MNRAS, 347, 101
Sandquist, E. L., Latham, D. W., Shetrone, M. D., & Milone, A. A. E. 2003, AJ, 125, 810
Stetson, P. B., McClure, R. D., & VandenBerg, D. A. 2004, PASP, 116, 1012
Sturch, C. 1972, PASP, 84, 666
Sturch, C. 1973, PASP, 85, 724
Taylor, B. J. 1992, PASP, 104, 500
Taylor, B. J. 1994, PASP, 106, 444

Taylor, B. J. 2000, A&A, 362, 563
Taylor, B. J. 2007, AJ, 133, 370
Taylor, B. J. 2008, AJ, 136, 1388
Taylor, B. J., & Croxall, K. 2005, MNRAS, 357, 967
Taylor, B. J., & Joner, M. D. 1992, PASP, 104, 911
Taylor, B. J., & Joner, M. D. 1996, AJ, 111, 1338
Taylor, B. J., & Joner, M. D. 2005, ApJS, 159, 100
Taylor, B. J., & Joner, M. D. 2006, PASP, 118, 1716
Taylor, B. J., Joner, M. D., & Jeffery, E. J. 2008, ApJS, 176, 262
van Beuren, H. G. 1952, Bull. Astron. Inst. Neth., 11, 432
VandenBerg, D. A., & Stetson, P. B. 2004, PASP, 116, 997
van den Berg, M., Orosz, J., Verbunt, F., & Stassun, K. 2001, A&A, 375, 375

Chapter 11

New *BV(RI)*$_c$ Photometry for the Praesepe: Further Tests of Broadband Photometric Consistency

The final paper is still in manuscript form and is titled "New *BV(RI)*$_c$ Photometry for the Praesepe: Further Tests of Broadband Photometric Consistency". The current plans are to publish this manuscript as Joner et al. (2011) in the *Astronomical Journal*. This paper is temporarily on hold while waiting for a few more observations from SAAO to be added to a preliminary data table for the Praesepe cluster that was current with new observations through the end of the 2008 observing season. When the table is complete, there will be new *BV(RI)*$_C$ photometric data secured using the SAAO modular photometer mounted on the 0.5-m telescope for at least 14 Praesepe stars and 5 comparison stars in the Hyades. The preliminary analysis of the new measurements supports the previously determined *V* zero-point for the Praesepe, Hyades, and M67 as well as the joint zero-point found in Taylor, Joner, and Jeffery (2008) in *(V-R)*$_C$, and *(R-I)*$_C$ for the stars in the Praesepe and NGC 752 clusters. For the standard system as used at SAAO, corrections of +3 mmag in *V* and -9 mmag in *B-V* are reasonably well determined. For the Landolt (1983) equatorial system, the zero-point compared to the Johnson system is found to be indistinguishable from zero. The new manuscript concludes this chapter.

NEW $BV(RI)_C$ PHOTOMETRY FOR THE PRAESEPE: FURTHER TESTS OF BROADBAND PHOTOMETRIC CONSISTENCY

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ABSTRACT

New $BV(RI)_C$ measurements of Praesepe made at the South African Astronomical Observatory are presented. When those measurements are combined with those reported in previous papers in this series, it is found that they support previously determined V zero points for Praesepe, M67, and the Hyades. Support is also found for joint $(V-R)_C$ and $(R-I)_C$ zero points established previously for Praesepe and NGC 752. For the SAAO system of standard stars, corrections to the Johnson system of about +3 mmag in V and −9 mmag in $B-V$ appear to be reasonably well established. For the Landolt (1983) V system, zero point identity with the Johnson system at a 2σ level of 3.4 mmag is established.

Subject headings: open clusters and associations: individual: Praesepe – stars: fundamental parameters – techniques: photometric – methods: statistical

1. INTRODUCTION

This paper is the third in a series in which new photometric measurements from the South African Astronomical Observatory (SAAO) participate in tests of the accuracy of extant $BV(RI)_C$ photometry. The papers in this series have each presented new photometric observations of nearby open clusters secured using an instrumental system that has been shown to be stable over a period of many years. The focus of the first paper was on the consistency of a new set of homogeneous Hyades photometry (see Joner et al. 2006, hereafter Paper I). The second paper presented new photometry and consistency tests for the Hyades, M67, and values of $B - V$ in the SAAO system of standard stars (see Joner et al. 2008, hereafter Paper II). In this paper, new Praesepe photometry is presented and tested relative to prior results. This paper concludes with an assessment of the accuracy of standard-star V magnitudes in the SAAO and Landolt (1983) systems.

The structure of this paper is as follows. A brief discussion of observing procedures appears in §2. Comparisons of new and extant color indices are discussed in §3. In §4, a search is made for color terms in the SAAO V magnitude system and that of Landolt (1983). Zero point comparisons of V magnitudes are discussed in §5. Some perspectives on the cluster results are set forth in §6 and the results of this investigation are summarized in §7.

2. OBSERVING PROCEDURES

As in Papers I and II, new measurements from the 0.5 m telescope and modular photometer at the SAAO Sutherland station are reported. Hyades stars were measured during 2007 November and December, while Praesepe stars were measured in the interval from 2008 February to 2008 May. For the most part, the adopted observing and reduction procedures will not be reviewed here because they have already been described in some detail (see §2 of Paper I and §2 of Paper II). We note that the color equations determined to transform these data have remained remarkably stable over the years that we have used this instrumental system. In fact, the transformation coefficients are not substantially different than those published more than a decade ago in the Appendix of Kilkenny et al. (1998). This level of stability over time has made it possible to continue this series of tests of broadband photometric consistency.

However, one precaution that has not been taken previously will be noted. As seen from Sutherland, the declination of Praesepe (about +20 degrees) yields a relatively large minimum air mass of about 1.64. To gauge the effect of that limit, measurements have been made of some of the Hyades stars that have been observed previously and are also at a declination of about +20 degrees. Consistency checks derived from those data will be described just below.

3. TESTS OF COLOR INDICES

The new data (given in Table 1) are put to use by comparing them with extant measurements and evaluating the results statistically. The first such exercise considered here is a set of comparisons of color indices. The results of those comparisons are given in Table 2, and they are evaluated in the following discussion.

Entries 1–3.–Here, offsets of the new Hyades photometry from the Paper I measurements are given in the form $x \pm \sigma_x$. A simple way to assess these data is to note that if $|x| \leq 2\sigma_x$, no difference from zero has been detected with a confidence level $C \geq 0.95$. Since that condition is fulfilled for all three entries, one concludes that the new measurements are on the Paper I zero points. It should be noted that this conclusion is based on data for only four stars (see the last column of Table 2). However, each color index comparison is based on 19 new measurements of those stars. Since the standard errors of the resulting differences are < 3 mmag, it is fair to conclude that an adequate number of data are being used.

Entries 4–5.–The new data are now compared to Praesepe *VRI* measurements published by Taylor et al. (2008, hereafter TJJ). Besides offsets, values of an adjusted slope s are calculated, with $s \equiv 100|S - 1|$ and

$$(R - I)_{\rm SAAO} = S_{RI}(R - I)_{\rm T08} + Z_{RI} \tag{1}$$

in straightforward notation. An equivalent regression relation is calculated for $V - R$, with due allowance being made for the scale factor difference between the Cousins and Landolt (1983) versions of that color index (see eq. [1] of Paper I). The regressions are performed by applying a two-error least-squares algorithm (see the Appendix to Paper I).

By design, if values of s cannot be distinguished from zero, there are no detectable differences between the scale factors of the new color indices and those of TJJ. This condition is in fact inferred for both $V - R$ and $R - I$ (see footnote "a" of Table 2). Judging from the offsets listed in Table 2, there are also no detectable differences between the zero points of the new and extant data.

Entries 6–7.–In the next step, the new values of $B - V$ are compared to published photometry by Johnson (1952) and Dickens et al. (1968). Those data sources are both based on Johnson $B - V$ standards and have a common zero point (see §II of Dickens et al.). In this case, the intent is to test a previously deduced zero point correction for the SAAO $B - V$ system (see entry 4 in Table 4 of Paper II):

$$\Delta(B - V) = -9.4 \pm 1.5 \text{ mmag.} \tag{2}$$

Unfortunately, agreement between the new and extant data is obtained whether the correction is applied or not (compare the offsets listed for the two entries). The correction is therefore consistent with the results of the analysis, but those results do not strengthen the case for adopting the correction.

Entries 8–9.–Here, the new $B-V$ data are compared to transformed Strömgren photometry from Joner & Taylor (2007). The latter source is part of an extensive project designed to yield uniform zero points for both cluster data and calibrating field star data (see, e. g., §1 of Joner & Taylor 2007). The calibration relation appears in §4 of Paper II.

Note that for both entries 8 and 9, $|x| > 2\sigma_x$. To assess such results, a more powerful statistical procedure than the one applied so far is required. Values of the Student's t statistic are therefore calculated for all differences listed in Table 2, and the results are evaluated using false-discovery rate (see §3 of Miller et al. 2001). This procedure is adopted because simultaneous tests of multiple hypotheses are now being performed (see §2 of Miller et al. 2001).

