CCD UBVRI PHOTOMETRY OF THE GALACTIC OPEN CLUSTERS\textsuperscript{1}: BE 89, RU 135, AND BE 10

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RESUMEN
Presentamos los parámetros fundamentales de enrojecimiento, metalicidad, edad y distancia de los cúmulos abiertos poco estudiados Be 89, Ru 135 y Be 10, derivados de la fotometría CCD UBVRI de los mismos. Las distancias y edades de los cúmulos se obtuvieron ajustando las isocronas apropiadas a las secuencias observadas de los cúmulos para cinco diferentes diagramas color–magnitud. Los promedios pesados de módulos de distancia y de distancias heliocéntricas, \((V_0–M_V), d(\text{kpc})\) encontrados son los siguientes: \(11^\text{m}90\pm0^\text{m}06, 2.4\pm0.06\) para Be 89, \(9^\text{m}58\pm0^\text{m}07, 0.81\pm0.03\) para Ru 135 y \(11^\text{m}16\pm0^\text{m}06, 1.7\pm0.05\) para Be 10, mientras que los promedios pesados para las edades \((\log(A), A(\text{Gyr}))\) son \(9.58\pm0.06, 3.8\pm0.6\) para Be 89, \(9.58\pm0.06, 3.8\pm0.7\) para Ru 135 y \(9.06\pm0.05, 1.08\pm0.08\) para Be 10.

ABSTRACT
The fundamental parameters of reddening, metallicity, age, and distance are presented for the poorly studied open clusters Be 89, Ru 135, and Be 10, derived from their CCD UBVRI photometry. By fitting the appropriate isochrones to the observed sequences of the clusters in five different color–magnitude diagrams, the weighted averages of distance moduli and heliocentric distances \((V_0–M_V), d(\text{kpc})\) are \(11^\text{m}90\pm0^\text{m}06, 2.4\pm0.06\) for Be 89, \(9^\text{m}58\pm0^\text{m}07, 0.81\pm0.03\) for Ru 135, and \(11^\text{m}16\pm0^\text{m}06, 1.7\pm0.05\) for Be 10, and the weighted averages of the ages \((\log(A), A(\text{Gyr}))\) are \(9.58\pm0.06, 3.8\pm0.6\) for Be 89, \(9.58\pm0.06, 3.8\pm0.7\) for Ru 135, and \(9.06\pm0.05, 1.08\pm0.08\) for Be 10.

1. INTRODUCTION
Galactic open clusters, which contain a few tens to a few tens of thousands of stars and are a few parsecs across, are sparsely populated, loosely concentrated, and gravitationally bound systems. With systematic image searches and follow-up photometric surveys, new open clusters are currently being discovered. By fitting the photometric observations of open clusters to synthetic photometry resulting from stellar models (i.e. theoretical isochrones), which include the newest input physics, stellar structure, and differing heavy-element abundances, fundamental parameters such as interstellar reddening, metallicity, distance modulus, and age can be precisely and accurately determined. These parameters have great importance concerning the age–metallicity relation and the metal-abundance gradient in the Galactic disk (e.g. Camer\textsuperscript{on} \textsuperscript{1983}, Carraro & Chiosi \textsuperscript{1994}, Friel \textsuperscript{1995}), as well as the luminosity and mass functions of the open clusters (Piskunov \textsuperscript{et al.} \textsuperscript{2008}). Open clusters are also very useful for testing the stellar evolutionary models, given that their stars were formed at the same time, out of the same cloud, and under similar environmental conditions. Thus, open clusters are ideal entities for the study of stellar evolution since physical properties are tightly constrained, being mainly distinguished by the stellar mass, so that theoretical models of stellar formation and evolution can be compared with real clusters without excessive complications. For these analyses, the fundamental parameters such as interstellar reddening, metallicity, distance modulus, and age should be determined as precisely and accurately as possible.

In Galactic studies, one of the more severe observational limitations is due to the absence of photometric data for nearly half of the approximately 1500...
open clusters known. Furthermore, there is a lack of homogeneity in the observations and analyses of the clusters studied. The catalogue of Lyngå (1987), that resulted from a collection of data from many different sources and which includes 422 open clusters, constituted the observational basis for a large number of astronomical studies, led to important conclusions about the Galactic disk, and has been very useful for planning subsequent observations by other astronomers. However, this catalogue has been built from parameters obtained by various authors, with diverse observing techniques, distinct calibrations, and different criteria for determining the stellar ages, rendering it very inhomogeneous and limited for studies requiring precision in the measurement of these fundamental parameters. As an example of the precision and accuracy that one can expect due to the effects of these inhomogeneities, we refer to Janes & Adler (1982), who found that distance moduli of a given cluster obtained by two or more authors have a mean difference of 0.55.

Within the Sierra San Pedro Mártir, National Astronomical Observatory (hereafter SPM) open cluster project (cf. Schuster et al. 2007; Michel et al. 2010), the aims are the following:

1. A common UBVRI photometric scale for open clusters,
2. An atlas of color–color and color–magnitude diagrams for these clusters,
3. A homogeneous set of cluster reddenings, distances, ages, and, if possible, metallicities,
4. An increased number of old, significantly reddened, or distant, open clusters, and
5. A selection of interesting clusters for further study.

The open clusters for the present study were selected from the large (and most complete) catalogue “Optically visible open Clusters and Candidates” (Dias et al. 2002), which is now also available at the CDS (Centre de Données Astronomiques de Strasbourg). This work aims to provide the fundamental parameters of reddening, metallicity, distance modulus and age for the open clusters Be 89, Ru 135, and Be 10. Our final intention is to publish a set of homogeneous photometric UBVRI data for over 300 Galactic clusters (Schuster et al. 2007; Tapia et al. 2010).

This paper is organized as follows: §2 describes the observations and reduction techniques. §3 contains the derivation from the UBVRI photometry of reddening and metallicity of the clusters from two–color diagrams, and the inference of distance moduli and ages from color–magnitude diagrams. Their uncertainties are also discussed. Comparisons of these parameters with previous results from the literature are made in §4, and the conclusions are given in §5.

2. OBSERVATION AND REDUCTION TECHNIQUES
2.1. The observations

This CCD UBVRI project of northern open clusters has been undertaken at SPM using always the same instrumental setup (telescope, CCD-detector, and filters), observing procedures, reduction methods, and system of standard stars (Landolt 1983, 1992). A par focal set of UBVRI Johnson-Cousins filters was used for our observations. The 0.84-m f/13 Cassegrain telescope hosted the filter-wheel “Mexman” provided with the SITE#1 (S1003) CCD camera, which has a 1024×1024 square pixel array and a 24µm×24µm pixel size; this CCD has nonlinearities less than 0.45% over a wide dynamical range, no evidence for fringing even in the I band, and Metachrome II and VISAR coverings to increase sensitivity in the blue and near ultraviolet. The sky-projected pixel size was 0.5393, and the field of view of the detector was 6.73×6.73 arcmin². Here the results of UBVRI images for the open clusters Be 89, Ru 135, and Be 10 are presented, which were acquired in July 2001 (Be 89 and Ru 135) and February 2002 (Be 10). The exposure times were typically 3×240 seconds for the U filter, 3×180 for B, 3×100 for V, 3×100 for R, and 3×120 for I. Several standard-star fields from Landolt (1992) were observed nightly to permit the derivation of the photometric transformations to the Johnson-Cousins’ system and the atmospheric extinction coefficients. For the July 2001 observing run, seven Landolt groups were used, containing 26 different standard stars with color ranges, −0.25 ≤ (B−V) ≤ +1.14, −1.09 ≤ (U−B) ≤ +1.14, and −0.30 ≤ (V−I) ≤ +1.14. Sixteen to twenty-five observations of these Landolt standards were made per night. For the February 2002 run, eight Landolt groups were employed, containing 35 different standard stars with color ranges, −0.30 ≤ (B−V) ≤ +1.42, −1.18 ≤ (U−B) ≤ +1.27, and −0.28 ≤ (V−I) ≤ +1.77. Fifty-two to seventy-two observations of these Landolt standards were made per night, except one night cut short by clouds, when
only 15 observations were managed. The standard-
star fields have been observed with exposures of
$1 \times 240$ seconds for the $U$ filter, $1 \times 120$ for $B$, $1 \times 60$
for $V$, $1 \times 60$ for $R$, and $1 \times 60$ for $I$. The observed
Landolt fields and the number of associated stars in
each one are summarized in Table 1.

