The Ages of Stars
Proceedings IAU Symposium No. 258, 2008
E.E. Mamajek, D.R. Soderblom & R.F.G. Wyse, eds.

doi:10.1017/S1743921309031858

Homogeneous photometry of globular clusters—a progress report

Peter B. Stetson

Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council, 5071 West Saanich Road, Victoria BC V9E 2E7
email: Peter.Stetson@nrc-cnrc.gc.ca

Abstract. Classical broad-band photometry can provide direct comparisons of star clusters both with each other and with theoretical models of stellar evolution. The confidence with which conclusions can be drawn is often limited by the accuracy of the measurements. The present work is part of a long-term attempt to improve photometric calibrations.

Keywords. Techniques: photometric, standards, globular clusters: general

1. Introduction

It has long been a goal of mine to eliminate photometric uncertainty as a major source of confusion in the analysis of Galactic star clusters and nearby galaxies. If we can reach the point where the uncertainty in the calibration of a particular photometric study is negligible compared to, say, the uncertainty in the foreground reddening of the target, I will consider that the job has been done.

For more than a third of a century, our species' first line of defense against photometric error has been the work of Arlo Landolt. His 1973 paper laid out a network of standards in the Johnson UBV system that were in a magnitude range ($7 \lesssim V \lesssim 14$) suitable for use with photomultipliers on the smallest to the largest research telescopes in use at the time. In 1983 and 1992 papers, he added measurements in the R and I photometric bandpasses of Cousins (1976), which was based on a similar system established by Kron, White, and Gascoigne (1953).

If one makes the arbitrary assumption that, to be reliable, a photometric standard star must have at least five observations in each filter and should have a standard error of the mean magnitude no larger than 0.02 mag in each index, then the three Landolt papers, combined, have about 275 stars meeting these criteria in at least the B, V, and I filters. These stars span a broad range of color: $-0.7 < B{-}I < +6.0$ (approximately equivalent to $-0.3 < B{-}V < +2.3$, or $-0.4 < V{-}I < +4.0$).

Nearly all of Arlo's standards are quite close to the celestial equator. This is valuable, because they are accessible to observers in both hemispheres, making it possible to relate observations over the entire sky to a single, common photometric system. However, this also means that the standard stars never pass truly overhead for most ground-based observatories, and from any given site they can be observed only over a restricted range of azimuth. As a result, long slews are often required to move from a target field to a standard field and back; this tends to discourage frequent observations of standard stars throughout a high-quality night, especially on larger telescopes. In addition, Landolt's best-observed fields—located at three-hour intervals—contain $\sim$17 stars each, spread over an area 20 or 30 arcminutes on a side. Thus, there are relatively few opportunities to get more than a few standards onto a typical CCD at a time, and it turns out that there are hardly any opportunities to observe, simultaneously, multiple stars of highly

Table 1. Individuals contributing CCD data for defining secondary photometric standards.

Abi Saha	Elena Pancino	Mike Bolte
Alfred Rosenberg	Howard Bond	Nancy Silbermann
Alistair Walker	Judy Cohen	Nick Suntzeff
Andy Layden	Luigi Bedin	Noelia Noël
Bart Pritzl	Manuela Zoccali	Peter Bergbusch
Carme Gallart	Márcio Catelan	Randy Zingle
Don Hamilton	Matteo Monelli	

Table 2. Archives utilized during the course of this work.

DAO
ESO
CFHT
Isaac Newton Group
Subaru
Telescopio Nazionale Galileo

dissimilar colors. Finally, not many of these stars are faint enough to be used effectively with modern 8–10 m telescopes, or your typical diffraction-limited 2.4 m telescope in space.

2. The project

When my colleagues and I began observing star clusters with CCDs on 0.9 m–4 m telescopes in the early 1980's, we made a point of observing those few asterisms where two or more of Arlo's equatorial standard stars could be placed on the chip at a given time. In many cases we had enough observations that other stars falling in the same images could be turned into *secondary* standards. Clearly, since photometric indices could only be assigned to these stars by reference to Landolt's primary standards, such secondary standards would not contribute to the absolute calibration of our observations to Arlo's photometric system. However, they could be useful for expanding the basis of comparison whereby data from different nights, different observing runs and, most notably, different telescopes could be placed on a common system. One example was the attempt by Stetson and Harris (1988) to define new secondary standards in some Landolt fields as well as in their target star clusters. In particular, they used the Kitt Peak 0.9 m telescope to define new faint secondary standards that could augment the comparatively few primary standards faint enough to be observed with the 4 m telescope. I now know that this attempt was not entirely successful: too great a faith placed in stars observed too few times produced an internal photometric system that was able to drift roughly 0.02 mag away from the true Landolt system.