The question of interest now is how to interpret entries 8 and 9. If equation (2) is not employed (see entry 9), a nonzero value of x is detected. If equation (2) is employed (see entry 8), the absolute size of x is reduced, but still appears to be nonzero. However, the revised procedure reveals that the entry 8 value of x actually does not differ from zero at an overall confidence level of 95%. This apparent success obtained using equation (2) is regarded as additional evidence for its adoption.

4. V ANALYSIS: COLOR TERMS

To begin an analysis of V magnitudes, regression equations with the following form are calculated:

$$\Delta V \equiv V_E - V_T = S_V(R-I)_{\rm C} + Z_V + C_\alpha \sin\alpha + C_\delta \delta. \quad (3)$$

Here V_E and V_T refer to "extrinsic" and "tested" data, respectively. Z_V is a constant, α is right ascension, and δ is declination (in degrees). Values of S_V derived from equation (3) are listed in Table 3 and are discussed below.

Entries 1–2.–Both of these entries result from tests in which the SAAO system is compared to that of Johnson et al. (1966, hereafter JMIW). Since $|x|$ does not exceed $2\sigma_x$ in either case, no color term in the SAAO system is detected. Note also that the result for entry 2 is substantially more precise than that for entry 1 and thus appears to be more definitive. At first glance, this conclusion might appear to be suspect because it is based on a proxy for the E region standards, with no direct use being made of the data for those standards. However, it should be noted that the proxy consists of measurements made by Cousins himself (see Cousins 1980). Because Cousins dependably exerted meticulous care on his work, it seems entirely proper that entry 2 be accepted at face value.

Entries 3–7.–The Landolt (1983) V system is now tested by comparing it to the SAAO system and that of Johnson & Harris (1954). In this case, it appears that the listed values of S_V disagree. That assessment may be tested by using a χ^2 algorithm described in the Appendix to Paper I. According to the result of that test, $P > 2.70$, so the hypothesis that the disagreement exists is strongly supported.[1]

One possible way to make progress from this point is to limit attention to values of ΔV derived for an average value of $(R-I)_{\mathrm{C}}$. The value chosen here (0.261 mag) is the average of the Hyades, M67, and Praesepe measurements reported in Papers I and II and in this paper. The resulting values of ΔV are listed in the last column of Table 3. Unfortunately, if to those values the χ^2 test is applied, one finds that excess scatter is detected with $P = 1.27$. Though this result is not as strong as the one just described, it is still strong enough to suggest that the listed values of $\Delta V(0.261)$ disagree.

To avoid this problem, attention is focused on entry 7. That entry is derived from Tycho photometry and is therefore very likely to be based on a photometric system that is uniform over the entire sky (see §9 of Paper II). In the discussion given below, entry 7 will be adopted on an initially provisional basis.

5. V ANALYSIS: ZERO POINTS

Attention is now shifted to differences between sets of V magnitudes. The results are given in Table 4, and are discussed below.

Entry 1.–Here, a comparison of Hyades data from Taylor & Joner (1992) and Taylor & Joner (2005) implies that they are effectively on the same zero point.

Entries 2–5.–Combined Hyades data from those two sources are now tested, as are M67 and Praesepe data from TJJ. Note that corrections of those three sets of data to the SAAO zero point appear to be indistinguishable (see entries 2–4). A χ^2 test supports this assessment by failing to reveal the presence of excess scatter in those corrections. They are

[1] As in §3 of Paper II, $P \equiv -\log_{10}(20p)$ and $p \equiv 1 - C$. Note that if $P > 2.7$, $C > 0.9999$. In practice, deductions based on such high confidence levels do not require revision if they appear in multiple hypothesis testing (see §3).

therefore averaged, and the average is given in entry 5.

Entries 6–7.–Two sets of Hyades measurements on the SAAO system are now compared. One set is derived from Tycho photometry, while the other is Sutherland photometry reported in Paper I. For the value of ΔV listed in entry 6, the value of P derived from a Student's t test is 0.66 (implying that $C = 0.989$). Though this is a relatively modest significance level, it is concluded that $\Delta V \neq 0$.

Given the presumed uniformity of the Tycho photometry, a straightforward interpretation of this result is that a small declination effect has been detected in Sutherland photometry. To allow for that effect, entries 5 and 6 are added to yield entry 7.

Entries 8–9.–Entry 7 is a formal correction from the Landolt system to the SAAO system that is based exclusively on cluster photometry. In entry 7 of Table 3, there is an equivalent correction derived from field-star photometry. The latter is now brought forward to entry 8 of Table 4. An unequal-variance t test (see the review of statistical procedures in §3 of Paper II)is then applied to the difference between entries 7 and 8. Because it is found that the two entries do not differ with $C \geq 0.95$, they are averaged with inverse-variance weighting to yield the value of ΔV in entry 9.

Entries 10–12.–The value of ΔV in entry 9 is a final formal correction from the zero point of the Landolt system to the zero point of the SAAO system. A datum that has yet to be derived, however, is a formal correction from the SAAO zero point to that of the Johnson & Harris (1954) and JMIW photometry. Two values of that correction are therefore calculated, and they appear in entries 10 and 11. Here also, no difference between entries is found, so they are averaged to obtain the value of ΔV in entry 12.

Entries 13–14.–Using the data in entries 9 and 12, a net overall formal correction from the Landolt system to the JMIW system is derived and quoted in entry 13. Using the data in entries 7 and 12, an equivalent correction derived solely from cluster photometry is quoted in entry 14. Note that both corrections are indistinguishable from zero.

6. PERSPECTIVES ON CLUSTER RESULTS

As readers have doubtless noticed, the discussion given up to this point has been strictly tactical. No attempt has yet been made to put the derived cluster results in perspective. The implications of those results for the cluster photometry of TJJ will therefore be developed at this point.

Praesepe.–The principal aim of the new observing program was to resolve a problem with V magnitudes for this cluster. TJJ (see their §9) found that two extrinsic data sets supported the zero point of their V photometry, while two others did not. With entry 14 in Table 4 added to the reckoning, the balance of evidence now favors the zero point of the TJJ data. The 2σ limit implied by that entry is 4.6 mmag, so it is fair to conclude that no zero point correction of that size or larger is required.

The Hyades.–Judging from entries 2–4 in Table 4, the use of Landolt (1983) standard stars by TJJ has led to encouragingly consistent V magnitude zero points for Praesepe, the Hyades, and M67. A collateral conclusion is that there is now added support for the accuracy of the Hyades V magnitude zero point (see the fourth entry in Table 8 of TJJ).

M67.–The evaluation of V magnitudes for this cluster given by TJJ (see their Table 9) revealed substantial diversity. Photometry on a uniform system does support the TJJ zero point, but because the stars measured in M67 are faint, a correction to that zero point as large as 12 mmag could not be ruled out (see the last entry in Table 9 of TJJ). If this uncertainty is gauged by the so-called "FM" or "few-millimag" standard (see §3 of TJJ), it is too large to be acceptable. Here, as for Praesepe, the revised limit for such an uncertainty is a more acceptable 4.6 mmag.

NGC 752.–The TJJ photometry of this cluster was obtained during the same nights as their Praesepe photometry. One test of the resulting $(R-I)_{\rm C}$ values of NGC 752 yielded a zero point discrepancy (see the third from the last entry in Table 7 of TJJ). In addition, the only $(V-R)_{\rm C}$ zero point test for the two clusters that was feasible at the time was a test of the Praesepe photometry (see the fourth entry in Table 7 of TJJ). SAAO measurements cannot be used in direct tests of photometry for NGC 752 because the cluster declination is about +38 degrees. However, additional indirect tests can be performed by employing the Praesepe photometry. Entries 4 and 5 in Table 2 strengthen the balance of evidence that for stars on and near the main sequence, the zero points of the published $(V-R)_{\rm C}$ and $(R-I)_{\rm C}$ measurements of the Praesepe and NGC 752 require no corrections larger than about 4 mmag. Given these results, the only remaining unresolved uncertainty in the TJJ photometry concerns data for the NGC 752 giants (see the last two entries in Table 7 of TJJ).

7. SUMMARY

New SAAO measurements of Praesepe are presented. When those measurements are combined with those reported in Papers I and II, it is found that they support the TJJ V zero points for Praesepe, M67, and the Hyades at the 4.6 mmag level. Support is also found for that paper's joint $(V-R)_{\rm C}$ and $(R-I)_{\rm C}$ zero points for Praesepe and NGC 752. For the SAAO system of standard stars, corrections to the Johnson system of about +3 mmag in V and −9 mmag in $B-V$ appear to be reasonably well established. For the Landolt (1983) V system, there is a zero point identity with the Johnson system at a 2σ level of 3.4 mmag.

As in Paper I, we gratefully acknowledge SAAO for granting telescope time on such a well-established observing system. We also thank Lisa Joner for reading the manuscript carefully, Dr. D. Kilkenny for providing data reductions for the paper and for a careful evaluation of its reasoning. The WEBDA data base (operated at the Institute for Astronomy at the University of Vienna), the SIMBAD data base (operated at CDS, Strasbourg, France), the General Catalogue of Photometric Data (Mermilliod et al. 1997), the Asiago Database on Photometric Systems (Moro & Munari 2000), and the Smithsonian/NASA ADS listings have all contributed to this investigation, and we thank the operators of these Web sites with alacrity. Finally, we note with thanks that page charges for this series of papers have been generously underwritten by the College of Physical and Mathematical Sciences and the Physics and Astronomy Department of Brigham Young University.

