STRÖMGREN PHOTOMETRY OF GALACTIC GLOBULAR CLUSTERS. II. METALLICITY DISTRIBUTION OF RED GIANTS IN ω CENTAURI

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Received 2009 March 28; accepted 2009 September 30; published 2009 November 11

ABSTRACT

We present new intermediate-band Strömgren photometry based on more than 300 u, v, b, y images of the Galactic globular cluster ω Cen. Optical data were supplemented with new multiband near-infrared (NIR) photometry (350 J, H, K_s images). The final optical–NIR catalog covers a region of more than 20 × 20 arcmin squared across the cluster center. We use different optical–NIR color–color planes together with proper-motion data available in the literature to identify candidate cluster red-giant (RG) stars. By adopting different Strömgren metallicity indices, we estimate the photometric metallicity for ≈4000 RGs, the largest sample ever collected. The metallicity distributions show multiple peaks ([Fe/H]_phot = −1.73 ± 0.08, −1.29 ± 0.03, −1.05 ± 0.02, −0.80 ± 0.04, −0.42 ± 0.12, and −0.07 ± 0.08 dex) and a sharp cutoff in the metal-poor (MP) tail ([Fe/H]_phot ≲ −2 dex) that agree quite well with spectroscopic measurements. We identify four distinct subpopulations, namely, MP ([Fe/H]_phot ≲ −1.49), metal-intermediate (MI; −1.49 < [Fe/H]_phot < 0.93), metal-rich (MR; −0.95 < [Fe/H]_phot < −0.15), and solar metallicity ([Fe/H]_phot ≈ 0). The last group includes only a small fraction of stars (~8% ± 5%) and should be confirmed spectroscopically. Moreover, using the difference in metallicity based on different photometric indices, we find that the 19% ± 1% of RGs are candidate CN-strong stars. This fraction agrees quite well with recent spectroscopic estimates and could imply a large fraction of binary stars. The Strömgren metallicity indices display a robust correlation with α-elements ([Ca+Si/H]) when moving from the MI to the MR regime ([Fe/H]_phot ≳ −1.7 dex).

Key words: globular clusters: general – globular clusters: individual (Omega Centauri) – stars: abundances – stars: evolution

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

The Galactic globular cluster (GGC) ω Cen (NGC 5139) is currently the target of significant observational efforts covering the whole wavelength spectrum. This huge star cluster, the most massive known in our Galaxy (2.5 × 10^6 M_☉; van de Ven et al. 2006) hosts at least three separate stellar populations with a large undisputed spread in metallicity (Norris & Da Costa 1995, hereinafter ND95; Norris et al. 1996, hereinafter N96; Suntzeff & Kraft 1996, hereinafter SK96; Smith et al. 2000, hereinafter SM00; Kassier et al. 2006, hereinafter KA06; Villanova et al. 2007). The most relevant morphological and structural parameters of ω Cen are summarized in Table 1.

The unusual spread in color of the red giant branch (RGB) in ω Cen was revealed for the first time by Dickens & Woolley (1967) using photographic photometry by Woolley (1966), and later verified by Cannon & Stobie (1973) using photoelectric photometry. The width in color of the RGB was interpreted as an indication of an intrinsic spread in chemical abundance, as subsequently confirmed by spectroscopic data (Freeman & Rodgers 1975). Moreover, recent photometric surveys by Lee et al. (1999), Pancino et al. (2000, hereinafter PA00), Rey et al.
More recent spectroscopic studies of red-giant (RG) stars have refined our knowledge of the intrinsic spread in heavy elements in ω Cen (ND95; N96; SK96). In particular, the low-resolution study of ≈500 RGs performed by N96 and by SK96, based on the Ca H, K lines, and on the infrared Ca T triplet (CaT), provided a metallicity distribution with a dominant peak located at [Fe/H] ≈ −1.6, a secondary peak at [Fe/H] ≈ −1.2, and a long, asymmetric tail extending toward higher metallicities ([Fe/H] ≈ −0.5). This distribution agrees quite well with the metallicity distributions obtained by Hilker & Richtler (2000, hereinafter HR00; ≈1500 RGs) and by Hughes et al. (2004; ≈2500 MS, SGB, RG) using the Strömgren (m0, b−y) metallicity diagnostic and by S05a using the (B − V) color of ≈1400 RG stars.

Moreover, α-element abundance differences have been detected among ω Cen RGs. They show typical overabundances ([α/Fe] ≈ 0.3−0.4) up to iron abundances of [Fe/H] ≈ −0.8 (SM00; Cunha et al. 2002; Vanture et al. 2002) and evidence of a decrease in the overabundance to [α/Fe] ≈ 0.1 in the more metal-rich (MR) regime (Pancino et al. 2002, hereinafter PA02; Gratton et al. 2004). The large range of heavy element abundances observed among cluster RGs was also detected among subgiant branch (SGB) and main-sequence turnoff (MSTO) stars. In particular, Hilker et al. (2004, hereinafter H04) and KA06, based on medium-resolution spectra of more than 400 SGB and MSTO stars, found a metallicity distribution with three well-defined peaks around [Fe/H] = −1.7, −1.5, and −1.2, together with a handful of MR stars with [Fe/H] ≈ −0.8. Furthermore, MR stars seem to be CN-enriched, while metal-poor (MP) stars show high CH abundances (KA06). Using the infrared CaT of 250 SGB stars, Sollima et al. (2005b, hereinafter S05b) found a similar metallicity distribution with four peaks located at [Fe/H] = −1.7, −1.3, −1.0, and −0.6 dex. The recent metallicity distribution based on low-resolution spectroscopy of 442 MSTO and SGB stars by Stanford et al. (2006) confirmed the occurrence of a sharp rise at low metallicities, [Fe/H] < −1.7, and the presence of a MR tail up to [Fe/H] ≈ −0.6 dex. Moreover, Stanford et al. (2007), using the same spectra, showed that ω Cen is a 16%−17% of the SGB stars are enhanced in either C or N. In order to explain this interesting evidence, they suggested that these enhancements might be due to primordial chemical enrichment either by low (1−3 M\(_{\odot}\)) to intermediate (3−8 M\(_{\odot}\)) mass AGB stars, or by massive rotating stars (Maeder & Meynet 2006).

This is the second paper of a series devoted to Strömgren photometry of GGCs. In the first paper, we provided new empirical and semiempirical calibrations of the metallicity index m1 = (u−b) − (b−y) based on cluster RG stars and on new sets of semiempirical and theoretical color−temperature relations (CTRs; Calamida et al. 2007a, hereinafter CA07).

The structure of the paper is as follows. In Section 2, we discuss in detail the multiband Strömgren (u, v, b, y) and near-infrared (NIR; J, H, K) images we collected for this experiment. In Sections 3 and 4, we lay out the data reduction techniques and the calibration strategies adopted for the different data sets. Section 5 deals with the selection criteria adopted to identify candidate field and cluster RG stars using both optical and NIR photometry. In Section 6, we present a new calibration of the Strömgren m1 metallicity index based on the b−y color and compare the new relation with similar relations available in the literature. In Section 7, we discuss the comparison between spectroscopic and photometric metallicities of ω Cen RG stars based on different metallicity index color (MIC) relations and different calibrations (empirical, semiempirical). In this section, we also address the impact that CN-strong stars have on photometric metallicity estimates. Section 8 deals with metal-abundance distributions—in particular, we discuss the occurrence of different metallicity regimes—while abundance anomalies (C, N, α-elements) are discussed in Section 9. Finally, in Section 10 we summarize the results of this investigation and briefly outline possible future extensions of this medium-band photometric experiment.

### 2. OBSERVATIONS

#### 2.1. Strömgren Data

A set of 110 uvyb Strömgren images centered on the cluster ω Cen was collected by one of us (LF) over 11 nights between 1999 March 27 to April 9, with the 1.54 m Danish Telescope (ESO, La Silla). Weather conditions were good, typically with humidity from 40% to 60%, conditions frequently photometric, and seeing ranging from 1.3′ for the y band to 2.3′ for the u band. On clear photometric nights, ω Cen was observed with exposure times of 1200 s, 480 s, 240 s, 120 s for the uvyb bands, while on less photometric nights, we used exposure times of 2000 s, 900 s, 600 s and 450 s. The CCD camera was a 2048 × 2048 pixel Ford-Loral CCD, with a pixel scale of 0.39′ and a field of view (FoV) of 13.7′ × 13.7′. The CCD has two amplifiers, A and B, and we used A in high-gain mode for our observations. The gain and the readout noise (RON) of the CCD were measured to be 1.3 ± 0.01 e− ADU−1 and 8.25 ± 0.1 e−, respectively.

This data set has been supplemented with 30 uvy by images of the SW quadrant of ω Cen collected by one of us (FG) during four nights in 1999 April and two nights in 1999 June with the Danish Telescope. During these nights, a set of 112 HD standard stars was observed in the uvyb bands. These were selected from the catalogs of photometric standards by Schuster & Nissen

| Table 1 |
| --- |
| Positional, Photometric and Structural Parameters of the Galactic Globular Cluster ω Cen |

| Parameter | Reference |
| --- | --- |
| α (2000) | 13.26.45 |
| δ (2000) | −47.28.37 |
| M1 (mag) | −10.3 |
| r (arcmin) | 2.58 |
| r (arcmin) | 44.8 |
| e² | 0.15 |
| σv (km s⁻¹)² | 15 |
| E(B−V) | 0.11 ± 0.02 |
| (m−M)0 (mag) | 13.70 ± 0.12 |
| μa × coså, μl (mas yr⁻¹)² | −3.97, −4.38 |
| Position angle (deg) | 100 |
| Notes: |
| a | References: (1) Harris 1996; (2) Trager et al. 1995; (3) van de Ven et al. 2006; (4) Reijns et al. 2006; (5) Calamida et al. 2005; (6) Del Principe et al. 2006; Bonf et al. 2008; (7) van Leeuwen et al. 2000. |
| b | Total visual magnitude. |
| c | Core radius. |
| d | Tidal radius. |
| e | Eccentricity. |
| f | Stellar central velocity dispersion. |
| g | Mean cluster reddening. |
| h | True distance modulus. |
| i | Mean proper motion. |

