Homogeneous Photometry for Star Clusters and Resolved Galaxies.
II. Photometric Standard Stars

Research Note

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ABSTRACT. Stars appearing in CCD images obtained over 224 nights during the course of 69 observing runs have been calibrated to the Johnson/Kron-Cousins BVRi photometric system defined by the equatorial standards of Landolt (1992, AJ, 104, 340). More than 15,000 stars suitable for use as photometric standards have been identified, where “suitable” means that the star has been observed five or more times during photometric conditions and has a standard error of the mean magnitude less than 0.02 mag in at least two of the four bandpasses, and shows no significant evidence of intrinsic variability. Many of these stars are in the same fields as Landolt’s equatorial standards or Graham’s (1982, PASP, 94, 244) southern E-region standards but are considerably fainter. This enhances the value of those fields for the calibration of photometry obtained with large telescopes. Other standards have been defined in fields containing popular objects of astrophysical interest, such as star clusters and famous galaxies, extending Landolt-system calibrators to declinations far from the equator and to stars of subsolar chemical abundances. I intend to continue to improve and enlarge this set of photometric standard stars as more observing runs are reduced. The full current database of photometric indices is being made freely available via a site on the World Wide Web or via direct request to the author. Although the contents of the database will evolve in detail, at any given time it should represent the largest sample of precise BVRi broadband photometric standards available anywhere.

1. INTRODUCTION

Accurate photometry with modern detectors on large telescopes is hampered by the scarcity of suitable photometric standard stars. At present, the largest and most definitive collection of fundamental standard stars in the Johnson UBV Kron-Cousins RI broadband photometric system is that of Landolt (1992), which consists of 526 stars that are mostly quite close to the celestial equator. However, if one restricts oneself to only those stars that were observed a minimum of five times each (for instance), with standard errors of less than 0.02 mag in both V and B − V (say), then the total number of Landolt’s “good” standards is reduced to 318. Of these, perhaps of order 200 are appropriate for use with a 2.5 m telescope (V ≥ 12), maybe ∼130 can be used with a 4 m telescope (V ≥ 13), and ≤ 40 are suitable for use with an 8 m telescope or a 2.4 m telescope in space (V ≥ 14.5). Graham (1982) has published a list of some 103 stars with UBVRI photometry in nine fields at declination −45°; if one again considers only those stars having at least five observations and standard errors in V and B − V less than 0.02 mag, the number of “good” Graham standards is reduced to some 61, of which only 11 are fainter than V = 12.

There are places on the sky where several standards can be imaged onto a CCD at the same time, but many of the Landolt and Graham stars are comparatively isolated, so that trying to observe a diverse sample of standards over a range of colors and air masses with a CCD can be quite inefficient. Furthermore, since these standards are primarily equatorial or far south, they never reach the zenith at many good terrestrial observing sites and cannot cover the same range of azimuth as many scientifically interesting targets. Observers trying to make the most of their large-telescope time are often reluctant to undertake large slews from the science target to one or more standard fields more than a few times per night. Another drawback of Landolt’s and Graham’s standards is that few or no Population II stars are included.
However, when one does observe fundamental standards like Landolt’s or Graham’s with a CCD, one usually gets for free the images of nearby stars, most of which are fainter than the official standards. I expect that most CCD photometers have toyed with the notion of combining these serendipitous observations of neighbor stars for the purpose of defining new, fainter standards, and this is what I have begun to do. As of this date (Spring 2000) I have combined photometric data from a total of 69 observing runs consisting of 224 individual nights, of which 135 nights were completely clear, while on the remaining 89 nights observations were obtained through thin cloud during at least part of the night. (CCD observations made through cloud can contribute to the precision of photometric indices provided that each image contains either fundamental standards or secondary standards that have also been observed under photometric conditions on numerous occasions. Differential photometry relative to the brighter, well-established stars reduces the random errors of the mean magnitudes estimated for the fainter stars in the same field.) These observations have been made by many different observers using 10 telescopes at five sites (Kitt Peak National Observatory: 4 m, 2.1 m, 0.9 m; Cerro Tololo Inter-American Observatory: 4 m, 1.5 m, 0.9 m; La Palma: Isaac Newton Telescope, Jacobus Kapteyn Telescope; Canada-France-Hawaii Telescope; Wyoming Infrared Observatory) over the period 1983–1999. Many of these observations were made by me or my collaborators, but I have also obtained data for many of these observing runs through the excellent services of the Isaac Newton Group Archive and the Canadian Astronomy Data Centre.