REFERENCES

Bessell, M. S. 2000, PASP, 112, 961

Cousins, A. W. J. 1978, Mon. Notes Astron. Soc. South Africa, 37, 62

Cousins, A. W. J. 1980, South African Astron. Obs. Circulars, 1, 234

Dickens, R. J., Kraft, R. P., & Krzeminski, W. 1968, AJ, 73, 6

Johnson, H. L. 1952, ApJ, 116, 640

Johnson, H. L., & Harris, D. L. 1954, ApJ, 120, 196

Johnson, H. L., Mitchell, R. I., Iriarte, B., & Wiśnewski, W. Z. 1966, Comm. Lunar Planet. Lab., 4, 99

Joner, M. D., & Taylor, B. J. 2007, PASP, 109, 1093

Joner, M. D., Taylor, B. J., Laney, C. D., & van Wyk, F. 2006, AJ, 132, 111

Joner, M. D., Taylor, B. J., Laney, C. D., & van Wyk, F. 2008, AJ, 136, 1546

Klein-Wassink, W. J. 1927, Publ. Kapteyn Astr. Lab., no. 41

Kilkenny, D., van Wyk, F., Roberts, G., Marang, F., & Cooper, D. 1998, MNRAS, 294, 93

Landolt, A. U. 1983, AJ, 88, 439

Menzies, J. W., Banfield, R. M., & Laing, J. D. 1980, South African Astron. Obs., 13, 1

Menzies, J. W., Marang, F., Laing, J. D., Coulson, I. M., & Engelbrecht, C. 1991 MNRAS, 248, 642

Mermilliod, J.-C., Mermilliod, M., & Hauck, B. 1997, A&AS, 124, 349

Miller, C. J., et al. 2001, AJ, 122, 3492

Moro, D., & Munari, U. 2000, A&AS, 147, 361

Oja, T. 1994, A&A, 286, 1006

Sung, H., & Bessell, M. S. 2000, Publ. Astron. Soc. Australia, 17, 244

Taylor, B. J. 2008, AJ, 136, 1388

Taylor, B. J., & Joner, M. D. 1992, PASP, 104, 911

Taylor, B. J., & Joner, M. D. 1996, AJ, 111, 1338

Taylor, B. J., & Joner, M. D. 2005, ApJS, 159, 100

Taylor, B. J., Joner, M. D., & Jeffery, E. J. 2008, ApJS, 176, 262

van Beuren, H. G. 1952, Bull. Astron. Inst. Netherlands, 11, 432

Table 1. New SAAO $BV(RI)_C$ data for Praesepe and the Hyades

vB/KW[a]	Number	V[b]	$B-V$[b]	$V-R$[b]	$R-I$[b]	$V-I$[b]
vB	15	8.046(8.0)	0.664(4.2)	0.356(3.8)	0.340(3.8)	0.696(5.5)
vB	35	6.776(9.0)	0.441(5.5)	0.252(4.9)	0.239(4.9)	0.491(7.1)
vB	44	7.158(8.0)	0.466(4.2)	0.264(3.8)	0.254(3.8)	0.518(5.5)
vB	48	7.102(8.0)	0.534(4.2)	0.287(3.8)	0.282(3.8)	0.569(5.5)
vB	81	7.086(8.0)	0.481(2.4)	0.280(3.8)	0.275(3.8)	0.555(5.5)
KW	31	9.724(4.2)	0.552(4.9)	0.304(4.3)	0.287(5.1)	0.591(3.5)
KW	34	9.453(4.2)	0.431(4.9)	0.238(4.3)	0.242(5.1)	0.480(3.5)
KW	40	7.755(4.2)	0.190(4.9)	0.094(4.3)	0.087(5.1)	0.180(3.5)
KW	45	8.246(4.2)	0.237(4.9)	0.131(4.3)	0.126(5.1)	0.257(3.5)
KW	124	8.983(4.9)	0.331(5.7)	0.179(5.0)	0.181(5.9)	0.360(4.1)
KW	155	9.410(4.9)	0.424(5.7)	0.233(5.0)	0.231(5.9)	0.464(4.1)
KW	250	9.787(4.2)	0.463(4.9)	0.261(4.3)	0.265(5.1)	0.526(3.5)
KW	265	6.602(4.2)	−0.007(4.9)	−0.004(4.3)	0.006(5.1)	0.002(3.5)
KW	295	9.358(4.2)	0.423(4.9)	0.235(4.3)	0.233(5.1)	0.468(3.5)
KW	318	8.648(4.2)	0.298(4.9)	0.156(4.3)	0.160(5.1)	0.316(3.5)
KW	439	9.419(4.9)	0.394(5.7)	0.235(5.0)	0.230(5.9)	0.465(4.1)
KW	458	9.706(4.9)	0.566(5.7)	0.310(5.0)	0.294(5.9)	0.604(4.1)
KW	459	9.215(4.9)	0.396(5.7)	0.230(5.0)	0.217(5.9)	0.447(4.1)
KW	478	9.684(4.9)	0.445(5.7)	0.262(5.0)	0.250(5.9)	0.512(4.1)

NOTE.–None of the tabulated data have been corrected for reddening.

[a]The prefixes designate Hyades numbers from van Beuren (1952) and Praesepe numbers from Klein-Wassink (1927).

[b]Entries in parentheses are standard deviations in millimags derived separately for Praesepe and the Hyades by averaging squares of rms errors. The $B-V$ data are on the SAAO (not the Johnson et al. 1966) zero point. Values of $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see eq. [5] of Taylor & Joner 1996.)

Table 2. Hyades, Praesepe: Color-Index Differences

Entry	Cluster	Extrinsic source	Extrinsic index	Tested source	Tested index	Difference (mmag)	n
1	Hyades	SAAO (Paper I)	$(R-I)_C$	SAAO (Table 1)	$(R-I)_C$	$+2.8 \pm 2.2$	4
2	Hyades	SAAO (Paper I)	$(V-R)_C$	SAAO (Table 1)	$(V-R)_C$	-0.9 ± 2.3	4
3	Hyades	SAAO (Paper I)	$B-V$	SAAO (Table 1)	$B-V$	-4.5 ± 2.8	4
4	Praesepe	SAAO (Table 1)	$(R-I)_C$	TJJ[a]	$(R-I)_C$	-3.6 ± 2.0	14
5	Praesepe	SAAO (Table 1)	$(V-R)_C$	TJJ[a]	$(V-R)_C$	-1.6 ± 1.7	14
6	Praesepe	SAAO (Table 1)[b]	$B-V$	J52, DKK68[c]	$B-V$	-6.7 ± 3.4	11
7	Praesepe	SAAO (Table 1)[d]	$B-V$	J52, DKK68[c]	$B-V$	$+2.7 \pm 3.0$	11
8	Praesepe	SAAO (Table 1)[b]	$B-V$	JT07[e,f]	$b-y, m_1$	$+9.3 \pm 3.3$	13
9	Praesepe	SAAO (Table 1)[d]	$B-V$	JT07[e,f]	$b-y, m_1$	$+18.7 \pm 1.9$	13

NOTE.–The entries in the penultimate column are differences in the sense (extrinsic source minus tested source). The standard errors quoted in that column include allowances for accidental errors introduced by reduction and transformation relations when such allowances are required.

[a]The source paper is Taylor et al. (2008). The values of s are 1.7 ± 3.5 for $(R-I)_C$ and 1.9 ± 2.7 for $(V-R)_C$, respectively.

[b]A correction of -9.4 ± 1.5 mmag is applied to these data (see entry 4 in Table 4 of Paper II).

[c]The source papers are Johnson (1952) and Dickens et al. (1968).

[d]No zero point correction is applied to these data.

[e]The source paper is Joner & Taylor (2007). The value of s is 1.2 ± 1.0.

[f]The transformation from Strömgren indices to $B-V$ is performed by using equation (1) of Paper II. No metallicity corrections are made to the results because Praesepe has very nearly the solar metallicity (see Table 7 of Taylor 2008).

Table 3. Praesepe: Slope Tests for V

Entry	Extrinsic system[a]	Source[b]	Tested system[a]	Source[c]	S_V (mmag/mag)	$\Delta V(0.261)$[d]
1	JMIW	–	SAAO	Tycho[e]	-12 ± 6	–
2	JMIW	–	SAAO	C80[f]	-1 ± 1	–
3	SAAO	M80	L83	TJ96	$+18 \pm 3$	-1.3 ± 0.9
4	JH54	O94	L83	L83	-32 ± 7	-3.3 ± 2.4
5	SAAO	SB00	L83	L83	$+35 \pm 11$	$+4.7 \pm 2.6$
6	SAAO	M91[g]	L83	L83	$+3 \pm 2$	$+3.4 \pm 1.1$
7	SAAO	Tycho[e]	L83	L83	$+4 \pm 8$	-0.4 ± 2.1

[a]"JMIW" is Johnson et al. (1966), "JH54" is Johnson & Harris (1954), and "L83" is Landolt (1983).