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Table 2
Strömgren Data Adopted in this Investigation

| Field | Images | FoV | RA | DEC |
|-------|--------|-----|----|-----|
| LF    | 25a, 28b, 22b, 30y | 13.7 × 13.7 | 13 26 24 | -47 28 12 |
| FG-1  | 3u, 3v, 3b, 3y | 13.7 × 13.7 | 13 26 24 | -47 28 12 |
| FG-2  | 4v, 4b, 4h, 6y | 13.7 × 13.7 | 13 25 48 | -47 38 24 |
| MH-1  | 2v, 2b, 2y | 6.3 × 6.3 | 13 26 57 | -47 33 09 |
| MH-2  | 3v, 3b, 3y | 6.3 × 6.3 | 13 26 59 | -47 38 50 |
| MH-3  | 3v, 3b, 3y | 6.3 × 6.3 | 13 27 26 | -47 28 54 |
| MH-4  | 3v, 3b, 3y | 6.3 × 6.3 | 13 27 55 | -47 28 01 |
| MH-5  | 3v, 3b, 3y | 6.3 × 6.3 | 13 28 21 | -47 27 52 |
| MH-A  | 4v, 4b, 4y | 6.3 × 6.3 | 13 28 01 | -47 28 32 |
| MH-B  | 3v, 3b, 3y | 6.3 × 6.3 | 13 27 48 | -47 24 06 |
| MH-C  | 3v, 3b, 3y | 6.3 × 6.3 | 13 27 17 | -47 22 26 |
| MH-D  | 2v, 2b, 2y | 6.3 × 6.3 | 13 26 50 | -47 19 06 |
| MH-E  | 5v, 5b, 5y | 6.3 × 6.3 | 13 26 42 | -47 24 06 |
| MH-F  | 3v, 3b, 3y | 6.3 × 6.3 | 13 26 15 | -47 26 56 |
| MH-G  | 3v, 3b, 3y | 6.3 × 6.3 | 13 25 45 | -47 26 56 |
| MH-H  | 3v, 3b, 3y | 6.3 × 6.3 | 13 25 15 | -47 26 56 |
| MH-I  | 2v, 2b, 2y | 6.3 × 6.3 | 13 24 45 | -47 26 57 |
| MH-O  | v, b, y | 6.3 × 6.3 | 13 26 50 | -47 28 33 |
| MH-a  | v, b, y | 6.3 × 6.3 | 13 25 30 | -47 26 46 |
| MH-b  | v, b, y | 6.3 × 6.3 | 13 25 59 | -47 17 46 |
| MH-c  | v, b, y | 6.3 × 6.3 | 13 26 28 | -47 27 46 |
| MH-d  | v, b, y | 6.3 × 6.3 | 13 25 30 | -47 31 16 |
| MH-e  | v, b, y | 6.3 × 6.3 | 13 26 00 | -47 32 27 |
| MH-f  | v, b, y | 6.3 × 6.3 | 13 26 29 | -47 32 27 |
| MH-g  | v, b, y | 6.3 × 6.3 | 13 26 59 | -47 34 56 |
| MH-h  | v, b, y | 6.3 × 6.3 | 13 27 24 | -47 33 06 |
| MH-i  | v, b, y | 6.3 × 6.3 | 13 27 24 | -47 28 34 |
| MH-j  | v, b, y | 6.3 × 6.3 | 13 27 48 | -47 24 05 |
| MH-k  | v, b, y | 6.3 × 6.3 | 13 28 12 | -47 23 36 |
| MH-l  | v, b, y | 6.3 × 6.3 | 13 28 27 | -47 28 15 |
| MH-m  | v, b, y | 6.3 × 6.3 | 13 27 18 | -47 23 05 |
| MH-n  | v, b, y | 6.3 × 6.3 | 13 26 50 | -47 21 47 |
| MH-o  | v, b, y | 6.3 × 6.3 | 13 26 47 | -47 17 17 |
| MH-p  | v, b, y | 6.3 × 6.3 | 13 26 16 | -47 16 38 |
| MH-s  | v, b, y | 6.3 × 6.3 | 13 25 30 | -47 35 07 |
| MH-t  | v, b, y | 6.3 × 6.3 | 13 28 15 | -47 32 26 |

Notes.
- a Data set collected with the 1.54 m DANISH Telescope available at ESO (La Silla).
- b Field of view (arcmin).
- c Field coordinates (J2000): units of right ascension are hours, minutes, and seconds, while units of declination are degrees, arcminutes, and arcseconds.

Table 3
Log of Scientific CCD Images of ω Cen Collected by LF and by FG

| Frame | Datea | HJDb | ETc | Filterd | Seeingg |
|-------|-------|------|-----|---------|---------|
| (1)   | (2)   | (3)  | (4) | (5)     | (6)     |
| dfSc0656 | 1999 Mar 28 | 2451265.7938 | 450 | y | 1.32 |
| dfSc0660 | 1999 Mar 28 | 2451265.8398 | 2000 | u | 2.59 |
| dfSc0661 | 1999 Mar 28 | 2451265.8519 | 900 | v | 1.50 |
| dfSc0662 | 1999 Mar 28 | 2451265.8600 | 600 | b | 1.58 |
| dfSc0663 | 1999 Mar 28 | 2451265.8665 | 450 | y | 1.82 |

Notes.
- a UT date.
- b Heliocentric Julian Date.
- c Individual exposure time (s).
- d The u, v, b, y Strömgren filters of the 1.54 m Danish Telescope (ESO, La Silla).
- g Individual seeing (arcsec).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

(1988, hereinafter SN88) and by Olsen (1993, hereinafter O93). Tables 2 and 3 give the log of these observations together with the seeing conditions.

Together with the aforementioned images, we also acquired 210 vby images collected with the same telescope by two of us (MH, TR) in two observing runs (1993 and 1995; see Hilker 2000, hereinafter H00; HR00). The CCD used for these observations was a Tektronix 1024 × 1024 chip, with a pixel scale of 0.50 and an FoV of 6.3 × 6.3. The log of this data set is given in Table 4 and specifics concerning the 33 fields used in this investigation are given in Table 2. To obtain a homogeneous photometric catalog, these frames were reanalyzed adopting the same procedure as was applied to the two other data sets. Figure 1 shows the location of the three different data sets across the cluster area.

Table 4
Log of Scientific CCD Images of ω Cen Collected by MH

| Frame | Field | Datea | HJDb | ETc | Filterd | Seeingg |
|-----------------|--------|-------|------|-----|---------|---------|
| (1)             | (2)    | (3)   | (4)  | (5) | (6)     | (7)     |
| dfSc0660        | MH-1   | 1993 May 13 | 2449120.6384 | 30 | y | 2.36 |
| dfSc0661        | MH-1   | 1993 May 13 | 2449120.6427 | 60 | b | 2.57 |
| dfSc0662        | MH-1   | 1993 May 13 | 2449120.6474 | 120 | v | 2.65 |
| dfSc0663        | MH-2   | 1993 May 13 | 2449120.7222 | 30 | y | 2.05 |
| dfSc0664        | MH-2   | 1993 May 13 | 2449120.7265 | 60 | b | 2.21 |

Notes.
- a UT date.
- b Heliocentric Julian Date.
- c Individual exposure time (s).
- d The u, v, b, y Strömgren filters of the 1.54 m Danish Telescope (ESO, La Silla).
- g Individual seeing (arcsec).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
2. Near-infrared Data

NIR J-, H-, and Ks-band images of ω Cen were collected in two different runs—2001 February 5, 7, and 2002 February 2, 3, 24, 25—with the NIR camera SOFI at the NTT (ESO, La Silla). SOFI can operate at low and high spatial resolution. In the former case, the pixel scale is 0′′.292 and the FoV is 4.9′ × 4.9′, while in the latter the pixel scale is 0′′.145 and the FoV is 2.47′ × 2.47′. We observed three different fields at low resolution: field A (36J, 55Ks) is located at the cluster center, field C (33J, 55Ks) is located ∼10.5′′ NW of the center, and field D (12J, 20Ks) is located ∼10.7′′ SW of the center (see Table 5 and Figure 2). The observing time was split between target observations on ω Cen and reference sky observations. For each pointing, we acquired a set of J (detector integration time [DIT] = 3 s, number of DIT [NDIT] = 1) and Ks (DIT = 3 s, NDIT = 4) images. To supplement these data, we retrieved from the ESO archive a mosaic of nine pointings (11J, 11Ks; Sollima et al. 2004) which covers an area of ∼13′ × 13′ across the cluster center. These images were collected on 2000 January 12, 13, using the same equipment in low-resolution mode.

Moreover, we also retrieved from the ESO archive two more data sets collected during the nights 2004 June 3, 4 and 2005 April 2. These data sample three different positions: field α (15J, low resolution) located at the cluster center; field β (15J, low resolution) located ∼5′′NW of the center; and field γ located ∼5′′SE of the center. This last field was observed both at low (γ1, 12J, 12H, 12Ks) and high (γ2, 24Ks) spatial resolution.

The above data were further supplemented with a set of NIR images from the NIR camera ISAAC at the VLT (ESO, Paranal). Its pixel scale is 0′′.145 and the FoV is 2.5′ × 2.5′. The images were collected using two narrowband filters centered on λ = 1.21 μm (Δλ = 0.018 μm; 8 images) and λ = 2.19 μm (Δλ = 0.03 μm; 24 images). We adopted the same DIT of 6 s, but NDIT = 13 and 11 for the NB1.21 band and the NB2.19 band, respectively. The log of the entire NIR data set is given in Table 6, and the area covered by the different SOFI and ISAAC fields is shown in Figure 2.

3. DATA REDUCTION

3.1. Strömgren Data

Flat fields for the central LF field (see Table 2 and Figure 1) were collected for the different filters and CCD settings at dusk and at dawn. The Danish Faint Object Spectrograph and Camera (DFOSC) was mounted with its File and Shutter Unit (FASU) on the telescope instrument adaptor. The 90 mm Strömgren filters were installed in the FASU. The main DFOSC instrument with the CCD camera can rotate with respect to the FASU around the optical axis, so to average out background gradients in the flat fields—typically introduced by scattered light in the telescope and in the instrument due to inadequate baffling—we introduced offsets of 90° between flat fields in the same bandpass. Because DFOSC is a focal-reducer instrument, low-level multiple reflections in the optics are known to cause effects such as sky concentration (Andersen et al. 1999). The science frames were similarly obtained with rotation offsets. For each science image, a two-dimensional bias frame was subtracted, then they were scaled in level according to prescan and overscan.
areas, and flat-fielded using standard IRAF\textsuperscript{16} tasks based on nightly averaged calibration images. The 90 mm filters turned out to be affected by the artifact known as “filter ghosts.” The ghosts are located on the CCD images ∼20 pixels leftward of saturated stars and typically have the shape of a flattened doughnut or a fan. The orientation of the ghost star may slightly change across the CCD field, but on average it is quite constant. The separation between the saturated star and its ghost is also rather constant. The orientation of the ghosts in the CCD images collected with different orientations is rotated by the same angle. This evidence indicates that the ghost is not caused by double reflected light between the filter and the CCD camera, but must occur in the filter itself. A similar effect was found by O’Connor et al. (1998) in optical images collected with the MOMI CCD camera available at the Nordic Optical Telescope (NOT; La Palma), and also in Hubble Space Telescope (HST) images collected with the WFPC2 (Krist 1995). The overall effect on our images is of the order of 0.4%–1.1% in flux in $b$, $y$-band images and smaller in $u$, $v$-band images. This means that this effect is smaller than the typical photometric accuracy along the RGB. However, to avoid spurious effects in the point-spread function (PSF) photometry, we chose no PSF stars located in the neighborhood of saturated stars.

Raw images of the FG data set (see Table 2 and Figure 1) were preprocessed using tasks available in the IRAF data-analysis environment for bias subtraction and flat-fielding. To flat-field these data, we adopted median sky flats collected during the observing nights. The reader interested in the details of the reduction process adopted for the MH images is referred to H00.