### TABLE 1

| Landolt’s fields of standard stars | July 2001 | February 2002 |
|-----------------------------------|----------|---------------|
| region                           | $N_{stds}$ | region        | $N_{stds}$ |
| PG1528+062                       | 3         | PG0918+029    | 5          |
| PG1530+057                       | 3         | PG0942-029    | 5          |
| PG1633+099                       | 5         | PG1047+003    | 4          |
| PG1657+078                       | 4         | PG1323-086    | 5          |
| PG2213-006                       | 4         | PG1528+062    | 3          |
| PG2331+055                       | 3         | SA 95         | 5          |
| MARK A                           | 4         | SA104         | 4          |
|                                  |           | SA107         | 4          |
| TOTAL                            | 26        | TOTAL         | 35         |

Usually one or more Landolt fields were re-
observed nightly with an air-mass range of at least
0.70 in order to measure the coefficients of the atmo-
spheric extinction of the SPM site, which has excel-
lient sky conditions. To improve the accuracy, preci-
sion, and efficiency of the photometric observations
when required, the filters were observed in forward
and backward sequences (i.e. $UBVRI-IRVBU$), espe-
cially for the large air-mass observations.

#### 2.2. Data reduction

The usual (night and run) calibrations for
CCD photometry were done during each of our
observing periods (i.e. bias, twilight-sky flat fields,
and dark-current determinations) to determine the
(night and run) mean correcting frames. Standard
data reduction procedures have been used within
**IRAF**\(^5\)** the CCDRED and DAOPHOT tasks (ap-
erture and PSF photometry, see **Howell** 1989, 1990;
**Stetson** 1987, 1990). More details concerning the
instrumentation and the observing and reduction
procedures of this project will be given in the
near future in the succeeding paper of this project
(Michel et al. 2010, and references therein). To
obtain the magnitudes and colors on the standard
system for the stars associated with these clusters,
we followed Jordi et al. (1995), and Rosselló et
al. (1998, and references therein). We proceeded
twofold:

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\(^5\)IRAF is distributed by NOAO (operated by the Associ-
ation of Universities for Research in Astronomy, Inc.) under
cooperative agreement with NSF

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Fig. 1. DSS red-filter images of the Galactic open clus-
ters Be 89 (panel a), Ru 135 (b), and Be 10 (c). The
regions analyzed with the ELIPSE inspection tool, to
derive first estimates for the fundamental parameters, are
enclosed by ellipses. Orientation as usual: north is up,
and east to the left.
i) The natural magnitude of the filter N is defined as:

$$\lambda_{Nn} = -2.5 \cdot \log (ADU's)_N,$$

where $$\lambda_N$$ stands for the corresponding filters U, B, V, R, and I, ADU's for the analog-to-digital counts, and the subscript n for the corresponding quantity in the natural photometric system. The atmospheric extinction coefficients for a given filter have been estimated by transforming the nightly $$\lambda_{Nn}$$'s to the corresponding magnitudes in the standard system, $$\lambda_N$$'s, with the following equation:

$$\lambda_{Nn} - \lambda_{N} = (\text{zero point})_N - \kappa'_N \cdot X_{Nn} - \kappa''_{N,12} \cdot X_{Nn} \cdot (\lambda_1 - \lambda_2)_s \cdot (1)$$

where $$X_{Nn}$$ is the air-mass when measuring $$\lambda_{Nn}$$. The subscript N, 12 indicates that the color $$(\lambda_1 - \lambda_2)_s$$ was used to determine the second-order extinction coefficient of filter N. Here we follow the convention that the effective wavelength $$\lambda_{1eff} < \lambda_{2eff}$$ to construct the color $$(\lambda_1 - \lambda_2)_s$$. Finally, for a proper determination of $$\kappa_N$$ and $$\kappa''_{N,12}$$ by a least square solution, sufficiently large ranges in the airmasses and colors of the standard stars ($$\Delta X_N \geq 0.7$$ and $$\Delta(\lambda_1 - \lambda_2)_n \geq 0.8$$ for SPM) must be obtained. Note that the standard magnitudes and colors are known to an accuracy of about two percent, reflected in the errors of the final transformations of the (bright) standard stars, and that the observed magnitudes and airmasses are measured quantities that can have an even better precision. To further simplify the equations, the extra-atmospheric instrumental magnitudes were then introduced using the extinction coefficients of the night:

$$\lambda_{N_i} = \lambda_{Nn} - \kappa'_N \cdot X_{Nn} - \kappa''_{N,12} \cdot X_{Nn} \cdot (\lambda_1 - \lambda_2)_s \cdot (2)$$

An instrumental color is the subtraction of two instrumental magnitudes with different passbands, $$(\lambda_1 - \lambda_2)_i = \lambda_{i1} - \lambda_{i2}$$.

ii) Once the atmospheric extinction coefficients $$\kappa'_N$$ and $$\kappa''_{N,12}$$ have been determined and applied, the nightly transformation coefficients are calculated (i.e. $$\beta_{12}$$ and $$\gamma_{12}$$) with the following relations for the colors:

$$(\lambda_1 - \lambda_2)_i = \kappa_{0,12} + \beta_{12} \cdot (\lambda_1 - \lambda_2)_s + \gamma_{12} \cdot (\lambda_2 - \lambda_3)_s \cdot (3)$$

Due to the Balmer discontinuity that lies in both the U and B passbands, a better transformation for the U–B color has been achieved by substituting the quadratic term on the right side of the above equation with a linear term in the color B–V, obtaining the following expression:

$$(\lambda_1 - \lambda_2)_i = \kappa_{0,12} + \beta_{12} \cdot (\lambda_1 - \lambda_2)_s + \gamma_{12} \cdot (\lambda_2 - \lambda_3)_s, (4)$$

where $$\lambda_{1eff} < \lambda_{2eff} < \lambda_{3eff}$$. For the case of the magnitude V, Equation (3) has been used as follows:

$$V_i - V_s = \kappa_{01} + \beta_{12} \cdot (\lambda_1 - \lambda_2)_s + \gamma_{12} \cdot (\lambda_1 - \lambda_2)_s^2. (5)$$

For Equations (3)–(5), $$\kappa_{0,12}$$ and $$\kappa_{01}$$ are the zero-points of the transformations of the colors $$(\lambda_1 - \lambda_2)_s$$, i.e. U–B, B–V, V–R, V–I, ..., and of the V magnitude, respectively. The coefficients $$\beta_{12}$$ and $$\gamma_{12}$$ are the respective first- and second-order transformation coefficients.

In general, the second-order atmospheric extinction coefficient $$\kappa''_{V,R}$$ is expected to be close to zero due to the nearly constant level (ozone-band contribution) of the atmospheric extinction curve at SPM near 5500Å (Schuster & Parrao 2001). The second-order extinction and linear-transformation coefficients for correcting to extra-atmospheric standard magnitudes and colors are very similar from night to night, and also from run to run, because, i) the SPM has excellent sky conditions, and ii) the same instrumental setup, observing techniques, and data reduction procedures were used for all nights during both observing runs. In Table 2 the mean zero-point corrections, atmospheric extinction, and transformation coefficients are given.

In Tables 3, 4, and 5 are given the final transformed CCD UBVRi photometric values for the open clusters, Be 89, Ru 135, and Be 10, respectively. In the text only the first three lines of each table are shown as examples. The full versions will be available online at the CDS and WEBDA. In these tables the columns 1 and 2 give the following: X and Y (pixels), the position of a star in the CCD field; columns 3, 5, 7, 9, and 11: the magnitude and color indices, $$V_i$$, (B–V), (U–B), (V–R), and (V–I), respectively (in magnitudes); and columns 4, 6, 8, 10, and 12: the respective photometric errors, $$\sigma_V$$, $$\sigma_{B-V}$$, $$\sigma_{U-B}$$, $$\sigma_{V-R}$$, and $$\sigma_{V-I}$$ (in magnitudes), as provided by IRAF.