[b]"M80" is Menzies et al. (1980), "M91" is Menzies et al. (1991), "O94" is Oja (1994), and "SB00" is Sung & Bessell (2000).

[c]'C80" is Cousins (1980), "L83" is Landolt (1983), and "TJ96" is Taylor & Joner (1996).

[d]The entries are values of V(extrinsic) $-V$(tested) at $(R-I)_C = 0.261$.

[e]"Tycho" represents Tycho photometry transformed to the SAAO system. The transformation relation is given in Table 2 of Bessell (2000). To rescale S_V from its value for $B-V$ to its value for $(R-I)_C$, a factor of 2.2 is applied (see Cousins 1978).

[f]The original solution for this data base is based on the Cousins (1980) values of $(V-R)_C$. The solution also yields the following coefficients: $Z_V = 0.1 \pm 0.6$ mmag, $C_\alpha = 1.3 \pm 0.6$ mmag, and $C_\delta = -0.61 \pm 0.17$ mmag (degree)$^{-1}$. To rescale the derived value of S_V to its value for $(R-I)_C$, a scaling factor of 1.14 is applied (see Cousins 1978).

[g]The solution for this data set also yields $C_\alpha = 4.1 \pm 0.9$ mmag.

Table 4. V Differences

Entry	Stars or sources[a]	Extrinsic system[b]	Source[c]	Tested system[b]	Source[c]	ΔV (mmag)
1	Hyades	Str	TJ92	L83	TJ05 (§3.2)	-3.0 ± 2.1
2	Hyades	SAAO	Paper I[d]	L83	Str, TJ05[d]	-8.0 ± 1.9
3	M67	SAAO	Paper II	L83	TJJ	-7.0 ± 2.0
4	Praesepe	SAAO	Table 1	L83	TJJ	-10.8 ± 1.9
5	2,3,4	SAAO	–	L83	–	-8.7 ± 1.5
6	Hyades	SAAO	Tycho[e]	SAAO	Paper I	$+4.2 \pm 1.6$
7	5,6	SAAO	–	L83	–	-4.5 ± 2.2
8	Field	SAAO	Tycho[f]	L83	L83[f]	-0.4 ± 2.1
9	7,8	SAAO	–	L83	–	-2.4 ± 1.5
10	Field	Johnson	JH54	SAAO	Tycho[e]	$+5.3 \pm 1.6$
11	Field	Johnson	JMIW	SAAO	C80	$+2.7 \pm 0.8$
12	10,11	Johnson	–	SAAO	–	$+3.2 \pm 0.7$
13	9,12	Johnson	–	L83	–	$+0.8 \pm 1.7$[g]
14	7,12	Johnson	–	L83	–	-1.3 ± 2.3[h]

[a]If numbers are listed, they are entry numbers from column 1.

[b]"L83" is Landolt (1983), and "Str" refers to Strömgren photometry.

[c]"C80" is Cousins (1980), "JH54" is Johnson & Harris (1954), "JMIW" is Johnson et al. (1966), "TJ92" is Taylor & Joner (1992), "TJ05" is §3.2 of Taylor & Joner (2005), and "TJJ" is Taylor et al. (2008).

[d]This entry applies at $V < 9.0$ mag, and it corrects and supersedes the corresponding entry in Table 8 of Taylor et al. (2008).

[e]"Tycho" represents Tycho photometry transformed to the SAAO system. The transformation relation is given in Table 2 of Bessell (2000).

[f]See entry 7 of Table 3.

[g]This entry is the general formal correction from the L83 system to the Johnson system.

[h]This entry is a counterpart to entry 13 for the cluster photometry on the L83 system cited in entries 2–4.

Chapter 12

Concluding Comments

This dissertation has presented a summary of methods used in observational stellar astrophysics with an emphasis on stellar photometry using the broadband $BV(RI)_C$ system. The nearly 30 year collaboration of Benjamin Taylor and this author has been described. Several publications that have been presented by this team using broadband photometric systems are summarized earlier in this dissertation. The introductory chapters presented information on the history and specifics of several photometric systems that use filters of various widths. Suggestions were presented to assist photometrists in establishing an observing routine and maintaining an instrumental system in order to produce high-quality photometric observations. The majority of the literature review that has been presented has provided background information and historical perspectives on problems that have been addressed in the individual publications that form the main body of the current investigation.

12.1 Summary of Conclusions

The papers presented in chapters 7 through 11 of this dissertation convincingly demonstrate that the photometry presented in TJ85 and subsequent papers are on a system that is closely tied to the Cousins system in scale-factor and zero-point at such a level that any differences are no more than a few mmags. The extensive consistency checks of previous work and the quality of the new photometric observations fully resolve the concerns that were raised by VandenBerg and Clem (2003), Pinsonneault et al. (2004), and VandenBerg and Stetson (2004) regarding the accuracy of the TJ85 and JT88 photometry. Studies done since the publication of the two papers that appear in chapters 7 and 8 indicate that the Taylor and Joner results are recognized as a source of high-quality cluster photometry. A few examples of this can be found in recent work by An et al. (2007), VandenBerg, Casagrande, and Stetson (2010), and Clem et al. (2011).

In conclusion, it has been demonstrated in this dissertation that the broadband photometry produced during the Taylor and Joner collaborations form a high-quality data set that has been: 1) stable for a period of more than 25 years; 2) monitored and tested for consistency relative to the broadband Cousins system, and 3) shown to have well-understood transformations to other versions of broadband photometric systems. The results from the Taylor and Joner catalogs provide a useful database for a variety of calibrations that require high-quality broadband photometric observations of the benchmark open clusters.

12.2 Suggestions and Plans for Future Work

One of the areas where the cluster stars that were examined in this investigation were different from some of the more exotic field stars is that the nearby clusters do not contain examples of stars of extreme spectral type. This deficiency can likely be remedied by making observations of young open clusters and relating those hot stars to the extreme blue stars that are part of the Landolt (1983, 1992) standard lists. However, it seems clear that both clusters and standard lists are lacking in examples of the reddest stars. A reasonable goal for the future would be to monitor as many examples of red stars as possible on a frequent basis and extend the baseline for existing transformations to more objects outside of the current range.

Another topic that can be addressed by future work in the area of high-quality photometry is in the area of standardization of fields around the sky that contain one or more stars of extreme color, along with one or two dozen additional stars having a range of about three magnitudes in any one color. This would be a worthwhile endeavor in that it is very important to demonstrate that CCD detectors are able to reproduce both accurate and precise measurements in different photometric systems. A good place to start would be with a field like M67 that was observed intensively with two to four of the Landolt areas on the same nights. I propose a series of $BV(RI)_C$ measurements during a number of nights with photometric conditions in order to prove this concept. The data could be examined in terms of the cluster stars serving as standards for the fields containing the Landolt stars to see if the Landolt values can be recovered within acceptable limits. Future work could extend this system all through the equatorial standard fields and perhaps to fields located in the northern B regions as well.

Yet another area of interest for future work would also involve CCD photometry and an examination of transformations to the *UBV* system using a UV enhanced CCD detector such as the Fairchild 3041-UV detector now in use on the 0.9-m telescope at the West Mountain Observatory. As far as I have been able to determine, there are no successful instances of large-scale transformations of *U-B* photometry from an instrumental system using a CCD detector. The *U-B* index is difficult to transform with many photomultiplier systems, but it is generally believed that the poor response of most CCD detectors in the *U* filter makes it almost impossible to do work other than photometry that is left on yet another unique instrumental system. A complete investigation of this problem would make for a challenging project.

One last suggestion for future work in high-quality photometry also involves the use of a CCD in standardization. The suggestion is to do intermediate-band work in the *uvbyβ* system and do a close examination of the transformations from the instrumental to the standard system. This project has the potential of being a little less challenging than the *UBV* work, since the *uvbyβ* filters are all narrow enough that the system can be viewed as filter defined and therefore much less dependent on the response function of the detector being utilized. This could also be a valuable study since there are stars in the nearby clusters that are faint enough to be easily observed with a modest sized telescope equipped with a CCD photometer. It should be fairly easy to observe many fields in nearby clusters such as the Pleiades, Praesepe, NGC 752, or M67, where an observer could image a dozen or more program stars in each frame. Since many of these stars have high-quality observations with photomultiplier photometers, the investigation of transformation relations for a system such as this should be relatively straightforward.

Thus, further work is suggested for: 1) the transformation relationships for the reddest stars available for use as standards; 2) the standardization of more fields for use with CCD detectors; 3) a further investigation of transformations of blue color indices for observations done using CCD detectors with enhanced UV sensitivity, and 4) a continuation of work on methods to produce high-quality observations of assorted star clusters (both open and globular) with CCD-based instrumentation and intermediate-band photometric systems.

