A Star Catalog for the Open Cluster NGC 188

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ABSTRACT. We present new \(BVRI\) broadband photometry for the old open cluster NGC 188, based on an analysis of 299 CCD images either obtained by us, donated by colleagues, or retrieved from public archives. We compare our results on a star-by-star basis with data from 11 previous photometric data sets for the cluster. We homogenize and merge the data from all the photometric studies, and also merge membership probabilities from four previous proper-motion studies of the cluster field. Fiducial cluster sequences in the \(BV\) (Johnson) \(RI\) (Cousins) photometric system of Landolt (1993, AJ, 104, 340) represent the principal result of this paper. These are compared to reference samples defined by (1) Landolt’s standard stars, (2) the old open clusters M67 and NGC 6791, and (3) stars within 25 pc having modern photometry and precise Hipparcos parallaxes. In a companion paper, we show that our derived cluster results agree well with the predictions of modern stellar interior and evolution theory, given reasonable estimates of the cluster chemical abundances and foreground reddening. The individual and combined data sets for NGC 188 have been made available through our Web site.

1. INTRODUCTION

The study of star clusters provides important clues to the formation and enrichment history of the Milky Way Galaxy. To the extent that we can consider the different stars in a given cluster to have a common distance, age, chemical content, and foreground extinction, they provide stronger constraints on models of stellar evolution than field stars, whose distances, reddensings, and metallicities must be estimated on an individual basis. While studies of field stars can provide important insights into extremes of the local stellar population (the oldest, the most metal-rich, the most metal-poor stars; e.g., Sandage et al. 2003), in the middle of the Hertzsprung-Russell diagram there is such a congestion of stars with a range of ages, metallicities, and evolutionary states that extremely high accuracy and precision in estimates of effective temperature, metal abundance, and distance are required to derive a reliable age estimate for any given isolated star.

The study of star clusters relaxes the need for extreme accuracy and precision, at least to some extent. Spectroscopic abundance determinations can be derived for a number of different stars in the same cluster, and the average of those determinations can be applied to the cluster as a whole with a precision that is probably higher than would be possible for any single star. More important, the presence of stars of different masses within a cluster allows us to estimate a common cluster age and distance by forcing consistency with a given set of theoretical isochrones over a range of luminosities and temperatures, and hence of evolutionary states. At least to the extent that relative ages among different clusters can be estimated from the \(\text{shapes}\) of the principal sequences (e.g., Anthony-Twarog & Twarog 1985; VandenBerg et al. 1990; Sarajedini & Demarque 1990; Stetson et al. 2003), uncertainties in distance and reddening become less critical.

Ever since it was first noted that the open cluster NGC 188 was likely to be very old (van den Bergh 1958) appears to be the first published mention, although Sandage [1962] noted that Ivan King apparently recognized the particular interest of this cluster in 1948), it has been the subject of numerous photometric and astrometric studies. Photometric observations that have made significant contributions to our understanding of NGC 188 were reported by Sandage (1962), Sharov (1965), Cannon (1968), Eggen & Sandage (1969), McClure & Twarog (1977), Caputo et al. (1990), Dinescu et al. (1996), von Hippel & Sarajedini (1998), Sarajedini et al. (1999), and Platais et al. (2003). In addition, Kaluzny & Shara (1987), Zhang et al. (2002), and Kafka & Honeycutt (2003) have published photometric studies of variable stars in the cluster field. Finally, Cannon, Upgren et al. (1972), Dinescu et al., and Platais et al.
have published membership probabilities for stars in the NGC 188 field, based on measurements of their proper motions.

In the present paper, we present newly derived photometric indices for stars in NGC 188 from CCD images that we have either obtained ourselves, received from colleagues, or recovered from public domain archives. These photometric results are compared and then combined on a star-by-star basis with photometric data from previous studies of the cluster. We also merge the results of previous astrometric studies of the cluster and combine them with the photometric information to provide color-magnitude and color-color diagrams of probable cluster members.3

2. OLD OBSERVATIONS AND NEW

2.1. Photometry

As mentioned in § 1, NGC 188 has been the subject of numerous photometric studies. Table 1 presents an at-a-glance summary of the properties of the previous and present photometric studies of the cluster. Here and henceforth in this paper, when discussing a particular photometric data set (as opposed to a paper), we save space by labeling that data set with the name of the first author of the publication only, with terse modifiers when needed. For each data set that we consider distinct (col. [1] of the table), we list the technology used to acquire the data (col. [2]), the number of stars for which photometric data are presented (col. [3]), the limiting magnitudes in $U$, $B$, $V$, and $I$ (cols. [4] through [7]), and the source of the data that were employed to calibrate the photometry of the given study (col. [8]). Here we define “limiting magnitude” simply as the 95th percentile of the magnitudes listed in the data set; this is intended purely as a crude indicator of the greatest depth effectively probed, and we make no claims concerning the completeness of any sample. We have not listed the limiting magnitude in $R$, but each of the two studies that provides $I$ magnitudes also gives $R$ magnitudes to a corresponding magnitude limit. The Upgren study is included in this table for completeness, but most of the photometry presented in that paper was not original with them; rather, they tabulated a compilation of previous values taken from the literature, with magnitudes estimated from their plates only when data from other sources were not available. We were unable to locate copies of the original von Hippel & Sarajedini (1998) data tables. This study is therefore not included in the analysis that follows.

We obtained 86 CCD images of NGC 188 with the f/5 Newtonian camera on the Plaskett 1.8 m telescope of the Dominion Astrophysical Observatory (DAO) on the nights of 1996 July 11 and 12 (UT). The CCD camera covered a field 9.3 square, with a sampling of 0.55 pixel.1 We took 28 images in the $B$ photometric bandpass, 33 in $V$, and 25 in $R$, divided among three separate subfields, and exposure times ranged from 6 to 900 s. Conditions were judged to be nonphotometric when these observations were made. During the same nights, observations were obtained for eight different equatorial standard fields from Landolt (1993). In addition, we acquired from the DAO archive copies of images obtained by Manuela Zoccali using the same equipment on the nights of July 15 and 16; she had observed secondary standard fields in the globular cluster M92 and the old open cluster NGC 6791 (see Stetson 2000 and Stetson et al. 2003). Because all these data were obtained under nonphotometric conditions, we are not able to fully calibrate them to a fundamental magnitude system on the basis of internal information alone. However, we can exploit the fact that stars of differing colors were imaged on the detector simultaneously to determine the color-dependent terms in the transformation equations from the instrumental to the standard magnitude sys-

3 The present paper and a companion paper by VandenBerg & Stetson (2004) represent a fulfillment and extension of the paper “D. A. VandenBerg & R. D. McClure (2003, in preparation)” cited by Sandage et al. (2003) in their critical comparison of the old open clusters M67, NGC 188, and NGC 6791 to the old field stars of the solar neighborhood.
tem. Later on, we use the results of previous photometric studies of the cluster to determine the calibration zero point for each of the individual images.

Howard Bond has given us copies of his images from 13 different observing runs at the Kitt Peak 4 and 0.9 m and the Cerro Tololo 0.9 m telescopes. Among the Kitt Peak 0.9 m data were 12 images of NGC 188—four in each of the B, V, and I filters—obtained on 1996 September 21. We also searched the available public archives for other images of NGC 188 and found 201 of them: six exposures with the four-chip Isaac Newton Telescope (INT) Wide-Field Camera (24 images in total), and a further 177 images obtained with single-CCD cameras from three different observing runs on the INT. Of these data, only two observing runs were judged to be photometric on the basis of standard-star calibration residuals, a point that we discuss in greater detail below.

We requested from the Isaac Newton Group (ING) archive all images—both scientific and calibration—from observing runs in which NGC 188 was observed, and we derived and applied the bias and flat-field corrections in the usual way. This was also done for the Plaskett data, of course, but Howard Bond had provided us with images already in rectified form. The DAOPHOT, ALLSTAR, DAOMATCH, DAOMASTER, and ALLFRAME software packages (Stetson 1987, 1993, 1994) were used to detect and measure the positions and brightnesses of astronomical sources in all 299 of the CCD images that were available to us. The star-subtracted images were stacked and examined by eye to designate stars that had been missed by the automatic routines, and the ALLFRAME reductions were repeated until we judged that everything that we could see had been reduced.

The images were then subjected to a routine growth-curve analysis to determine corrections from the profile-fitting magnitudes to a system of aperture magnitudes in a large synthetic aperture (Stetson 1990), and calibration equations relating the instrumental-system magnitudes to the standard system of Lan-dolt (1993) were derived. Full transformations, complete with zero points and extinction coefficients, in addition to linear and quadratic color terms, were possible only for the two INT observing runs in which apparently photometric conditions prevailed. For the remaining data, it was possible to determine only the color terms of the transformation equations.