In addition to photometric measurements for faint neighbors of Landolt and Graham standards, I have defined new standard sequences on the same photometric system in fields where the presence of an astrophysically interesting object (e.g., a star cluster or a nearby galaxy) has led to the field’s being observed several times during the observing runs at my disposal. In the case of star clusters or dwarf galaxies very near the Milky Way, many new standards will actually be members of the science target. In the case of more distant galaxies and other types of extragalactic objects, the new standard stars obviously belong to the Galactic foreground. At the present moment, the available data permit the definition of more than 15,000 primary and secondary standards in 198 fields, where the following criteria are satisfied: at least five independent observations under photometric conditions and standard errors of the mean magnitude smaller than 0.02 mag in at least two of BVRI, and no evidence for intrinsic variation in excess of 0.05 mag, rms, based upon consideration of all available bandpasses. The Johnson U bandpass is not much observed with CCDs because of a variety of inconveniences, such as the low and highly wavelength-dependent relative quantum efficiency of many CCDs at these short wavelengths. Although I do have and have tabulated some U-band observations for a number of these stars, I have not considered the availability of U data to be relevant in making the decision whether a given star warrants being considered a photometric standard for my present purposes.

Lists of these standards are available to interested photometrists via the World Wide Web or by direct communication with me. The available data are digital finding charts (FITS format images) on a common 0.5 pixel^-1 scale, with x increasing east and y increasing north; ASCII files with astrometric positions, both absolute right ascensions and declinations, and relative (x, y) positions in the finding charts; and lists of photometry, consisting of mean apparent magnitudes in UBVRI, the standard errors of those quantities, the number of independent observations in each filter (the number of observations made on photometric occasions and the total number of observations, including those made through thin cloud, are both tabulated), and a measure of the intrinsic rms photometric variation. All of these observations have been placed on the system of Landolt (1992) with an accuracy of order 0.001 mag in the mean. It is my intention to keep the database up to date as additional observing runs become reduced, so the random photometric errors should go down and the number of individual standards and independent fields may be expected to grow with time. However, at any given moment the instantaneous state of the database should represent the largest and most precise sample of BVRI broadband photometric standards available anywhere.

2. DETAILED DISCUSSION

At the moment, the total set of CCD observations considered here consists of some 1,092,401 individual magnitude measurements for 28,552 stars. The instrumental magnitudes are based entirely on synthetic aperture photometry (bright, isolated stars) or profile-fitting photometry with aperture growth-curve corrections (fainter stars, or those with neighbors less than a few arcseconds away) obtained with CCDs and extracted by means of software written by me (Stetson 1987, 1990, 1993, 1994). The instrumental magnitudes are transformed to the standard system using nightly equations that generally include linear and quadratic color terms as well as linear extinction terms. Whenever practical, mean color coefficients are determined for all the nights of a given observing run with a particular instrumental setup. However, extinction coefficients and photometric zero points are determined on a night-by-night basis, except for a few cases where the range of air mass spanned by the observations is too small for a meaningful extinction measurement; in such cases mean extinction coefficients for the site are imposed. The equations for non-photometric nights do not model the effects of extinction.
Instead, a separate photometric zero point for each frame is determined from measurements of at least two standard stars included within that frame; color terms determined from photometric nights during the same run and/or from individual frames containing standards that span a broad range of color are employed just as for the photometric nights. After the transformation equations for all nights have been determined, all the observations for each star are collected and transformed to the best possible magnitudes in $U$, $B$, $V$, $R$, and $I$ based on a simultaneous least-squares optimization involving all available data for the star.

The whole process is iterated. Initially transformation equations are determined only from observations of the fundamental standard stars. Then standard-system magnitudes can be derived for other stars contained within the same fields as the fundamental standards and for stars in other program fields that were observed on photometric nights. The subset of these stars that meet the criteria mentioned above, namely, at least five observations made under photometric conditions and standard errors smaller than 0.02 mag in at least two of the four $BVRI$ filters, and no significant evidence of intrinsic variability, may now be considered to be additional standards. Improved transformations are then determined using this enlarged set of standard stars. Starting with this second iteration, the newly defined “standards” allow the inclusion of nonphotometric observations for the former program fields, increasing the precision (but not the accuracy) of their derived photometric magnitudes. Another iteration of this process is undertaken every time a new observing run is added to the database, resulting in some new standard stars, more precise mean magnitudes for the previously existing standard stars, and occasionally the loss of a putative standard if the new observations suggest intrinsic variability.