Bibliography

An, D., Terndrup, D.M., Pinsonneault, M.H., Paulson, D.B., Hanson, R.B., & Stauffer, J.R. 2007, ApJ, 655, 233

Bell, R.A., & Vandenberg, D.A. 1987, ApJS, 63, 335

Bessell, M.S. 1979, PASP, 91, 589

Bessell, M.S. 1990, PASP, 102, 1181

Bessell, M.S. 2005, ARA&A, 43, 293

Bonifazi, A., Fusi Pecci, F., Romeo, G., & Tosi, M. 1990, MNRAS, 245,15

Boyle, R.P., Kazlauskas, A., Vansevicius, V., Straizys, V., Vrba, F.J., Sudzius, J., & Smriglio, F. 1998, Baltic Astronomy, 7, 369

Campbell, B. 1984, ApJ, 283, 209

Carney, B.W., & Aaronson, M. 1979, AJ, 84, 867

Clem, J.L., Landolt, A.U., Hoard, D.W., & Wachter, S. 2011, arXiv:1101.3268

Clem, J.L., VandenBerg, D.A., Grundahl, F., & Bell, R.A., 2004 AJ 127, 1227

Cousins, A.W.J. 1973, MmRAS, 77, 223

Cousins, A.W.J. 1974, Mon. Notes Astr. Soc. South Africa, 33, 149

Cousins, A.W.J. 1976, MmRAS, 81, 25

Cousins, A.W.J. 1983, South African Astronomical Observatory Circular, 7, 47

Cousins, A.W.J. 1984, South African Astronomical Observatory Circular, 8, 69

Crawford, D.L. 1975, AJ, 80, 955

Crawford, D.L. 1978, AJ, 83, 48

Crawford, D.L. 1979, AJ, 84, 1858

Crawford, D.L., Barnes, J.V., Faure, B.Q., & Golson, J.C. 1966, AJ, 71, 709

Crawford, D.L., & Mander, J. 1966, AJ, 71, 114

Di Benedetto, G.P. 1998, A&A, 339, 858

Eggen, O.J. 1972, ApJ, 172, 639

Eggen, O.J. 1978, ApJS, 37, 251

Eggen, O.J. 1982, ApJS, 50, 221

Eggen, O.J. 1983, AJ, 88, 813

Eggen, O.J. 1986, AJ, 92, 910

Graham, J.A. 1982, PASP, 94, 244

Gutiérrez-Moreno, A., Moreno, H., & Cortés, G. 1981, PASP, 93, 97

Houdashelt, M.L., Frogel, J.A., & Cohen, J.G. 1992, AJ, 103, 163

Janes, K.A. 1975, ApJS, 29, 161

Janes, K.A. 1977, PASP, 89, 576

Johnson, H.L., & Harris, D.L. 1954, ApJ, 120, 196

Johnson, H.L., Mitchell, R.I., Iriarte, B., & Wisniewski, W.Z. 1966, Comm. Lunar and Planetary Laboratory, 4, 99 [No. 63]

Johnson, H.L., MacArthur, J.W., & Mitchell, R.I. 1968, ApJ, 152, 465

Johnson, H.L., & Morgan, W.W. 1953, ApJ, 117, 313

Joner, M.D., & Taylor, B.J. 1988, AJ, 96, 218

Joner, M.D., & Taylor, B.J. 1990, PASP, 102, 1004

Joner, M.D., Taylor, B.J., Laney, C.D., & van Wyk, F. 2006, AJ, 132, 111

Joner, M.D., Taylor, B.J., Laney, C.D., & van Wyk, F. 2008, AJ, 136, 1546

Joner, M.D., Taylor, B.J., Laney, C.D., & van Wyk, F. 2011, in preparation

Kron, G.E., & Smith, J.L. 1951, ApJ, 113, 324

Kron, G.E., White, H.S., & Gascoigne, S.C.B. 1953, ApJ, 118, 502

Landolt, A.U. 1973, AJ, 78, 959
Landolt, A.U. 1983, AJ, 88, 439

Landolt, A.U. 1992, AJ, 104, 340

Landolt, A.U. 2007, The Future of Photometric, Spectrophotometric and Polarimetric Standardization (Astron. Soc. Of the Pacific: San Francisco) ASP Conference Series 364, 27

Landolt, A.U. 2009, AJ, 137, 4186

McClure, R.D. 1976, AJ, 81, 182

McClure, R.D., & Forrester, W.T. 1981, Publications of the Dominion Astrophysical Observatory Victoria, 15, 439

Mendoza, E.E. 1967, Boletin de los Observatorios Tonantzintla y Tacubaya, 4, 149

Menzies, J.W., Cousins, A.W.J., Banfield, R.M., & Laing, J.D. 1989, South African Astronomical Observatory Circular, No. 13, p. 1

Mermilliod, J.C. 1987, A&AS, 71, 413

Mermilliod, J.C. 2006, VizieR Online Data Catalog, 2122, 0

Montgomery, K.A., Marschall, L.A., & Janes, K.A. 1993, AJ, 106, 181

Nissen, P.E., & Schuster, W.J. 1991, A&A, 251, 457

Pinsonneault, M.H., Terndrup, D.M., Hanson, R.B., & Stauffer, J.R. 2004, ApJ, 600, 946

Sagar, R., Naidu, B.N., & Mohan, V. 2001, Bull. Astr. Soc. India, 29, 519

Sandquist, E.L. 2004, MNRAS, 347, 101

Schuster, W.J., & Nissen, P.E. 1989, A&A, 221, 65

Spinrad, H. & Taylor, B.J. 1969, ApJ, 157,1279

Strömgren, B. 1951, AJ, 56, 142

Strömgren, B. 1966, ARA&A, 4, 433

Sturch, C. 1972, PASP, 84, 666

Sturch, C. 1973, PASP, 85, 724

Taylor, B.J. 1978, ApJS, 36, 173

Taylor, B.J. 1980, AJ, 85, 242

Taylor, B.J. 1986, ApJS, 60, 577

Taylor, B.J. 2000, A&A, 362, 563

Taylor, B.J., Johnson, S.B., & Joner, M.D. 1987, AJ, 93, 1253

Taylor, B.J., & Joner, M.D. 1985, AJ, 90, 479

Taylor, B.J., & Joner, M.D. 1988, AJ, 96, 211

Taylor, B.J., & Joner, M.D. 1996, AJ, 111, 1338

Taylor, B.J., & Joner, M.D. 2005, ApJS, 159, 100

Taylor, B.J., & Joner, M.D. 2006, PASP, 118, 1716

Taylor, B.J., Joner, M.D., & Jeffery, E.J. 2008, ApJS, 176, 262

Upgren, A.R., & Weis, E.W. 1977, AJ, 82, 978

Upgren, A.R., Weis, E.W., & Hanson, R.B. 1985, AJ, 90, 2039

Vandenberg, D.A., & Bell, R.A. 1985, ApJS, 58, 561

VandenBerg, D.A., Casagrande, L., & Stetson, P.B. 2010, AJ, 140, 1020

VandenBerg, D.A., & Clem, J.L. 2003, AJ, 126, 778

Vandenberg, D.A., & Poll, H.E. 1989, AJ, 98, 1451

VandenBerg, D.A., & Stetson, P.B. 2004, PASP, 116, 997

West, M., Hintz, E.G., & Joner, M.D. 2010, BAAS, 42, 477

Weis, E.W., Deluca, E.E., & Upgren, A.R. 1979, PASP, 91, 766

Weis, E.W., & Hanson, R.B. 1988, AJ, 96, 148

Weis, E.W., & Upgren, A.R. 1982, PASP, 94, 821

Wing, R.F. 1967, "Infrared Spectrophotometry of Red Giant Stars," PhD thesis, Univ. Calif., Berkeley

Appendix

Cousins *VRI* Data Catalogs for Coma, M67, Praesepe, and NCG 752 from Taylor, Joner, and Jeffery (2008)

Cousins *VRI* Data for Coma

WEBDA*	Name	V	σ	V-R	σ	R-I	σ
19	T 19	8.073	0.0016	0.240	0.0032	0.237	0.0023
36	T 36	8.089	0.0111	0.238	0.0032	0.244	0.0023
49	T 49	7.846	0.0022	0.215	0.0032	0.204	0.0023
76	T 76	9.052	0.0017	0.318	0.0032	0.313	0.0023
85	T 85	9.295	0.0031	0.334	0.0032	0.319	0.0023
86	T 86	8.508	0.0031	0.271	0.0032	0.273	0.0023
90	T 90	8.523	0.0032	0.271	0.0032	0.271	0.0023
92	T 92	8.553	0.0082	0.317	0.0032	0.327	0.0023
97	T 97	9.090	0.0063	0.322	0.0032	0.321	0.0023
101	T 101	8.379	0.0136	0.264	0.0039	0.257	0.0028
102	T 102	9.319	0.0111	0.349	0.0039	0.343	0.0028
111	T 111	8.325	0.0055	0.310	0.0039	0.303	0.0028
114	T 114	8.565	0.0022	0.270	0.0039	0.269	0.0028
118	T 118	8.339	0.0027	0.259	0.0039	0.259	0.0028
132	T 132	9.850	0.0024	0.373	0.0039	0.355	0.0028
150	T 150	9.717	0.0033	0.440	0.0039	0.412	0.0028
162	T 162	8.555	0.0034	0.275	0.0039	0.271	0.0028

* This research has made use of the WEBDA database, operated at the Institute for Astronomy of the University of Vienna for star names within clusters and name cross-referencing. http://www.univie.ac.at/webda/