### 2.2. Astrometry

In order to compile a master star list for the region of NGC 188, we supplemented our own CCD images with 10 other star lists from the archives and literature. (1) We extracted from the US Naval Observatory USNO-A2.0 Guide Star Catalog (Monet et al. 1998) all 9503 sources within a square box 66′ on a side, centered on coordinates α = 00°47′27.52″, δ = +85°16′10.7″ (J2000.0). (2)–(5) Employing the services of the Canadian Astronomy Data Centre, we extracted images 54′ on a side, centered on the same coordinates, from the Digitized Sky Survey 1 (DSS1) “O” plate, and the Digitized Sky Survey 2 (DSS2) “B,” “R,” and “I” plates. These were analyzed with a modernized version of the Stetson (1979) software. (6) Cannon (1968), (7) Upgren et al. (1972), (8) Dinescu et al. (1996), (9) A. Sarajedini et al. (2003, private communication), and (10) Platais et al. (2003) all provided positional determinations, along with their photometric indices. The program DAOMASTER was then used to transform the data from these star lists and our own ALLFRAME analysis of the 299 CCD images to a common reference system and numbering scheme. Ten-parameter cubic fits in x and y were used to effect the transformations. The USNO-A2.0 positions were used as the primary reference, so the (x, y) coordinates in our composite star list should be accurately aligned with the cardinal directions, with x increasing east and y increasing north. Positions are expressed in units of arcseconds, with the origin of the coordinate system at the celestial coordinates given above. A critical match-up tolerance was gradually decreased from 9″ to 4″ in deciding whether entries in different star lists referred to the same object. This tolerance was larger than we normally employ, but in this case it was necessary in order to deal with the Upgren et al. (1972) positions, which were given only to the nearest one-tenth arcminute. Table 2 indicates the number of stars from each sample that were successfully merged into the master list, and also the precision of the positions as inferred from the fitting residuals. It would be unfair to interpret these precision estimates as reflecting the relative astrometric accuracy or precision of the various studies, since different researchers probably adopted different tolerances for the degree of crowding or the limiting signal-to-noise ratio for the detections they chose to tabulate, and the ơ’s here will be strongly influenced by the worst data each study chose to report. The point here is that when appropriate weighted combinations are formed from the reported positions of objects in the NGC 188 field, we can generally expect them to be precise to well under 0″.1.

### Table 2

| Sample                  | Stars (1) | σ(α) (arcsec) | σ(δ) (arcsec) |
|-------------------------|-----------|---------------|---------------|
| USNO-A2 GSC             | 6953      | 0.42          | 0.33          |
| DSS1 “O”                | 7457      | 0.64          | 0.60          |
| DSS2 “B”                | 8792      | 0.39          | 0.39          |
| DSS2 “R”                | 9763      | 0.19          | 0.19          |
| DSS2 “I”                | 7727      | 0.50          | 0.49          |
| Cannon                  | 289       | 0.87          | 0.61          |
| Upgren                  | 135       | 1.64          | 1.64          |
| Dinescu                 | 355       | 0.07          | 0.08          |
| Sarajedini              | 1520      | 0.08          | 0.09          |
| Platais                 | 7812      | 0.11          | 0.09          |
| Present work            | 4863      | 0.04          | 0.04          |

(1) (2) (3) (4)
3. (RE)CALIBRATION AND COMBINATION

Calibrating photometry for NGC 188 is unusually difficult. The cluster lies at a declination of +85°, which means that it stays at a high air mass (≈1.8) from sites in the southern United States and the Canary Islands, regardless of the time of night or time of year. This declination also places the cluster just about as far as it can possibly be from the best established faint photometric standard stars, which are concentrated near the equator and in the southern hemisphere.

We have at hand seven data sets that were obtained under nominally photometric conditions, so they can be used to estimate the zero point of the magnitude scale in the field of NGC 188: (1) the photoelectric $UBV$ photometry of Sandage (1962); (2) the photoelectric photometry attributed to Eggen in Eggen & Sandage (1969); (3) the photoelectric photometry attributed to Sandage in the same paper; (4) the CCD photometry of Sarajedini et al. (1999), who had one photometric night during which they referred their NGC 188 data to 38 of Landolt’s (1993) equatorial standards; (5) the CCD photometry of Platais et al. (2003), which, they state, was calibrated by unpublished photometric observations attributed to Hainline et al. (2000) and employed color terms privately provided by P. Massey—we can only presume that these were based on Landolt and/or Johnson standards, as are other WIYN open cluster studies; and (6) and (7) two of the data sets that we obtained through the services of the ING archive, specifically ones that we designate “CMR2” and “WKG” (labels based on the initials of the observer, which are the only personal identifiers available from the image headers). Of these, the former comprised a single night of photometric observations (1993 June 24/25) from which we were able to obtain 5673 individual measurements in $V$ and 4678 in $B$ of primary and secondary standard stars from Stetson’s online compilation (see Stetson 2000), plus three images in each of $B$ and $V$ for a single 12.5 $\times$ 12.5 field in NGC 188. The latter consisted of three nights of observations (1987 July 31/August 1 to August 2/3) providing from 550 to 1100 standard-star measurements in each filter on each night, plus 139 images of nine distinct east-west $\times$ north-south subfields in the cluster. Any given subfield had as few as two observations in each of $B$ and $V$, or as many as eight observations in each of $B$, $V$, $R$, and $I$. (Interested readers can recover the placement of these fields on the sky from the stellar positions and cross-identifications that we have posted on our Web site or by querying the ING archive4 for observations obtained with the INT on the dates indicated above.) For each of these ING data sets, ex post facto consideration of the standard-star residuals from the photometric calibration solution suggests that conditions were photometric at a level of 0.01–0.03 mag per observation. Accordingly, zero points derived from the CMR2 data alone, for instance, are not likely to be more accurate than $\sim$0.02 mag from the final analysis they are based on only three observations in each filter, and the photometric errors associated with those observations are not likely to be completely independent.

It is possible that the Hainline et al. (2000) observations alluded to by Platais et al. (2003) are actually the same as those reported by Sarajedini et al. (1999): both were obtained with the Kitt Peak 0.9 m telescope, and some (but not all) authors are common to the published abstract and the two refereed papers. However, Platais et al. state that the Hainline et al. observations span 40′ on the sky, whereas the Sarajedini et al. data span only about 23′. Furthermore, as we show below, comparison of the Platais and Sarajedini magnitudes shows both a small net offset and considerable scatter in the differences. We therefore assume the two data sets to be statistically independent.

It is also not immediately obvious that data sets (1), (2), and (3) are mutually independent. In describing the origins of the data in their Table 1, Eggen & Sandage (1969) state that they have tried to “make the best combination of new 200 inch observations by Eggen with the older data by Sandage” by determining and removing systematic differences between the two data sets. The “older data by Sandage” would most obviously mean the data from Sandage (1962). However, there is no obvious one-to-one correspondence between the data from the earlier paper and the observations attributed to Sandage in the later one: Sandage (1962) reports photoelectric results for 123 stars, while the observations attributed to Sandage in Eggen & Sandage (1969) represent only 97. There are 28 stars that are in the first paper but not the second. A comparison of the magnitude values for stars common to the two data sets indicates net offsets of ∼0.03 mag in the $UBV$ magnitude systems, which could, of course, be the result of the recalibration undertaken in the 1969 paper. However, the star-by-star comparison also shows dispersions in the magnitude differences of ∼0.05 mag in $U$ (72 stars in common) and ∼0.04 mag in $B$ and $V$ (95 stars) between the Sandage (1962) magnitudes and the “S” magnitudes of Eggen & Sandage (1969). It is evident that the latter are not simply the former with an additive calibration correction applied. Furthermore, plots of $\Delta V$ and $\Delta B$ (Sandage 1962 vs. Eggen & Sandage 1969 “S”) against $B-V$ show no clear trend, so we are not dealing with a simultaneous adjustment of zero-point and color transformation. Changes to the extinction correction cannot explain the dispersion in the magnitude differences, since NGC 188 lies at a virtually constant air mass, so changes to the extinction coefficients should affect all stars in the field equally. Instead, the two data sets seem to derive from different observations. Similarly, the Eggen & Sandage “E” stars that are in common with the “S” stars in the same table show a net offset of 0.02 mag in $V$ and 0.01 mag in each of $B$ and $U$ (17 stars in $BV$ and 16 in $U$), so it is not obvious that the latter have been placed on the magnitude system of the former

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4 See http://archive.ast.cam.ac.uk/ingarch/ingarch.html.
by a simple zero-point adjustment. Therefore, for the purposes of this paper, we assume that these three data sets, Sandage (1962) and the Eggen & Sandage (1969) “E” and “S” data, are all mutually independent.

Under this assumption, then, we have seven mutually independent attempts to establish a fundamental magnitude scale in the field of NGC 188. The three oldest data sets (Sandage, Eggen “E,” and Eggen “S”) were explicitly calibrated to the UBV system of Johnson & Morgan (1953) and Johnson (1955); the fourth and fifth (Sarajedini and Platais) employed the standard photometric system of Landolt (1993), who did his best to place his UBV magnitudes on the system of Johnson & Morgan and Johnson (see Landolt 1983); the two other photometric data sets (CMR2 and WKG), we employed the standard stars tabulated by Stetson (see Stetson 2000), who is doing his best to ensure that his magnitudes are on the same system as Landolt’s. Therefore, we further assume that the seven data sets represent independent attempts to establish the same magnitude scale, and that they differ only as a result of systematic errors that vary at random among the different data sets.

To determine the net study-to-study systematic magnitude offsets in order to define an optimum average system, we began by using the Sarajedini photometry as an initial reference, since that data set is unique in including measurements in all five of the UBVRI bandpasses. The top section of Table 3 lists the unweighted arithmetic mean magnitude differences between each of the other six studies and the Sarajedini results in those filters for which data are available. (The Platais study lists the V magnitude of star III-138 as 12.07. For this star, the Sandage (photoelectric), Eggen “S,” McClure, and our own data sets all give V in the range 9.71 to 9.80 mag. The Platais data for this star are not used here.) Only the Platais data, the Sarajedini data, and our revaluations of the ING archival data provide a standard-error estimate for each derived standard-system magnitude. We have used these to reject any measurement with a claimed uncertainty $\geq 0.10$ mag, but apart from this, no use was made of the standard errors in weighting the magnitude differences. The three photoelectric data sets from the 1960s provided no individual error estimates, and all published measurements were retained in the analysis, except that it was necessary to manually exclude variable stars. V5 = I-11 and V11 = I-116 from these comparisons. We note from the data in Table 3 that the Sarajedini magnitudes are fainter than all six of the other studies in both B and V; the Sarajedini magnitudes are also fainter than the one other available study in R and I.