Since then, the body of data that I am using to define secondary standards has grown by about three orders of magnitude. At first, the images mostly came from observing runs personally carried out by my collaborators and me. Then friends, colleagues and well-wishers (see Table 1 for a partial list) began contributing their data to the cause. More recently, I have been mining the international data archives that have become increasingly valuable over the years (Table 2).

As of now, I have acquired and reduced 1,195 observation sets, where an "observation set" may be loosely defined as a corpus of data obtained from one CCD on one photometric night *or* on one or more consecutive, usable, but not strictly photometric nights with the same instrumental setup. (Data from poorer-quality nights can be used

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

to improve the relative photometry for multiple stars recorded in the same images, but not to intercompare photometric indices among stars in different images.) Note that I treat data from the individual CCDs of a mosaic camera as coming from *independent* photometers: *i.e.*, the CFH12k mosaic produced twelve data sets per night of observing, and the ESO 2.2m+WFI produces eight.

The current data sets contain 9,288,741 individual measurements of 99,054 distinct stars, virtually all of which have been individually chosen by hand and eye from deep, stacked images. Among these nearly 10^5 stars, 48,768 have at least five observations *and* standard error of the mean magnitude $\sigma < 0.02$ mag in B, V, and I, and show no evidence of intrinsic variability as large as 0.05 mag (r.m.s.). Fig. 1 is a color-magnitude diagram (CMD) for these stars; the larger filled squares represent the 275 Landolt standards that meet these same selection criteria. The new secondary standards reach about seven magnitudes fainter than Arlo's primary photometric standards. One may also note that Arlo has done a good job of including in his sample standards that are as blue as the bluest stars known. However, there are in the Solar Neighborhood at least a few stars significantly redder than the reddest stars that he observed; my own results for these stars obviously depend upon extrapolation (or, rather, the average of many extrapolations) of Arlo's photometric system.

3. How standard are these stars?

The obvious question is, of course, "How can one claim to define a homogeneous photometric system from heterogeneous data?" The *sine qua non* for defining a homogeneous photometric system has always been to restrict oneself to a single detector and a single

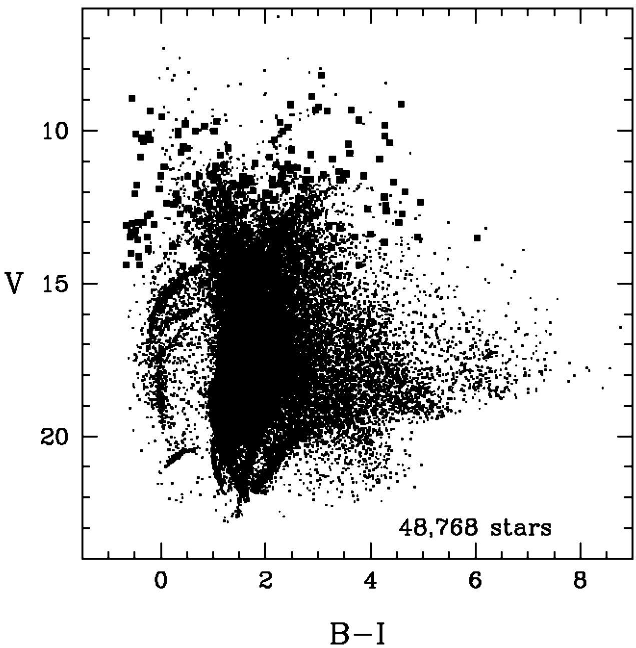

Figure 1. Color-magnitude diagram containing 48,768 stars with measurements considered good enough to serve as secondary photometric standards: at least five observations on fully photometric occasions in *each* of B, V, and I, standard errors of the mean magnitude no larger than 0.02 mag in each filter, and no evidence of intrinsic variability exceeding 0.05 mag r.m.s. Larger filled squares represent 275 Landolt stars meeting the same acceptance criteria.