The photometry was performed using DAOPHOT IV/ALLSTAR and ALLFRAME (Stetson 1987, 1991, 1994). We first estimated a PSF for each frame from ∼100 bright, isolated stars, uniformly distributed on the chip. We assumed a spatially varying Moffat function for the PSF. We performed preliminary PSF photometry on each image with the task ALLSTAR. Then, we used the task DAOMATCH/DAOMASTER (Stetson 1994) to merge the individual detection lists from the 328 images of the three different data sets into a single global star catalog referred to a common coordinate system. Twelve images were neglected, due to either bad seeing or poor image quality. As a reference

\textsuperscript{16} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3.2. Near-infrared Data

The reduction process for the NIR data was the same as for the optical data. The photometry was performed using standard IRAF procedures, and initial photometry for individual images was performed with DAOPHOT/ALLSTAR. Then, the individual detection lists were merged into a single star catalog and a new photometric reduction was performed with ALLFRAME. To improve the photometric accuracy, we did not stack individual images, and the spatially varying PSFs were derived from at least 50 bright, isolated stars uniformly distributed across each image.

4. PHOTOMETRIC CALIBRATION

4.1. Strömgren Data

Standard stars for the Strömgren photometry were selected from the lists of Henry Draper stars published by SN88 and O93; these were observed during four nights in 1999 April and two nights in 1999 June (see Grundahl et al. 2002 for more details). Tables 7 and 8 show the observation logs for these stars. We applied the same prereduction strategy and performed aperture photometry on the standard frames, ending up with a list of ∼20 HD stars per night. Extinction coefficients were estimated from observations of HD stars obtained at different air-mass values (see Table 9). Coefficients estimated for three out of the four nights in April are mutually consistent, but the values obtained for June 6 are slightly larger (see Table 10). We estimated independent color transformations for each night and

\textsuperscript{17} The catalog of local standards can be downloaded from the Photometric Standard Stars archive available at the following URL: http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/
Figure 3. Calibration curves for the reference night June 6.

Table 9
Log of HD Standard Stars Observed at Different Air-mass Values

| Star      | Air Mass | HD   | ET  | Filter |
|-----------|----------|------|-----|--------|
|           | (1)      | (2)  | (3) | (4)    | (5)   |
| HD119896  | 1.263    | 51334.9467 | 7   | y      |
| HD119896  | 1.262    | 51334.9471 | 15  | b      |
| HD119896  | 1.260    | 51334.9475 | 25  | v      |
| HD119896  | 1.258    | 51334.9480 | 70  | u      |
| HD119896  | 1.134    | 51334.9895 | 7   | y      |
| HD119896  | 1.133    | 51334.9898 | 15  | b      |
| HD119896  | 1.132    | 51334.9902 | 25  | v      |
| HD119896  | 1.132    | 51334.9908 | 70  | u      |
| HD119896  | 1.068    | 51335.0353 | 7   | y      |
| HD119896  | 1.068    | 51335.0357 | 15  | b      |
| HD119896  | 1.067    | 51335.0361 | 25  | v      |
| HD119896  | 1.065    | 51335.0366 | 70  | u      |

Notes.

a HD standard stars observed during the reference night, 1999 June 6, with the 1.54 m Danish Telescope available at ESO (La Silla).
b Individual air-mass value.
c Heliocentric Julian Date.
d Individual exposure time (s).

thus obtained a set of six calibration curves. These agree quite well with each other and we finally selected the best photometric night (June 6) to perform an absolute calibration of the scientific frames collected during this night. The calibration curves for the reference night are (see also Figure 3)

\[
\begin{align*}
  u &= u_i - (3.012 \pm 0.015) + (0.0127 \pm 0.0010) \times (u_i - b_i), \\
  v &= v_i - (2.820 \pm 0.008) + (0.002 \pm 0.016) \times (v_i - b_i), \\
  b &= b_i - (2.488 \pm 0.012), \\
  y &= y_i - (2.736 \pm 0.010),
\end{align*}
\]

where \( i \) stands for the instrumental magnitude.

On the basis of this calibration, we defined a set of secondary standard stars, by selecting both according to photometric precision (\( \sigma_{u,v,b,y} \leq 0.05 \) mag) and according to the “separation index” (\( \text{sep}_{v} > 5 \))\(^{18} \) in the calibrated star catalog of the reference night. We ended up with a sample of \( \sim5000 \) stars having measurements in all the Strömgren bands. We extended the photometric system of the reference data to each overlapping field by an iterative procedure.

In estimating the mean calibrated magnitudes, we neglected the \( b \) and \( y \) frames of the LF data set because the estimate of the aperture correction was hampered by the severe stellar crowding. For two pointings of the MH data set, namely, fields \( q \) and \( r \) (see Figure 1 of H00), the number of local standards was too small to provide a robust estimate of the calibration curves and they have not been included in the final catalog.

A slightly different approach was applied to the MH 1993 data. This data set included many non-photometric nights (see Table 4), and there were only a few secondary standards in this region of \( \omega \) Cen. Therefore, the estimate of the relative zero points between the different frames was difficult. Thus, we used the final calibrated star catalog based on the other observations as a new set of local standard stars to individually calibrate each frame of the 1993 data set. However, fields 3, 4, and 8 (see Figure 1 of HR00) were not included because the number of secondary standards was still too small in this cluster region. The typical accuracy of the absolute zero-point calibration is \( \sim0.02 \) mag for the \( u, v \)-band data and \( \sim0.015 \) mag for the \( b, y \)-band data.

\(^{18}\) The “separation index” quantifies the degree of crowding (Stetson et al. 2003). The current \( \text{sep}_{v} \) value allow us select stars that have required corrections smaller than \( \sim1\% \) for light contributed by known neighbors.
We compared our calibration with the absolute calibrations provided by Richter et al. (1999), by Mukherjee et al. (1992), and by Hughes & Wallerstein (2000). Figure 4 shows the comparison between the \( m_1 \) index based on the current photometry and the \( m_1 \) index based on the Richter et al. photometry. The mean difference is \( \Delta(m_1) \sim 0.00 \) with a dispersion of \( \sigma \sim 0.03 \) mag. The mean differences between our and the other two studies are \( \Delta(m_1) \sim 0.01 \), with \( \sigma \sim 0.06 \) based on 139 stars in common with the Mukherjee et al. catalog, and \( \Delta(m_1) \sim -0.02 \), with \( \sigma \sim 0.05 \), based on 228 stars in common with the Hughes & Wallerstein catalog.

The off-center field covered by the Mukherjee et al. (1992) \( uvby \)-band photometry does not overlap with fields for which \( u \)-band images are available in our catalog. On the other hand, an independent check on the accuracy of our \( u \)-band calibration has been performed comparing the location of hot horizontal branch (HB) stars (\( T_{\text{eff}} \geq 8500 \) K) in the \( [c] = [(u-b)-(b-y)] - 0.2 \times (b-y) \) versus \( u-y \) plane with similar stars in other globular clusters (Calamida et al. 2005, hereinafter CA05).

Finally, we estimated the weighted mean magnitudes between the different data sets, ending up with a merged catalog that includes \( \approx 185,000 \) stars, with an accuracy of \( \sim 0.03 \) mag at \( y \sim 19 \) mag. To our knowledge, this is the largest Strömgren photometric catalog ever collected for a GC.

The final catalog has been filtered by photometric accuracy and stars have been plotted in the \( y, b-y \) (left panel), \( y, v-y \) (middle), and \( y, u-y \) (right) color–magnitude diagrams (CMDs; Figure 5). In order to verify the current absolute calibrations, we performed a detailed comparison with theoretical predictions. In particular, we adopted the estimated true \( \omega \) Cen distance modulus provided by Del Principe et al. (2006), \( \mu = 13.70 \pm 0.06 \), and a mean reddening value of \( E(B-V) = 0.11 \pm 0.02 \) (CA05). The reader interested in a more detailed discussion of the \( \omega \) Cen distance is referred to Bono et al. (2008). The extinction coefficients for the Strömgren colors were estimated from the Cardelli et al. (1989) reddening law: \( E(m_1) = -0.3 \times E(b-y), E(b-y) = 0.70 \times E(B-V), E(v-y) = 1.33 \times E(B-V), \) and \( E(u-y) = 1.84 \times E(B-V) \). The solid lines in Figure 5 show two cluster isochrones at fixed age (\( t = 12 \) Gyr) and different chemical compositions, \( Z = 0.006, Y = 0.246 \) and \( Z = 0.004, Y = 0.251 \), while the dashed lines represent the corresponding zero-age horizontal branch (ZAHB) models. The evolutionary models, the bolometric corrections, and the CTRs adopted in this investigation were discussed by Cassisi et al. (2004) and by Pietrinferni et al. (2006). The stellar models and the color transformations were computed by assuming an \( \alpha \)-element enhancement of \([\alpha/Fe] = +0.4\) (Lee et al. 1999; PA00; Freyhammer et al. 2005) marked with a horizontal leftward arrow in the figure. A detailed fit to this small subpopulation is not a goal of the current investigation. On the other hand, the \( v-y \) and the \( u-y \) colors of some RGs are redder than those predicted by models. This scatter toward redder colors might be due to differential reddening or to CN/CH enhancements. Such enhancements typically produce redder \( v-y/u-y \) colors (Grundahl et al. 2002; CA07) than for chemically normal stars. Note that in a recent investigation

\[ \text{(CA05)} \]

Figure 5. From left to right (a) \( y, b-y \); (b) \( y, v-y \); and (c) \( y, u-y \) Strömgren CMDs of \( \omega \) Cen. Stars were selected according to photometric accuracy—\( \sigma - u, v \leq 0.05 \) mag, \( \sigma_{b-y} \leq 0.03 \) mag—and separation—\( \text{sep}_b, \text{sep}_{b-y}, \text{sep}_{v-y} \geq 3 \). The red and the green solid lines represent two cluster isochrones at fixed age (\( t = 12 \) Gyr) and different chemical compositions (see labeled values). The dashed lines show two ZAHBs for the same chemical compositions and a progenitor mass of 0.8\( M/\odot \). The turquoise solid line shows a young (\( t = 600 \) Myr), metal-poor cluster isochrone. The true distance modulus (\( \mu \)) and the reddening adopted to overlap the theoretical predictions are also labeled. Error bars plotted on the right side show the intrinsic photometric uncertainties in color at different \( y \) magnitudes. The horizontal arrows mark the location of the \( \omega \) 3 metal-rich RGB, while the other arrows represent the reddening vector. (A color version of this figure is available in the online journal.)
Stanford et al. (2007) suggested that ≈16%–17% of ω Cen SGB stars are either C or N enhanced.

The blue straggler (BS) sequence can be easily identified in the y, b–y and in the y, v–y CMDs, but they can barely be identified in the u–y CMD. This effect is due to the fact that the u and the y magnitudes of main-sequence (MS) structures (log $\sim$ 4.75), at fixed metal content ($Z \sim$ 0.0006), show similar decreases (1.42 versus 1.35 mag) when moving from an effective temperature of $\sim$10,000 K to $\sim$7000 K (see the turquoise 600 Myr isochrone plotted in Figure 5). In comparison, the b and the v magnitudes decrease, in the same temperature range, by 1.58 and 1.74 mag.