The rms standard deviation of the magnitude differences in each comparison is provided in the second section of the table. Some portion of these dispersions is the result of random errors in the individual measurements, but it is likely that there is also some contribution from filter mismatch. Stetson et al. (2003) provided evidence that even when measurements of arbitrarily high precision are obtained with a given filter/detector combination, there still tends to be an irreducible scatter on the order of 0.01–0.02 mag when these observations are transformed to a photometric system that is nominally the same but that was defined with a different filter/detector combination. (This conclusion was based on observations in the B, V, and I bandpasses. There is no reason to assume that it does not apply equally well to the R bandpass. The study-to-study repeatability of U magnitudes may well be worse than this, since the U bandpass is atmosphere-defined on the short-wavelength side, and moreover, it includes the Balmer convergence and jump, which are affected nonlinearly by temperature and are also sensitive to surface gravity.) These study-to-study differences are not simply correlated with color (if they were, they could be removed in the transformation), and they cannot be improved by taking better data with the same equipment. Thus, they do not depend on the internal precision of any given investigation. This justifies our refusal to weight individual measurements on the basis of their published standard errors or the number of independent measurements in any given study as we compare the different photometric systems.

The third section of Table 3 lists the median magnitude differences found between the Sarajedini data and each of the other photometric studies. Since astronomical measurements are subject to many small random uncertainties and sometimes to large sporadic mistakes, they often do not follow a simple Gaussian probability distribution. When mistakes happen, a few large deviations can dominate a traditional statistical analysis. Therefore, we present these median offsets because they are more “robust” or “resistant” than the arithmetic mean; they are more representative of the typical magnitude difference without being as strongly influenced by a few extreme outliers that might be due to the inclusion of variable stars, typographical errors, or unrecognized peculiar anomalies caused, for instance, by contrails, cosmic rays, or insects in the apparatus. For the same reason, the fourth section of the table lists $(\pi/2)^{1/2}$ times the mean absolute difference between the tabulated magnitudes in each study and the Sarajedini data after removal of the median offset. This is a measure of the dispersion in the magnitude differences that is less affected by the most extreme outliers than the more commonly used rms statistic. If the frequency distribution of the magnitude differences were accurately Gaussian in form, then the expectation value of the standard deviation $\sigma$ would be equal to $(\pi/2)^{1/2} \approx 1.2533$ times the mean absolute deviation (MAD).

A comparison of the mean and median magnitude differences shows that they are practically the same, suggesting little or no skewness in the distributions—there is no evidence that any one study tended to have large errors that were preferentially too bright or too faint. However, the robust estimators of dispersion in the fourth section of the table are systematically smaller than the standard deviations given in the second section,

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\(^5\) See http://cadcwww.hia.nrc.ca/cadcbin/wdb/astrocat/stetson/query.
TABLE 3
Comparison of Photometric Studies for NGC 188

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| (1)          | (2)     | (3)     | (4)     | (5)     | (6)     |

1. Mean magnitude offsets (Sarajedini minus other)

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| Sandage pe   | 0.031   | 0.014   | 0.011   |         |         |
| Eggen E      | 0.064   | 0.066   | 0.080   |         |         |
| Eggen S      | 0.014   | 0.038   | 0.039   |         |         |
| Platais      |         | 0.015   | 0.022   |         |         |
| CMR2         |         | 0.072   | 0.003   |         |         |
| WKG          |         | 0.089   | 0.044   | 0.086   | 0.050   |
| Average      | 0.005   | 0.042   | 0.029   | 0.043   | 0.025   |
| Standard deviation (incl. Sarajedini) | 0.041 0.034 0.031 0.061 0.036 |

2. Standard deviations

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| Sandage pe   | 0.114   | 0.070   | 0.071   |         |         |
| Eggen E      | 0.076   | 0.055   | 0.042   |         |         |
| Eggen S      | 0.072   | 0.066   | 0.056   |         |         |
| Platais      |         | 0.049   | 0.038   |         |         |
| CMR2         |         | 0.040   | 0.032   |         |         |
| WKG          |         | 0.078   | 0.099   | 0.083   | 0.080   |
| Average      | 0.087   | 0.060   | 0.056   | 0.083   | 0.080   |
| Standard deviation (incl. Sarajedini) | 0.043 0.033 0.029 0.062 0.042 |

3. Median magnitude offsets (Sarajedini minus other)

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| Sandage pe   | 0.032   | 0.009   | 0.002   |         |         |
| Eggen E      | 0.066   | 0.063   | 0.081   |         |         |
| Eggen S      | 0.018   | 0.032   | 0.035   |         |         |
| Platais      |         | 0.019   | 0.021   |         |         |
| CMR2         |         | 0.072   | 0.004   |         |         |
| WKG          |         | 0.082   | 0.036   | 0.087   | 0.060   |
| Average      | 0.004   | 0.040   | 0.026   | 0.044   | 0.030   |
| Standard deviation (incl. Sarajedini) | 0.043 0.033 0.029 0.062 0.042 |

4. $({\sigma}/2)^{1/2} \times$ MAD

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| Sandage pe   | 0.085   | 0.051   | 0.048   |         |         |
| Eggen E      | 0.077   | 0.052   | 0.041   |         |         |
| Eggen S      | 0.063   | 0.057   | 0.045   |         |         |
| Platais      |         | 0.035   | 0.028   |         |         |
| CMR2         |         | 0.036   | 0.030   |         |         |
| WKG          |         | 0.078   | 0.085   | 0.080   | 0.083   |
| Average      | 0.075   | 0.052   | 0.046   | 0.080   | 0.083   |

5. Number of stars used in the comparison

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| Sandage pe   | 80      | 110     | 111     |         |         |
| Eggen E      | 67      | 69      | 69      |         |         |
| Eggen S      | 63      | 89      | 90      |         |         |
| Platais      |         | 1379    | 1506    |         |         |
| CMR2         |         | 332     | 337     |         |         |
| WKG          |         | 293     | 303     | 299     | 300     |

6. Additive correction to be applied

| Sample       | $U$     | $B$     | $V$     | $R$     | $I$     |
|--------------|---------|---------|---------|---------|---------|
| Sandage pe   | -0.036  | -0.029  | -0.022  |         |         |
| Eggen E      | 0.061   | 0.023   | 0.052   |         |         |
| Eggen S      | -0.020  | -0.006  | 0.009   |         |         |
| Sarajedini   | -0.004  | -0.041  | -0.028  | -0.043  | -0.028  |
| Platais      |         | -0.024  | -0.006  |         |         |
| CMR2         |         | 0.031   | -0.024  |         |         |
| WKG          |         | 0.045   | 0.010   | 0.043   | 0.027   |

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indicating that the magnitude measurements have probability distributions that are somewhat non-Gaussian in form, with an excess of unusually large discrepancies (positive kurtosis). The fifth section of the table indicates the number of stars used in each comparison.

The first and third sections of Table 3 should each be considered to contain a row of zeros for the offset of the Sarajedini data set with respect to itself. If we include those zeros and average together the seven offsets in each filter (in B and V, fewer in U, R, and I), then we get the average offset of the entire ensemble of seven photometric systems relative to the Sarajedini system, in addition to the standard deviation of those systems about the mean system. These numbers are contained in the rows labeled “average” and “standard deviation.” These show that whether we judge by mean or median offset, in every filter the Sarajedini magnitude scale is fainter than the average of all seven by amounts ranging up to ~0.04 mag. Accordingly, we infer that the optimum compromise magnitude scale in each filter is one that is brighter than the Sarajedini system by the indicated amounts. We also see that the standard deviation of the offsets in the different studies and filters averages ~0.04 mag. This indicates that any one attempt to establish a magnitude scale in the field of NGC 188 has typically been subject to an unknown systematic error with a standard deviation of roughly 0.04 mag. Therefore, we hope that by thus averaging the results of seven different calibration attempts, we have been able to establish a compromise magnitude scale that is probably on the true Johnson system to within 0.04 mag, \( \Delta \approx 0.015 \) mag (standard error of the mean) in each of B and V, with correspondingly poorer confidence in U, R, and I.

Examination of Table 3 reveals at most a slight tendency for the offsets in B and V to be correlated. If they were in fact correlated one to one, it would be possible to consider the zero point of the \( B-V \) scale to have been established with essentially negligible uncertainty. But in the present case, splitting the difference between the mean and median offsets and rounding to the nearest 0.01 mag, we find that the zero point of Sandage’s \( B-V \) color scale is 0.01 mag bluer than Sarajedini’s, that the Eggen “E” colors are 0.02 mag redder, the Eggen “S” data agree with Sarajedini’s, Platais’s are 0.01 redder, and the CMR2 and WKG colors are 0.07 and 0.04 mag bluer, respectively. With the data as they are, it seems a worse case scenario is more likely: while the mean of the seven color scales is about 0.02 mag bluer than Sarajedini’s, B and V are largely uncorrelated, and the standard deviation of the different color zero points is about 0.03 mag. Therefore, we expect that the systematic uncertainty of the zero point of the color scale is probably ~0.01 mag: the absolute Johnson \( B-V \) colors of NGC 188’s stars will be uncertain by at least this amount, quite apart from any uncertainty in the foreground reddening.

Splitting the difference between the mean and median offsets, we conclude that the optimum compromise magnitudes will be brighter than Sarajedini’s by 0.004, 0.041, 0.028, 0.043, and 0.028 mag in U, B, V, R, and I, respectively. At the same time, for instance, the Eggen “E” photoelectric B magnitudes should be shifted fainter. That is, to remove the 0.064 mag net offset between the Sarajedini B-band magnitudes and those of the Eggen “E” sample, we shift the former brighter by 0.041 mag and the latter fainter by 0.023 mag, bringing both to the average system of all seven studies. This is done for all the data sets and filters, with the individual corrections listed in the last section of Table 3. Having referred every data set to a common magnitude system, we are now able to form unbiased averages of the various studies’ magnitudes for stars in common. When this is done, we find that we have a total of 896, 7519, 7819, 1549, and 1543 stars with at least one valid measurement in \( U, B, V, R, \) and I, respectively. If we restrict the sample to stars with at least two independent measurements in a given filter, they number 140, 1440, 1560, 299, 300.