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

set of filters, or—at the very least—to detectors and filter sets that have been carefully designed to be as similar as humanly possible. However, when you do not control your own telescope, you usually do not have this luxury; you request your observing time, and if the time is granted and scheduled, you show up at the telescope and use the equipment that has been provided. This equipment is not always a perfect match to that with which the photometric system was defined, or—indeed—to the equipment that was available for your previous observing runs.

A filter combines with the detector to define each photometric bandpass: the sensitivity of the system to incoming photons as a function of their wavelength. In some cases, these bandpasses can also be significantly altered by the passage of the light through Earth's atmosphere and the telescope optics. It requires only a few minutes of surfing the internet or perusing the relevant literature to learn that it is quite difficult to reproduce in detail a given sensitivity curve with different photodetectors and pieces of colored glass. Since a magnitude measurement is the product of a stellar spectral-energy distribution (SED) multiplied by a sensitivity curve and integrated over wavelength, it is clear that slightly different bandpasses can produce different magnitudes for the same star; two similar but not identical stars may produce the *same* magnitude measurement for one photometer, and *different* magnitudes for another.

However, stellar SEDs are not completely arbitrary functions of wavelength; rather, they form a rather well-defined, nearly one-parameter family of curves. The single dominant parameter determining the form of a star's SED, of course, is its effective temperature. Smaller perturbations to the SED corresponding to a particular temperature are produced by, for instance, the star's effective surface gravity, chemical composition, and rotation speed. Foreground reddening also alters the perceived SED is a fashion that is very similar, but not quite identical, to a reduction in the star's effective temperature.

Since the family of stellar SEDs is comparatively well behaved, it is generally found that for most practical purposes one can model empirically the differences between a particular filter-detector combination and the corresponding standard photometric bandpass. You use direct observations of standard stars to determing the fitting parameters a_i in transformation equations of the form

$$v' \equiv v(\text{observed}) - k_V \cdot X = V + a_0 + a_1 \cdot (\text{COLOR}) + a_2 \cdot (\text{COLOR})^2 + \cdots,$$

where I use lower-case text to denote an observed magnitude in the particular *instrumental* photometric system defined by the equipment that one is actually using, and upper-case text represents photometric indices in the *standard* system that one is attempting to reproduce. "COLOR" represents a color index—in the standard photometric system—defined at wavelengths near the photometric bandpass in question: for the V bandpass, one might use the B–V color, the V–I color, or whatever is most convenient. The "..." might represent additional high-order terms involving colors, airmass, azimuth, time of night, or anything that might be affecting the atmospheric and instrumental throughput in a systematic way. Thus, one is using observations of stars of known photometric properties to produce an empirical model representing the difference between the ideal and the actual photometric bandpass, in the sense of a Taylor-series expansion in variables describing the morphology of the star's SED. (However, note that it is potentially quite misleading to apply such empirical transformations derived from normal stars to objects having distinctly nonstellar spectral-energy distributions, such as supernovae or quasars.)

I assert that if one assiduously attempts to determine the transformations that correct observations from any one instrumental system to the equivalent indices that *would have been* obtained with Arlo Landolt's equipment, and that if one does this for many different instrumental setups and then averages the results so obtained, then one eventually approaches, asymptotically, a well defined and robust average photometric system.

Fig. 2 shows the absolute differences, on a star-by-star basis, between Arlo's published magnitudes and my own for stars in common. In the left panel, the absolute V-magnitude differences are plotted against the number of photometric measurements in my data for stars that Arlo measured ten or more times; the right panel shows absolute V differences against the number of Arlo's observations, for stars that have at least ten photometric measurements in my data set. Since the x-axes are linear in the square root of the number of observations, if the magnitude differences were due solely to random measuring errors one would expect a wedge-shaped distribution of points declining to the right. This is not seen. In fact, if one ignores the points for stars with fewer than three or four observations in one data set or the other, there is essentially no change in the distribution of photometric errors with increasing number of observations. This implies that random measuring errors are *not* the dominant cause of the perceived magnitude differences. Rather, they must be due to the (small) range of SEDs that are capable of producing the same observed magnitude when integrated over the bandpass of a particular filter/detector combination, but produce different results for a different approximation of the same bandpass. After making a minor correction for that part of the dispersion that *can* be attributed to observational error (readout noise, Poisson photon statistics, unmodeled extinction variations, ...), I find that this irreducible scatter amounts to ~0.012 mag in V, ~0.014 mag in R, and ~0.016 mag in B and I. This represents the irreducible difference between Arlo's *particular* photometric system and the average of many independent attempts to reproduce his system, caused by the variety of stellar SEDs that are actually out there. Presumably, the irreducible differences between Arlo's system and any *one* attempt to reproduce it (*i.e.*, the results of any one given observing run, empirically transformed to