2.3. The data inspection tools ELIPSE and SAFE

Since the stellar density of a cluster increases towards its center with respect to the field stars, an AWK macro (ELIPSE, Moitinho 2003) was used to extract the data of the central region of a given cluster, as defined by visual inspection in a visual (V) or red (R) image, thus increasing the contrast of the cluster with respect to the surrounding field stars. An ellipse was fitted visually to the image in order to extract the photometric data of the central region of the cluster. To further support the analyses of the clusters, a java-based computer program (SAFE,
TABLE 2
ATMOSPHERIC EXTINCTION AND TRANSFORMATION COEFFICIENTS

| color  | \( \lambda_1 \) | \( \lambda_2 \) | \( \lambda_3 \) | \( \kappa'_1 \) | \( \kappa'_1_{12} \) | \( \kappa_{0,12} \) | \( \beta_{12} \) | \( \gamma_{12} \) | rms    |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------|
| \((U-B)\) | \( U \) | \( B \) | \( V \) | \( V \) | \( R \) | \( V \) | \( I \) | \( V \) | \( I \) | \( V \) | \( I \) |
| July 2001 | 0.472 | -0.056 | 1.625 | 0.711 | +0.263 | 0.028 |
| \((B-V)\) | \((B-V)\) | \( V \) | \( R \) | \( V \) | \( R \) | \( V \) | \( I \) | \( V \) | \( I \) | \( V \) | \( I \) |
| | 0.243 | -0.050 | +0.409 | 1.016 | -0.050 | 0.010 |
| | 0.106 | +0.079 | +2.375 | 0.033 | -0.008 | 0.016 |
| \((V-R)\) | \((V-R)\) | \( V \) | \( R \) | \( V \) | \( R \) | \( V \) | \( I \) | \( V \) | \( I \) | \( V \) | \( I \) |
| | 0.104* | +0.030* | +0.027 | 0.973 | +0.011 | 0.012 |
| | 0.087* | -0.035* | -0.151 | 0.923 | +0.070 | 0.010 |

\* indicates that extinction coefficients refer to \( \lambda_2 \), otherwise to \( \lambda_1 \)

TABLE 3
CCD UBVRI photometry of Be 89

| X     | Y     | V     | \( \sigma_V \) | \( \sigma_{B-V} \) | \( \sigma_{U-B} \) | \( \sigma_{V-R} \) | \( \sigma_{V-I} \) | \( \sigma_{V-J} \) |
|-------|-------|-------|--------------|----------------|-----------------|----------------|----------------|----------------|
| 767.7 | 538.3 | 11.261 | 0.006 | 0.441 | 0.009 | 0.002 | 0.315 | 0.009 | 9.999 | 9.999 |
| 466.5 | 496.2 | 12.118 | 0.011 | 1.362 | 0.018 | 1.091 | 0.011 | 0.271 | 0.013 | 1.399 | 0.013 |
| 511.7 | 742.6 | 12.172 | 0.008 | 0.443 | 0.011 | 0.268 | 0.005 | 0.296 | 0.011 | 0.569 | 0.017 |
| 294.0 | 387.3 | 11.871 | 0.008 | 0.742 | 0.013 | 0.405 | 0.038 | 0.450 | 0.038 | 0.895 | 0.014 |

Note to table: The full version of this table is available online at the CDS and WEBDA.

TABLE 4
CCD UBVRI photometry of Ru 135.

| X     | Y     | V     | \( \sigma_V \) | \( \sigma_{B-V} \) | \( \sigma_{U-B} \) | \( \sigma_{V-R} \) | \( \sigma_{V-I} \) | \( \sigma_{V-J} \) |
|-------|-------|-------|--------------|----------------|----------------|----------------|----------------|----------------|
| 862.7 | 231.5 | 11.132 | 0.003 | 0.597 | 0.004 | 0.212 | 0.002 | 0.360 | 0.010 | 9.999 | 9.999 |
| 237.1 | 325.4 | 11.689 | 0.003 | 0.710 | 0.003 | 0.364 | 0.003 | 0.387 | 0.014 | 0.860 | 0.011 |
| 294.0 | 387.3 | 11.871 | 0.008 | 0.742 | 0.013 | 0.405 | 0.004 | 0.450 | 0.038 | 0.895 | 0.014 |
| ...   | ...   | ...   | ...          | ...             | ...             | ...             | ...             | ...             |

Note to table: The full version of this table is available online at the CDS and WEBDA.

TABLE 5
CCD UBVRI photometry of Be 10.

| X     | Y     | V     | \( \sigma_V \) | \( \sigma_{B-V} \) | \( \sigma_{U-B} \) | \( \sigma_{V-R} \) | \( \sigma_{V-I} \) | \( \sigma_{V-J} \) |
|-------|-------|-------|--------------|----------------|----------------|----------------|----------------|----------------|
| 374.5 | 153.4 | 11.244 | 0.004 | 0.433 | 0.004 | 0.246 | 0.002 | 0.220 | 0.005 | 0.500 | 0.004 |
| 528.6 | 217.9 | 12.352 | 0.002 | 1.483 | 0.004 | 1.346 | 0.009 | 0.851 | 0.003 | 1.631 | 0.003 |
| 804.6 | 881.2 | 12.746 | 0.003 | 0.738 | 0.014 | 0.231 | 0.004 | 0.440 | 0.014 | 0.873 | 0.005 |
| ...   | ...   | ...   | ...          | ...             | ...             | ...             | ...             | ...             |

Note to table: The full version of this table is available online at the CDS and WEBDA.

McFarland (2010) was developed and used to help us in the visualization and analysis of the photometric data (e.g. Schuster et al. 2007). These programs facilitate the elimination of field and apparent non-member stars of a given cluster from the diagnostic diagrams used to enhance the apperception of cluster features. Once a satisfactory first estimate of the parameters was obtained, a full-frame solution was
also consulted and refined.

SAFE is capable of displaying simultaneously in different color-color (CC) and color-magnitude (CM) diagrams the cluster’s data and has an interactive way to identify a (group of) star(s) in one particular diagram and to see where it falls in the other diagrams. This program is capable of displaying up to 16 different diagrams for a given cluster and is very useful for the determination of a cluster’s physical parameters. Figure 1(a–c) presents the DSS red-filter images of Be 89 (panel a), Ru 135 (b) and Be 10 (c), with the regions analyzed in this work enclosed by ellipses. The central (X, Y) pixel coordinates of the nearly circular regions in Figure 1(a–c), which are considered for the photometric analyses are the following: (584, 488) pixels for Be 89, (542, 504) for Ru 135, and (517, 493) for Be 10. The diameters in arcminutes (ΔX, ΔY) of nearly circular regions in Figure 1(a–c) are the following: (2.27, 2.65) for Be 89, (2.62, 2.67) for Ru 135, and (3.12, 2.34) for Be 10.

3. ANALYSES OF THE OPEN CLUSTERS
BE 89, RU 135, AND BE 10

The (U–B, B–V), two-color or CC, diagram, and five CM diagrams have been used together with the zero-age-main-sequence (ZAMS) intrinsic-color calibrations of Schmidt-Kaler (1982, hereafter SK82) and with the Padova isochrones (Girardi et al. 2000, hereafter GBBC; Bertelli et al. 2008; Marigo et al. 2008, MGBG) to obtain reddenings, metallicities, distance moduli, and ages for these clusters.

Our analysis technique for our program clusters places particular emphasis upon the fit of the ZAMS intrinsic colors and Padova isochrones to the observational data of the clusters, and this depends in turn upon important characteristics of the CM and CC diagrams for open clusters (e.g. Paunzen & Netopil 2006, their §3), which are summarized as follows:

1. A procedure for eliminating non-members,
2. A determination of the interstellar reddening as accurately as possible,
3. Visibility of the turn-off,
4. Compensation for binary stars which tend to widen the main-sequence distribution,
5. Consideration of the red-clump stars (if present) to improve the isochrone fit, and
6. An appropriate choice of the isochrone which corresponds to the correct heavy-element abundance (Z).

Regarding the locus of the main sequence in a CM diagram, and independent of any cosmic dispersion, the main-sequence strips or bands in the CM diagrams are affected by the contamination of binary and multiple stars; particularly, the mid-points are shifted to brighter magnitudes and the colors to redder values due to this contamination, and also sometimes due to variable intercluster extinction. For this reason, the SK82 ZAMS and the MGBG isochrones have been fitted to the blue- and faint-most concentrations within the observed broad main-sequence bands whenever possible, assuming that these concentrations reflect the single-star distribution (e.g. Carney 2001), and that most stars observed red- and bright-ward of these are in fact binary, or multiple, systems.

In the absence of proper-motion/radial-velocity measurements to insure cluster membership, and to minimize the effects of field-star contamination, we have concentrated more on the central regions of the clusters rather than using the full-frame CCD images; this has been accomplished by using the ELIPSE or SAFE programs, described above. These have been used to select an elliptical, or polygonal area (with as many as 10 sides), centered on the open cluster as seen in a V or R image, excluding stars outside this area from further analyses. (See Figure 1). These interactive analyses increase greatly the contrast of cluster members with respect to the field stars, and thus the scatter in the CM and CC diagrams is significantly reduced.

Also, the observational errors, e.g. σ(U–B), of these three clusters have been considered as a criterion in selecting the more reliable data for further analyses. The values of σ(U–B) are almost always larger than the ones of σ(B–V) due to the smaller sensitivity of the CCD in the ultraviolet, and the errors σ(R–I), σ(V–I), and σ(V–R) are among the smallest. The observational errors, such as σ(U–B), σ(B–V), and σ(B–R), have been selected to be less than ≈ 0.05 (and sometimes < 0.05) in some of the diagnostic diagrams presented in the analyses to follow, such as the (U–B, B–V), (V, B–V), and (V, B–R) diagrams.