For our immediate purposes, we selected the 299 stars in the sample that have at least two independent calibrated measurements in each of \( B, V, R, \) and I. These were then used as local in-frame standards, which permitted us to recalibrate our own CCD reductions, including images that were obtained under nonphotometric conditions (i.e., the Plaskett, Bond, and non-CMR2, non-WKG INT images), to the same magnitude system as the rest. From the results of this analysis of our own CCD images, we extracted 1041 well-observed stars with (1) at least five measurements and an estimated standard error of the mean magnitude not worse than 0.1 mag in all of \( B, V, R, \) and I, and (2) a modified Welch-Stetson variability index (Welch & Stetson 1993) not larger than 2.5 times the median value.

Next, the calibrated magnitudes for these 1041 stars were averaged with the five previous independent photometric samples (viz., Sandage photoelectric, Eggen “E,” Eggen “S,” Sarajedini, and Platais) after application of the previously determined offsets to the previous data, so they should now all be on the same photometric system. Once known variable stars and the blended star I-128 were excluded, there emerged from this stage 1722 stars that had satisfactory (\( \sigma < 0.10 \) mag) measurements in each of \( B \) and \( V \) from at least two different studies. These stars should now represent just about the best reference list that we can achieve—a gold standard—for determining and removing systematic photometric offsets from the remaining six data sets, which did not previously have fully independent calibrations: the Sandage (1962) photographic data and the Sharov (1965), Cannon (1968), McClure & Twarog (1977), Caputo et al. (1990), and Dinescu et al. (1996) results. There is no need to impose a selection on the \( U, R, \) and I filters at this point, since none of these studies presented \( U, R, \) or I data. The offsets we derive for these samples are listed in Table 4, but several of the data sets need a bit more discussion.

Sandage photographic.—Photographic magnitudes are listed for six stars that we could not find on the published charts: I-123, I-125, I-126, I-127, I-159, and II-33. None of the other studies that employed Sandage designations (Sharov, McClure, Caputo, and Platais) includes any entries for these stars, implying that they could not find them either. Three other stars, I-158, II-178, and II-205, were manually removed from the
Comparison of Photometric Studies for NGC 188

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| (1)          | (2)   | (3)   |

Mean offsets (adopted minus other)

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | −0.038| −0.023|
| Sharov       | −0.040| −0.025|
| Cannon       | −0.033| −0.007|
| McClure      | +0.003| +0.034|
| Caputo       | −0.024| +0.033|
| Dinescu      | −0.016| −0.004|

Standard deviations

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | 0.109 | 0.078 |
| Sharov       | 0.047 | 0.125 |
| Cannon       | 0.057 | 0.094 |
| McClure      | 0.075 | 0.057 |
| Caputo       | 0.150 | 0.046 |
| Dinescu      | 0.138 | 0.124 |

Median offsets (adopted minus other)

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | −0.042| −0.027|
| Sharov       | −0.036| −0.030|
| Cannon       | −0.041| −0.013|
| McClure      | +0.009| +0.031|
| Caputo       | +0.008| +0.037|
| Dinescu      | −0.020| −0.007|

$(\pi/2)^{10} \times$ MAD

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | 0.069 | 0.054 |
| Sharov       | 0.044 | 0.084 |
| Cannon       | 0.052 | 0.045 |
| McClure      | 0.056 | 0.043 |
| Caputo       | 0.100 | 0.035 |
| Dinescu      | 0.112 | 0.092 |

Number of stars used in the comparison

| Sample       | $B$ | $V$ |
|--------------|-----|-----|
| Sandage pg   | 543 | 544 |
| Sharov       | 74  | 74  |
| Cannon       | 77  | 77  |
| McClure      | 585 | 585 |
| Caputo       | 277 | 277 |
| Dinescu      | 245 | 245 |

Additive corrections to be applied

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | −0.040| −0.025|
| Sharov       | −0.038| −0.028|
| Cannon       | −0.037| −0.010|
| McClure      | +0.006| +0.032|
| Caputo       | −0.008| +0.036|
| Dinescu      | −0.018| −0.006|

Comparison of Photometric Studies

BV: 1012–1030

Mean offsets (adopted minus other)

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | −0.038| −0.023|
| Sharov       | −0.040| −0.025|
| Cannon       | −0.033| −0.007|
| McClure      | +0.003| +0.034|
| Caputo       | −0.024| +0.033|
| Dinescu      | −0.016| −0.004|

Standard deviations

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | 0.109 | 0.078 |
| Sharov       | 0.047 | 0.125 |
| Cannon       | 0.057 | 0.094 |
| McClure      | 0.075 | 0.057 |
| Caputo       | 0.150 | 0.046 |
| Dinescu      | 0.138 | 0.124 |

Median offsets (adopted minus other)

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | −0.042| −0.027|
| Sharov       | −0.036| −0.030|
| Cannon       | −0.041| −0.013|
| McClure      | +0.009| +0.031|
| Caputo       | +0.008| +0.037|
| Dinescu      | −0.020| −0.007|

$(\pi/2)^{10} \times$ MAD

| Sample       | $B$   | $V$   |
|--------------|-------|-------|
| Sandage pg   | 0.069 | 0.054 |
| Sharov       | 0.044 | 0.084 |
| Cannon       | 0.052 | 0.045 |
| McClure      | 0.056 | 0.043 |
| Caputo       | 0.100 | 0.035 |
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Number of stars used in the comparison

| Sample       | $B$ | $V$ |
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| Sandage pg   | 543 | 544 |
| Sharov       | 74  | 74  |
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Additive corrections to be applied

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| Cannon       | −0.037| −0.010|
| McClure      | +0.006| +0.032|
| Caputo       | −0.008| +0.036|
| Dinescu      | −0.018| −0.006|

correction, because their magnitudes differed from our adopted reference magnitudes by more than 1 mag in one or both filters.

Sharov.—Sharov star 93 had a magnitude residual a bit larger than 1 mag in $V$. This star was manually removed from the comparison.

McClure.—Photometry is provided for stars identified as 125, 136, and 137, but we were unable to locate these stars on the published finding chart. The tabulated $V$ magnitudes for stars 173 and 174 are 11.94 and 12.55, respectively, and for both, the $B-V$ color is given as $-0.28$. This is clearly a mistake. The two stars are blended together, but it is evident from McClure & Twarog’s (1977) finding chart and other available images that each component of the blend is fainter than the nearby star 140, for which the authors list $V = 14.81$. Our own $V$ magnitudes for stars 173 and 174 are 15.48 and 16.69, while for 140 we get $V = 14.80$. We exclude the McClure values for 173 and 174 from further consideration.

Caputo.—Three distinct but partially overlapping CCD fields were studied in NGC 188. As a result, 19 stars in areas of overlap were each measured twice. We employed the mean of the two magnitudes in each filter for each of these stars, but weighted them the same as stars that were measured once, since our purpose here is to compare photometric systems, and the number of observations for a given star does not affect the system that it is on. Also, the Caputo study lists the visual magnitude of star II-212 as 15.15. We suspect this is a typographical error: changing the value to 17.15 brings this observation into excellent agreement with all the other studies that measured this star. Finally, the Caputo $B$-band magnitudes for stars I-E3 and I-E18 are both more than a magnitude fainter than those found by Sarajedini, Platais, and our own study, while the $V$-band magnitudes for both stars are in reasonable agreement. These differences are less easy to explain as typographical errors, so we omit Caputo’s measurements of these stars from the rest of our analysis.

Dinescu.—Five stars, Dinescu 644, 645, 680, 720, and 734, were manually removed from the comparison, because their magnitudes differed from our adopted reference magnitudes by more than 1 mag in one or both filters.

Now, with photometric results from all 12 studies presumably on a common system, it is our goal to compile a master list that combines all available results for stars in common. At this point, it becomes useful to consider the photometric precision of each individual observation. Our own reductions and the results of Sarajedini and Platais associate a standard error with each photometric measurement. The Sandage (1962) and Eggen & Sandage (1969) photoelectric lists, and the Sharov and the Dinescu photographic data do not include standard errors per se, but they do specify the number of times each star was observed. Caputo et al. (1990) list only one magnitude in each filter for most stars, but 19 stars were measured twice because they fell in overlapping regions of different subfields. Finally, McClure & Twarog (1977) list only photometric indices on a star-by-star basis, with no indication of precision or the number of independent measurements for any given star.

For the nine studies that do not list quantitative standard errors, we estimate the precision from a comparison with our gold standard. These results are summarized in Table 5. For each study (col. [1]), columns (2) and (3) give the average rms difference between the gold-standard values and the offset-corrected measurements of that study in the $B$ and $V$ filters; columns [4] and [5] give $1.2533 \times$ the mean absolute differ-
ence; and column [6] gives the arithmetic average of these four
estimates of the observational scatter. Column (7) gives the
mean number of observations per star in the study, and column
(8) gives the inferred standard error of one observation; for the
first three samples, this has been multiplied by a further factor
of \((6/5)^{1/2}\) to account for the fact that each of these studies was
included in the definition of the gold-standard system. For the
nine studies in this table, the uncertainty of an individual tab-
ulated magnitude will be assumed to be the value in the last
column, divided by the square root of the number of times that
star was observed. The same formula will apply without dis-
tinction to the \(U\), \(B\), and \(V\) bandpasses. This approach is not
strictly rigorous in a mathematical sense, but it should be good
enough for our purposes, given the limitations of the data.