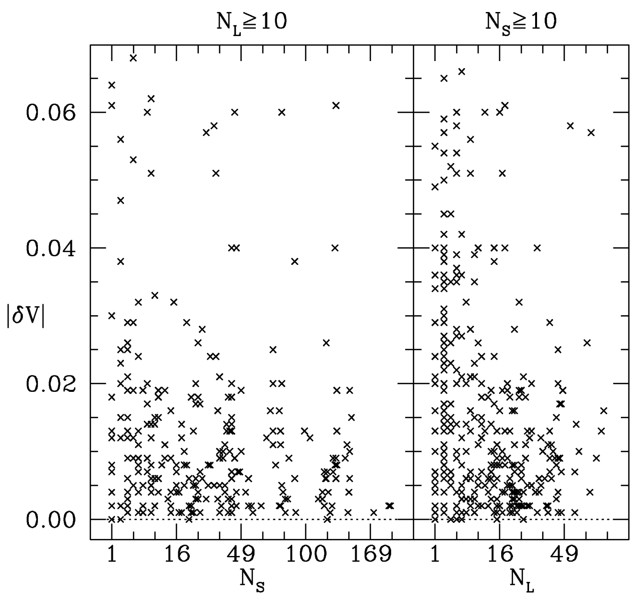

Figure 2. (*Left*) Absolute difference in V-band magnitude between Landolt's published photometry and mine for stars in common; stars observed at least 10 times by Arlo are plotted against the number of photometric observations in my database. (*Right*) The same, except that here stars that I have observed at least ten times are plotted against the number of Landolt observations.

Table 3. Properties of four globular clusters

	$R_\odot$ (Harris)	M_V (Harris)	[Fe/H] (Harris)	$[Fe/H]_{ZW}$ (Rutledge)	$[Fe/H]_{CG}$ (Rutledge)	E_{B-V} (Harris)	E_{B-V} (Schlegel+)
NGC 288	8.8	–6.7	–1.24	–1.40	–1.14	0.03	0.013
NGC 362	8.5	–8.4	–1.16	–1.33	–1.09	0.05	0.032
NGC 1851	12.1	–8.3	–1.22	–1.23	–1.03	0.02	0.037
M5 = NGC 5904	7.5	–8.8	–1.27	–1.38	–1.12	0.03	0.037

Table 4. Observations of four globular clusters

	288	362	1851	5904
observing runs	11	11	13	36
CCD images	386	340	485	2665
B measurements (max)	54	33	78	79
V measurements (max)	84	45	83	136
I measurements (max)	58	36	59	132
median seeing ($''$)	1.1	1.4	1.0	1.1

Arlo's system through observations of his standards) may be expected to be a factor of order $\sqrt{2}$ larger.

4. Example of use

The people that I work with and I have been most interested in producing CMDs for star clusters in the Milky Way Galaxy, and for nearby galaxies that can be resolved into individual stars. Moreover, in attempting to bolster this secondary photometric system I have combed the available data archives for the most popular fields—those having the greatest number of images from the various observatories—and it turns out that most of these are star clusters and nearby galaxies as well. This results in a data set that allows a more critical comparison of the fiducial sequences of different star clusters than has been possible in past.

For instance, consider the four globular clusters NGC 288, NGC 362, NGC 1851, and NGC 5904 (= Messier 5). According to, for instance, the Harris (1996) compilation catalog, these clusters are all comparatively luminous and minimally reddened, and have indistinguishable chemical abundances (Table 3). Here I list, for each of the four clusters, the heliocentric distance, absolute magnitude, and metallicity from Harris's compilation. Since his metallicities are taken from heterogeneous sources, I supplement them with metallicities from a particular single source, namely the Rutledge *et al.* (1997) catalog of values derived from the infrared calcium triplet in giant stars; these latter have been expressed both on the so-called "Zinn-West" scale and the so-called "Carretta-Gratton" scale—which are rather different in this abundance range—but they rest upon the same observational data. It is evident that the range of metallicities among these clusters is small compared to the uncertainty of the estimates. The last two columns of Table 3 give foreground reddening values for each of the clusters, first from the Harris catalog, and then from the all-sky reddening map of Schlegel *et al.* (1998).