The HB is well populated ($\sim$2550 stars) in all the CMDs, and among them we find $\sim$270 are extreme horizontal branch (EHB) stars, i.e., HB stars with $y > 17.8$ and $u-y \sim 0$. It is noteworthy that in the same cluster area we identified $\approx$2900 HB stars in ground-based images collected with the Wide Field Imager (WFI@2.2 m ESO/MPG, La Silla) and in images collected with the Advanced Camera for Surveys (ACS; HST; Castellani et al. 2007, hereinafter CAS07). The combined catalog (WFI+ACS) can be considered complete in the magnitude range (14.5 $\lesssim y \lesssim$ 18). These star counts indicate that the current Strömgren images have allowed us to identify $\sim$ 90% of the HB stars measured in the WFI–ACS images. The ω Cen CMDs also show that our photometric catalog is contaminated by field stars, see, e.g., the vertical plume of stars located at $y < 14.5$ and $b-y \sim 0.4$, $v-y \sim 0.9$, and $u-y \sim 1.7$ mag. In Section 5, we briefly describe and adopt the procedure devised by CAS07 and by CA07 to properly identify candidate field and cluster stars.

4.2. Near-infrared Data

The final calibrated NIR star catalog includes $\sim$150,000 stars with photometric precision better than 0.1 mag, i.e., objects with at least 10 $\sigma$ detection significance. Panel (a) of Figure 6 shows the $K_s$, $J-K_s$ CMD selected according to $\sigma_{J,K_s}\leq 0.045$ mag and $sep_{K_s} > 10$ mag. The current NIR photometry has very good accuracy well below the TO region. To our knowledge, this is the largest IR CMD ever collected for a globular cluster. This notwithstanding, we have only marginally detected EHB stars ($K_s \gtrsim 17.5$) since they are very faint in the NIR bands. The cluster isochrones and the ZAHBs plotted in this figure are the same as in Figure 5. We also adopted the same distance and reddening, while for the extinction coefficients we have used $A_J = 0.282 \times A_V$ and $A_{K_s} = 0.116 \times A_V$, according to the Cardelli et al. reddening law. Theoretical models were transformed from the Bessell & Brett (1988) NIR photometric system to the Two Micron All Sky Survey (2MASS) photometric system using the transformations provided by Carpenter (2001). The cluster isochrones bracket, within the errors, the bulk of evolved and MS stars, while the ZAHBs appear to be, at fixed color, slightly brighter than hot HB stars.

5. SELECTION OF RG STARS

To study the ω Cen RG metallicity distribution, we selected only stars with magnitudes $y \lesssim 16.5$ mag, ending up with a sample of $\approx$13,000 stars. However, in order to avoid subtle systematic uncertainties in the metallicity estimates, this sample needs to be purged of the contamination of field stars. To do this, we used the optical–NIR color–color planes suggested by CAS07 and by CA07. The Strömgren photometry was cross-correlated with our NIR photometry in the central cluster regions (FOV $\approx 13 \times 13$, see Figure 2), while for the external regions we adopted the 2MASS NIR catalog (see Section 2.2). The 2MASS catalog has an astrometric precision of $\sim 100$ mas, and the magnitude limit ranges from $\sim 14.3$ for the K band to $\sim 15.8$ for the J band. In ω Cen these magnitude limits fall near the base of the RGB and the TO. The positional cross-correlation was performed with DAOMASTER, and we ended up with a
sample of \( \sim 64,000 \) stars having measurements in at least three of the four Strömgren bands and at least two of the three NIR bands.

Figure 6 shows representative optical–NIR CMDs, namely, \( K \), \( u-J \) (panel (b)), \( v-K \) (panel (c)), and \( b-J \) (panel (d)). The temperature sensitivity of optical–NIR colors is quite large, and indeed the \( u-J \) color increases by 8 mag when moving from hot HB stars (\( u-J \sim 0 \)) to cool giant stars (\( u-J \gtrsim 8 \)) near the RGB tip. The same applies to the \( v-K \) color, where the aforementioned star groups span a range of \( \approx 7 \) mag. In particular, the discrete nature of \( \omega \) Cen RGBs (S05a) and the split between asymptotic giant branch (AGB) and RGB stars can be easily identified in the three optical–NIR CMDs. The red and green lines display the same cluster isochrone as in Figure 5, and they correspond to the same distance modulus and extinction coefficients. Data plotted in Figure 6 show that, within the current uncertainties, theory and observations agree quite well. It is worth noting that BSs in the \( K \), \( b-J \) CMD (panel (d)) form a spur of blue stars well separated from the bulk of the old population at \( K \sim 16.5, \ b-J \sim 0.9 \). A more detailed comparison between theory and optical–NIR data will be discussed in a future paper.

In what follows, we have adopted the \( v-K \) versus \( u-J \) color–color plane to fully exploit the temperature sensitivity of optical–NIR colors in distinguishing cluster from field stars.

We first selected RG stars with measurements in the four Strömgren bands (\( u, v, b, y \)) and two NIR bands (\( J, K \)), ending up with a sample of more than 12,000 stars (see top panel of Figure 7). To define the fiducial cluster sequence in the \( u-J, v-K \) plane, we selected the stars at distances from 0.5 to 1' from the cluster center (see black dots in the top panel of Figure 7). In this plane, the distribution of the cluster RG sequence is not linear, so we adopted a fourth-order polynomial to represent the RGB.\(^\text{20}\) Then, we estimated the difference in color between individual RG stars and the fiducial cluster sequence. The bottom panel of Figure 7 shows the logarithmic distribution of the color excess \( \Delta (u-J) \) for the entire sample. We fitted the distribution with a Gaussian function and considered only those stars with \( \Delta (u-J) \lesssim 2.5 \times \sigma_{u-J} \) as \( \text{bona fide} \) \( \omega \) Cen RG stars. The red dots in the top panel of Figure 7 mark the candidate field stars after this selection.

Subsequently, we selected only stars from the MH data set with measurements in the Strömgren \( v, b, y \) bands (1497 RGs) \( \text{and in the } J, K \) NIR bands that were not included in the previous

\(^{20}\) CA07 found that in the \( u-J \) versus \( b-H \) color–color plane, RG stars in typical GCs obey linear trends. The nonlinear trend we have found for \( \omega \) Cen RG stars here is due partly to the adoption of a different optical–NIR color–color plane and partly to the metallicity dispersion among \( \omega \) Cen stars.
those stars having the distribution with a Gaussian function, we considered only the distribution (bottom panel) of the color excess the selected stars plotted in this plane, and the logarithmic the RG sample of field star contamination. Figure 8 shows the $b–J$ selection. In this case, we adopted the Str"omgren bands and in two NIR bands. The original sample was thus reduced by roughly 10%.

Subsequently, in order to improve the selection of candidate field stars we also re-identified a subsample of our optical catalog in the proper-motion catalog of van Leeuwen et al. (2000, hereinafter LE00). The average proper-motion precisions catalog in the proper-motion catalog of van Leeuwen et al. were 14 mas. The cross-identification was performed in several steps: (1) the IRAF/IMMATCH package was used to establish a preliminary spatial transformation from the Str"omgren catalog CCD coordinates to the reference catalog equatorial (J2000.0) system for a subsample of matched entries separated by more than 0.56 arcsec. This provided us with reliable equatorial coordinates and proper motions for matching stars in the Str"omgren data set.

Then, we performed a selection by proper motion. In particular, we considered as cluster members those stars with membership probabilities (see LE00) higher than 65%. This additional selection further decreased the sample of candidate RG members by $\approx 2\%$. The final catalog includes 12,700 probable \Cen RG stars.

To test the plausibility of the procedures adopted to disentangle \Cen members from field stars, the top panels of Figure 9 show from left to right the distribution in the $m_1$, $u–y$ plane of the original RG sample selected by photometric precision ($\sigma_{u–y} < 0.015$ mag and $\text{sep}_{r,b,y} \geq 3$) and of the sample after the selection in the optical–NIR color–color plane. Figure 9 shows that \Cen RGs do not follow a well-defined sequence on the $m_1$, $u–y$ plane, as the other GCs do (see CA07). The RG stars in \Cen show a wide spread in color that cannot be explained as photometric errors or differential reddening (see the error bars and the reddening vector plotted in Figure 9). The bottom panels of Figure 9 show the same RG sample (black dots) plotted in the $y$, $u–y$ (left) and in the $b–y$ (right) CMDs; overplotted are the candidate field stars after the selection in the optical–NIR color–color plane (red dots), and after the selection by proper motion (turquoise dots). It is noteworthy that most of the field stars have magnitudes and colors that are very similar to the probable cluster RG stars.

As a final validation of the two selection procedures, we compared the radial distribution of candidate \Cen RGs and field stars. Figure 10 shows the two logarithmic distributions and the flat trend of field stars (dashed line) is quite evident when compared with the steeper and more centrally concentrated distribution of likely \Cen stars (solid line). It was already noted by CA07 that the mild decrease in the number of apparent field coincidence and initially also on apparent stellar brightness, (3) the previous steps were reiterated two or three times until the ultimate transformation permitted a near-complete matching, and then (4) the final, matched sample of common stars excluded entries separated by more than 0.56 arcsec. This provided us with reliable equatorial coordinates and proper motions for matching stars in the Str"omgren data set.

A color version of this figure is available in the online journal.

**Figure 9.** Top: \Cen RG stars selected in photometric error ($\sigma_{b–y} < 0.015$ mag) and separation ($\text{sep}_{r,b,y} \geq 3$) and plotted in the $m_1$, $u–y$ plane (left). The right panel shows candidate \Cen RG stars ($Ms = 3940$) plotted in the same plane. Candidate cluster stars were selected according to optical–NIR colors ($\Delta(b–J) \leq 1.5 \times \sigma_{b–y}$) and membership probability higher than 65%. Bottom: Str"omgren CMDs $y$, $u–y$ (left) and $b–y$ (right) for cluster and field star candidates. The black dots mark candidate \Cen RG stars, while red dots mark candidate field stars selected according to the optical–NIR color–color selection (NM$_s = 490$). The turquoise dots mark probable field stars according to the proper-motion selection (NM$_s = 135$). The error bars account for uncertainties in intrinsic photometric errors. The arrows show the reddening vector.

**Figure 10.** Radial distribution of candidate \Cen RG stars (solid line) and of field stars (dashed line). The latter sample includes stars selected according to the optical–NIR color–color planes and to the proper motions.
stars in the outskirt of the cluster suggests that our color–color selection is very conservative, and some real cluster members have probably been erroneously rejected. However, in these photometric selections it is more important to keep the probable nonmembers out than to keep probable members in (ATT00).