Interstellar reddenings of the program clusters have been estimated from shifts of the intrinsic-color sequences of SK82 in the (U–B, B–V) diagram, until the best fit to the data of the clusters: along the U–B axis by 0.72E(B–V)+0.05E(B–V)² and along the B–V axis by E(B–V). For this, F-type stars have been fitted above the main sequence of SK82 (i.e. blue-ward in (U–B)), and simultaneously the red-clump stars above the red-giant colors of SK82 with consis-
tent ultraviolet excesses according to the normalizations of Sandage (1969). The two-color sequence of SK82 has been constructed from the intrinsic colors of SK82 for zero-age dwarfs \((B-V)_0 \lesssim 0.075\) and for giants \((B-V)_0 \gtrsim 0.75\).

Once the two-color sequence of SK82 has been fixed as indicated above, to determine the photometric metal abundance, \([\text{Fe}/\text{H}]\), one first locates the F-type stars in the \((U-B, B-V)\) diagram and compares their location with that of their counterparts of known metallicity (e.g. the SK82’s ZAMS calibration). Deviations between the two are due mainly to their differences in metal content, an ultraviolet excess, \(\delta(U-B)\), being caused by differences in line blanketing. The metal-deficient F-type cluster stars, if present, lie blue-ward of the “hump region” of the ZAMS sequence, where an eyeball-fitted osculating curve similar to “the hump” has been fitted to the data points of the F-stars (i.e. the thick line above the hump of the F-star region in Figures 2, 5, and 8) and, simultaneously, to the red-clump stars (if present), since they also will lie blue-ward of the red-giant colors of SK82 with a corresponding ultraviolet excess. This ultraviolet excess is correlated with the photometric metallicity of the cluster. Then, a metallicity value, \([\text{Fe}/\text{H}]\), for a cluster can be derived from the empirical calibration, \([\text{Fe}/\text{H}] - \delta(U-B)_{0.6}\), of Karataş & Schuster (2006), allowing the determination of \([\text{Fe}/\text{H}]\) independently of the isochrones to be fitted to the data, thus reducing from three to two the free parameters to be derived from the CM diagrams. Heavy-element abundances \((Z)\) of the three clusters have been obtained from the photometric metal abundances \([\text{Fe}/\text{H}]\) with the expression

\[ Z = Z_\odot \cdot 10^{[\text{Fe}/\text{H}]/12}, \quad Z_\odot = +0.019. \]  

Finally, the appropriate isochrones of MGBG were computed online in terms of the resulting heavy-element abundance for further analyses of the clusters (distances and ages).

To estimate the age of a cluster \((A)\) and the true distance modulus \((DM= V_0-M_V)\) in a CM diagram, for example the \((V, B-V)\) diagram, the absolute magnitudes, \(M_V\), of the MGBG isochrones have been shifted by \(DM + 3.1E(B-V)\) along the magnitude axis and their corresponding colors, \((B-V)_0\), reddened by adding the color excess \(E(B-V)\) until some DM value provides a good fit of the appropriate isochrone to the faint/blue concentration of the observed lower main sequence of the cluster and, if present, of the red-clump stars. One has to take into account when determining the DM that metal-poor stars are sub-luminous as compared with their solar-like counterparts by determining a reliable value for \(Z\) from the CC diagram. To infer the age of the cluster, the (logarithm of the) age of the isochrones, \(log A\), has been varied until a good match with the observed sequences, i.e. the upper main-sequence (MS), the turn-off (TO) stars, and, if present, the red-clump (RC) stars, has been achieved. A fine tuning of the DM has been made if necessary. The uncertainties of \(E(B-V), Z, DM,\) and \(log A\) are discussed in Section 4.

Following a similar procedure to that outlined above, the distance moduli and cluster ages have also been derived from analyses of four other CM diagrams for each of the clusters. The corresponding color excesses applied in the diagrams were iterated starting with the previously derived color excess estimates, \(E(B-V)\), and the results were inter-compared by means of the standard interstellar extinction law adopted (see Table 6 below; also cf. Dean et al. 1978, Mathis 1990, Straizys 1995) until satisfactory solutions were obtained for all the CM diagrams. The derived extinction laws do not differ significantly from that of Table 6.

**TABLE 6**

| \(E(V-I)/E(B-V)\) | \(E(R-I)/E(B-V)\) | \(E(V-R)/E(B-V)\) | \(E(B-R)/E(B-V)\) |
|---------------------|-------------------|-------------------|-------------------|
| 1.25                | 0.69              | 0.56              | 1.56              |

3.1. Be 89

The \((U-B, B-V)\) diagram of Be 89 is shown in Figure 2. An interstellar reddening of \((B-V) = 0.0^{m}60 \pm 0.0^{m}09\) has been derived by shifting the intrinsic two-color stellar sequence of SK82 along the reddening vector as described in the previous section. (Another possibility, to fit the stars by \(E(B-V) \approx 0.073\) to the blue (B-star) branch of the ZAMS curve, would leave many stars far from a good fit). Six stars apparently in the cluster are noticed with \((B-V) \approx 1^{m}6\) and \((U-B) \approx 1^{m}4\) (big open circles in Figure 2) lying near, but above (i.e. blue-ward of) the giant sequence of SK82, the expected location of the RC stars; their subsequent locations in the CM diagrams confirm this classification (see Figures 3 and 4). A seventh candidate falls further from the expected RC locus in four of the five CM diagrams.

The F-type and RC stars of Be 89 (cf. Figure 2, \((B-V) \approx 1^{m}0\) and \(\approx 1^{m}6\), respectively) lie above the
Fig. 2. The \((U−B, B−V)\) diagram of Be 89. The “S” curves (upper parts, ZAMS, and lower parts, red giants) have been taken from the two–color relations of SK82 and are displayed for the interstellar reddening values \(E(B−V) = 0\,^{\prime\prime}00\) and \(0\,^{\prime\prime}60\) (the bluer and redder versions, respectively). A reddening vector is also shown as an arrow, and big open circles mark the six RC candidates. and open squares, the blue-straggler ones. A heavy solid curve represents our best fit to the data which has been adjusted to the main-sequence F-type stars above (i.e. blue-ward of) the ZAMS colors of SK82 and, simultaneously, to the RC stars above the red-giant colors of SK82. This fit has been used to estimate the heavy-element abundance of the cluster, which is shown in Table 7.

(reddened) ZAMS two-color calibration of SK82 by \(\delta(U−B) ≃ 0\,^{\prime\prime}1\). Our best eyeball fit to the data is shown as the heavy solid curve in Figure 2. In the dereddened two-color diagram, the heavy line gives a value of \((U−B)_0 = −0\,^{\prime\prime}10 ± 0\,^{\prime\prime}02\) at \((B−V)_0 = 0\,^{\prime\prime}44\), and at this same color index, the highest point of the SK82 hump has \((U−B)_0 = −0\,^{\prime\prime}02\). The resulting ultraviolet excess, \(\delta(U−B) = +0\,^{\prime\prime}08 ± 0\,^{\prime\prime}02\), has been converted to \(\delta(0.6) = +0\,^{\prime\prime}10 ± 0\,^{\prime\prime}02\) at \((B−V) = +0\,^{\prime\prime}60\) with the normalization ratios given by Sandage (1969, his Table 1A). These values have been listed in Table 7, together with the corresponding photometric metallicity \([\text{Fe/H}] = −0.35 ± 0.02\) dex derived with help of the calibration \([\text{Fe/H}] = \delta(0.6)\) of Karataş & Schuster (2006). Note that the \(\delta(0.6)\) in the notation of the latter authors corresponds to \(\delta(0.6)\) in the notation of Sandage (1969). Applying the above relation between \([\text{Fe/H}]\) and \(Z\), where \([\text{Fe/H}]\) has been estimated as \(−0.35 ± 0.02\) dex, gives \(Z = +0.008 ± 0.0003\). The online isochrones of MGBG have been iterated using this metal abundance when further analyzing Be 89.