The last three studies are those of Sarajedini, Platais, and
the present paper. In the case of the Platais study, their data
table lists a “standard deviation” for each photometric index.
We assume that this represents the standard error of one mea-
surement, because it varies with magnitude but is almost com-
pletely independent of the number of times the star was mea-
sured. Accordingly, we divide this standard deviation by the
square root of the number of measurements. Furthermore, the
Platais data set lists \(\sigma (V)\) and \(\sigma (B-V)\); for our purposes, we
take \(\sigma^2(B) = \frac{1}{2}[\sigma^2(V) + \sigma^2(B-V)]\). The Sarajedini data
and our own analysis give uncertainties for the individual magni-
tudes rather than for derived colors, and these are what we will
use. However, for all three studies—Sarajedini, Platais, and
ours—we add a further uncertainty of 0.015 mag in quadrature
to lessen the impact of individual measured magnitudes that,
because of random statistical fluctuations and round-off effects,
have tabulated standard errors of \(~0.000\) mag. (If the listed
uncertainties were taken literally, a star with a standard error of
0.001, for instance, should have 4 times the weight of one
with a standard error of 0.002. We believe this would be un-
realistic.) This additional error component can be taken to re-
represent the irreducible star-to-star photometric differences due
to filter mismatch. In the case of our own photometric study,
this is likely to be unduly pessimistic, since we combined data
from six observing runs on three telescopes employing six
different detectors, which should beat down the net effects of
bandpass mismatch.

Given these precepts, the data from the 12 different sets were
merged into a single star list with weighted mean magnitude
values in each filter for which observations were available. The
weights were the inverse square of the observational uncer-
tainties as laid out in Table 5 and the previous paragraph, and
the uncertainty of a final averaged magnitude was taken to be
the inverse square root of the sum of the weights. The actual
study-to-study repeatability of the results for any individual
star was not considered, except insofar as observations dis-
crepant by more than 1 mag were discarded. The information
posted on our Web site allows interested readers to recover the
various studies’ separate results for any given star.

We would like to mention a couple of small items that came
to our attention as we were working with these data sets. We
present them here in case they might help future researchers.
Kaluzny & Shara (1987) identify variable star V8 as Sandage
star III-9; we believe that it is actually III-89. Zhang et al.
(2002) have east and west reversed in their Figure 1. They also
did not note that their V12 = Sandage III-51.

### 4. PROPER MOTIONS

Four previous studies have used measurements of stellar
proper motions to define membership indicators for stars in the
NGC 188 field: Cannon (1968); Upgren et al. (1972); Dinescu
et al. (1996); and Platais et al. (2003). The last three studies,
in particular, published quantitative membership probabilities
based on each star’s proper motion relative to the average
cluster and field proper-motion distributions. The Dinescu et
al. paper also presented a second probability estimate that in-
cludes consideration of the star’s position on the sky as well
as its proper motion, but we will not employ this here, in order
to simplify the comparison with the other studies. The different
sets of membership probabilities are generally in good, al-
though not perfect, agreement. Figure 1, for example, shows
the membership probabilities from Dinescu plotted against
those of Platais for 345 stars in common. The Dinescu et al.
paper lists photometric and astrometric results only for “prob-
able members and stars of special interest,” so this plot contains
very few stars with Dinescu membership probabilities below
60%. Among these, however, it is noteworthy that there are

| Sample            | \(\sigma_1\) | \(\sigma_2\) | \((\pi/2)^{1/2}(\text{MAD})_1\) | \((\pi/2)^{1/2}(\text{MAD})_2\) | \(\bar{\sigma}\) | \(n\) | \(\sigma(1\text{ obs.})\) |
|-------------------|-------------|-------------|-------------------------------|-------------------------------|----------------|-----|-----------------|
| Sandage pe        | 0.047       | 0.048       | 0.033                         | 0.032                         | 0.040          | 1.8 | 0.060           |
| Eggen “E”         | 0.035       | 0.029       | 0.035                         | 0.029                         | 0.032          | 1.8 | 0.045           |
| Eggen “S”         | 0.045       | 0.034       | 0.038                         | 0.029                         | 0.036          | 1.4 | 0.048           |
| Sandage pg        | 0.107       | 0.066       | 0.067                         | 0.050                         | 0.072          | 1.0 | 0.072           |
| Sharov            | 0.042       | 0.074       | 0.040                         | 0.066                         | 0.056          | 2.7 | 0.091           |
| Cannon            | 0.057       | 0.094       | 0.052                         | 0.045                         | 0.062          | 1.0 | 0.062           |
| McClure           | 0.078       | 0.048       | 0.058                         | 0.041                         | 0.056          | 1.0 | 0.056           |
| Caputo            | 0.089       | 0.030       | 0.060                         | 0.027                         | 0.058          | 1.1 | 0.054           |
| Dinescu           | 0.120       | 0.110       | 0.104                         | 0.087                         | 0.105          | 2.0 | 0.149           |
The Cannon study of proper motions does not present membership probabilities close to 100% and Platais probabilities close to 0%. Between these extremes, there is no perceptible correlation between the membership determinations, apart from the general statement that there are a few stars for which both studies find the membership evidence inconclusive. Finally, there are a very few stars that the Dinescu study considers to be nonmembers but nevertheless “of interest,” and that the Platais study finds to be members. We have no way of guessing which other stars Dinescu et al. may have measured and determined to be highly probable nonmembers, so if a star is not included in their data table, we must assume that it is a nonmember. It is curious that although there are stars for which Upgren, Dinescu, and Platais considered probable members, it is evident that Platais et al. find a number of stars they consider to be certain nonmembers. There are also at least two stars that Dinescu et al. consider to be interesting nonmembers but that Platais et al. find to be almost certain members.

The Cannon study of proper motions does not present membership probabilities per se, but rather gives a ratio of the amount by which the motion of a given star differs from the presumed cluster mean motion, divided by the uncertainty of the measurement. In Figure 2 we plot Cannon’s ratio \( \chi \) against the arithmetic mean of the membership probabilities for stars that appear in one or more of the Upgren, Dinescu, and Platais studies. The results are more or less as expected, in the sense that stars for which Cannon finds a proper motion close to the cluster mean tend to have membership probabilities that are high in the other studies. Conversely, when Cannon has measured a large motion for a star, the other studies are emphatic that it is a nonmember. It is curious that although there are stars for which Upgren, Dinescu, and Platais alone or in combination find membership probabilities of 90%–100%, none of these stars were included in Cannon’s sample. Perhaps Cannon’s stars were simply too bright for reliable astrometry in the more recent investigations. The correlation between Cannon’s \( \chi \) and the other studies’ membership probabilities is not perfect: even for stars with Cannon’s lowest \( \chi \) values, there is a considerable range in the membership probabilities found by others. Specifically, we find for stars with \( 0 \leq \chi < 5 \), the arithmetic mean membership probabilities from the other studies is 53% (based on 84 stars); for \( 5 \leq \chi < 15 \), the mean membership probability is 22% (52 stars); for \( 15 \leq \chi < 30 \), it is 6% (43 stars); and for \( \chi \geq 30 \), it is 0% (112 stars). Therefore, in order to convert Cannon’s \( \chi \) to quantities that can be averaged with the membership probabilities from the other studies, we assign...
these numerical probabilities within the stated bins, except that we convert \( \chi < 5 \) to a membership probability of precisely 50%. That way, if we divide a sample of “members” from “non-members” by making a cut at 50%, Cannon’s measurements will not change the decision one way or the other if \( \chi < 5 \) and the star has been included in any of the other studies. If Cannon’s \( \chi \geq 5 \), then it will have the potential to represent a tie-breaking vote against membership if the other studies are inconclusive among themselves.

5. DEFINING THE FIDUCIAL SEQUENCES

Figure 3 presents a \((B−I, V)\) color-magnitude diagram for probable NGC 188 members based on all the photometric and astrometric data discussed in the previous sections. Here we have plotted only stars for which the photometric uncertainty \( \sigma(B−I) < 0.10 \) mag. Crosses have been used for stars with measured membership probabilities \( \geq 50\% \), and dots have been used for stars without measured proper motions. Stars with membership probabilities determined to be below 50% on average among the astrometric studies have not been plotted. (We note that nobody ever assigns a membership probability of 100%; the highest membership probability listed in any of the studies is 99%). Therefore, if a star appears in two proper-motion studies with a membership probability of 99% in one and 0% in the other—the most extreme case of disagreement possible—such a star will have a mean membership probability of 49.5% and will be excluded from the sample of probable members.) The cluster turnoff and subgiant branch are quite well defined, and a population of blue stragglers and a binary-star main sequence are also clear. The color-magnitude diagram shows the appearance of a “subdwarf sequence” consisting of roughly a dozen stars either a magnitude fainter or 0.4 mag bluer than the principal main sequence. However, if we apply the more stringent selection criteria \( \sigma(B−I) < 0.05 \) mag and membership probability above 90%, none of these stars survives the cut. Therefore, they do not likely represent a challenge to our understanding of NGC 188’s stellar population.