6. A NEW CALIBRATION OF THE $m_1$, $b$–$y$ METALLICITY RELATION

In CA07, we provided new empirical and semiempirical calibrations of the $m_1$ metallicity index based only on cluster RG stars. These new MIC relations were then validated on the basis of GC and field RGs with known spectroscopic iron abundances in the Zinn & West (1984) metallicity scale, and were found to provide metallicity estimates with an accuracy of the order of 0.2 dex. The main difference between the CA07 MIC relations and similar relations available in the literature is that the former adopt the $u$–$y$ and $v$–$y$ colors instead of $b$–$y$. The main advantage of the $u$–$y$ and $v$–$y$ colors is the stronger temperature sensitivity, and the MIC relations show a linear and well-defined slope in the $m_1, u - y/v - y$ planes. However, the $u$–$y$ and the $v$–$y$ colors also have a drawback: they are affected by carbon (C) and/or nitrogen (N) enhancements (CA07). To investigate the different behavior of the $u$–$y$, $v$–$y$, and $b$–$y$ colors as a function of the CH and the CN abundances, we also performed a metallicity calibration based on the $b$–$y$ color. We found that this MIC relation shows a nonlinear trend over the typical color range of RG stars, namely, $0.42 < (b - y)_0 < 1.05$ (see Figure 2 of Calamida et al. 2007b, hereinafter CA07b). Therefore, we included a quadratic color term to characterize the calibration (see also HR00; CA07b). Specifically, we estimated a semiempirical calibration based on the $b$–$y$ color of the theoretical evolutionary models by Pietrinferni et al. (2006) for an $\alpha$-enhanced ([\alpha/Fe] = 0.4) mixture. Theoretical predictions were transformed to the observational plane with the semiempirical CTRs provided by Clem et al. (2004). We adopted the procedure described in CA07 and applied a multilinear regression fit to estimate the coefficients of the MIC relation:

$$m_0 = \alpha + \beta \cdot [\text{Fe/H}] + \gamma \cdot \text{CI}_0 + \delta \cdot ([\text{Fe/H}] \cdot \text{CI})_0 + \epsilon \cdot \text{CI}_0^2 + \zeta \cdot ([\text{Fe/H}] \cdot \text{CI})_0^2,$$

where $m_0 = m_{10}$ and CI$_0$ are the unreddened color indices. Similar relations were also derived for the reddening-free $m_1 = m_{10} + 0.3 \times (b - y)$ index. Together with the calibration of semiempirical MIC relations, we performed an independent empirical calibration using the observed colors of RG stars in selected GCs, M92, M13, NGC 1851, and NGC 104, for which accurate Strömgren photometry is available (Grundahl et al. 1998; CA07). These GCs cover a broad range in metal abundances ($-2.2 < [\text{Fe/H}] < -0.7$) and are minimally affected by reddening ($E(B - V) \leq 0.04$). The coefficients of the fit of both semiempirical and empirical MIC relations are listed in Table 11. In order to validate the new MIC relations, we decided to apply them to nine GCs for which accurate Strömgren photometry, absolute calibration, and sizable samples of RG stars are available. They are M92, NGC 6397, M13, NGC 1851, NGC 104. Table 12 lists spectroscopic and photometric metallicities for these clusters. Note that five out of the nine GCs had been adopted to calibrate the empirical MIC relations. We find a good agreement for both the empirical and the semiempirical MIC relations. The comparison between the mean photometric metallicity estimates and the spectroscopic measurements indicates that they agree with each other within 1$\sigma$ uncertainties. It is noteworthy
that the accuracy of photometric metallicity estimates applies not only to metal-intermediate (MI) clusters with low reddening corrections (NGC 288, $E(B - V) \approx 0.02$), but also to more MR clusters with high reddening (M71, $E(B - V) \approx 0.30$; Harris 1996).

To further constrain the calibration of the new MIC relations, we decided to compare them with $m_0, (b - y)_0$ metallicity calibrations available in the literature. We adopted the field RG sample by Anthony-Twarog & Twarog (1994, hereinafter ATT94) and Anthony-Twarog & Twarog (1998, hereinafter ATT98), already used by CA07. The interested reader is referred to this paper for more details concerning the selection of the RG sample.

We compared the photometric metallicities of 59 out of the 79 stars for which ATT94 provided an estimate. The spectroscopic and the photometric metallicity distributions are in fair agreement. The mean differences are $0.02 \pm 0.03$, with a dispersion of $0.22$ dex (ATT94) and $0.13 \pm 0.03$, with a dispersion of $0.20$ dex (H00). The small difference between the current errors and the original ones derived by ATT94 and H00 is only due to the different selection criteria. The mean differences using the same 59 stars and current empirical and semiempirical MIC relations are $-0.12 \pm 0.02$ and $-0.15 \pm 0.02$ dex, with a dispersion of $0.15$ and of $0.18$ dex, respectively. Figure 11 shows the comparison between the spectroscopic metallicity distribution (dashed line) and the metallicity distribution obtained with the empirical MIC relation based on the $(m_0, (b - y)_0)$ calibration by ATT94. The middle panel shows the comparison with the metallicity distribution based on our empirical and semiempirical $(m_0, (b - y)_0)$ MIC relations for the complete sample of 79 RG stars. The bottom panel shows the comparison with the metallicity distribution based on the empirical MIC relation $(m_0, (b - y)_0)$ provided by H00 for 73 out of the 79 RG stars with $-2.3 < [Fe/H] < -0.4$. Data plotted in the top and in the middle panel of Figure 11 indicate that spectroscopic and photometric metallicity distributions agree quite well. The metallicity distribution based on the H00 calibration appears slightly more MR ($\sim 0.13$ dex). These data show that metal-abundance estimates for the ATT98 sample based on the $(m_0, (b - y)_0)$ MIC relations are shifted by $\sim 0.14$ dex, as already found by CA07 for empirical and semiempirical $(m_0, (b - y)_0); m_0, (u - y)_0)$ relations. They suggested that this difference might be due to the different approach (cluster versus field RGs) in the calibration of the $m_1$ index. In spite of this systematic difference, the intrinsic dispersion of the difference between photometric and spectroscopic metallicities is smaller than 0.2 dex, and it is mainly due to photometric, reddening, and spectroscopic errors (see Figure 2 of CA07b).

7. COMPARISON BETWEEN PHOTOMETRIC AND SPECTROSCOPIC IRON ABUNDANCES

To estimate the metal content of the selected $\omega$ Cen RG stars, we adopted the MIC relations provided by CA07 (see their Table 3) and based on the $u - y$ and on the $v - y$ color, together with the new MIC relation derived in Section 6. The photometric metallicities were estimated using both the empirical and the semiempirical calibrations. The individual metallicities were estimated by assuming for $\omega$ Cen a mean reddening value of $E(B - V) = 0.11$ (CA05) and the extinction coefficients for the Strömgren colors discussed in Section 4.

To verify the accuracy of the metallicity estimates, we cross-correlated our RG sample with the iron abundances—based on high-resolution spectra—of 40 ROA stars provided by ND95. We found 39 RG stars in common. Moreover, we matched our photometric catalog with the iron abundances—again based on high-resolution spectra—of 10 MR RGs provided by PA02. Two of these stars (ROA 179, 371), are also in the ND95 sample. We also adopted the iron abundances provided by SM00 for four RGs in common with the ND95 sample (ROA 102, 213, 219, 253) based on similar high-resolution spectra. We ended up with a sample of 47 RGs with accurate iron measurements for which we have either three (47, vby) or four (28, wbv) independent Strömgren magnitudes. The difference between the inferred photometric metallicities and the spectroscopic measurements are plotted versus spectroscopic abundances in Figure 12. The four different panels display metallicity estimates based on different empirical MIC relations. Data plotted in this figure indicate that photometric and spectroscopic abundances are in reasonable agreement. The mean difference for the four MIC relations is $\langle \Delta [Fe/H] \rangle = \langle [Fe/H]_{\text{spec}} - [Fe/H]_{\text{phot}} \rangle = 0.17 \pm 0.01$ dex, with a dispersion of $0.31$ dex. Once we remove CN-strong and chemically peculiar stars (vide infra), the scatter around the mean is mainly due to photometric and spectroscopic measuring errors. The error bars on the top panel of Figure 12 display the entire error budget. Note that throughout the paper with the symbol $[Fe/H]_{\text{phot}}$ we mean the overall stellar metallicity, i.e., the sum of all elements beyond helium (VandenBerg et al. 2000).

Uncertainties in reddening corrections minimally affect the current metallicity estimates, and indeed the photometric metallicities based on the reddening-free metallicity index, $[m_i]$ have similar differences and dispersions (panels (b) and (d)). The
same outcome applies to photometric metallicities based on empirical and on semiempirical MIC calibrations. However, eight RG stars with iron abundance ranging from $[\text{Fe/H}]_{\text{spec}} = -1.7$ to $-0.9$ (ROA 53, 100, 139, 144, 162, 253, 279, 480) present larger $(\Delta[\text{Fe/H}] > 0.3$ dex) differences. Interestingly, six of them (marked with crosses in Figure 12) are CN-strong stars, while ROA 279 (marked with an asterisk) is a CH-star (see, e.g., ND95). The CN-weak star ROA 53 has $\Delta[\text{Fe/H}] \approx 0.8$ dex, but the photometric metallicity is probably affected by poor photometric precision ($\sigma_{v,b,y} \approx 0.05$). The other three discrepant stars, with $[\text{Fe/H}]_{\text{spec}} \gtrsim -1.0$, belong to the PA02 sample. However, the PA02 spectroscopic measurements for the two ROA stars in common with ND95 are more MR by $\approx 0.2$ dex. This systematic difference has already been discussed by PA02. On the other hand, the iron abundances provided by ND95 and SM00 for the same RGs agree within the uncertainties. This suggests that these more MR discrepant objects deserve further investigation.

If we neglect the CN-strong stars, the CH-star, the ROA 53, and the three stars from the PA02 sample, the mean difference for the four MIC relations is $0.02 \pm 0.02$ dex, with a dispersion of the residuals of $\sigma \approx 0.16$ dex.

To further constrain the plausibility of our findings, we performed the same comparison using 28 stars for which $u$-band photometry is available. Figure 13 shows the difference between photometric and spectroscopic abundances using both empirical (panels (a) and (b)) and semiempirical (panels (c) and (d)) calibrations. The result is quite similar to the MIC relation based on the $v-y$ color, and indeed the mean difference is $\langle \Delta[\text{Fe/H}] \rangle = 0.26 \pm 0.02$ dex, and the dispersion of the residuals is $\sigma \approx 0.36$ dex. The star ROA 248 ($[\text{Fe/H}] = -0.78$ dex) shows a large discrepancy $\Delta[\text{Fe/H}] \approx 0.6$. However, ROA 248 could be a candidate CN-strong star, as suggested by the large value of the cyanogen index, $S3839 = 0.51$ (ND95), and its peculiar position in the $m_0, (v-y)_0$ plane and in the $y_0, (v-y)_0$ CMD (see Figure 14). If we neglect the five CN-strong stars, the stars ROA 248, ROA 53, and the three stars from PA02, for which the discrepancy in this plane is even larger, the mean difference for the four MIC relations is $0.07 \pm 0.03$ dex, with a dispersion of $\sigma = 0.16$ dex.

We performed the same test using the empirical and the semiempirical $m_0, (b-y)_0$ MIC relations and we found that the mean difference over a sample of 47 objects is $\langle \Delta[\text{Fe/H}] \rangle = 0.22 \pm 0.05$ dex, and the dispersion of the residuals is $\sigma \sim$
σ = The mean difference is ND95. The error bars account for both photometric and spectroscopic errors. have a spectroscopic CN-band measurement. a mean difference of 0.05 ± σ/3 dex. The stars with δCN > 0.2, see Section 9) or to that of ND95. Data plotted in this figure show that CN-strong stars are, as expected, concentrated among the more MR stars ([Fe/H] ⩾ −1.5; Gratton et al. 2004). The mean difference between photometric and spectroscopic abundances, using the six different MIC relations, is Δ[Fe/H] = 0.05 ± 0.03 and σ = 0.37 dex. Once again we found that the dispersion of the residuals is larger in the m0, (b−y)b plane than in the m0, (v−y)b relation (0.36 versus 0.42, empirical; 0.33 versus 0.40, semiempirical).