In Figures 3 and 4, the isochrones of MGBG for \(Z = +0.008\) have been over-plotted in five CM diagrams: \((V, B−V), (V, R−I), (V, V−I), (V, V−R),\) and \((V, B−R)\) after reddening the isochrones along the color axis with a color excess corresponding to \(E(B−V) = 0\,^{\prime\prime}60\), converted with help of Table 6, and adding a visual extinction of \(A_{V} = 3\,^{\prime\prime}1 \cdot E(B−V) = 1\,^{\prime\prime}86\) to the absolute magnitudes of the isochrones. The isochrones have then been shifted vertically to

Fig. 3. CM diagrams, \((V, B−V)\) and \((V, R−I)\), for Be 89. Solid lines show the interpolated \(Z = +0.008\) isochrones of MGBG (cf. Table 7 for the inferred metallicity). Big open circles denote the RC candidates, and open squares, the blue-straggler ones. See the text and Table 8 for the inferred values of the distance modulus and age.
Fig. 4. CM diagrams, \((V, V-I), (V, V-R),\) and \((V, B-R)\), (top, middle and bottom panels, respectively) for Be 89. The isochrone curves and the symbols have the same meaning as in Figure 3. See the text and Table 7 for the inferred values of the reddening and metallicity, and Table 8 for the distance modulus and age.

Fig. 5. The CC diagram of Ru135. The SK82 curves and the symbols have the same meaning as in Figure 2. See the text and Table 7 for the inferred values of the reddening and metallicity.

obtain the best fit to the observed lower-MS and and RC sequences. This vertical shift is the (true) distance modulus, \(DM = (V_0 - M_V)\). The best fit for Be 89 is \(DM = 11.90 \pm 0.06\) (d = 2.4 \pm 0.06 kpc, cf. Table 8).

To derive an age estimate for Be 89, the isochrones of MGBG for \(Z = +0.008\) have been shifted in the CM planes as above, i.e. \(M_V + 3.1E(B-V) + DM\) and \(C_0(\lambda_1 - \lambda_2) + E[C(\lambda_1 - \lambda_2)]\), respectively, where the latter color excesses have been computed from \(E(B-V)\) with help of Table 6, and then the isochrone ages have been varied until a satisfactory fit to the data has been obtained through the observed upper-MS, TO, and RC sequences of the cluster (cf. Figures 3–4). The resulting inferred mean age of Be 89 is \(log(A) = 9.58 \pm 0.06\) dex (\(A = 3.8 \pm 0.6\) Gyr).

For all of these CM diagrams of Be 89, two isochrones have been plotted to provide a means for appreciating the uncertainties of the derived distances and ages. In Table 8 the range in ages provided by these isochrone pairs, the final values for the distances and ages from each CM diagram, and the mean values for each cluster are given. Error estimates of \((V_0 - M_V)\) and \(log(A)\) are discussed in §3.4 below, and the mean results given in Table 8 have been calculated with Equations (8) and (9) inserting the corresponding parameters summarized in the table.
Fig. 6. The \((V, B-V)\) and \((V, R-I)\) diagrams for Ru 135. Solid lines show the isochrones of MGBG interpolated to \(Z = +0.004\). See the text, and Tables 7 and 8, for the inferred values of reddening, metallicity, distance modulus, and age. Stars shown with open-square symbols are most likely field, or blue-straggler, stars.

3.2. Ru 135

The same procedures outlined in §3, and §3.1 for Be 89, have also been used for the clusters Ru 135 and Be 10. A reddening of \(E(B-V) = 0\text{^m}63 \pm 0\text{^m}12\) has been derived for Ru 135 (cf. Figure 5). However, a clump of A-type stars at \((B-V) \approx 0\text{^m}3\) and \((U-B) \approx 0\text{^m}4\) seems to be present, with a horizontal-like distribution which does not fit satisfactorily the reddened two-color ZAMS curve of SK82. These stars (Sp \(\approx\) A-types) are probably less reddened than Ru 135 by \(\approx 0\text{^m}3\) in \(E(B-V)\), nearer, and most probably not cluster members (cf. the open squares in the CC and CM diagrams of Figures 5, 6, and 7), or they could be blue stragglers belonging to the cluster. For this latter case, they would be peculiar because of an ultraviolet-flux excess present in their spectral energy distributions (SEDs), and only a spectroscopic study with good signal-to-noise ratios would reveal more about their true nature.

Ru 135 contains a considerable number of F- and later-type stars, and appears to have its blue-most turn-off limit at \((B-V) \approx +1\text{^m}0\) and \((U-B) \approx 0\text{^m}4\), corresponding to a dereddened \((B-V) \approx +0\text{^m}43\) (i.e. Sp \(\approx\) F5V). The best fit to the observed F-hump sequence in the \((U-B, B-V)\) diagram is the solid curve shifted blue-ward with respect to the two-color SK82 curve (cf. Figure 5). From the ultraviolet excess of these cluster F stars and following the procedure outlined at the beginning of §3, \([\text{Fe/H}] = -0.71 \pm 0.02\) dex \((Z = +0.004 \pm 0.0002)\) has been derived. The isochrones of MGBG with this metallicity have been computed on line and used in the following analyses.

The five CM diagrams, \((V, B-V)\) through \((V, B-R)\), of Ru 135 are displayed in Figures 6 and 7 together with the reddened isochrones that best fit the data for the derived color excess and metallicity, \(E(B-V) = 0\text{^m}63\) and \(Z = +0.004\). The distance moduli, \((V_0-M_V)\), and ages, \(A\), found from these five CM diagrams and their respective isochrone fittings are given in Table 8.

In these CM diagrams a significant number of stars are seen extending to brighter magnitudes and red-ward from the fainter and redder observational limits of the main sequences, i.e. the stars extending red-ward and upward from \((V, B-V) \approx (18\text{^m}5, 1\text{^m}5)\) or \(V, (R-I) \approx (18\text{^m}5, 0\text{^m}9)\) (cf. Figure 6). These are probably field red-giant stars contributed by the Galactic bulge, as suggested by the Galactic longitude and latitude of Ru 135, \(\ell \approx 16\text{^d}4\) and \(b \approx +62\text{^d}\) (see Binney & Merrifield 1998; Stanek et al. 1999). Ru 135 lies near the direction of the Galactic central region also explains the significant number of
3.3. Be 10

In Figure 8 the loci of stars observed in the direction of Be 10 are shown in the 
(U–B, B–V) diagram, together with the standard interstellar reddening vector and the two-color curve of SK82, shifted along this vector to procure the best fit to the data. From the fits along the (B–V) and (U–B) axes, $E(B–V) = 0.075 \pm 0.009$ and ([Fe/H], $Z$) = ($-0.49 \pm 0.02$ dex, $+0.006 \pm 0.0003$) are found, following the procedures described in §3 and §3.1 (see Table 8 for partial and mean results). Again, the appropriate isochrones of MGBG have been computed online with this corresponding metallicity and are used below for further analyses of Be 10.

For Be 10, $DM = (V - 3.1 \cdot E(B–V) - M_V) = 11^m16 \pm 0^m06$, the distance, $d = 1.7 \pm 0.05$ kpc, the metallicity, $Z = +0.006 \pm 0.0003$, $log(A) = 9.06 \pm 0.05$, and the age, $A = 1.08 \pm 0.08$ Gyr have been measured. Our results are listed in Tables 7 and 8. The resulting (best) isochrone fitting to the corresponding Be 10 data in the (V, B–V), (V, R–I), (V, V–I), (V, V–R) and V, (B–R) diagrams are displayed in Figures 9 and 10, where one can see that the isochrones reproduce well the observed lower and upper MS, the TO, and RC sequences of this cluster.

3.4. Estimated errors and weighted averages

In Table 7, the ultraviolet excesses and the metallicities are given for Be 89, Ru 135, and Be 10, and in Table 8, the mean values for the distance moduli, heliocentric distances, logarithmic ages, and ages, together with the corresponding estimates of precision. The errors were calculated in a straightforward manner (cf. Bevington & Robinson 2003, and references...
Fig. 9. The \((V, B-V)\) and \((V, R-I)\) diagrams for Be 10. Solid lines show the isochrones of MGBG interpolated to \(Z = +0.006\). The larger open circles identify the RC candidates. See the text, and Tables 7 and 8, for the inferred values for reddening, metallicity, distance modulus, and age.

Fig. 10. The \((V, V-I)\), \((V, V-R)\) and \((V, B-R)\) diagrams for Be 10. The symbols are the same as in Figure 9. See the text, and Tables 7 and 8, for the inferred values for reddening, metallicity, distance modulus, and age.

therein). In the following the details of this error analysis are presented.