Eggen & Sandage (1969) found a gap roughly a tenth of a magnitude wide, containing no cluster stars just below the main-sequence turnoff of NGC 188, centered at magnitude \( V = 15.55 \). McClure & Twarog (1977) failed to reproduce the gap with their new photographic data, but nevertheless presented arguments supporting its reality. In particular, a gap near this magnitude was found when only the data from the innermost zone of the cluster were considered. However, such a gap is not predicted by modern stellar evolution models if we have correctly judged the chemical abundances and age of the cluster, even when diffusive effects are taken into account (e.g., Michaud et al. 2004). Even in 1977, McClure & Twarog considered the gap to be “only marginally expected,” on the basis of then-current theory. The inset in Figure 3 shows an enlargement of the main-sequence turnoff region of NGC 188. The lower of the two arrows marks \( V = 15.55 \), which is the center of the Eggen & Sandage gap. The present data clearly do not support the presence of a gap at this apparent magnitude. The upper arrow, marking a gap that does appear in these data, lies at \( V = 15.14 \). McClure & Twarog also found a gap near this magnitude in their photometry for stars in Sandage’s ring II, but not for ring I. We are not prepared at present to argue that this gap is real and requires modifying current stellar evolution models. However, the anonymous referee of the first submitted draft of this paper has raised an interesting question: is the apparent color offset between the brightest stars below the gap and the faintest stars above it real? Morphologically, this sort of jog would be expected if the theoretical models did predict a gap for NGC 188. However, the referee’s question can probably only be answered with better photometry than is currently available. The referee has also made the interesting point that the Eggen-Sandage gap does appear to coincide with a lack of stars on the binary main sequence in our data. If so, it is difficult to see how it could be a consequence of stellar evolution. Rather, it is almost certainly a fluke of small-number statistics.

To define the cluster fiducial sequences, we began by printing five diagrams for probable cluster members and stars without membership determinations: \( V \) versus \( B−V \), \( V \) versus \( I−V \), \( V \) versus \( B−I \), \( B−V \) versus \( V−I \) for stars fainter than \( V = 15.5 \) (mostly member dwarfs), and \( B−V \) versus \( V−I \) for stars brighter than \( V = 15.5 \) (mostly member subgiants and giants). Into each of these five diagrams a fiducial sequence was sketched by hand, and the locations of representative points along that se-
sequence were measured with a ruler. Each of the five diagrams was measured twice, in orthogonal directions. That is to say, consider the \(V\) versus \(B-I\) plot: when the color position of the hand-sketched locus is measured at equally spaced intervals of \(V\), we can say that we have measured the dependent variable \(B-I(V)\) as a function of the independent variable \(V\). Conversely, when the magnitude position of the locus is measured at fixed intervals of color, we can say that we have measured the dependent variable \(V(B-I)\) as a function of the independent variable \(B-I\). Measurements were made at constant intervals of 0.5 mag in brightness when \(V\) was the independent variable, 0.10 mag when \(V-I\) or \(B-I\) was the independent variable, and 0.05 mag when \(B-V\) was independent.

When all five plots have been measured in the two orthogonal directions, we now have five different ways to define a \(V\) versus \(B-I\) locus: we can plot \(V\) versus \(B-I(V)\); we can plot \(V(B-I)\) versus \(B-I\); we can plot \(V\) versus \(B-V(V) + V-I(V)\); we can plot \(V(B-V)\) versus \(B-V + V-I(B-V)\); and we can plot \(V(V-I)\) versus \(B-V(V-I) + V-I\). We hope that by combining these different approaches to defining the mean cluster locus, we can beat down the random error in our placement of the pencil line through the swarm of data points, any systematic bias in our placement of the millimeter ruler with respect to the plot tick marks, or any random or systematic error in the way that we judge the intersection of the pencil line with the edge of the ruler. Figure 4 shows these five different versions of the \(V\) versus \(B-I\) color-magnitude diagram, in which different symbols are used to designate the different definitions of the fiducial locus. It is apparent that the five different curves are in excellent agreement, except for some slight ambiguity at the top of the giant branch.

We then printed a new copy of Figure 4 at twice the scale used for the previous plots, sketched a smooth curve through the normal points, and read out compromise representative positions along the curve, again in both directions, this time at 0.25 mag intervals in \(V\), and 0.05 mag in \(B-I\). This was subsequently checked by overplotting the resulting curve on a color-magnitude diagram for the individual stars, and modest adjustments were made. We regard this fiducial sequence as the fundamental result of the present paper. The \(B-I\) color is attractive for this purpose because it provides the greatest possible ratio of range to measuring error; it is therefore optimally sensitive to temperature among the photometric bandpasses available to us at this time. This sensitivity also has the effect of providing the greatest possible discrimination between single main-sequence stars and the unresolved binaries that lie above and on the red side of the main sequence. The \(B-I\) color has the additional desirable quality of being very nearly statistically independent of \(V\), given the way that we have calibrated the raw measurements. Therefore, there is little or no correlation between random temperature errors and random luminosity errors (see, e.g., McClure & Tinsley [1976] to see why this can be relevant).

Having produced a smoothed \(V\) versus \(B-I\) fiducial curve, we then plotted color versus \(B-I\) diagrams for probable member stars and stars of undetermined membership having photometric color uncertainties less than 0.10 mag, where “color” in this case stands for \(U-B\), \(B-V\), \(V-R\), and \(V-I\), each in turn. Separate \(B-I\)-color plots were produced for stars respectively brighter and fainter than \(V = 15.5\) so as not to confuse member dwarfs with member giants. The distinction turns out to be important for colors involving the \(V\) filter, in which dwarfs and giants show perceptibly different behavior (as Stetson et al. 2003 also found in NGC 6791, in the case of the \(V-I\) color). We also produced \(V\) versus color plots for each of the four colors and measured them in both directions. The fiducial points listed in Table 6 represent a compromise between values visually measured in the color-\(V\) color-magnitude and \(B-I\)-color color-color diagrams. At the end of this process, there remains a certain amount of jitter in the tabulated curves—due mostly to differences of perception in the two orthogonal directions—that is probably a fair representation of the random uncertainties in the adopted fiducial points.

### 6. COLOR-COLOR DIAGRAMS

The top panel of Figure 5 illustrates the \(V-R\) versus \(B-V\) color-color diagram for NGC 188. Here we have plotted only the 796 stars with at least a 50% membership probability and estimated color uncertainties below 0.10 mag. Stars with membership probabilities measured to be less than 50%, and stars without membership determinations, have been omitted. Stars with \(V\)-band magnitudes \(\geq 15.5\) have been plotted as crosses, and those brighter than 15.5 have been plotted as open circles.
The middle panel of the figure is the analogous plot for \(V-\) versus \(B-V\). As Stetson et al. (2003) found in the case of the \(V-I\) versus \(B-V\) color-color diagram for NGC 6791, there is a clear separation of cluster giants and dwarfs for the reddest colors, in the sense that at long wavelengths giants are bluer than dwarfs for fixed \(B-V\) colors. There is no clear separation with luminosity in an \(R-I\) versus \(B-I\) plot, which establishes an extra absorption component in the \(V\) bandpass at high surface gravity as the most likely cause of the difference. The bottom panel of Figure 5 plots the sum of the two long-wavelength colors versus \(B-V\); combining the long-wavelength colors produces a slight improvement in the ratio of separation to scatter. The solid line in this plot represents the equation \((V-R) + (V-I) = 1.70(B-V) - 0.04\), which we use later as a discrimi-

### TABLE 6

**Fiducial-Sequence Normal Points for NGC 188**

| \(V\) | \(B-I\) | \(U-B\) | \(B-V\) | \(V-R\) | \(V-I\) |
|------|--------|--------|--------|--------|--------|
| (1)  | (2)    | (3)    | (4)    | (5)    | (6)    |
| 12.500 | 2.484 | ...   | 1.241 | 0.676 | 1.243 |
| 12.647 | 2.450 | ...   | 1.222 | 0.667 | 1.228 |
| 12.750 | 2.424 | ...   | 1.201 | 0.661 | 1.223 |
| 12.859 | 2.400 | 1.122 | 1.190 | 0.654 | 1.210 |
| 13.000 | 2.376 | 1.089 | 1.175 | 0.649 | 1.201 |
| 13.104 | 2.350 | 1.069 | 1.161 | 0.640 | 1.189 |
| 13.250 | 2.319 | 1.049 | 1.146 | 0.633 | 1.173 |
| 13.351 | 2.300 | 1.025 | 1.129 | 0.628 | 1.171 |
| 13.500 | 2.272 | 1.000 | 1.119 | 0.620 | 1.153 |
| 13.611 | 2.250 | 0.972 | 1.103 | 0.617 | 1.147 |
| 13.750 | 2.224 | 0.951 | 1.093 | 0.608 | 1.131 |
| 13.905 | 2.200 | 0.921 | 1.077 | 0.606 | 1.123 |
| 14.000 | 2.186 | 0.906 | 1.070 | 0.598 | 1.124 |
| 14.250 | 2.152 | 0.874 | 1.049 | 0.596 | 1.103 |
| 14.267 | 2.150 | 0.865 | 1.044 | 0.592 | 1.106 |
| 14.500 | 2.121 | 0.832 | 1.030 | 0.580 | 1.091 |
| 14.664 | 2.100 | 0.805 | 1.015 | 0.579 | 1.085 |
| 14.750 | 2.096 | 0.794 | 1.008 | 0.575 | 1.088 |
| 15.000 | 2.057 | 0.752 | 0.993 | 0.568 | 1.064 |
| 15.016 | 2.050 | 0.742 | 0.984 | 0.567 | 1.066 |
| 15.091 | 2.000 | 0.688 | 0.958 | 0.559 | 1.042 |
| 15.091 | 1.950 | 0.636 | 0.932 | 0.548 | 1.018 |
| 15.077 | 1.900 | 0.588 | 0.907 | 0.536 | 0.993 |
| 15.063 | 1.850 | 0.540 | 0.881 | 0.522 | 0.969 |
| 15.042 | 1.800 | 0.496 | 0.854 | 0.506 | 0.946 |
| 15.012 | 1.750 | 0.450 | 0.828 | 0.490 | 0.922 |
| 15.000 | 1.718 | 0.425 | 0.815 | 0.487 | 0.903 |
| 14.982 | 1.700 | 0.408 | 0.801 | 0.475 | 0.891 |
| 14.952 | 1.650 | 0.363 | 0.775 | 0.459 | 0.876 |
| 14.892 | 1.600 | 0.320 | 0.748 | 0.445 | 0.852 |
| 14.895 | 1.550 | 0.275 | 0.721 | 0.432 | 0.829 |
| 14.906 | 1.500 | 0.233 | 0.694 | 0.418 | 0.806 |
| 15.000 | 1.454 | 0.200 | 0.670 | 0.402 | 0.784 |
| 15.012 | 1.450 | 0.191 | 0.669 | 0.406 | 0.781 |
| 15.250 | 1.422 | 0.165 | 0.660 | 0.388 | 0.762 |
| 15.500 | 1.433 | 0.160 | 0.661 | 0.394 | 0.772 |
| 15.689 | 1.450 | 0.170 | 0.671 | 0.397 | 0.779 |
| 15.750 | 1.461 | 0.180 | 0.676 | 0.403 | 0.785 |
| 15.975 | 1.500 | 0.212 | 0.699 | 0.418 | 0.801 |
| 16.000 | 1.506 | 0.221 | 0.705 | 0.417 | 0.801 |
| 16.176 | 1.550 | 0.254 | 0.727 | 0.434 | 0.823 |
| 16.250 | 1.567 | 0.272 | 0.733 | 0.436 | 0.834 |
| 16.388 | 1.600 | 0.299 | 0.752 | 0.450 | 0.848 |
| 16.500 | 1.632 | 0.334 | 0.775 | 0.457 | 0.857 |
| 16.561 | 1.650 | 0.347 | 0.781 | 0.465 | 0.869 |
| 16.731 | 1.700 | 0.402 | 0.802 | 0.472 | 0.898 |
| 16.750 | 1.708 | 0.412 | 0.808 | 0.475 | 0.900 |
| 16.879 | 1.750 | 0.439 | 0.826 | 0.494 | 0.924 |
| 17.000 | 1.798 | 0.480 | 0.856 | 0.504 | 0.942 |