The fundamental basis for the photometric system employed here is that of Landolt (1992), consisting of (mainly) equatorial standards observed in $UBVRI$ with photomultipliers. I have augmented this primary set of reference stars with the data in Landolt (1973; photomultiplier-based $UBV$ observations that are apparently independent of those of Landolt 1992, unlike the observations in Landolt 1983, which appear to be a subset of those included in the 1992 catalog), Landolt (1983; a very few stars that were not republished in the 1992 paper), Graham (1982; photomultiplier $UBVRI$ photometry of stars in the E regions at declination $-45^\circ$), Graham (1981; photomultiplier $UBVRI$ photometry of a standard sequence near the spiral galaxy NGC 300), W. E. Harris (unpublished; photomultiplier $UBV$ photometry of stars in the equatorial open cluster M11 = NGC 6705); and L. Davis (unpublished; CCD $UBVRI$ photometry of stars in the Kitt Peak consortium fields in the star clusters NGC 4147, 2419, 6341 = M92, 7006, and 7790; Christian et al. 1985).

All these data must be assumed a priori to be on effectively the same photometric system as Landolt (1992)—within the errors—with two exceptions. (1) There are enough stars in common between Landolt (1973) and Landolt (1992) that a direct comparison of the two systems can be undertaken in $U$, $B$, and $V$. In fact, I base this comparison on only those stars that are common among Landolt (1973), Landolt (1992), and the set of Landolt stars included among my observations. This restriction is made just in case any difference between Landolt (1973) and Landolt (1992) might depend in some systematic way on the stars’ magnitudes, colors, right ascensions, or other properties; if such should be the case, obviously we want to know the value for any 1992 minus 1973 difference that would be appropriate specifically for the sorts of stars considered here. When the comparison is made, I find that the Landolt (1992) magnitudes differ from those of Landolt (1973) by $-0.0034 \pm 0.0011$ mag (standard error of the mean difference) in $V$, $-0.0026 \pm 0.0013$ mag in $B$, and $+0.0022 \pm 0.0023$ mag in $U$, based upon 81 stars common to all three data sets. Landolt’s 1973 $UBV$ magnitudes have been adjusted by these offsets and combined with his 1992 data. (2) According to L. Davis (2000, private communication), her data for NGC 7790 were taken under dubious photometric conditions. The way in which these data are included will be described below.

The assumption that the remaining Graham, Harris, and Davis data are on essentially the same system as Landolt (1992), at least within the standard errors of the available data sets, can be tested a posteriori, as I will now describe. Specifically, after each iteration I compare my photometry with Landolt’s for those stars where (a) Landolt has at least four observations and a standard error of the mean magnitude less than 0.03 mag in a given filter, and (b) I have at least four observations and a standard error of the mean magnitude less than 0.03 mag in the same filter, and (c) the star shows no evidence in my data for intrinsic variability greater than 0.05 mag, rms, in all filters considered together. (Selection criteria more restrictive than these resulted in a sample size too small to be very meaningful.) Any net difference remaining between my weighted-average results and the combined results of Landolt (1992) and Landolt (1973) for stars meeting these criteria is evaluated and added to all my magnitudes, forcing my photometric system to be identically equal, in the mean, to that of Landolt with a high level of accuracy. After the most recent iteration these corrections were all less than 0.0005 mag in $B$, $V$, $R$, and $I$, with standard errors of the correction better than 0.0013 mag in each case, based on 144 stars in $B$, 144 stars in $V$, 30 stars in $R$, and 79 stars in $I$; in $U$ the correction was $0.0009 \pm 0.0084$ mag based on only three stars. Figures 1–4 show the differences between my photometry and Landolt’s for these stars versus magnitude and color. The observed rms magnitude residuals between Landolt’s results and
The differences between my photometry in the $B$ bandpass and that of Landolt (1992) vs. magnitude (upper panel) and color (lower panel). In each panel the abscissa is the average of my and Landolt’s photometry, and the ordinate is in the sense my magnitude minus Landolt’s.

mine exceed the quadrature sum of both our estimated standard errors by less than 10%. This leaves very little room for systematic errors as a result of neglected high-order transformation terms occasioned by, for instance, filter-bandpass mismatch.