3.4.1. Errors in \(E(B-V)\) and \(Z\)

The random errors in the color excess \(E(B-V)\) and photometric metallicity \([Fe/H]\) were estimated
as follows:

i) By moving the two-color curve of SK82 backward and forward along the standard reddening vector in the \((U-B, B-V)\) diagram until a good fit with the observed GK-type, RC, and F-hump sequences was achieved. (No BA-type sequences were present for these clusters.) The precision of the determinations also depends on the scatter of the data points (cf. Figure 5 of Ru 135 and Figure 8 of Be 10 for good and regular cases, respectively). The uncertainties given in Tables 7 and 8 reflect this. Following this procedure, a typical error in \(E(B-V)\) for the quality of the reduced data of our clusters is (conservatively) \(\approx 0.004\). The systematic error in \(E(B-V)\) depends on the color calibration used. In the case of SK82, the uncertainty can be safely assumed to be, at the most, of the order of the difference between two adjacent spectral subclasses.

ii) The random photometric-metallicity uncertainty has then been estimated from the parabolic (eyeball) fit to the data of the maximum characterizing the ultraviolet flux excess of the stars at the dereddened color \((B-V)_0 \approx 0.044\) (Sp \(\approx F5\)) and then following Sandage’s (1969) normalization procedure. The uncertainty of the metal content \(Z\) was determined from the relation (e.g. Bevington & Robinson 2003):

\[
\sigma_Z = \ln 10 \times Z \times \sigma_{[Fe/H]}.
\]

\(\sigma_{[Fe/H]}\) has been estimated from the uncertainty in the ultraviolet excess \(\delta(U-B)\) at the F hump between the observed and the SK82 two-color curves and is typically \(\pm 0.02\). Assuming \((Z) = 0.006\) (the mean of the three clusters) \(|\sigma_Z| \leq 0.0003\) is obtained with Equation (7) above. Assuming an error of about 0.001 for \(Z\) is, in our case, a quite conservative estimate.

iii) On the other hand, the deviation of the assumed reddening vector from the “true” one depends on the quotient \(\frac{E(U-B)}{E(B-V)}\), which can strongly deviate locally from its canonical value of 0.72 (see Chavarría-K et al. 1987, Johnson 1977, and references therein). This uncertainty may produce errors larger than the precision quoted above. For a crude estimate, using the extremes of the cited values of \(\frac{E(U-B)}{E(B-V)}\) and a typical color excess of \(E(B-V) = 0.50\), the uncertainty in \(\delta(U-B)\) could be as large as \(0.05\). However, since our displacements of the SK82 curve in the CM-diagrams are consistent with the canonical value for the interstellar extinction law, we assume that this error contribution is negligible statistically.

iv) Another systematic uncertainty results from the two-color calibration of SK82: from the uncertainty of \((U-B)\) or \((B-V)\) in the two-color calibration curve of SK82, which is expected to be of the order of the difference between two typical spectral subclasses (in our case \(\leq 0.05\)) for the \((U-B)\) index; and from the fit of the whole curve to a cluster data set, of the order \(\leq |\sigma_{\delta(U-B)}|\), where there are \(N\) pivotal points considered when adjusting the SK2 two-color curve (the BA-type, the F-hump, the GK-type, and the RC sequences; i.e. \(N \geq 3\)). Summarizing, the systematic uncertainty in \(\delta(U-B)\) should be less than roughly three times that given by the precision of the flux measurements.

3.4.2. Errors in the distance moduli and ages

i) The uncertainties \(\sigma_{DMi}\) for the moduli given in Table 8 that result from fitting the appropriate isochrones to the data in the CM diagrams depend on the photometric uncertainties (flux measurement and standard-transformation errors), the absolute magnitude and intrinsic color calibration errors (see for example, SK82), the color excess uncertainty of a given color (which depends on \(E(B-V)\)), and on the reddening law adopted. We assume that the isochrones only contain the errors of the absolute magnitude and intrinsic-color-calibrations and that the photometric and transformation errors are small (\(\approx 0.03\)) when compared to the other sources of error. In our case, the largest contribution to the distance modulus uncertainty is due to the uncertainty in the absolute-magnitude scale, followed by the uncertainty in the slope of the reddening vector, and the color-excess error, about \(0.03\), \(0.05\) and \(0.12\), respectively, which combine to give an expected total uncertainty as large as \(\sigma_{DMi} \approx 0.25\).

The moduli resulting from the CM diagrams of each object and the mean moduli for the three clusters are given in Table 8, and the mean of the moduli has been derived from the five moduli, weighted with their respective (usually un-
equal) precisions, with the following expression:

$$\frac{DM}{\sigma_{DM}} = \frac{\Sigma_D (DM)_i / \sigma_{DM_i}^2}{\Sigma_1 / \sigma_{DM_i}^2}; \quad (i = 1, ... , 5),$$

and the associated mean uncertainty is estimated from the individual uncertainties of the five CM-diagrams of a given cluster by the relation:

$$\frac{1}{(\sigma_{\text{mean}})^2} = \sum \frac{1}{(\sigma_{DM})_i^2}$$

The combined error is the square root of the sum of the squared uncertainties and is expected to be about $0^\text{m}15$, or even less.

ii) The uncertainty in the log($A$) has a random error due to the (eyeball) fit of the isochrone with the appropriate metallicity to a given CM-diagram of a cluster in question, and a quantitative estimate is obtained by jiggling bright-ward and faint-ward the isochrone curve until a good fit of the lower main sequence produces the $DM$. Then the age of the isochrone is varied until a good fit to the upper main sequence, the TO, and the RC sequences is achieved. The two isochrones shown in the CM diagrams of the program clusters give a quantitative estimate of this last error. Several different authors have computed isochrones as function of the metallicity, and the physics behind seems to be well understood. One does not expect a large variation in the log($A$) error due to any uncertainty in the physics, and the uncertainties of $E(B-V)$ and $(V_0-M_V)$ play a secondary role because the age errors depend more on the form of the isochrone curve and how it embraces the data (i.e. the upper main-sequence and TO regions and the RC sequence) and, less significantly, on the reddening law (except perhaps the blue and near-ultraviolet filters). More problematic is the case when the TO region is not well defined (i.e. isolated from field stars) and/or the RC sequence is not present. In our case, the errors for the different colors of Table 8 reflect these uncertainties.

4. COMPARISON OF FUNDAMENTAL PARAMETERS OF THE THREE CLUSTERS

The reddening values of our three clusters have been compared to ones derived from the dust maps of Schlegel, Finkbeiner & Davis (1998; hereafter, SFD); these are based on the COBE/DIRBE and IRAS/ISSA maps, and take into account the dust absorption all the way to infinity. $E(B-V)(\ell,b)_{\infty}$ values of our three clusters have been taken from SFD maps using the web pages of NED\footnote{http://nedwww.ipac.caltech.edu/forms/calculator.html}. These $E(B-V)(\ell,b)_{\infty}$ values are $0^m99$ for Be 89, and $1^m06$ for both Ru 135 and Be 10. However, Arce & Goodman (1999) caution that SFD reddening maps overestimate the reddening values when the color excess $E(B-V)$ is more than $\approx 0^m15$. For the revision of SFD reddening estimates, the equations of Bonifacio, Monai & Beers (2000) and Schuster et al. (2004) have been adopted. Then the final reddening, $E(B-V)_A$, for a given star is reduced compared to the total reddening $E(B-V)(\ell,b)_{\infty}$ by a factor $[1 - \exp(-d \sin b/H)]$, where $b$, $d$, and $H$ are the Galactic latitude (Column 2 of Table 9), the distance from the observer to the object (Column 7 of Table 9), and the scale height of the dust layer in the Galaxy, respectively; here we have assumed $H = 125 \text{ pc}$ (Bonifacio, Monai & Beers 2000). Note that Galactic latitudes of our three clusters are less than $10^\circ$. These reduced final redenings are $E(B-V)_A = 0^m54$ for Be 89, $0^m36$ for Ru 135, and $0^m64$ for Be 10.

For Be 89, our reddening value of $0^m60$ is in good agreement with the value of $0^m54$ obtained from the dust maps of SFD. For Be 10 our reddening value of $E(B-V) = 0^m75$ is within about $1\sigma$ of the value $0^m64$ derived from the SFD dust maps, and for Ru 135, our reddening value of $0^m63$ differs by about $2\sigma$ from the value of $0^m36$ obtained from these SFD maps. These reddening values derived by different methods are in reasonable agreement with each other, giving confidence to our results.