Cousins *VRI* Data for M67

WEBDA	Name	V	σ	V-R	σ	R-I	σ
28	F 28	12.766	0.0065	0.326	0.0061	0.320	0.0072
30	F 30	11.969	0.0061	0.345	0.0056	0.330	0.0065
31	F 31	13.630	0.0061	0.337	0.0056	0.320	0.0065
33	F 33	14.101	0.0065	0.355	0.0059	0.333	0.0066
36	F 36	13.369	0.0061	0.334	0.0056	0.324	0.0065
37	F 37	12.861	0.0064	0.519	0.0058	0.465	0.0043
39	F 39	13.292	0.0061	0.369	0.0072	0.366	0.0065
42	F 42	13.468	0.0061	0.352	0.0061	0.328	0.0065
43	F 43	13.441	0.0061	0.358	0.0062	0.342	0.0065
46	F 46	12.750	0.0061	0.444	0.0056	0.405	0.0065
48	F 48	12.722	0.0061	0.416	0.0056	0.389	0.0065
50	F 50	13.491	0.0061	0.319	0.0081	0.327	0.0065
54	F 54	12.653	0.0061	0.352	0.0065	0.342	0.0065
55	F 55	11.317	0.0049	0.163	0.0044	0.173	0.0048
56	F 56	13.385	0.0064	0.326	0.0083	0.324	0.0065
58	F 58	14.041	0.0061	0.395	0.0056	0.368	0.0065
61	F 61	13.518	0.0053	0.362	0.0047	0.332	0.0041
62	F 62	13.739	0.0066	0.340	0.0051	0.340	0.0057
63	F 63	13.315	0.0061	0.337	0.0056	0.339	0.0065
64	F 64	14.028	0.0067	0.395	0.0062	0.376	0.0067
70	F 70	11.552	0.0040	0.254	0.0032	0.259	0.0035
71	F 71	13.564	0.0065	0.335	0.0050	0.337	0.0056
72	F 72	12.380	0.0044	0.520	0.0037	0.471	0.0034
73	F 73	13.778	0.0039	0.338	0.0034	0.330	0.0036
75	F 75	13.417	0.0044	0.326	0.0038	0.318	0.0036
76	F 76	13.984	0.0065	0.407	0.0051	0.379	0.0051
77	F 77	13.368	0.0044	0.333	0.0037	0.328	0.0041
79	F 79	12.787	0.0061	0.411	0.0066	0.387	0.0065
80	F 80	13.851	0.0050	0.342	0.0041	0.329	0.0044
81	F 81	10.021	0.0036	-0.033	0.0029	-0.035	0.0029
82	F 82	13.778	0.0065	0.341	0.0040	0.332	0.0044
83	F 83	13.205	0.0044	0.345	0.0030	0.341	0.0036
84	F 84	10.520	0.0069	0.567	0.0048	0.505	0.0044
85	F 85	13.624	0.0065	0.340	0.0050	0.330	0.0051
86	F 86	13.562	0.0080	0.582	0.0056	0.550	0.0065

Cousins *VRI* Data for M67 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
87	F 87	13.596	0.0047	0.322	0.0048	0.320	0.0050
89	F 89	13.374	0.0065	0.337	0.0050	0.337	0.0055
90	F 90	10.956	0.0065	0.268	0.0039	0.259	0.0043
91	F 91	12.824	0.0065	0.326	0.0050	0.317	0.0055
93	F 93	14.135	0.0048	0.357	0.0037	0.329	0.0044
94	F 94	12.789	0.0044	0.332	0.0034	0.317	0.0035
95	F 95	12.674	0.0065	0.296	0.0050	0.289	0.0051
97	F 97	14.350	0.0065	0.326	0.0054	0.312	0.0054
98	F 98	12.811	0.0061	0.333	0.0056	0.327	0.0065
99	F 99	13.550	0.0061	0.347	0.0059	0.317	0.0065
100	F 100	13.441	0.0044	0.343	0.0039	0.330	0.0046
101	F 101	13.150	0.0065	0.339	0.0050	0.344	0.0051
102	F 102	12.398	0.0047	0.421	0.0040	0.388	0.0038
104	F 104	11.134	0.0065	0.564	0.0050	0.526	0.0051
105	F 105	10.295	0.0036	0.653	0.0029	0.578	0.0031
106	F 106	13.080	0.0065	0.333	0.0087	0.306	0.0089
107	F 107	13.922	0.0065	0.336	0.0053	0.330	0.0063
108	F 108	9.695	0.0048	0.714	0.0042	0.635	0.0040
109	F 109	13.506	0.0065	0.339	0.0050	0.330	0.0052
110	F 110	13.560	0.0061	0.330	0.0058	0.323	0.0065
111	F 111	12.729	0.0045	0.330	0.0035	0.323	0.0035
112	F 112	13.281	0.0061	0.337	0.0058	0.326	0.0065
113	F 113	14.123	0.0061	0.361	0.0079	0.333	0.0065
114	F 114	13.418	0.0061	0.333	0.0056	0.323	0.0065
115	F 115	12.640	0.0065	0.350	0.0045	0.340	0.0043
116	F 116	14.153	0.0066	0.399	0.0052	0.375	0.0060
117	F 117	12.625	0.0047	0.459	0.0039	0.432	0.0042
118	F 118	14.047	0.0061	0.324	0.0080	0.330	0.0076
119	F 119	12.542	0.0065	0.352	0.0045	0.331	0.0043
120	F 120	13.676	0.0053	0.329	0.0043	0.338	0.0042
122	F 122	13.715	0.0061	0.327	0.0059	0.323	0.0065
123	F 123	13.907	0.0065	0.367	0.0062	0.363	0.0065
124	F 124	12.121	0.0037	0.280	0.0031	0.280	0.0048
125	F 125	13.867	0.0061	0.336	0.0045	0.322	0.0054
126	F 126	13.943	0.0050	0.346	0.0041	0.335	0.0049

Cousins *VRI* Data for M67 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
127	F 127	12.763	0.0036	0.324	0.0032	0.322	0.0033
128	F 128	13.151	0.0065	0.334	0.0053	0.315	0.0051
129	F 129	13.189	0.0065	0.333	0.0051	0.314	0.0058
130	F 130	12.896	0.0065	0.275	0.0052	0.251	0.0056
131	F 131	11.168	0.0045	0.253	0.0040	0.259	0.0041
132	F 132	13.091	0.0035	0.350	0.0030	0.329	0.0032
133	F 133	13.671	0.0061	0.331	0.0063	0.329	0.0065
134	F 134	12.257	0.0046	0.335	0.0037	0.327	0.0036
135	F 135	11.433	0.0044	0.555	0.0034	0.496	0.0035
136	F 136	11.294	0.0043	0.360	0.0038	0.346	0.0043
137	F 137	14.055	0.0080	0.381	0.0072	0.376	0.0078
140	F 140	13.194	0.0037	0.332	0.0033	0.323	0.0036
141	F 141	10.460	0.0035	0.565	0.0028	0.502	0.0030
142	F 142	14.159	0.0063	0.356	0.0053	0.342	0.0053
143	F 143	11.483	0.0065	0.484	0.0050	0.453	0.0051
145	F 145	0.000	0.0000	0.000	0.0000	0.327	0.0075
147	F 147	13.251	0.0065	0.350	0.0050	0.320	0.0053
148	F 148	13.260	0.0061	0.342	0.0056	0.330	0.0065
149	F 149	12.539	0.0035	0.343	0.0029	0.329	0.0032
150	F 150	13.231	0.0065	0.332	0.0050	0.327	0.0052
151	F 151	10.487	0.0062	0.558	0.0044	0.495	0.0038
152	F 152	13.481	0.0065	0.337	0.0057	0.333	0.0057
153	F 153	11.270	0.0044	0.048	0.0039	0.066	0.0046
155	F 155	10.494	0.0036	0.339	0.0030	0.326	0.0032
156	F 156	10.941	0.0062	0.049	0.0049	0.038	0.0051
157	F 157	12.750	0.0062	0.334	0.0071	0.321	0.0050
159	F 159	13.310	0.0071	0.353	0.0083	0.334	0.0065
161	F 161	12.790	0.0075	0.291	0.0041	0.297	0.0036
162	F 162	0.000	0.0000	0.000	0.0000	0.325	0.0080
164	F 164	10.530	0.0040	0.574	0.0031	0.519	0.0030
165	F 165	12.836	0.0064	0.340	0.0082	0.329	0.0065
166	F 166	12.910	0.0044	0.496	0.0037	0.447	0.0033
170	F 170	9.655	0.0038	0.699	0.0030	0.622	0.0031
171	F 171	13.134	0.0061	0.334	0.0056	0.328	0.0065
174	F 174	12.684	0.0065	0.345	0.0050	0.340	0.0051