Table 4 summarizes the observations available for these clusters in the current body of data. The first two lines give the number of independent observing runs (generally meaning independent instrumental setups, detectors, filters) and number of individual CCD images for each target. Since the various CCDs did not observe exactly the same part of the sky (in particular, with a mosaic camera containing N chips, no given star can fall within more than $1/N$ of the available images) the number of measurements per star can be much less than the total number of images. Accordingly, the next three lines

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

give the *maximum* number of photometric measurements available for any given star in the B, V, and I bandpasses. Finally, the last line gives the median seeing among the images available for each target.

Even given the large body of data available for each of these targets, the quality of the photometry can differ significantly from one star to another. Obviously, the signal-to-noise ratio will decrease for stars of increasing apparent magnitude. Furthermore, crowding and hence photometric reliability will both become systematically worse as the center of the cluster is approached. Finally, the outermost parts of the field will be covered by comparatively few images. Therefore, it is worthwhile to pay attention to how the sample of stars is selected from among all those for which photometry is available.

First, for each cluster I selected out stars in two magnitude ranges, one around the level of the horizontal branch (HB) and one around the level of the main-sequence turnoff (TO). Having determined the center position of each cluster, I then plotted the color uncertainty σ_{B-I} as a function of radius for stars in each of these two magnitude bins. From this I identified a range of clusterocentric radius where the error distribution was independent of radius for both samples. This typically turned out to be something like 2–6 arcmin. The inner limit of each annulus was defined by increasing photometric scatter due to crowding, and the outer limit was defined by increasing scatter due to a smaller number of available observations. Field contamination was not a serious issue for any of these clusters. Second, I divided the stars within the chosen annulus into V-magnitude bins 0.02 mag high; within each such bin I sorted the stars in order of increasing σ_{B-I}. Then I plotted *only* those stars with the smallest values of σ_{B-I} in each magnitude bin. This permits the tracing-out of the principal sequences of each cluster based on only those stars likely to have the best photometry. Fig. 3 shows such CMDs for our four target clusters, based upon the best three stars in each 0.02-mag bin of luminosity.

As has long been known, these clusters—despite their indistinguishable metal abundances—display four distinctly different HB morphologies: NGC 288 has an HB almost

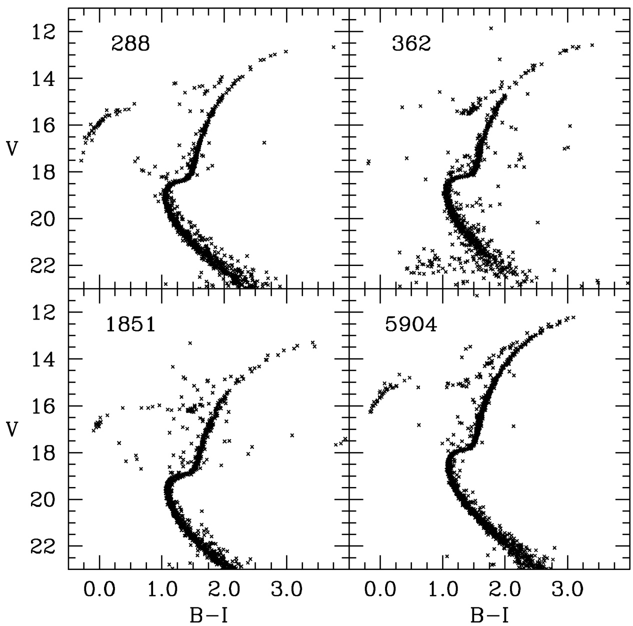

Figure 3. Color-magnitude diagrams for the four globular clusters discussed in the text. The band of faint blue stars in the NGC 362 panel belong to the Small Magellanic Cloud, which lies behind the cluster.