It is worth mentioning that 25 out of the 118 stars show discrepancies in iron abundance larger than 0.3 dex. The measurement of the CN index is available for thirteen of these stars and among them 10 are CN-strong. If we move the limit down to 0.2 dex, the number of discrepant stars is 46, and the CN index is available for 20 of them. The fraction of CN-strong stars becomes of the order of 75%. On the other hand, 17 stars appear to be underabundant in iron by more than 0.3 dex; among them 10 have measurements of the CN index and only one is a CN-strong star. The current findings thus indicate that stars with large positive discrepancies in the photometric metallicity are highly correlated with the occurrence of strong CN bands. The stars with large negative discrepancies require a more detailed spectroscopic investigation to constrain their abundance pattern. If we neglect the CN-strong stars, we find a mean difference of Δ[Fe/H] = 0.02 ± 0.04 and σ = 0.37 dex (93 stars).

As a final test of the intrinsic accuracy of the photometric abundances, we plotted the 118 RGs by J08 (open circles), the
39 ROA stars (open triangles), and the 8 RGs by PA02 (open diamonds) onto the \( m_0 \), \((v−y)_0 \) plane (Figure 15, top panel). The spectroscopic stars have the expected \( m_0 \)/color distribution with the eight MR RGs by PA02 attaining the largest \( m_0 \) values and color the faintest apparent \( y_0 \) magnitudes at fixed color (bottom panel). The plausibility of their MR nature is also supported by the fact that six of them are located along the anomalous RGB \((ω \text{ Cen})\). It is noteworthy that CN-strong stars (crosses) possess intermediate \( m_0 \) values and apparent \( y_0 \) magnitudes. This finding should not be affected by selection effects, since the low-resolution spectra collected by V07 cover a significant fraction of the RG branch in \( ω \text{ Cen} \) (down to \( V \sim 16 \)). The same outcome applies for the CH-star (asterisk), while the candidate CN-strong star ROA 248 (plus) shows the largest \( m_0 \) value and the reddest \((v−y)\) color in the sample, thus supporting its peculiar nature.

The above results highlight three relevant findings. (1) Photometric iron abundances agree quite well with spectroscopic measurements, and indeed the mean difference is, within the errors, negligible. This supports the hypothesis suggested by CA07 (see also Section 6) that the discrepancy between photometric and spectroscopic abundances found for field RG stars is caused by an intrinsic difference in their abundance patterns. (2) The MIC relations based on the \((u−y)\) and \((v−y)\) color are more affected by C and N enhancements. Two strong CN absorption bands at \( λ = 4142 \) and \( λ = 4215 \) Å are close to the effective wavelength of the \( v \) \((λ_{\text{eff}} = 4110 \) Å \)) filter, while the two CN bands at \( λ = 3590 \) and \( λ = 3883 \) Å affect the \( u \) \((λ_{\text{eff}} = 3450 \) Å \)) filter (see, e.g., Smith 1987; Bell & Gustafsson 1978; ATT94; H00; Grundahl et al. 2002; CA07). Although these MIC relations depend on CN both in the \( m_1 \) index and in the color, they provide more robust photometric abundances when compared with the \( m_0 \), \((b−y)_0 \) relation, due to their stronger temperature sensitivity. (3.) The dispersion of the residuals between photometric and spectroscopic abundances is of the order of \( 0.3\)–\(0.4 \) dex. However, the dispersion decreases by at least a factor of 2 if all the stars appearing to have abundance anomalies (ND95 data) are removed from the sample.

8. PHOTOMETRIC METAL-ABUNDANCE DISTRIBUTIONS

In the previous section, we have investigated pros and cons of the different MIC relations to estimate the metal content of RG stars. To constrain the metallicity distribution of \( ω \text{ Cen} \) RGs, we selected the stars with photometric precision \( σ_{u,b,y} ⩽ 0.015 \) and, \( σ_u \leq 0.02 \) mag, and \( sep > 3 \). Moreover, we excluded all the stars with colors redder/bluer than the color range covered by empirical and semiempirical calibrations (CA07). We ended up with a sample of 3953 RGs; among them 2846 stars also have the \( u\)-band measurement. Independent estimates of the photometric metallicity were obtained from the three different MIC relations and the two calibrations.21 Figure 16 shows the six different metallicity distributions for the selected RGs. The individual distributions were smoothed with a Gaussian kernel having a standard deviation equal to the photometric error in the \( m_1 \) index. To provide a robust fit of the metallicity distributions, we developed an interactive program that performs a preliminary Gaussian fit of the main peaks. On the basis of the residuals between the metallicity distributions and the analytical fit, the software allows us to insert manually new Gaussian components. At each step, the code computes a new global solution and the procedure is iterated until the residuals are vanishing. We fit the distributions with a sum of seven Gaussians and the dashed lines plotted in Figure 16 display the cumulative fits, while the asterisks mark the position of the different Gaussian peaks. The peaks and the sigma of the different Gaussian fits are listed in Table 13.

The shape of the metallicity distributions is, as expected, asymmetric with a sharp cutoff in the MP tail \([\text{Fe/H}]_{\text{phot}} < −2\) and a MR tail approaching solar iron abundances. The different MIC relations and the different calibrations show, within the errors, very similar metallicity distributions. The same conclusion applies to the peaks in the metallicity distribution (see Table 13). The peaks according to the six calibrations are located at \([\text{Fe/H}]_{\text{phot}} = −1.73 \pm 0.08, −1.29 \pm 0.03, −1.05 \pm 0.02, −0.80 \pm 0.04, −0.42 \pm 0.12, \) and \( −0.07 \pm 0.08 \) dex, where the uncertainties are the standard errors of the mean. A handful of objects seems to show supersolar iron abundance—\([\text{Fe/H}]_{\text{phot}} ≈ 0.24 \pm 0.13\)—but this sample vanishes in the \( m_0 \), \((u−y)_0 \) distribution and might be caused by CN-strong stars of the MR peak at \([\text{Fe/H}]_{\text{phot}} ≈ −0.07 \) dex. These findings are minimally affected by uncertainties in reddening corrections, since the metallicity distributions based on the reddening-free \([m]\) index are very similar (Calamida 2007).

The four most significant peaks \((-1.73 < [\text{Fe/H}] < −0.80)\) in the photometric iron distributions agree quite well with the spectroscopic peaks measured by J08 (see their Figure 10). Iron abundances based on high-resolution spectra also suggest the presence in \( ω \text{ Cen} \) of more MR stars \(([\text{Fe/H}] = −0.60 \pm 0.15 \) stars (ND95; PA02; Pancino 2004). The outcome is the same if we compare photometric abundances with metallicity distributions based on low- and medium-resolution spectra. These investigations are typically based on measurements of the calcium triplet \((N96, 517 \text{ RGBs}; SK96, 343 \text{ RGBs}; S05b, 152 \text{ SGBs}; Stanford et al. 2006, 442 \text{ MSs})\) that are transformed into iron abundances via empirical relations, or on direct iron line measurements \((H04, \sim 400 \text{ MSs and SGBs}; van Loon et al. 2007, hereinafter VL07, \sim 1500 \text{ HBs and RGBs}; Villanova et al. 2007, 80 \text{ SGBs})\). In particular, the MR tail in the metallicity distributions based on larger cluster samples approaches \([\text{Fe/H}] \sim −0.5 \pm 0.2 \) dex. The metallicity distributions based on photometric indices \((HR00, m_1\text{-index}, \sim 1500 \text{ RGs}; Rey et al. 2000, kk\text{-index} 131 \text{ RR Lyrae}; Hughes et al. 2004, m_1\text{-index}, \sim 2500 \text{ MSs, SGBs, RGBs})\) also provide similar results.

The large number of RGs allows us to identify four different metallicity regimes: MP with \([\text{Fe/H}] < −1.5, \) MI with \( −1.5 < [\text{Fe/H}] < −1.0, \) MR with \( −1.0 < [\text{Fe/H}] < −0.1, \) and solar metallicity \((\text{SM})\) with \([\text{Fe/H}] ≈ 0 \) dex (see vertical dotted lines in Figure 16). The limits of these metallicity regimes are arbitrary, though identified with the occurrence of either a local minimum or a shoulder in the metallicity distribution.

Following the anonymous referee suggestion, we estimated the average metallicity distributions of both empirical and semiempirical MIC relations (see Figure 17). We performed on the average distributions the same Gaussian fits adopted for the individual distributions. Data plotted in Figure 17 (see also Table 13) show that both the peaks and the metallicity regimes are, within the errors, quite similar. The difference between the cumulative fits and the metallicity distributions suggests the possible occurrence of a secondary peak located at the edge between the MR and SM regime \(([\text{Fe/H}] \sim −0.25)\).

21 The selected photometric catalogs including colors and metallicity can be retrieved from the following URL:
http://www.mporzio.astro.it/~marco/spress/
Figure 16. Distribution of photometric iron abundances based on empirical (top) and semiempirical (bottom) calibrations of different MIC relations. The sample size of the $m_0, (u-y)_0$ (left), of the $m_0, (v-y)_0$ (middle), and of the $m_0, (b-y)_0$ (right) relations are also labeled. The metallicity distributions were smoothed with a Gaussian kernel with a $\sigma$ equal to the individual intrinsic error on the $m_1$ index. The dashed line shows the fit of the metallicity distribution computed as the sum of seven Gaussians. The asterisks mark the peaks of the seven Gaussians. The vertical dotted lines display the different metallicity regimes: metal-poor (MP), metal-intermediate (MI), metal-rich (MR), and solar-metallicity (SM).

Table 13
Peaks and Sigmas of Multi-Gaussian Fits to the RG Metallicity Distributions Based on the Different MIC Relations

| Relation | MP | MI | MR | SM | Average | SemiAverage |
|----------|----|----|----|----|---------|-------------|
| $m_0, (u-y)_0$ | -1.74/0.32 | -1.26/0.09 | -1.03/0.11 | -0.81/0.11 | -0.48/0.24 | -0.07/0.21 | 0.32/0.09 |
| $m_0, (v-y)_0$ | -1.70/0.32 | -1.29/0.10 | -1.06/0.07 | -0.79/0.29 | -0.20/0.11 | -0.02/0.02 | 0.16/0.22 |
| $m_0, (b-y)_0$ | -1.79/0.26 | -1.30/0.15 | -1.04/0.09 | -0.79/0.16 | -0.46/0.15 | -0.06/0.21 | 0.35/0.10 |
| Average | -1.72/0.31 | -1.30/0.09 | -1.09/0.09 | -0.88/0.10 | -0.61/0.22 | -0.03/0.17 | 0.32/0.08 |

Notes.

a Peak and sigma in the metal-poor (MP) regime ([Fe/H] $\leq -1.49$ dex).

b Peaks and sigmas in the metal-intermediate (MI) regime ($-1.49 < [Fe/H] \leq -0.93$ dex).

c Peaks and sigmas in the metal-rich (MR) regime ($-0.93 < [Fe/H] \leq -0.19$ dex).

d Peaks and sigmas in the solar metallicity (SM) regime ([Fe/H] $> -0.19$ dex).

e Average either of empirical or semiempirical calibrations (see Figure 17).

f Weighted mean peak values of the six MIC relations. The uncertainties are the errors on the mean. The typical uncertainty in the position of the individual peaks is $\pm 0.04$ dex, i.e., the bin size adopted in the metallicity distributions.
The main findings concerning the metallicity distributions in ω Cen according to the photometric abundance estimates are the following.