As can be seen from the summarized results given in Table 9, the reddening value $0^m60$ found here for Be 89 is smaller than the $E(B-V) = 1^m03$ of Tadross (2008; hereafter T08a), and than the $E(B-V) = 1^m05$ of Subramaniam et al. 2010 (hereafter S10). Our derived distance modulus and distance for Be 89, $(V_0-M_V), d(\text{kpc}) = (11^m90 \pm 0^m06, 2.4 \pm 0.06)$, are smaller than the values of $(12^m39, 3.00)$ of T08a and larger than the $(11^m54, 2.04)$ of S10. Our inferred age (log($A$), A(Gyr)) = (9.58, 3.8 Gyr) for this cluster is considerably older than (8.93, 0.85 Gyr) given by T08a and larger than the estimate (9.02, 1.06 Gyr) by S10. For the analysis of Be 89, T08a used $JHK$ photometry and the isochrones of Bonatto et al. (2004) with a solar metallicity. This is, partially, the origin of the disagreement between the two age estimates, since our lower metallicity for Be 89 will necessarily lead to a larger age for a given TO. Also, most probably, the differences are partially due to the different procedural approaches for estimating the fundamental parameters; we de-
rive in a straightforward manner the estimates for the interstellar extinction and metallicity: by fitting SK82’s ZAMS to the data in the \((U−B, B−V)\) diagram, by then measuring the ultraviolet excess of the F-type stars to derive a cluster metallicity, and finally using the appropriate isochrones in CM diagrams to estimate the true distance modulus and age of Be 89. Two parameters (reddening and metallicity) are estimated in a CC diagram separately from the other two parameters (distance and age) from the CM diagrams. S10 have also assumed a solar metallicity \((Z_0)\) for their isochrones (from GBBC) and have used only CM diagrams to estimate the reddening, distance, and age of Be 89.

Previous results in the literature for Ru 135 are found in the work by Tadross (2008; hereafter T08b), and for Be 10 in the papers by Lata et al. (2004; L04) and Maciejewski & Niedzielski (2007; MN07). Our reddening value \(E(B−V) = 0.0^m 63 \pm 0.0^m 12\) for Ru 135 is significantly smaller compared to the reddening value of \(1^m 10\) given by T08b. Also, our derived distance modulus and distance, \(((V_0−M_V), d(kpc)) = (9^m 58, 0.81)\), for Ru 135 are significantly smaller than \((11^m 33, 1.85)\), and our inferred age \((\log(A), A) = (9.58, 3.80 \text{ Gyr})\) is considerably older than \((8.70, 0.50 \text{ Gyr})\), values by T08b.

In defense of the present results, our value for \(E(B−V) (0^m 63)\) falls between the value derived from SFD \((0^m 36)\) and the value of T08b \((1^m 10)\); our value is in much better agreement with SFD. T08b used the solar-metallicity isochrones of Bonatto, Bica, & Girardi (2004), and his results are based on the comparison of isochrones to observed data in the \(J, (J−H)\) and \(K, (J−K)\) planes of infrared photometry. These differences between our values and those of T08b are probably due mainly to the largely different values for the interstellar reddening, but also to the difference in the assumed metallicities, to the use of different stellar models and isochrone sets, which make use of differing input physics and colour-temperature transformations, and to distinct photometric data sets.

For the Be 10 open cluster, our reddening value \(E(B−V) = 0.75^m\) is in reasonable agreement with the value of \(E(B−V) = 0.87^m\) given by L04, and in good agreement with \(E(B−V) = 0.71^m\) by MN07. For the metallicity of the Be 10 cluster, L04 adopt the \(Z = +0.008\) isochrones of Girardi et al. (2002), and MN07 adopt the solar isochrones of Bertelli et al. (1994). From our two-color diagram, \(Z = +0.006\) has been derived (see §3.3), which is in agreement, within the error bars, with the value of L04. Our distance modulus and distance for Be 10, \(((V_0−M_V), d(kpc)) = (11^m 16, 1.70)\) differ from the values \((11^m 8, 2.3)\) of L04, but very little from the values of MN07, \((11^m 26, 1.79)\). Our inferred age \((\log(A), A) = (9.06, 1.08 \text{ Gyr})\) for this cluster disagrees by almost a factor of two \((0.5 \text{ Gyr})\) with L04, but is in good agreement with MN07, \((9.00, 1.00 \text{ Gyr})\). Again, our interstellar reddening for Be 10, \(E(B−V) = 0.75^m\) falls between the value derived from SFD \((0^m 64)\) and the value \(0^m 87\) by L04.

The age values in Table 9 have been compared to ages estimated with the \((\log(A), A)\) calibration given by Carraro & Chiosi (1994; their equation (3)). Note that this last calibration does not consider the metal abundance of the cluster. Here, \(\Delta V\) means the magnitude difference between the RC and TO, which is well known as an age indicator. Both open clusters Be 89 and Be 10 have RC candidates (see the CM plots for these two clusters, Figures 3–4, and Figures 9–10, respectively). TO values occur at \(V \approx 16^m 5\) for Be 89 and \(V \approx 14^m 8\) for Be 10, whereas the RCs occur at \(V \approx 15^m 3\) and \(V \approx 14^m 7\), respectively. From this age–\(\Delta V\) calibration of Carraro & Chiosi (1994), ages have been estimated as \(\log(A) = 9.1 \text{ (1.3 Gyr)}\) for Be 89 and \(\log(A) = 8.6 \text{ (0.4 Gyr)}\) for the Be 10.

The average age values given by us, \(\log(A) = 9.58 \text{ (3.8 Gyr)}\) for Be 89 and \(\log(A) = 9.06 \text{ (1.08 Gyr)}\) for Be 10 are somewhat older than the ones estimated from this relation of Carraro & Chiosi (1994). However, these age differences are at least partially explained by the sub-solar metallicities of these two clusters \([\text{Fe/H}] = −0.35\) dex for Be 89 and \(−0.49\) dex for Be 10; see §3.1, §3.3, and Table 9). Lower metallicities require larger ages for the same TO.

In Table 9 our results are summarized for Be 89, Ru 135, and Be 10: Columns 1 and 2 contain the cluster name and Galactic coordinates, respectively. The resulting reddening, \(E(B−V)\), is given in Column 3. The metallicity and heavy-element abundances, \([\text{Fe/H}]\) and \((Z)\), are given in Columns 4 and 5, respectively. True distance modulus values, \((V_0−M_V)\), and their corresponding heliocentric distances to the observer are given in Columns 6 and 7, respectively. Column 8 gives the average age \((\log(A); \text{where A is in years})\), as derived from the five CM diagrams. Different isochrones used by us and by other authors are referenced in Column 9. Average Galactocentric distances are listed in Column 10. The corresponding references from the literature are listed in Column 11.

5. CONCLUSIONS

CCD \(UBVRI\) photometry of three poorly studied Galactic open clusters, Be 89, Ru 135, and Be 10,
has been analyzed, based on new SPM observations. The fundamental parameters of reddening, metallicity, age, and distance of these open clusters have been inferred and presented in Tables 7–9.

The interstellar reddenings and metallicities of these three clusters have been determined from two-color, $(U-B, B-V)$, diagrams prior to the use of the CM diagrams. Heavy element abundances, $Z$, of the three clusters have been found from the ultraviolet excess, $\delta(U-B)$, of the F-stars by comparison with the two-color curve of SK82 ($Z_{SK82} = Z_\odot$), by using the normalizations of Sandage (1969), and by applying the calibration, $[\text{Fe/H}] - \delta(0.6)$, of Karataş & Schuster (2006), with the advantage of reducing by two the number of free parameters of the isochrones when fitting to the data in the CM diagrams. When necessary, we have iterated slightly afterwards for a better, more consistent, solution for the four cluster parameters (reddening, metallicity, distance, and age). Deeper U frames would improve our determinations employing this method, which allows us to estimate the reddening and metallicity independently using a CC diagram, in contrast to the exclusive fitting of isochrones to CM diagrams and the use of the solar metallicity, which are the more common techniques used in the literature.

The present adjustments of the SK82, CC relations to the MS and RC stars, and of the MGBG isochrones to MS, TO, and RC stars in the CM diagrams show good consistency and appropriate fits for all three open clusters, in the one CC diagram and all five CM diagrams. Good consistency is seen in the Figures 2–4 for Be 89, Figures 5–7 for Ru 135, and Figures 8–10 for Be 10.

The CC and CM diagrams of Be 89 and Ru 135 suggest that they are metal-poor and old for their location in the Galaxy, compared to other open clusters. For Be 89, stars with $V < 16^m2$ and $(B-V) \leq 0^m9$ are most likely foreground or blue-straggler stars. The blue-straggler and RC candidates in the field of Be 89 need spectroscopic and/or astrometric observations to test their cluster membership and to elucidate their nature.