Cousins *VRI* Data for M67 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
175	F 175	0.000	0.0000	0.351	0.0086	0.344	0.0092
176	F 176	12.618	0.0044	0.336	0.0037	0.327	0.0040
178	F 178	14.019	0.0068	0.340	0.0087	0.363	0.0067
179	F 179	13.654	0.0070	0.363	0.0096	0.341	0.0065
180	F 180	12.632	0.0061	0.338	0.0056	0.326	0.0065
184	F 184	12.265	0.0135	0.155	0.0066	0.142	0.0066
187	F 187	13.198	0.0064	0.362	0.0069	0.343	0.0065
189	F 189	12.850	0.0061	0.312	0.0059	0.305	0.0065
190	F 190	10.905	0.0083	0.142	0.0051	0.144	0.0051
193	F 193	12.272	0.0073	0.525	0.0094	0.475	0.0042
194	F 194	13.606	0.0061	0.337	0.0062	0.323	0.0065
195	F 195	12.691	0.0061	0.395	0.0056	0.377	0.0065
201	F 201	14.007	0.0061	0.367	0.0062	0.351	0.0065
205	F 205	13.531	0.0388	0.326	0.0311	0.335	0.0132
208	F 208	14.141	0.0061	0.338	0.0068	0.341	0.0077
209	F 209	13.715	0.0061	0.374	0.0056	0.348	0.0065
210	F 210	12.247	0.0061	0.325	0.0062	0.320	0.0065
211	F 211	13.795	0.0076	0.338	0.0082	0.325	0.0065
213	F 213	13.837	0.0049	0.334	0.0044	0.339	0.0050
214	F 214	13.803	0.0049	0.340	0.0048	0.326	0.0049
215	F 215	12.792	0.0079	0.327	0.0104	0.316	0.0065
216	F 216	12.713	0.0061	0.329	0.0056	0.325	0.0065
217	F 217	11.265	0.0072	0.563	0.0078	0.510	0.0043
221	F 221	12.418	0.0061	0.341	0.0057	0.346	0.0065
223	F 223	10.530	0.0055	0.567	0.0078	0.509	0.0039
224	F 224	10.767	0.0045	0.590	0.0039	0.516	0.0038
225	F 225	0.000	0.0000	0.000	0.0000	0.312	0.0085
226	F 226	12.781	0.0061	0.402	0.0058	0.382	0.0065
227	F 227	12.972	0.0061	0.490	0.0056	0.444	0.0065
228	F 228	13.210	0.0061	0.322	0.0056	0.323	0.0065
231	F 231	11.507	0.0061	0.549	0.0064	0.491	0.0042
233	F 233	13.383	0.0061	0.320	0.0057	0.317	0.0065
235	F 235	13.393	0.0061	0.331	0.0070	0.318	0.0065
236	F 236	12.532	0.0072	0.374	0.0083	0.350	0.0065
237	F 237	12.908	0.0089	0.504	0.0133	0.455	0.0065

Cousins *VRI* Data for M67 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
238	F 238	10.908	0.0065	0.107	0.0073	0.119	0.0065
239	F 239	14.038	0.0061	0.338	0.0065	0.336	0.0065
241	F 241	0.000	0.0000	0.351	0.0114	0.323	0.0080
243	F 243	0.000	0.0000	0.353	0.0114	0.330	0.0080
244	F 244	10.751	0.0048	0.498	0.0042	0.450	0.0037
248	F 248	12.794	0.0094	0.331	0.0134	0.317	0.0065
254	F 254	13.356	0.0061	0.336	0.0057	0.334	0.0065
255	F 255	12.730	0.0063	0.331	0.0063	0.320	0.0050
257	F 257	11.462	0.0061	0.320	0.0056	0.324	0.0065
258	F 258	14.056	0.0061	0.391	0.0066	0.364	0.0065
259	F 259	13.910	0.0051	0.382	0.0065	0.362	0.0049
261	F 261	10.579	0.0084	0.127	0.0110	0.128	0.0065
262	F 262	12.919	0.0071	0.526	0.0092	0.467	0.0065
263	F 263	13.969	0.0051	0.354	0.0053	0.322	0.0051
265	F 265	12.466	0.0066	0.352	0.0078	0.348	0.0065
266	F 266	10.507	0.0089	0.561	0.0051	0.508	0.0040
267	F 267	12.821	0.0090	0.333	0.0119	0.320	0.0065
268	F 268	13.367	0.0073	0.335	0.0093	0.327	0.0065
269	F 269	13.180	0.0065	0.332	0.0077	0.326	0.0065
271	F 271	12.720	0.0064	0.325	0.0068	0.320	0.0065
280	F 280	10.653	0.0063	0.048	0.0049	0.059	0.0079
1002	I-2	14.174	0.0065	0.412	0.0050	0.374	0.0053
1003	I-3	14.507	0.0077	0.427	0.0052	0.415	0.0068
1004	I-4	15.714	0.0082	0.529	0.0090	0.476	0.0087
1010	I-10	15.789	0.0123	0.620	0.0132	0.533	0.0103
1013	I-13	15.111	0.0094	0.435	0.0087	0.415	0.0117
1018	I-18	15.052	0.0078	0.512	0.0075	0.451	0.0082
1019	I-19	14.544	0.0065	0.394	0.0060	0.363	0.0077
1021	I-21	15.815	0.0089	0.438	0.0124	0.439	0.0137
1022	I-22	15.363	0.0079	0.453	0.0085	0.434	0.0085
1047	I-47	14.626	0.0074	0.463	0.0077	0.409	0.0069
1050	I-50	15.374	0.0079	0.503	0.0047	0.626	0.0059
1051	I-51	14.112	0.0044	0.336	0.0034	0.335	0.0042
1057	I-57	14.481	0.0061	0.367	0.0067	0.357	0.0104
1058	I-58	14.698	0.0069	0.446	0.0061	0.409	0.0083

Cousins *VRI* Data for M67 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
1061	I-61	14.530	0.0083	0.394	0.0091	0.392	0.0089
1065	I-65	14.536	0.0065	0.331	0.0089	0.320	0.0090
1129	I-129	15.097	0.0091	0.738	0.0134	0.598	0.0119
1160	I-160	14.481	0.0067	0.375	0.0079	0.351	0.0067
1161	I-161	14.781	0.0063	0.395	0.0056	0.373	0.0087
1166	I-166	13.951	0.0061	0.472	0.0056	0.431	0.0065
2001	II-1	13.802	0.0044	0.382	0.0040	0.377	0.0041
2002	II-2	15.742	0.0114	0.589	0.0119	0.517	0.0111
2003	II-3	15.856	0.0138	0.635	0.0116	0.556	0.0120
2004	II-4	14.153	0.0061	0.350	0.0056	0.325	0.0068
2007	II-7	14.463	0.0061	0.374	0.0074	0.345	0.0072
2008	II-8	14.941	0.0069	0.519	0.0077	0.446	0.0076
2012	II-12	14.177	0.0061	0.362	0.0062	0.337	0.0065
2014	II-14	14.099	0.0062	0.363	0.0077	0.346	0.0065
2023	II-23	15.826	0.0077	0.584	0.0102	0.539	0.0110
2029	II-29	14.579	0.0062	0.389	0.0058	0.360	0.0070
2033	II-33	14.565	0.0061	0.441	0.0057	0.403	0.0086
2035	II-35	14.358	0.0063	0.373	0.0085	0.362	0.0085
2039	II-39	14.483	0.0071	0.381	0.0058	0.356	0.0075
2041	II-41	14.796	0.0061	0.428	0.0090	0.402	0.0081
2042	II-42	14.329	0.0061	0.449	0.0062	0.412	0.0065
2048	II-48	14.380	0.0071	0.367	0.0076	0.357	0.0065
2054	II-54	12.872	0.0061	0.301	0.0057	0.306	0.0065
2058	II-58	14.866	0.0074	0.517	0.0103	0.469	0.0078
2068	II-68	14.382	0.0061	0.420	0.0060	0.411	0.0065
2112	II-112	14.625	0.0061	0.458	0.0087	0.420	0.0065
2115	II-115	14.365	0.0061	0.360	0.0056	0.354	0.0065
2119	II-119	14.722	0.0063	0.402	0.0065	0.376	0.0075
2121	II-121	13.723	0.0066	0.349	0.0077	0.353	0.0065
2123	II-123	14.792	0.0069	0.412	0.0083	0.405	0.0065
2125	II-125	14.577	0.0067	0.373	0.0081	0.359	0.0078
3008	III-8	15.752	0.0135	0.616	0.0098	0.537	0.0093
3009	III-9	14.396	0.0065	0.381	0.0053	0.366	0.0058
3010	III-10	14.376	0.0065	0.428	0.0050	0.401	0.0051
3019	III-19	14.897	0.0063	0.431	0.0059	0.418	0.0101