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

Table 5. Main-sequence TOs and HBs in the four globular clusters

	M_V (TO)	$(B–I)_{\rm TO}$	$(B–I)_{\circ,\rm TO}$	V_{HB}	ΔV(TO-HB)
NGC 288	19.049	1.055	1.024	15.58	3.47
NGC 362	18.856	1.056	0.980	15.46	3.40
NGC 1851	19.563	1.089	1.001	16.18	3.38
NGC 5904	18.537	1.089	1.001	15.13	3.41

entirely to the blue of the instability strip; NGC 362 has an HB almost entirely to the red of the instability strip; NGC 1851 has a compact red HB clump and a tight, blue clump with a sparse sprinkling of stars between, including a small number of RR Lyraes (∼30 in the whole cluster, only a fraction of these are in the annulus considered here); and NGC 5904 has a continuous HB from the blue to the red, with many RR Lyraes ($\gtrsim$ 130; scaled to the luminosity of NGC 1851, this would correspond to ∼85 RR Lyraes, or nearly 3× that cluster's specific frequency). These four clusters therefore illustrate the classical "second-parameter problem" in globular-cluster CMD morphology.

Many authors identify the second parameter with age (the "first parameter," of course, being metal abundance). For instance, Alfred Rosenberg, in his PhD dissertation at the University of La Laguna and in Rosenberg *et al.* (1999) concluded that NGC 288 and NGC 5904 were about the same age, and that NGC 362 and NGC 1851 were also about the same age but both about 2.5 Gyr younger than the other two clusters.

From a visual sliding shift of their HBs to that of NGC 5904 (after correction for the Schlegel *et al.* reddening estimates) I find that NGC 288 is 0.45 mag more distant in apparent modulus; NGC 362 is 0.35 mag more distant; and NGC 1851 is 1.05 mag more distant. I estimate that the uncertainty of each of these modulus differences is of order 0.05 mag, and since the luminosity of the HB is theoretically predicted to be independent

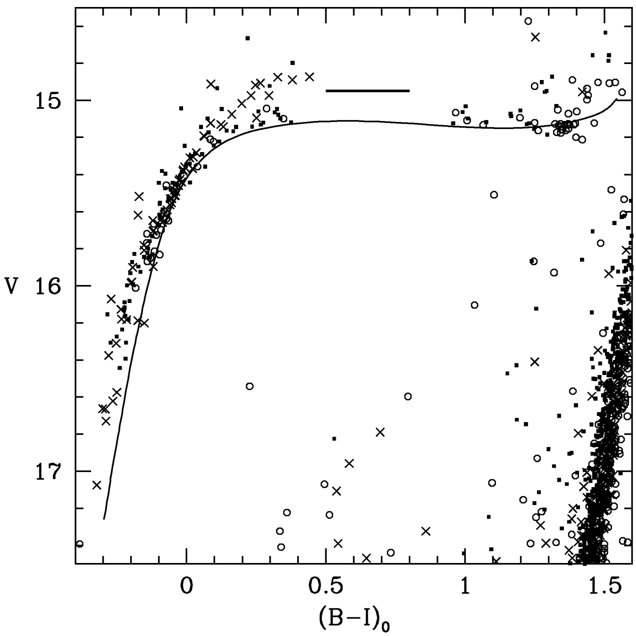

Figure 4. Expanded view of the dereddened HBs of NGC 5904 (small solid squares), NGC 1851 (hollow circles), and NGC 288 (×'s). The Victoria-Regina zero-age HB for [Fe/H] = –1.31, shifted down by 14.45 mag, is shown as a continuous curve. The solid horizontal line represents the zero-age HB level attributed to NGC 288 by Rosenberg *et al.* (1999).

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

of small age differences, and only weakly sensitive to the minor abundance differences seen among these four clusters, these distance ratios should be quite secure. The case of NGC 288 should be noted in particular. Fig. 4 shows the fit of NGC 288's dereddened HB ($\times$'s) to those of NGC 5904 (small solid squares) and NGC 1851 (hollow circles). With the Schlegel *et al.* reddening values, the blue end of the blue HBs match well with the modulus differences just given. However, as the instability strip is approached from the blue side, the HB stars in NGC 288 tend systematically brighter than those in the other two clusters. The probable explanation is that these stars have evolved away from the zero-age HB, having started from a point rather bluer and fainter. The solid horizontal bar in the figure represents the zero-age HB level attributed to this cluster by Rosenberg *et al.* Evidently not realizing the evolved nature of the reddest HB stars in this cluster, they have overestimated the luminosity of its zero-age HB; this accounts at least in part for the greater age they have assigned to this cluster.