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Fig. 5.—Plot showing the gravity sensitivity of BVRI colors for stars redder than $B-V \sim 0.95$. Top: $V-R$ plotted against $B-V$; middle: $V-I$ plotted against $B-V$. In each case, only stars having mean measured proper-motion membership probabilities ≥50% and $d$ (color) < 0.10 are shown; stars with undetermined membership have not been plotted. Open circles represent stars brighter than $V = 15.5$ (roughly the main-sequence turnoff), which should be subgiants and giants, while crosses represent fainter (i.e., main-sequence) stars. Bottom: Effect of plotting the sum of $V-R$ and $V-I$ against $B-V$: the separation between the giant and main-sequence branches, relative to the photometric scatter in each, is slightly improved. The sloping line represents the equation $(V-R) + (V-I) = 1.70(B-V) - 0.04$, which we use as a giant/dwarf discriminator for red stars, and an index of possible stellar peculiarity or photometric mistakes for blue stars.

Fig. 6.—Top: Plot of $(V-R) + (V-I)$ against $B-V$ color for stars in the NGC 188 field with proper-motion membership probabilities between 10% and 50%. Open circles represent stars having $(V-R) + (V-I) < 1.70(B-V) - 0.04$, and crosses represent stars lying below this line. For stars redder than $B-V = 0.95$ or so, which corresponds to $B-I \approx 2.0$, open circles are likely to be giants, and crosses are likely to be dwarfs. Bluer than this limit, normal stars are not expected to have $(V-R) + (V-I) < 1.70(B-V) - 0.04$; open circles with $B-V < 0.95$ probably represent peculiar stars or unusually large measuring errors. Bottom: $V$ vs. $B-I$ color magnitude diagram for the same stars as are shown in the top panel. Symbol types have the same significance, and the solid curve represents our adopted fiducial cluster sequence. This figure shows a striking concentration of these stars toward the mean cluster locus, especially near the turnoff and the lower main sequence. One star with the long-wavelength colors of a giant lies close to the cluster giant branch, and two others lie in a zone where few giant stars are found in the surrounding field population (cf. Fig. 7). It is likely that many or most of these stars are actually cluster members. A number of stars having marginal membership indices lying in the blue straggler region could also be actual cluster members.

nator between giants and dwarfs. This criterion is probably useful only for $B-V$ colors larger than 0.90–1.00 (or $B-I > 1.9–2.1$), but if a bluer star is found to be lying significantly above this line, it probably has large photometric errors or an unusual spectral-energy distribution.

This giant/dwarf discriminator can be used as a (weak) membership indicator for those stars for which the proper-motion evidence is marginal or lacking. The top panel of Figure 6 is the $(V-R) + (V-I)$ versus $B-V$ diagram for the 163 stars in the NGC 188 field with measured proper motions that imply membership probabilities $10% \leq p \leq 49\%$ and photometric uncertainties in $(V-R) + (V-I) < 0.10$ mag. Here we have plotted stars lying above the giant/dwarf dividing line (probable giants if the stars are red, possible photometric mistakes or peculiar stars if they are blue) as open circles, and stars below the line (probable normal dwarfs) as crosses. The bottom panel of this figure shows the $V$ versus $B-I$ color-magnitude diagram for the same stars, where the symbols have the same meaning as in the top panel and the solid curve is our adopted cluster fiducial sequence. Here we see that many stars with ambiguous proper-motion membership determinations fall very near NGC 188’s main sequence and have the photometric properties of dwarfs. It is likely that the membership probabilities of these stars have been underestimated, because their proper motions fall in the tail of the random distribution of measuring errors. This is a consequence of utilizing a fixed cluster/field star ratio in the probability calculations. If, for instance, the astrometrists were to consider the cluster/field star ratio only for stars that fell within a few standard deviations of the mean cluster photometric locus, that ratio would be much higher than the ratio for all stars considered together. With such a calculation, the membership probabilities of these stars would be significantly increased. (Of course, using one cluster/field ratio for stars near the principal locus and another for stars off of it would greatly reduce the likelihood of finding peculiar cluster members. Our point here is not to criticize the standard method of membership.
determination; it is merely to point out that adopting any arbitrary membership cutoff larger than 0% involves the near certainty of rejecting some genuine cluster members. Stars with intermediate membership probabilities—especially those with photometric properties consistent with cluster membership—should be considered possible members at least until other evidence, such as radial velocity or chemical abundances, can be included in the analysis.

There is one star with the photometric properties of a giant that lies very near the cluster giant branch. This is Sharov 61 (= Cannon 661 = Sarajedini 594 = Platais 4856 = our 8648), with an average proper-motion membership probability $p = 11\%$. There are also two stars with giant-like colors that lie well to the red of the cluster giant branch; the bluer of the two is Sandage III-94 (= Sharov 78 = Cannon 623 = Upgren 200 = Sarajedini 254 = Platais 5607 = our 10120), with $p = 45\%$, and the other is Sandage C (= Sharov 26 = Cannon 672 = Platais 4460 = Sarajedini 1086 = our 6522), with $p = 25\%$. In the direction of NGC 188, red field stars with giant-like photometric properties are quite rare, as can be seen in Figure 7, where we have produced the identical diagrams for 1971 stars with measured proper-motion membership probabilities $\leq 9\%$. Although this diagram contains 12 times as many stars as Figure 6, there are no field stars redder than $B-I = 2.2$ with the photometric properties of a giant down to at least $V = 20$. Therefore, in adopting a fixed (cluster/field) ratio for their probability calculations, regardless of color, magnitude, or other independent information, the proper-motion studies may well have underestimated the membership probabilities of these two stars. A quick search of the SIMBAD database produces no spectroscopic information for either star, but they probably do deserve spectroscopic study. If they are cluster members, they lie in the general region where carbon stars, barium stars, and related types can be found.

Figures 6 and 7 both show stars in the blue-straggler zone of the color-magnitude diagram in roughly similar numbers, although the latter diagram contains 12 times as many stars overall as the former. Again, this may suggest that the membership probabilities of at least some of these stars have been underestimated, because the number of true field stars in this box of magnitude and color is rather low compared to the rest of the color-magnitude diagram.

Figure 8 shows the same two diagrams for 140 stars with adequate photometric data but whose proper motions have not been measured. Since omission from the astrometric studies implies that a star is likely to be either faint or crowded, the precision of these photometric indices tends to be poor. As a result, the giant/dwarf discriminator is noisy and not very effective. Nevertheless, there is no evidence that any possible

table of Dinescu et al. (1996) also identifies this star as 1282 in their numbering scheme, but no data are provided for the star in their Table 2. This probably means that they, too, considered it to have a membership probability of less than 60%.

![Fig. 7.—Top: Plot of $(V-R) + (V-I)$ against $B-V$ color for stars in the NGC 188 field with proper-motion membership probabilities less than 10%. Open circles represent stars having $(V-R) + (V-I) < 1.70(B-V) - 0.04$, and crosses represent stars lying below this line. For stars redder than $B-V = 0.95$ or so, which corresponds to $B-I \approx 2.0$, open circles are likely to be giants, and crosses are likely to be dwarfs. Bluer than this limit, normal stars are not expected to have $(V-R) + (V-I) < 1.70(B-V) - 0.04$; open circles with $B-V < 0.95$ therefore probably represent peculiar stars or unusually large measuring errors. The solid curve represents our fiducial sequence for NGC 188. Bottom: $V$ vs. $B-I$ color magnitude diagram for the same stars as are shown in the top panel. Symbol types have the same significance, and the solid curve represents our adopted mean cluster locus. While some of the stars with low membership probabilities could belong to the cluster, there is no pronounced concentration of stars toward the fiducial cluster sequence. Rather, the impression is of a uniform sheet of stars spread across the diagram. Note in particular the almost complete absence of stars with the colors of giants (open circles) at any magnitude with colors redder than $B-I \sim 2.0$; in this color range, dwarfs appear to provide almost all of the field-star counts. This emphasizes the abnormality of the two stars Sandage III-94 and Sandage C, seeming giants that lie in an otherwise very sparsely populated region of the color-magnitude diagram.

giant members of the cluster have been missed by the astrometric studies, although there are a few additional faint stars that might belong to the cluster main sequence.