Cousins *VRI* Data for M67 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
3035	III-35	12.138	0.0065	0.528	0.0076	0.477	0.0065
3036	III-36	14.171	0.0064	0.358	0.0083	0.343	0.0065
3058	III-58	14.328	0.0086	0.389	0.0108	0.380	0.0065
3069	III-69	14.594	0.0093	0.381	0.0129	0.343	0.0065
3072	III-72	14.522	0.0085	0.449	0.0113	0.394	0.0108
3080	III-80	14.401	0.0071	0.478	0.0110	0.444	0.0065
3137	III-137	14.361	0.0089	0.381	0.0165	0.339	0.0079
3138	III-138	14.783	0.0089	0.422	0.0207	0.363	0.0107
4001	IV-1	14.729	0.0044	0.419	0.0042	0.401	0.0050
4004	IV-4	12.698	0.0044	0.331	0.0037	0.314	0.0040
4006	IV-6	13.268	0.0065	0.281	0.0050	0.276	0.0059
4007	IV-7	15.372	0.0081	0.478	0.0079	0.396	0.0081
4014	IV-14	15.617	0.0183	0.623	0.0130	0.518	0.0082
4015	IV-15	14.276	0.0065	0.386	0.0060	0.381	0.0056
4016	IV-16	14.302	0.0044	0.326	0.0039	0.322	0.0048
4017	IV-17	14.298	0.0061	0.371	0.0056	0.351	0.0065
4018	IV-18	13.016	0.0061	0.471	0.0056	0.431	0.0065
4023	IV-23	14.856	0.0092	0.440	0.0062	0.432	0.0058
4032	IV-32	15.545	0.0108	0.472	0.0085	0.417	0.0063
4033	IV-33	15.589	0.0093	0.522	0.0098	0.502	0.0075
4038	IV-38	15.640	0.0182	0.495	0.0243	0.509	0.0182
4039	IV-39	14.881	0.0069	0.415	0.0078	0.370	0.0090
4044	IV-44	14.151	0.0061	0.353	0.0056	0.343	0.0065
4057	IV-57	14.551	0.0061	0.479	0.0056	0.451	0.0065
4058	IV-58	14.816	0.0061	0.409	0.0060	0.365	0.0099
4070	IV-70	14.640	0.0062	0.383	0.0067	0.365	0.0080
4090	IV-90	14.437	0.0061	0.387	0.0077	0.352	0.0065
4091	IV-91	14.543	0.0061	0.380	0.0056	0.351	0.0072
4202	S 488	8.870	0.0081	0.850	0.0027	0.825	0.0056
5820	F 149b	14.731	0.0063	0.271	0.0058	0.296	0.0198
6470	S 364	9.930	0.0090	0.693	0.0038	0.605	0.0077

Cousins *VRI* Data for Praesepe

WEBDA	Name	V	σ	V-R	σ	R-I	σ
31	KW 31	9.726	0.0080	0.305	0.0062	0.282	0.0074
34	KW 34	9.457	0.0046	0.242	0.0039	0.253	0.0042
40	KW 40	7.767	0.0053	0.099	0.0037	0.091	0.0043
45	KW 45	8.256	0.0080	0.116	0.0074	0.152	0.0074
90	KW 90	10.913	0.0041	0.402	0.0029	0.372	0.0035
124	KW 124	9.000	0.0052	0.189	0.0036	0.189	0.0043
127	KW 127	10.800	0.0051	0.333	0.0039	0.324	0.0047
155	KW 155	9.426	0.0046	0.241	0.0039	0.232	0.0040
164	KW 164	11.335	0.0150	0.398	0.0026	0.365	0.0034
181	KW 181	10.488	0.0051	0.339	0.0039	0.325	0.0047
182	KW 182	10.314	0.0041	0.365	0.0029	0.335	0.0035
203	KW 203	7.736	0.0080	0.124	0.0044	0.123	0.0052
222	KW 222	10.114	0.0051	0.277	0.0039	0.271	0.0047
232	KW 232	9.238	0.0046	0.230	0.0032	0.230	0.0039
238	KW 238	10.293	0.0059	0.300	0.0040	0.287	0.0046
244	KW 244	10.014	0.0290	0.350	0.0039	0.324	0.0036
250	KW 250	9.796	0.0046	0.274	0.0031	0.261	0.0041
265	KW 265	6.606	0.0043	-0.007	0.0033	0.002	0.0039
268	KW 268	9.876	0.0062	0.277	0.0053	0.290	0.0052
271	KW 271	8.821	0.0046	0.180	0.0031	0.177	0.0037
276	KW 276	7.541	0.0057	0.072	0.0044	0.073	0.0052
279	KW 279	7.695	0.0057	0.095	0.0044	0.074	0.0063
288	KW 288	10.698	0.0046	0.333	0.0036	0.308	0.0058
295	KW 295	9.379	0.0062	0.252	0.0044	0.233	0.0052
318	KW 318	8.657	0.0062	0.162	0.0044	0.163	0.0052
341	KW 341	10.303	0.0049	0.296	0.0032	0.281	0.0035
370	KW 370	9.032	0.0057	0.210	0.0042	0.203	0.0046
371	KW 371	10.101	0.0051	0.279	0.0040	0.275	0.0047
418	KW 418	10.481	0.0046	0.317	0.0036	0.297	0.0058
439	KW 439	9.440	0.0080	0.227	0.0062	0.251	0.0074
445	KW 445	7.976	0.0080	0.102	0.0062	0.124	0.0074
458	KW 458	9.713	0.0080	0.315	0.0062	0.288	0.0074
459	KW 459	9.228	0.0052	0.227	0.0036	0.226	0.0046
478	KW 478	9.694	0.0052	0.260	0.0036	0.248	0.0043
495	KW 495	9.937	0.0051	0.358	0.0039	0.333	0.0063

Cousins *VRI* Data for Praesepe (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
508	KW 508	10.761	0.0051	0.334	0.0039	0.326	0.0047
515	KW 515	10.131	0.0059	0.287	0.0039	0.285	0.0047
553	KW 553	10.153	0.0051	0.263	0.0039	0.261	0.0047

Cousins *VRI* Data for NGC 752

WEBDA	Name	V	σ	V-R	σ	R-I	σ
1	H 1	9.484	0.0063	0.497	0.0046	0.463	0.0052
11	H 11	9.274	0.0063	0.490	0.0046	0.462	0.0052
24	H 24	8.914	0.0063	0.522	0.0046	0.479	0.0052
41	H 41	9.815	0.0063	0.291	0.0051	0.287	0.0052
66	H 66	10.925	0.0040	0.264	0.0067	0.266	0.0074
75	H 75	8.957	0.0080	0.517	0.0074	0.476	0.0074
77	H 77	9.375	0.0063	0.539	0.0046	0.491	0.0052
88	H 88	11.760	0.0100	0.297	0.0067	0.307	0.0126
105	H 105	10.249	0.0080	0.242	0.0062	0.256	0.0074
106	H 106	10.500	0.0039	0.229	0.0047	0.220	0.0062
108	H 108	9.160	0.0026	0.277	0.0036	0.267	0.0043
110	H 110	8.952	0.0046	0.464	0.0036	0.439	0.0043
123	H 123	11.191	0.0100	0.233	0.0067	0.244	0.0074
126	H 126	10.100	0.0080	0.254	0.0062	0.256	0.0074
129	H 129	10.895	0.0035	0.228	0.0062	0.222	0.0074
135	H 135	11.226	0.0046	0.270	0.0036	0.270	0.0044
137	H 137	8.909	0.0063	0.522	0.0046	0.479	0.0052
139	H 139	11.758	0.0046	0.277	0.0037	0.274	0.0044
145	H 145	12.330	0.0103	0.309	0.0094	0.324	0.0074
166	H 166	9.857	0.0028	0.242	0.0039	0.243	0.0043
171	H 171	10.188	0.0034	0.263	0.0046	0.267	0.0058
186	H 186	10.219	0.0057	0.508	0.0044	0.465	0.0055
187	H 187	10.440	0.0048	0.259	0.0067	0.251	0.0074
189	H 189	11.287	0.0100	0.264	0.0067	0.255	0.0074
193	H 193	10.200	0.0030	0.223	0.0050	0.234	0.0060
196	H 196	10.252	0.0047	0.251	0.0062	0.257	0.0077
197	H 197	11.602	0.0051	0.269	0.0039	0.273	0.0049
201	H 201	11.765	0.0057	0.186	0.0042	0.199	0.0051
205	H 205	9.898	0.0028	0.263	0.0045	0.259	0.0047
206	H 206	10.021	0.0034	0.289	0.0050	0.275	0.0063
208	H 208	8.950	0.0040	0.557	0.0031	0.510	0.0035
209	H 209	9.740	0.0024	0.005	0.0031	0.013	0.0038
213	H 213	9.032	0.0065	0.520	0.0050	0.477	0.0063
217	H 217	10.429	0.0046	0.263	0.0050	0.249	0.0063
218	H 218	10.075	0.0063	0.275	0.0046	0.271	0.0053

Cousins *VRI* Data for NGC 752 (continued)

WEBDA	Name	V	σ	V-R	σ	R-I	σ
220	H 220	9.593	0.0042	0.539	0.0031	0.460	0.0037
222	H 222	10.964	0.0040	0.243	0.0050	0.248	0.0060
234	H 234	10.673	0.0065	0.262	0.0050	0.242	0.0060
238	H 238	9.961	0.0080	0.263	0.0062	0.273	0.0074
261	H 261	11.179	0.0040	0.286	0.0031	0.281	0.0036
263	H 263	10.947	0.0046	0.230	0.0036	0.233	0.0044
273	H 273	11.289	0.0100	0.796	0.0067	0.755	0.0074
295	H 295	9.297	0.0080	0.504	0.0062	0.463	0.0074
300	H 300	9.586	0.0080	0.242	0.0065	0.252	0.0074
311	H 311	9.057	0.0038	0.534	0.0028	0.486	0.0034
320	H 320	11.334	0.0100	0.160	0.0081	0.176	0.0074