1. The metallicity distribution shows a very sharp cutoff in the MP regime, and the fraction of stars more MP than [Fe/H] ≈ −2.0 dex is vanishing.

2. The main iron peak is located at [Fe/H] ≈ −1.73 ± 0.08 dex, and the weighted mean fraction of stars in this MP regime ([Fe/H] ≤ −1.49) is ∼39% ± 1%. However, four out of the six metallicity distributions show either a double peak or a shoulder (m0, (u−y)0; m0, (v−y)0; see Figure 16). The distance between the two peaks is on average of the order 0.2 dex. The large number of stars per bin and the minimal impact of CN-strong stars in this metallicity range suggest that the split is real.

3. The MI regime (−1.49 < [Fe/H] ≤ −0.93) includes two secondary peaks ([Fe/H] ≈ −1.29 ± 0.03 [MII], −1.05 ± 0.03 [M2] dex) and a weighted mean fraction of stars of ∼32% ± 1%.

4. The MR regime (−0.93 < [Fe/H] ≤ −0.19) also includes two secondary peaks ([Fe/H] ≈ −0.80 ± 0.04 [MR1] −0.42 ± 0.13 [MR2] dex) and has a weighted mean fraction of stars of ∼19% ± 4%. In the spectroscopic metallicity distributions available in the literature, the last two peaks become more evident as soon as the sample size becomes of the order of several hundred stars.

5. In the SM regime ([Fe/H] ≈ 0) two secondary peaks are also present ([Fe/H] ≈ −0.07 ± 0.08 [SM1], 0.24 ± 0.13 [SM2] dex), but only with a small fraction of stars (∼8% ± 5%). This tail should be treated with caution, since we still lack firm spectroscopic evidence for the presence of RGs with solar iron abundances in ω Cen. Moreover, we cannot exclude the possibility that these objects either are affected by strong C and/or N enhancements, or belong to the Galactic field population.

6. The difference in iron content among the individual peaks is roughly constant and equal to a factor of 3–4 (−1.7, −1.2, −0.6, and 0 on the logarithmic abundance scale).

7. The fraction of stars belonging to the different metallicity regimes steadily decreases when moving from the MP to the MR domain. The relative fractions based on the different photometric diagnostics are in fair agreement (see Table 14). There are three exceptions. (1) The m0, (u−y)0 indicates a larger fraction of MP stars when compared with the other MIC relations (48% ± 2% versus 38% ± 1%). The difference might be due to the stronger sensitivity of this color in the faint RG limit (see left panel of Figure 18 and Figure 11 in CA07). To validate this working hypothesis, we estimated the same fractions using only bright RGs (y0 < 15) and we found that the new values, within the uncertainties, agree quite well (52% ± 2% versus 49% ± 2%). This evidence suggests that the current fraction of MP stars should be considered as a lower limit. (2) The m0, (v−y)0 indicates a larger fraction of MR stars when compared with the other MIC relations (24% ± 1% versus 17% ± 1%). The difference is almost certainly due to the stronger sensitivity of this color to CN-strong stars. This hypothesis is also supported by the slow decrease that the metallicity distribution shows in this abundance interval (see the middle panels in Figure 16). (3) The m0, (b−y)0 diagram indicates a significantly larger fraction of SM stars when compared with the other MIC relations (14% ± 1% versus 6% ± 1%). The difference is due to the lesser sensitivity of this color in the MR regime (see the right panel in Figure 18).

Current findings agree well with the metallicity distribution function obtained by S05a using broadband photometry of RG stars (1364). In particular, they found a well-defined MP peak ([Fe/H] ≈ −1.6 dex), three MI peaks ([Fe/H] ≈ −1.4, −1.1, −0.9 dex) and a sharp peak in the MR tail ([Fe/H] ≈ −0.6 dex,
Figure 18. Unreddened Strömgren CMDs for RGs characterized by different mean iron abundances. The blue dots mark metal-poor (MP) RGs, the green dots metal-intermediate (MI) RGs, the red dots metal-rich (MR) RGs, and the purple dots the solar metallicity (SM) RGs. The individual sample sizes and the metallicity intervals are labeled.

(A color version of this figure is available in the online journal.)

see their Figure 8). The same outcome applies to the relative fraction of RG stars in the quoted metallicity regimes (see their Table 2).

To test the plausibility of the selected metallicity regimes, Figure 18 shows the distribution of four different stellar groups with different mean metal abundances in three different CMDs. The MP sample are RGs located around the main peak, i.e., $[\text{Fe}/\text{H}] \approx -1.70 \pm 0.08$, while the other samples are located near other three main peaks: MI for $[\text{Fe}/\text{H}] \approx -1.23 \pm 0.08$, MR for $[\text{Fe}/\text{H}] \approx -0.66 \pm 0.08$, and SM for $[\text{Fe}/\text{H}] \approx -0.10 \pm 0.08$ dex. Data plotted in the left panel show a well-defined $u-y$-color ranking over the entire magnitude range when moving from the MP (blue dots) to the MI (green dots), MR (red dots), and SM (purple dots) RGs. The result is the same for the $v-y$-color (middle panel), but the SM stars located along the $\omega 3$ branch show a larger color scatter and the four different groups merge in the faint magnitude range ($y_0 < 15$). The degeneracy becomes more evident when moving to the $b-y$-color (right panel).

The anonymous referee raised the problem that the CN molecular bands affect the Strömgren $u$ and $v$ bands. Therefore, the Strömgren MIC relations cannot be adopted to estimate $[\text{Fe}/\text{H}]$ values in complex systems unless one has a knowledge of the strength of those CN bands. However, some circumstantial evidence move against this working hypothesis.

1. In this investigation, we are not attempting to estimate an iron content that is identical to the iron abundance measured by spectroscopist using high-resolution spectra. We have clearly stated that with $[\text{Fe}/\text{H}]$, we mean a global metallicity, i.e., the sum of all elements beyond helium without explicit assumptions concerning the relative distribution among those elements. Plain physical arguments indicate that the sensitivity of the Strömgren indices to metallicity comes from changes to the stellar structure—such as envelope opacity, and consequently stellar radius as a function of luminosity—and not merely from atmospheric spectral features. For this reason, a photometric index representing “all metals” is a crude zeroth-order estimate of the chemical content of a star. These metallicity estimates are adopted to rank RG stars according to their heavy element content and to detect sample of stars characterized by different relative “metal” abundances.

2. The occurrence of strong molecular bands increases the dispersion in the mapping of heavy element abundances. However, even though the Strömgren indices do not provide an exact equivalence with the iron abundance they still give a meaningful correlation with the star global metallicity. The presence of this correlation is supported by these evidence: (1) metallicity distributions based on MIC relations, with different sensitivities to the CN molecular bands, show similar peaks and valleys (see Figure 16); (2) the position of peaks and valleys in the mean metallicity distributions (see Figure 17) are, within the errors, very similar to the individual ones; (3) the RG stars show a well-defined drift in color in the CMD, when moving from MP to MR stars (see Figure 18); (4) the main peaks of current metallicity distributions agree quite well with spectroscopic measurements. These findings indicate that metallicity estimates based on Strömgren MIC relations are a robust diagnostic to identify stellar populations characterized by different global metallicities.

3. Accurate spectroscopic measurements indicate variations in the heavy element abundance on a star-by-star basis in all GCs. Together with changes in the relative abundances of CNO elements, well-defined anticorrelations have been found between O and Na and between Mg and Al. Field RG stars do not show the above chemical anomalies (Gratton et al. 2004). To provide homogeneous metallicity estimates of cluster RGs, we provided new calibrations of the Strömgren metallicity indices using cluster RG stars. These calibrations appear to be more appropriate in dealing with cluster RGs than similar calibrations available in the literature. However, a detailed comparison between photo-
metric and spectroscopic (CNO, α-elements) metallicities is required before reaching a firm conclusion.

9. ABUNDANCE ANOMALIES AMONG RG STARS

9.1. CN-strong Stars

To further constrain the evolutionary and chemical properties of ω Cen RGs, we cross-correlated our photometric catalog with the large set (1519 stars) of low-resolution spectra recently collected by VL07. These spectra were cross-correlated with the proper-motion measurements by LE00 and candidate cluster stars were selected according to a membership probability larger than 90%. We found 373 RG stars in common. Figure 19 shows the S3839 (CN) index for these stars measured by VL07 following the definition of Norris et al. (1981). To select the CN-strong stars, we adopted the δCN parameter—the CN excess according to the definition by Smith (1987). We defined as CN-strong stars the objects that in the CN, (y – K)$_0$ plane attain S3839 values larger (δCN > 0.2) than the reference baseline CN = 0.158 × (V – K)$_0$ – 0.332. The baseline is based on MP synthetic spectra computed by Cohen & Bell (1986). We ended up with a sample of 181 stars shown as crosses in Figure 21. The above selection is arbitrary and driven by the evidence that the distribution of CN stars has a local minimum along the dotted line. A similar effect is typically detected in GCs showing a bimodal CN distribution (Norris et al. 1981; Smith 1987; Kayser et al. 2008).

To constrain the properties of CN-strong stars, Figure 20 shows their distribution in the S3839 versus [Fe/H] plane. The iron abundances are based on both photometric ([Fe/H]$^{m_0}$, (y – K)$_0$, top; [Fe/H]$^{i_{4215}}$(u – y)$_0$, bottom) and spectroscopic (J08, ND95) estimates. These data support the evidence suggested by VL07 that only a few CN-strong stars belong to the MP tail ([Fe/H] < −1.75), while the peak of the distribution is located around [Fe/H] ≈ −1 and extends to SM values. It is worth noting that CN-weak and CN-strong stars appear well separated, and indeed only a few objects are located at S3839 ≈ 0.18. This supports the criterion we adopted to distinguish CN-strong stars. Data plotted in Figure 20 also show that CN-weak stars range from [Fe/H] ≈ −2 to [Fe/H] ≈ −0.75 (see also KA06), while more MR RGs seem to be CN-strong stars.

As a whole, we find that the fraction of CN-strong stars among the objects with measured cyanogen indices is of the order of 50%. However, this fraction is affected by the adopted selection criteria and by possible selection effects in the VL07 sample. To provide an independent estimate of the relative frequency of candidate CN-strong stars, we computed the difference between the metallicity estimates based on the $m_0$, (u – y)$_0$ (more sensitive to the CN strength) and the $m_0$, (v – y)$_0$ semiempirical MIC relations. We found that 19% ± 1% (540 objects) of RG stars display a discrepancy larger than 0.2 dex. Unfortunately, the measurement of the S3839 index (VL07) is available for only 15 of these candidate CN-strong stars, but among them 14 were selected as candidate CN-strong stars according to their positions in the S3839 versus (y – K)$_0$ plane. This means that the above fraction of candidate CN-strong stars should be considered as a conservative estimate, due to the ubiquitous effects of the CN molecular bands. The current

22 The S3839 index and the CN index share the same definition and measure the strength of the λ3883 CN band. They should not be confused with the CN band located at λ4215 (see Smith 1987).