By the way, with the clusters dereddened and matched at the HB, NGC 5904 has an upper giant branch distinctly bluer than that of NGC 1851; the giant branches of NGC 288 and NGC 362 coincide and lie between those of the other two clusters. According to canonical understanding, then, NGC 5904 is the most metal-poor of these four clusters, NGC 1851 is the most metal rich, and NGC 288 and NGC 362 have nearly equal and intermediate abundances based upon this photometric criterion.

By robust weighted fits of parabolas to *all* stars within $\pm\,0.3$ mag of the main-sequence TO in the selected annular zones (*i.e.*, not just the stars with the smallest color uncertainties), I obtained the TO magnitudes and colors given in Table 5; again the colors have been dereddened according to the Schlegel reddening estimates, with $E_{B-I} = 2.38\,E_{B-V}$, appropriate for an I photometric bandpass near 800 nm. I estimate the center of the HB in NGC 5904 to lie at $V = 15.13$.† This, combined with the differential moduli given above and the observed apparent magnitudes at the main-sequence TO yields the vertical HB-TO magnitude differences given in the last column of the table.

Curiously, the clusters with the intermediate giant-branch colors, NGC 288 and 362, have the most extreme TO colors, while the most metal-rich cluster and the most metal-poor (by the photometric criterion) have intermediate TO colors. From the Victoria-Regina isochrones (Fig. 5), we would infer that NGC 362 is 1 Gyr younger than NGC 288 from the absolute magnitude of the TO (which, since we have registered the clusters' HBs, is the equivalent of the differential vertical method) or 2 Gyr younger according to the dereddened TO color. NGC 1851 and NGC 5904 appear to be about the same age as NGC 362 by the vertical method, or NGC 5904 may be intermediate between NGC 362 and NGC 1851 on the one hand and NGC 288 on the other, via the TO color. However, allowing 0.05 mag uncertainty in the vertical registration of the CMDs, and uncertainty at a level of 0.01 mag in E_{B-V} ($\sim$0.024 mag in E_{B-I}) in the Schlegel *et al.* reddenings, the error bars are such that age differences of 0 Gyr or 4 Gyr are also allowed at a 1.5σ confidence level—without even allowing for *any* photometric calibration uncertainty.

Ages from the absolute TO color are subject to the assumption that the reddening values are correct. When I attempt to repeat the analysis with the purely differential horizontal method (the color difference between the main-sequence TO and a selected fiducial point on the subgiant branch: Fig. 5, bottom), nonsense results. By this measure,

† The observed vertical shift between the HB in NGC 5904 and the Victoria-Regina (VandenBerg *et al.* 2006) zero-age HB for [Fe/H] = –1.31 is 14.45 mag, with an uncertainty $\sim$0.02 mag; the model HB has a local luminosity maximum of M_V (predicted) = +0.66 at $(B\text{–}I)_\circ = 0.57$ and a local minimum of +0.70 at $(B\text{–}I)_\circ = 1.14$; I accordingly adopt $M_V = 0.68$ as the predicted value for the "center" of the theoretical HB. With the 14.45 mag observation-minus-theory difference, this yields 15.13 as the apparent magnitude at the center of NGC 5904's HB.

NGC 362 and NGC 1851 have ages roughly consistent with those from the vertical method and the absolute TO color, but NGC 288 and NGC 5904 have ages that are off the scale of the Victoria-Regina isochrones: at least 4 Gyr older than the other two. The ages of the clusters could be reconciled if the second (or third) parameter is some detailed abundance ratio, such as [CNO/Fe], [Mg/Fe], [Na/Fe], or even—dare I say it—Y.