In fact, to the naked eye, some seemingly systematic differences between my photometry and Landolt’s may be seen in Figures 1–4. For instance, in Figure 1 it seems that for $10 \leq B \leq 11.5$ my $B$-band magnitudes are fainter than Landolt’s, while for $11.5 \leq B \leq 12.0$ my $B$ magnitudes are brighter. Similarly, my $B$ magnitudes for the bluest stars ($B - V < 0.00$) may be slightly fainter, on average, than Landolt’s. If such behavior is real, it would imply a subtle systematic nonlinearity in either Landolt’s photometry or mine. In either case, the nonlinearity would have to be a collective property of many devices, since Landolt used a number of different photomultipliers and cold boxes, while my results have certainly been based on a large number of different CCD and filter combinations. In each case, all data for each detector were placed on a common photometric system using appropriate transformation models. It is noteworthy that the apparently systematic differences in the $B$-band photometry are not duplicated in either the $V$ band or the $I$ band, while the plots for each of these other bandpasses have idiosyncrasies likewise not reflected in the other filters. I cannot come up with a plausible physical mechanism that would produce this variety of effects systemati-
cally across an ensemble of detectors of either technology. In the absence of more definitive data, it seems most likely that these seeming deviations are the result of small number statistics and the propensity of the human eye for finding patterns even in random data. After I have thus forced my mean results onto Landolt’s system, the net differences between Davis’s unpublished magnitudes for NGC 7790 stars and my results for the same stars are determined and applied to her mean magnitudes; these corrections, which are of order a few hundredths of a magnitude, place Davis’s NGC 7790 data on the same system as mine, in the mean, which is—via the previous step—the same as Landolt’s. Finally, a weighted average of my derived photometric magnitudes and the previous ones is determined for all stars in common. To the extent that the Graham results, the Harris results, and the rest of Davis’s results may not be inherently on the Landolt system, these weighted mean magnitudes will not be on exactly the Landolt system either. However, they will be much closer to the Landolt system inasmuch as my observations generally greatly outnumber the previous ones. In fact, these other data sets turn out to be fairly close to the Landolt system in comparison to their standard errors, as Table 1 shows. Here I have tabulated the robust mean magnitude differences and standard errors of the mean differences for all stars common to my and the previous data sets, without regard to the number of observations, the standard errors, or any evidence of variability. Only two elements of the table reveal systematic differences as large as 0.01 mag, and it is to be expected that the overall set of my observations combined with the previous ones will differ from the mean Landolt system by amounts much less than this. The column of mean differences for the comparison to Landolt’s photometry exemplifies the ultimate uncertainty of placing my photometry on his system: it represents the distinction between (a) comparing only those stars that he and I both measured “well,” in some sense, which has zero net difference after the procedure of the previous paragraph, and (b) comparing all stars common to the two data sets, which yields the differences in Table 1.

### 3. GENERAL DISCUSSION

For purposes of the remaining discussion, I will regard a star as being suitable to serve as a photometric standard if, when all my observations have been combined with all the data from the Landolt, Graham, Harris, and Davis star lists, it has been observed at least five times and has a standard error less than 0.02 mag in at least two of B, V, R, and I, and when a weighted average is taken of the standard deviations of the measured magnitudes in all available filters, the implied net intrinsic variation is less than 0.05 mag. At the moment, 15,419 stars in 198 fields satisfy these criteria. Among these, 96 fields have at least five standards in at least two of the filters, and 21 have at least five standards in all four filters within the area of a single CCD field.

Table 2 is a very partial listing of some of the fields containing standard stars defined in this way, intended only to give some sense of the declinations, field sizes, numbers of standards, and types of contexts that are available. The table lists the equatorial coordinates of each field for equinox 2000, the rectangular dimensions spanned by the standard stars in the field in units of arcminutes of right ascension and declination, and the number of stars with standard-quality magnitudes, defined by the criteria given above, in each of the four principal bandpasses. Observations were obtained in all four of the $BVRi$ filters during only a very few of the 69 observing runs treated here. The reader will therefore notice that generally there are not equal numbers of standards in all four filters. This is an unavoidable result of the fact that different fields were observed during different runs employing CCDs of different projected angular size and different combinations of two or more filters. It is also true that, although the absence of close, bright neighbors was one of the selection criteria for