Similar candidates for blue-straggler or bright foreground stars are seen in the CC and CM diagrams of Ru 135 and Be 10, Figures 5–7 and 8–10, respectively. In the case of Ru 135 and for stars with $V$ fainter than about $14^m2$, the onset of the cluster in the CM diagrams is clearly seen. Objects brighter than this limit and with $(B-V) \leq 0^m9$ are probably blue stragglers or bright foreground stars. Despite its similar age to Be 89, no RC stars are noticeable in the CM diagrams of Ru 135. On the other hand, the CC and CM diagrams of Be 10 show clear evidence for a RC grouping, although it is somewhat younger than the other two clusters. The lack of any RC stars in the CM diagrams of Ru 135, contrasting with Be 89 and Be 10, may result either from relative differences in mass segregation and our emphasis on the inner regions of these clusters, or from the poorness of these cluster fields and small-number statistics. Ru 135, being closer to the Galactic center, may be more perturbed and less dynamically relaxed than the other two clusters. Also, Be 89 and Be 10 each show only eight, or fewer, RC candidate stars, and it is not clear that all of these are in fact cluster members.

For the typical accuracy of photometric observations (and we are no exception), the final error estimates are fixed by the accuracy of the cluster parameters as given by the systematic uncertainties in the absolute-magnitude, intrinsic-color, and reddening-vector calibrations, for example, the adequacies, or not, of the SK82 colors, the MGBG isochrones, and the standard interstellar-reddening curve.

Finally, further radial velocity and proper motion information for these clusters will allow us to clean with more assurance most non-members from the CC and CM diagrams in order to obtain better determinations of their physical parameters and to better understand the nature of the blue-straggler and red-clump candidates in these three open clusters. Deeper photometric observations, especially in the $U$ and $B$ bands, will provide clearer, cleaner, and more precise solutions from the CC diagram.

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### TABLE 7
NORMALIZED (U–B) EXCESSES AND DERIVED METALLICITIES

| Cluster | \((U-B)_{SK82}\) | \((U-B)_{0,fit}\) | \(\delta(U-B)\) | \(\delta(0.6)\) | \([\text{Fe/H}]\) | \(Z\) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| Be 89   | -0.02           | -0.10           | 0.08            | 0.10            | -0.35           | 0.008|
| Ru 135  | -0.02           | -0.16           | 0.14            | 0.14            | -0.71           | 0.004|
| Be 10   | -0.02           | -0.09           | 0.07            | 0.11            | -0.49           | 0.006|
| error   | \(\leq \pm 0.01\) | \(\pm 0.02\) | \(\pm 0.02\) | \(\pm 0.02\) | \(\pm 0.02\) | \(\leq \pm 0.001\) |

### TABLE 8
DISTANCE AND AGE ESTIMATES OF THE CLUSTERS

| Color | \((V_0-M_V)\) | \(d\) | \(log(A)\) | \(log(A)\) | \(A\) |
|-------|---------------|-------|-------------|-------------|------|
|       | [mag] | [kpc] | range       | [Gyr]       |      |
| Be 89: | \(E(B-V)=0.60 \pm 0.09 \& Z = +0.008 \pm 0.001\) |
| \((B-V)\) | 11.90 ± 0.10 | 2.4 ± 0.1 | 9.45–9.55 | 9.55 ± 0.15 | 3.6 ± 1.4 |
| \((R-I)\) | 11.90 ± 0.20 | 2.4 ± 0.2 | 9.50–9.60 | 9.60 ± 0.20 | 4.0 ± 2.3 |
| \((V-I)\) | 11.90 ± 0.15 | 2.4 ± 0.2 | 9.50–9.60 | 9.60 ± 0.20 | 4.0 ± 2.3 |
| \((V-R)\) | 11.90 ± 0.10 | 2.4 ± 0.1 | 9.50–9.60 | 9.60 ± 0.15 | 4.0 ± 1.6 |
| \((B-R)\) | 11.90 ± 0.20 | 2.4 ± 0.2 | 9.45–9.55 | 9.55 ± 0.10 | 3.6 ± 0.9 |
| Mean | 11.90 ± 0.06 | 2.4 ± 0.06 | 9.58 ± 0.06 | 3.8 ± 0.6 |
| Ru 135: | \(E(B-V)=0.63 \pm 0.12 \& Z = +0.004 \pm 0.001\) |
| \((B-V)\) | 9.50 ± 0.15 | 0.75 ± 0.05 | 9.60–9.70 | 9.60 ± 0.15 | 4.0 ± 1.6 |
| \((R-I)\) | 9.70 ± 0.15 | 0.87 ± 0.06 | 9.55–9.65 | 9.55 ± 0.15 | 3.6 ± 1.5 |
| \((V-I)\) | 9.60 ± 0.20 | 0.83 ± 0.08 | 9.55–9.65 | 9.55 ± 0.15 | 3.6 ± 1.5 |
| \((V-R)\) | 9.60 ± 0.15 | 0.83 ± 0.06 | 9.55–9.65 | 9.60 ± 0.15 | 4.0 ± 1.5 |
| \((B-R)\) | 9.50 ± 0.20 | 0.75 ± 0.07 | 9.60–9.70 | 9.60 ± 0.15 | 4.0 ± 1.6 |
| Mean | 9.58 ± 0.07 | 0.81 ± 0.03 | 9.58 ± 0.06 | 3.8 ± 0.7 |
| Be 10: | \(E(B-V)=0.75 \pm 0.09 \& Z = +0.006 \pm 0.001\) |
| \((B-V)\) | 11.20 ± 0.11 | 1.7 ± 0.1 | 9.05–9.15 | 9.05 ± 0.10 | 1.1 ± 0.3 |
| \((R-I)\) | 11.10 ± 0.20 | 1.7 ± 0.2 | 9.10–9.20 | 9.10 ± 0.10 | 1.3 ± 0.3 |
| \((V-I)\) | 11.15 ± 0.15 | 1.7 ± 0.1 | 9.05–9.15 | 9.05 ± 0.15 | 1.1 ± 0.3 |
| \((V-R)\) | 11.15 ± 0.20 | 1.7 ± 0.2 | 9.05–9.15 | 9.05 ± 0.10 | 1.1 ± 0.3 |
| \((B-R)\) | 11.20 ± 0.10 | 1.7 ± 0.1 | 9.05–9.15 | 9.05 ± 0.05 | 1.1 ± 0.1 |
| Mean | 11.16 ± 0.06 | 1.70 ± 0.05 | 9.06 ± 0.05 | 1.08 ± 0.08 |
TABLE 9

FUNDAMENTAL PARAMETERS OF BE 89, RU 135, AND BE 10

| Cluster | (l°, b°) | E(B-V) [mag] | [Fe/H] | Z (V0-MV) [mag] | d [kpc] | log(A) | Isochrone | RGC [kpc] | Reference |
|---------|----------|---------------|--------|-----------------|--------|--------|-----------|----------|-----------|
| Be 89   | 83.16, +4.82 | 0.60 | -0.35 | +0.008 | 11.90 | 2.40 | 9.58 | m8† | 8.55 | this work |
|         |          | 1.03 | - | solar | 12.40 | 3.00 | 8.93 | b4 | – | Tadross 2008a |
|         |          | 1.05 | - | solar | 11.54 | 2.04 | 9.02 | g0 | – | Subramaniam et al. 2010 |
| Ru 135  | 16.42, +6.23 | 0.63 | -0.71 | +0.004 | 9.58 | 0.81 | 9.58 | m8 | 7.72 | this work |
|         |          | 1.10 | - | solar | 11.31 | 1.85 | 8.70 | b4 | – | Tadross 2008b |
| Be 10   | 138.62, +8.88 | 0.75 | -0.49 | +0.005 | 11.16 | 1.70 | 9.06 | m8 | 9.84 | this work |
|         |          | 0.87 | - | +0.008 | 11.80 | 2.30 | 8.80 | g2 | – | Lata et al. 2004 |
|         |          | 0.71 | - | solar | 11.26 | 1.79 | 9.00 | B4 | – | MN07 |

†Isochrone sources: B4 = Bertelli et al. (1994); b4 = Bonatto et al. (2004); g0 = GBBC; g2 = Girardi et al. (2002); m8 = MGBG
Supplementary material

The following material is available online at the CDS and WEBDA: (a) This manuscript. (b) Table 3, which presents standard $UBVRI$ CCD photometry and observing errors for the open cluster Be 89; the columns 1 and 2 give the following: $X$ and $Y$ (pixels), the position of a star in the CCD field; columns 3, 5, 7, 9, and 11: the magnitude and color indices, $V$, $(B-V)$, $(U-B)$, $(V-R)$, and $(V-I)$, respectively (in magnitudes); and columns 4, 6, 8, 10, and 12: the respective photometric errors, $\sigma_V$, $\sigma_{B-V}$, $\sigma_{U-B}$, $\sigma_{V-R}$, and $\sigma_{V-I}$ (in magnitudes), as provided by IRAF. (c) Tables 4 and 5, which have the same format as Table 3, but for Ru 135 and Be 10, respectively.