References

Cousins, A. W. 1996, *MNRAS*, 81, 25
Harris, W. E. 1996, *AJ*, 112, 1487 (on-line catalogue, revision 2/2003)
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
Rosenberg, A., Saviane, I., Piotto, G., & Aparicio, A., 1999, *AJ*, 118, 2306
Rutledge, G. A., Hesser, J. E., & Stetson, P. B. 1997, *PASP*, 109, 907
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
Stetson, P. B. & Harris, W. E. 1988, *AJ*, 96, 909
VandenBerg, D. A., Bergbusch, P. A., & Dowler, P. D. 2006, *ApJS*, 162 375

Discussion

R. Mathieu: Was your decision not to include a U band philosophical or operational? Follow up: Given that U-like wavelengths are astrophysically valuable, how should the community proceed?

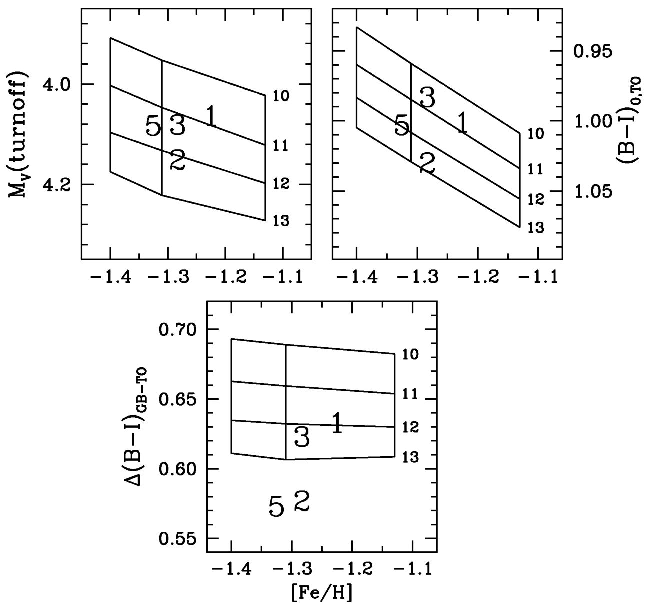

Figure 5. Age diagnostics as a function of metallicity: (*top left*) absolute visual magnitude of the TO; (*top right*) absolute B–I color of the TO; (*bottom*) color difference between the TO and a selected point on the subgiant branch. Numbers designate the different clusters: 1 = NGC 1851, 2 = NGC 288, 3 = NGC 362, 5 = M5 = NGC 5904. I have notionally assigned a lower metal abundance for NGC 5904, a higher abundance for NGC 1851, and intermediate and equal abundances for NGC 288 and NGC 362 as suggested by their giant-branch colors. Solid curves represent predictions of the Victoria-Regina isochrones for the ages shown, in Gyr. The exact placement of these grids is not necessarily correct, due to uncertain physics in the theoretical models, but the relative spacings and slopes should be valid.

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

P. Stetson: Both. The Johnson U filter is badly behaved. The long-wavelength side is filter-defined but the short- wavelength side is atmosphere-defined. So, the same filter and detector at different observatories will have a different bandpass. Second, CCDs have historically been insensitive at U, so people have avoided it. Since most of my data come from other observers, or archives, I have few U-band observations available to me. (Follow-up) First, CCDs should become sensitive at short wavelengths. Second, observers should agree on a U bandpass and use it consistently. I suggest Thuan-Gunn u or Sloan u.

G. Piotto: First of all I want to thank you for your superb talk, which showed us a very rare example of what good photometry means, as well as the limitations intrinsic to good photometry. I have a comment on the inconsistencies you found in the ages you had for your target clusters. I think they are the consequence of the complex chemical composition, peculiar to each cluster, and that we don't know sufficient details, yet.

P. Stetson: I agree with you completely. We are at a conference on stellar ages, and details of chemical abundance ratios, I think, currently represent a limit to our ability to measure globular-cluster ages in units of Earth-orbits around the Sun.

B. Weaver: How sure are you that you have distinguished yet-unknown CCD photometry problems vs. cosmic scatter? How do you do that?

P. Stetson: To the extent that the known problems are constant throughout the course of a night, and can be parameterized in terms of the intrinsic color and altitude of the star, these effects are removed empirically by the nightly transformation equations. Any remaining effects contribute to the observational scatter, and should decline when averaged over many observing runs. The cosmic scatter is what does not decrease when the number of observing runs increases.

C. Corbally: Are there any conclusions you can share with us on the merits of different filter sets?

P. Stetson: No.

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press

Peter Stetson

https://doi.org/10.1017/S1743921309031858 Published online by Cambridge University Press