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**TABLE 1**

| Parameter  | Landolt | Graham | Harris | Davis (except NGC 7790) | Total Stars |
|------------|---------|--------|--------|--------------------------|-------------|
| $\Delta B$ | $-0.0005$ | $-0.0026$ | $-0.0056$ | $-0.0015$ |                     |
| $\sigma$   | $0.0010$  | $0.0019$  | $0.0034$  | $0.0025$  |                     |
| $N$        | $326$    | $71$    | $80$    | $97$        | $574$         |
| $\Delta V$ | $+0.0002$ | $+0.0016$ | $-0.0064$ | $+0.0020$ |                     |
| $\sigma$   | $0.0006$  | $0.0017$  | $0.0031$  | $0.0016$  |                     |
| $N$        | $324$    | $70$    | $80$    | $97$        | $571$         |
| $\Delta R$ | $-0.0010$ | $-0.0128$ | $\ldots$ | $-0.0066$ |                     |
| $\sigma$   | $0.0011$  | $0.0036$  | $\ldots$ | $0.0021$  |                     |
| $N$        | $154$    | $12$    | $\ldots$ | $96$        | $262$         |
| $\Delta I$ | $-0.0002$ | $-0.0049$ | $\ldots$ | $+0.0096$ |                     |
| $\sigma$   | $0.0012$  | $0.0038$  | $\ldots$ | $0.0021$  |                     |
| $N$        | $225$    | $31$    | $\ldots$ | $97$        | $353$         |

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potential new standards, some of these stars may be too crowded for use with telescopes of short focal length or under conditions of particularly poor seeing. Similarly, some of these stars will be too bright for the largest telescopes or too faint for the smallest ones. Nevertheless, with reasonable care, interested photometrists should be able to find in the database a good selection of suitable standard fields as they plan observations utilizing any particular equipment and combination of bandpasses, for any given range of right ascension and north or south declinations.

Since the precision of the photometry of the Landolt, Graham, and Kitt Peak consortium standards has now been improved by the addition of many more observations, but more especially because numerous new standards have been added in many of these same fields, astronomers who want to can now make retroactive improvements to the photometric accuracy of any studies they have already undertaken that used the previously published standards. In addition, the many new standards that have been defined with apparent magnitudes as much as 6 mag fainter than those previously available offer a new opportunity for accurate future photometry with the largest telescopes. The much larger number of fields over a wide range of declinations greatly simplifies the task of finding standard fields relatively near specific science targets and allows for improved extinction determinations, including the possibility of testing for extinction variations as a function of azimuth. Finally, the provision of standard sequences on a common system within the very fields of some of the most popular science targets offers a new level of homogeneity in the intercomparison of stellar populations—a principal goal of the present series of papers (see Stetson, Hesser, & Smecker-Hane 1998).

One of the more noteworthy aspects of this work is that, with the inclusion of a number of globular clusters among the standard fields, for the first time we have now available...
a single, homogeneous system of broadband photometry based on standard stars spanning Populations I and II. To be strictly rigorous, it is not correct to state that Landolt's (1992) photometric system has now been extended to Population II. In order to claim that, I would have to be able to say that we now know accurately what magnitudes Arlo Landolt would have measured for any given random star with his photomultipliers and filters during the period 1977–1991. This is something I cannot claim. The most that I can say is that I have defined a system based on a somewhat more democratic principle: these are the magnitudes that an arbitrary astronomer using typical and commonly used CCD/filter combinations would be most likely to obtain for a large, heterogeneous sample of stars spanning a broad range of metal abundance and evolutionary state, after doing his or her best to transform the observed magnitudes in a consistent way to the system of Landolt (1992). These data represent a new photometric system which spans Populations I and II, but which very closely equates to the Landolt system, in the mean, at the Population I end.

As stated in § 1, finding charts, astrometric positions, and photometric indices may be obtained from a World Wide Web site hosted by the Canadian Astronomy Data Centre or by direct request to the author. At the present moment, 53 of the 198 fields are completely documented and ready for use by the general astronomical public. In general, these are the fields that have the most standards in the most filters. However, all 198 fields are listed in the complete version of Table 2 that is available at the Web site; a complete list of potential standard fields will also be provided by the author on request. If a particular photometrist has a need for one of the standard fields that happens not to be completely ready at any given time, I will, upon request, make every effort to complete the documentation of that field, usually within a matter of hours. If for whatever reason an interested photometrist desires standard stars selected on the basis of criteria other than those that I have used, I will do my best to provide a customized standard list.

I am very grateful to the Canadian Astronomy Data Centre and the Isaac Newton Group Archive/UK Astronomy Data Centre for the many valuable and extensive public domain data sets they have provided me. I would like also to thank the many individuals who have freely contributed their proprietary data to this effort, including most particularly Peter Bergbusch, Mike Bolte, Howard Bond, Pat Dowler, Mike Pierce, Alfredo Rosenberg, Nancy Silbermann, and Nick Suntzeff, plus anyone else whose name I have momentarily forgotten to mention. We are all much indebted to Arlo Landolt for his many years of strenuous and punctilious effort on our behalf.

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