23 We are assuming, as usual, that the y- and the V-band magnitudes are effectively the same (Crawford & Barnes 1970).
finding, within the errors, agrees quite well with the fraction of SGB stars that according to Stanford et al. (2007) display an enhancement in either C ($\Delta C \sim 17\%$) or N ($\Delta N \sim 16\%$; see their Table 4).

In passing, we note that CN-strong stars are distributed over the entire magnitude range covered by our RG sample (Figure 20). In particular, they are present above, below, and through the RG bump region (horizontal arrows in Figure 21). This further supports the evidence that these objects are related to MS and SGB stars apparently having enhancements in either C or N. Finally, Figure 21 shows the barium-rich stars according to the selection by VL07. The clear correlation of these objects with the MR RG stars located along the $\omega$ 3 branch strongly supports the recent findings by McDonald et al. (2008).

9.2. $\alpha$-Element Abundances

We took advantage of the accurate $\alpha$-element (O, Mg, Si, Ca, Ti) measurements of RG stars in $\omega$ Cen provided by ND95 (filled circles) and by PA02 (open circles) to investigate whether the photometric metallicities correlate with the abundance of these elements. We performed several tests and found that metallicities based on the $m_0$, $(v-y)_0$ and $m_0$, $(u-y)_0$ relations show very well-defined correlations with the abundance of $\text{[Ca+Si/H]}$. Data plotted in Figure 22 show that for metal abundances ranging from $\text{[Fe/H]} \sim -1.6$ up to SM they display a tight correlation. This correlation does not apply to more MP objects, and indeed for $\text{[Ca+Si/H]} \approx -1.5$ and $\text{[Fe/H]} \lesssim -1.7$ dex they form a plateau.

A good fraction of candidate CN-strong stars follows the same correlation, while the CH-star (asterisk) appears heavily depleted in Ca+Si abundance. A more detailed analysis concerning the possible occurrence of stars showing either a C, N and/or an $\alpha$-element enhancement or a large CH line blocking would require a larger sample of stars with accurate individual elemental abundances. Note that the correlation between the $\alpha$-elements and photometric metallicities might open new opportunities to discriminate between field and cluster RGs.

Figure 21. Unreddened $y, v-y$ CMD of bright RGs. Objects in common with VL07 are plotted as filled circles. The crosses mark candidate CN-strong stars ($\delta CN > 0.2$, see the text for more details), while the triangles the Ba-rich stars according to the selection by VL07. The two arrows display the region covered by RG bump stars.

Figure 22. $[\text{Ca+Si/H}]$ spectroscopic abundances for RG stars in common with ND95 (filled circles) and PA02 (open circles) as a function of photometric metallicities based on the $m_0$, $(v-y)_0$ (top) and $m_0$, $(u-y)_0$ (bottom) semiempirical MIC relations. The dashed lines display the bisector lines. Crosses mark CN-strong stars, the asterisk the CH-star, and the plus the candidate CN-strong star ROA 248. The error bars account for both photometric and spectroscopic errors.

10. SUMMARY AND CONCLUSIONS

We have presented new and accurate multiband Strömgren ($u, v, b, y$) and NIR ($J, H, K$) photometry of the GGC $\omega$ Cen. On the basis of the new data sets, we addressed several questions concerning the properties of the subpopulations present in this stellar system. The main findings are the following.

1. New calibrations of the $m_0, (b-y)_0$ MIC relation. We have provided new empirical and semiempirical calibrations and $m_0, (b-y)_0$ MIC relations. Photometric metallicities based on the new MIC relations agree quite well with spectroscopic data and with photometric metallicities based on similar MIC relations available in the literature.

2. Comparison between photometric and spectroscopic iron abundances. We performed a detailed comparison between photometric and spectroscopic iron abundances. We selected iron abundances based on high-resolution spectra collected by ND95 (39), P02 (8), and J08 (118). We found, using four different MIC relations, that the mean difference between photometric and spectroscopic (ND95; P02) abundances is $\langle \Delta[\text{Fe/H}] \rangle \equiv [\text{Fe/H}]_{\text{phot}} - [\text{Fe/H}]_{\text{spec}} = 0.17 \pm 0.01$ with a dispersion in the residuals of $\sigma = 0.31$ dex (47 stars). If we discard the RG stars affected by abundance anomalies in CN or CH, the mean difference becomes $\langle \Delta[\text{Fe/H}] \rangle = 0.02 \pm 0.02$ and the dispersion decreases by a factor of 2 ($\sigma = 0.16$ dex, 36 stars). The same conclusion applies if we use the spectroscopic sam-
ple by J08: the difference is \( \Delta [\text{Fe}/\text{H}] = 0.05 \pm 0.03 \), with \( \sigma = 0.37 \) dex (118 stars). When we remove the RGs affected by abundance anomalies, we find that the mean difference decreases \( \langle \Delta [\text{Fe}/\text{H}] \rangle = 0.02 \pm 0.04 \), while the dispersion in the residuals attains a similar value \( \sigma = 0.37 \) dex, 93 stars. Note that measurements of the S3839 index are available for only a small fraction of the sample, but these suggest that photometric and spectroscopic abundances are, on average, minimally different. The dispersion of the residuals decreases once we remove all the RGs affected by abundance anomalies. These findings do not depend significantly on the adopted MIC relations, although the \( m_0, (b-y) \) MIC relations do have, on average, larger dispersions.

3. Metallicity distributions based on different MIC relations. We have estimated the metallicity distribution using both empirical and semiempirical MIC relations. The six distributions based on two independent calibrations have similar properties, in particular, they show four main peaks at \([\text{Fe}/\text{H}]_{\text{phot}} = -1.73 \pm 0.08, -1.29 \pm 0.03, -1.05 \pm 0.02, \) and \(-0.80 \pm 0.04, \) and three minor peaks at \(-0.42 \pm 0.12, -0.07 \pm 0.08, \) and \(0.24 \pm 0.13 \) dex (where the uncertainties are standard errors in the centroid of each peak). The four main peaks agree quite well with low-resolution (N96, SK96), medium-resolution (H04, S05b), and high-resolution (J08) spectroscopic iron abundances and with previous photometric metallicities (HR00; S05a). Spectroscopic abundances also suggest the occurrence of MR \(([\text{Fe}/\text{H}] = -0.60 \pm 0.15 \) stars in \( \omega \) Cen (ND95; P00; Pancino 2004). The stars belonging to the SM tail should be regarded with caution since they might be either CN-strong stars or field RGs.

4. Identification of subpopulations according to their metal content. We identified four different metallicity regimes. The weighted mean fraction of stars in the MP \(([\text{Fe}/\text{H}] \leq -1.49) \) component is \( \sim 39\% \pm 1\% \), with a sharp cutoff for \([\text{Fe}/\text{H}] \approx -2.0 \) dex. In comparison, the weighted mean fraction of stars in the metal-intermediate \(([\text{Fe}/\text{H}] \leq -0.93) \) component is \( \sim 32\% \pm 1\% \), while the fraction of MR \(([\text{Fe}/\text{H}] \leq -0.15) \) stars is \( \sim 19\% \pm 4\% \), and the SM stars \(([\text{Fe}/\text{H}] \approx 0) \) represent only a small fraction of the total \((\sim 8\% \pm 5\%) \). This last apparent subpopulation lacks a firm spectroscopic confirmation.

The new mosaic cameras available at telescopes of the 4–8 m class, and the increased sensitivity of new CCDs to short wavelengths combine to make medium-band photometry very promising for constraining the nature of any composite stellar population that may be found in globular clusters. The same conclusion applies equally well to more complex systems such as the Galactic bulge and nearby dwarf galaxies (Faria et al. 2007).

5. Abundance anomalies. We have cross-correlated our optical–NIR photometric catalog with the large spectroscopic catalog collected by VL07. Using the S3839 index (cyanogen band) defined by VL07 and \((y - y_0)\) we selected a sample of 181 candidate CN-strong stars with a CN excess of \( \delta \text{CN} > 0.2 \). Taken at face value, this selection would imply a fraction of CN-strong stars of the order of 50%. We provided an independent estimate of the fraction of CN-strong stars from the difference between the iron content based on the semiempirical \( m_0, (b-y)_0 \) (more sensitive to the CN-band strength) and the semiempirical \( m_0, (u-y)_0 \) relations. We found that the fraction of candidate CN-strong RGs \(([\text{Fe}/\text{H}] > 0.2 \) dex) is of the order of 19% \pm 1%. This fraction agrees quite well with the fraction of SGB stars that, according to Stanford et al. (2007), display enhancements in either C \((\sim 17\%)\) or N \((\sim 16\%)\) (see their Table 4). If these enhancements are caused by binary interaction, as suggested by Stanford et al. (2007, and references therein), the current evidence would imply that \( \omega \) Cen hosts a population of binary stars that is at least a factor of 5 larger than suggested by spectroscopy (Mayor et al. 1996) and a factor of 2 larger than the typical binary fraction believed to be present in most GCs (Davies et al. 2006).

We also found that photometric metallicities correlate with the \([\text{Ca}+\text{Si}]/\text{H}\) abundance from \([\text{Fe}/\text{H}] \sim -1.6 \) up to SM. More MP stars display a plateau at \([\text{Ca}+\text{Si}]/\text{H} \sim 1.5 \) and \([\text{Fe}/\text{H}] \lesssim -1.7 \) dex.

This investigation is just a step in the ongoing effort to improve the use of Strömgren indices as measures of chemical content. This should certainly be refined as more discriminating data become available. Our results also suggest the potential power of simultaneous use of optical data collected with other medium-band photometric systems. The DDO system (McClure & van den Bergh 1968) with filters centered on the CN molecular band at \( \lambda \sim 4215 \) Å, on the G band near 4300 Å, and on the magnesium complex near 5160 Å appears particularly promising. The use of the \( h k \) index (ATT98) to estimate the calcium abundance of cluster HB and RG stars should also be explored further.

It is a real pleasure to thank J. van Loon for sending us his spectroscopic data in electronic form. We also thank S. Moehler for a detailed reading of an early draft of this manuscript and for several suggestions. We acknowledge an anonymous referee for his/her pertinent comments that helped us to improve the content and the readability of the manuscript. We also acknowledge the second referee, Professor B. Twarog, for his sharp and enlightening suggestions. This project was partially supported by the grant Monte dei Paschi di Siena (PI: S. Degl’ Innocenti), PRIN-INAFA2006 (PI: M. Bellazzini), ASI-Project2006 (PI: F.R. Ferraro), PRIN-MIUR2007 (PI: G. Piotto). This publication makes use of data products from VizieR (Ochsenbein et al. 2000) and from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We also thank the ESO and the HST Science Archive for their prompt support.

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