Figure 9 compares our fiducial sequence to Landolt’s photometric standards—which may be taken as least as a representative, if not random, sample of solar neighborhood stars dominated by the local Population I—in the $U-B$, $B-V$, $V-R$, and $V-I$ colors, each plotted against $B-I$. In each of the four panels, stars identified by Smith et al. (2002) as belonging to luminosity class III are shown as large filled circles, stars belonging to class V are indicated by large crosses, and stars of other or undetermined luminosity classes are represented by small crosses. Here we see that giants and dwarfs do indeed tend to
be separated in diagrams involving the $V$ magnitude. We also see that the agreement between the cluster sequence and the field stars is quite good in every panel except the one showing $V-R$, where our cluster-star $V-R$ colors are about 0.015 to 0.025 mag redder than the field-star colors for fixed $B-I$. Given that the differences in the reddening and metallicity between NGC 188 and the average field star are not likely to be substantial, and especially in view of the fact that such an offset appears in only the one panel (of all these colors, $V-R$ is the one least affected by reddening and line blanketing), our adopted $R$ magnitude scale is probably $-0.02$ mag too bright (i.e., the $R$ magnitudes are quantitatively too small, so the $V-R$ colors are too large). As the $R$ magnitude zero point was determined from only two independent studies, each of which is probably uncertain at a level of $\sim 0.03$ mag and differ between themselves by 0.09 mag (Table 3), such a level of systematic error is entirely plausible. Note that if this inference is correct, then Sarajedini et al. (1999) measured their $R$ magnitudes only 0.02 mag too faint, rather than the 0.04 mag given in Table 3; this is similar to their offsets in the $V$ and $I$ filters.

Figure 10 presents a comparison of the fiducial sequences of three of the most famous old open clusters: NGC 188 (crosses; present study), M67 (closed circles), and NGC 6791 (open circles). The latter two sequences were adapted by Sandage et al. (2003) from previous photometric investigations by Montgomery et al. (1993; M67) and Stetson et al. (2003; NGC 6791). Comparing these two clusters to an NGC 188 fiducial derived from unpublished photometry by D. A. VandenBerg & R. D. McClure (a preliminary analysis of the DAO images forming a part of the present study), Sandage et al. (2003) found that the lower main sequence of NGC 188 did not appear to lie parallel to those of the other two clusters. Conventional stellar-structure theory would have a very difficult time explaining this circumstance if the metal abundances and fore-
ground reddening values adopted for these systems were even remotely correct. The mean main sequence obtained in this paper from an appreciably expanded body of observational data does not confirm the disturbing trend found by Sandage et al.

In fact, not only does the NGC 188 sequence now parallel the new fiducial sequence for NGC 188 is not only parallel to that for M67, it also closely overlies it. This is to be expected if the two clusters have the same metal abundance and we have correctly estimated the relative distances and reddenings of the two systems. The unevolved main sequence of NGC 6791 lies appreciably to the red of those of the other two clusters, consistent with the conclusion that this cluster is significantly more metal rich than they are (see, e.g., Sandage et al. 2003).

Finally, Figure 11 shows a comparison between our fiducial main sequences in NGC 188 and those of the local field population as defined by the stars in the Gliese (1969) Catalogue of Nearby Stars having photometry by Bessell (1990) and Hipparcos parallaxes (Perryman et al. 1998) that are at least 10 times their standard errors. In the $(B-V)_0-M_V$ (top panel) and $(V-I)_{0.0}-M_V$ (bottom panel) color-magnitude diagrams, the agreement is excellent, as would be expected if (1) the local field population and NGC 188 have similar chemical abundances (both are estimated to have close to solar abundance patterns), (2) we have correctly judged the reddening and apparent distance modulus of the cluster, and (3) the systematic

As discussed by Sandage et al. (2003), there is considerable evidence that the reddening of NGC 6791 may be closer to $E(B-V) = 0.15$ mag than to

Finally, Figure 11 shows a comparison between our fiducial main sequences in NGC 188 and those of the local field population as defined by the stars in the Gliese (1969) Catalogue of Nearby Stars having photometry by Bessell (1990) and Hipparcos parallaxes (Perryman et al. 1998) that are at least 10 times their standard errors. In the $(B-V)_0-M_V$ (top panel) and $(V-I)_{0.0}-M_V$ (bottom panel) color-magnitude diagrams, the agreement is excellent, as would be expected if (1) the local field population and NGC 188 have similar chemical abundances (both are estimated to have close to solar abundance patterns), (2) we have correctly judged the reddening and apparent distance modulus of the cluster, and (3) the systematic

the value $E(B-V) = 0.10$ mag found by Stetson et al. (2003). If the lower reddening were adopted, it would be necessary to make a corresponding adjustment to the apparent distance modulus of the cluster—to something like 13.25—in order to bring its lower main sequence into coincidence with the red edge of the Hipparcos color-magnitude diagram for nearby stars. The resulting comparison with M67 and NGC 188 would still be very similar to that shown in Fig. 10.
errors in our photometry are small. Of course, as before, a conspiracy of errors in two or more of these assertions could produce spurious agreement. It is evident that the agreement in the \((V-R)_{\text{c}}-M_r\) diagram (middle panel) is perceptibly worse. Since, as we have stated before, \(V-R\) is the least sensitive to both metallicity and reddening effects, it would be hard to remove this discrepancy by altering one or both of these quantities, especially given the good agreement in \((B-V)_0\) and \((V-I)_0\). We believe that this diagram is additional evidence for a systematic error in the zero point of our adopted \(R\) magnitude scale, in the sense that we have measured NGC 188 stars too bright in \(R\), and therefore too red in \(V-R\), by about 0.02 mag. We have not removed this offset from the cluster data that we have posted on the Internet; users of these data for future research should be aware of this fact.

7. SUMMARY

We have obtained new CCD photometry for the old open cluster NGC 188 with the Dominion Astrophysical Observatory 1.8 m telescope. Because these data are difficult to calibrate, we have found it useful to consider additional data donated by Howard Bond, and data obtained from the Isaac Newton Group archive, as well as previous cluster photometry that we were able to locate in the literature. Direct star-by-star comparisons have been undertaken to determine and remove the systematic differences in photometric zero point that are found among the various studies. At the same time, we have merged the independent membership indices that have been produced by four different astrometric studies of the cluster field and matched those membership probabilities with the photometry for the same stars.

It has been our aim to combine all the available data sets for NGC 188, not to criticize them. It must be remembered that we have removed only differences of photometric zero point among the various published studies of the cluster. In actuality, systematic calibration errors can be more complicated than this: magnitude scales may vary with the color of the star if bandpass mismatch is not adequately modeled, or with the brightness of the star if the detector is not accurately linear, or with the position of the star on the sky when imaging detectors have significant distortions, aberrations, or scattered-light problems. The systematic errors between one data set and another can, in principle, be modeled as a Taylor expansion in these independent variables. We have contended ourselves with estimating and removing only the zeroth-order terms in these Taylor expansions. An attempt at more than this would have required appreciably more work, and furthermore, it likely would have involved choosing one of the data sets to be the “correct” one and adjusting the others to match it. By considering only mean values, it has been straightforward to define an “average” photometric system, without having to choose any one study as being more authoritative than the others.

As a consequence, any given study has been accurately referenced to the average of all studies only for stars near the average color, magnitude, and position; stars at extreme values of these variables may retain systematic differences from one study to another. We contend that these introduce mostly noise and not systematic error into the final data products, because—once the zero-point offsets have been removed—any study that has positive systematic errors in some regions of color-magnitude-position space will have comparable negative systematic errors in other parts of that space. Furthermore, there is little reason to expect that such systematic errors will be identical in the various studies (with the exception of the photographic studies that were calibrated on the basis of the photometric studies; in this situation, any color- or magnitude-dependent errors in the photometric work may well have been mapped into the photometric results). Average photometric indices determined from multiple investigations should therefore be more reliable than results for a star studied only once.

By adopting a single value for the photometric uncertainty inherent to each study, regardless of the brightness of the star or the filter used, we have again accounted for the different precisions of the various data sets only to zeroth order. Once again, we think this is a reasonable compromise and that a more complex approach to the weighting of the data would add a disproportionate amount of work for the improvement achieved. We believe that we have “done no harm” to the data, in the Hippocratic sense of the phrase; our homogenized results for any given star are probably no worse than the results from the best of the studies in which that star was included. Nevertheless, the reader is encouraged to remember the compromises that we have made, if using our results for future research. It would be unwise to base critical scientific conclusions on the photometric indices or membership status of any given star, especially if that star was observed only once or a few times. Conclusions based on the bulk properties of the stars in NGC 188 as they have been presented here are probably somewhat safer.

On our Web site\(^8\) we have posted ASCII data files containing (1) our final merged photometry, membership information, and J2000.0 equatorial coordinates for 9228 stars in the field of NGC 188, based on all available studies; (2) our derived photometry for 4863 stars, based on our own analysis of 299 CCD images; (3) a transit table relating our sequential identification numbers to the star identifications employed in all the previous studies that we have considered; and (4) data tables from previous published studies, which we have entered into the computer by hand, because we were unable to locate electronic copies. These files should make it easy for interested readers to reanalyze these data if our approach seems inadequate for their purposes.

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\(^8\) See http://cadcwww.hia.nrc.ca/stetson.
Canadian Astronomy Data Centre, and the ING archive for providing data for this and other ongoing studies. This work was supported in part by a Discovery Grant to D. A. V. from the Natural Sciences and Engineering Research Council of Canada.

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