THE INFRARED Ca II TRIPLET AS METALLICITY INDICATOR

R. CARRERA AND C. GALLART
Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain; rcarrera@iac.es, carme@iac.es

E. PANCINO
Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy

AND

R. ZINN
Department of Astronomy, Yale University, New Haven, CT 06520-8101, USA
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ABSTRACT

From observations of almost 500 red giant branch stars in 29 Galactic open and globular clusters, we have investigated the behavior of the infrared Ca II triplet (8498, 8542, and 8662 Å) in the age range 13 Gyr ≤ age ≤ 0.25 Gyr and the metallicity range −2.2 ≤ [Fe/H] ≤ +0.47. These are the widest ranges of ages and metallicities in which the behavior of the Ca II triplet lines has been investigated in a homogeneous way. We report the first empirical study of the variation of the Ca II triplet lines’ strength, for given metallicities, with respect to luminosity. We find that the sequence defined by each cluster in the luminosity-ΣCa plane is not exactly linear. However, when only stars in a small magnitude interval are observed, the sequences can be considered as linear. We have studied the Ca II triplet lines on three metallicity scales. While a linear correlation between the reduced equivalent width ($W'_{\lambda}$ or $W''_{\lambda}$) and metallicity is found in the Carretta & Gratton and Kraft & Ivans scales, a second-order term needs to be added when the Zinn & West scale is adopted. We investigate the role of age from the wide range of ages covered by our sample. We find that age has a weak influence on the final relationship. Finally, the relationship derived here is used to estimate the metallicities of three poorly studied open clusters: Berkeley 39, Trumpler 5, and Collinder 110. For the latter, the metallicity derived here is the first spectroscopic estimate available.

Key words: globular clusters: general — open clusters and associations: individual (Berkeley 39, Collinder 110, Trumpler 5) — stars: abundances — stars: late-type

Online material: color figures, machine-readable table

1. INTRODUCTION

The main functions defining the star formation history of a complex stellar system are the star formation rate, SFR(t), and the chemical enrichment law, Z(t), both functions of time. The SFR(t) can be derived in detail from deep color-magnitude diagrams. The Z(t) has traditionally been constrained by the color distribution of red giant branch (RGB) stars. However, this method of deriving metallicities from photometry is a very crude one, because in the RGB there is a degeneracy between age and metallicity. To break this degeneracy we can obtain metallicities from another source and then derive the age from the positions of stars in the color-magnitude diagram. Of course, the best way to obtain stellar metallicities is high-resolution spectroscopy, which also provides abundances of key chemical elements. However, a lot of telescope time is necessary to measure a suitable number of stars. The alternative is low-resolution spectroscopy, which allows us to observe a large number of stars in a reasonable time using modern multi-object spectrographs. At low resolution, the metallicity is obtained from a spectroscopic line strength index. The Mg, Ca ii H and K, Ca ii infrared triplet lines, Fe lines, etc., are the most widely used indexes for obtaining stellar metallicities. Different indexes are adequate for different types of stars. For example, Fe lines are useful for stars at the base of the RGB or in the main-sequence turnoff. Observation of these stars, however, is only possible for the closest systems, and even those require 8 m class telescopes and long integration times. Thus, for external galaxies the only stars that can be observed with modern multiobject spectrographs and reasonable amounts of telescope time are those near the tip of the RGB. A good spectroscopic index with which to obtain metallicities for these stars is the infrared Ca ii triplet (CaT), whose lines are the strongest features in the infrared spectra of red giant stars. Armandroff & Zinn (1988) demonstrated that in the integrated spectra of Galactic globular clusters, the equivalent widths of CaT lines are strongly correlated with metallicity. As the near-infrared light of globular clusters, where the CaT lines are, is dominated by the red giant contribution, this relation may also be true in these stars individually. Subsequent studies focused on the analysis of individual red giants in globular clusters (e.g., Armandroff & Da Costa 1991). These studies demonstrated that the strength of the CaT lines changes systematically with luminosity along the RGB. Moreover, for a given luminosity the strength of these lines is correlated with the cluster metallicity. Many authors have obtained empirical relationships between the combined equivalent width of the CaT lines and cluster metallicity. A very comprehensive work in this field was published by Rutledge et al. (1997b) based on 52 Galactic globular clusters covering a metallicity range of −2 ≤ [Fe/H] ≤ −0.7. They compared the resulting calibration in the Zinn & West (1984) and Carretta & Gratton (1997) metallicity scales. While in the Carretta & Gratton (1997) scale a linear correlation between metallicity and equivalent width of the CaT lines at the level of the horizontal branch (HB), $V - V'_{HB} = 0$ (known as reduced equivalent width), was found for all clusters, this relationship was not linear when the Zinn & West (1984) scale was used. In most studies, the run of CaT lines with metallicity has been investigated in globular clusters only, all of which have similar ages. If we wish to derive stellar metallicities in systems in which star formation has taken place in the last few Gyr, such as
dwarf irregular galaxies or open clusters, it is necessary to address the role of age on the CaT strength. Some authors have used (a few) young open clusters to study the behavior of the CaT with metallicity (e.g., Suntzeff et al. 1992), using the Zinn & West (1984) metallicity scale as reference. Cole et al. (2004) very recently obtained a new relationship, using open and globular clusters covering $-2 \leq [\text{Fe/H}] \leq -0.2$ and $2.5 \, \text{Gyr} \leq \text{age} \leq 13 \, \text{Gyr}$ in the Carretta & Gratton (1997) scale. They found a linear correlation among the reduced equivalent width and metallicity. This indicates a weak influence of age in the range of ages investigated (age $\geq 2.5 \, \text{Gyr}$). However, to apply this relationship to systems with star formation over the last Gyr and/or with stars more metal-rich than the solar metallicity, it is necessary to investigate its behavior further for younger ages and higher metallicities.

The purpose of this paper is to obtain a new relationship between the equivalent width of the CaT lines and metallicity, covering as wide as possible a range of age and metallicity. Our sample covers $-2.2 \leq [\text{Fe/H}] \leq +0.47$ and $0.25 \, \text{Gyr} \leq \text{age} \leq 13 \, \text{Gyr}$. The influence of age and the variation of the CaT lines along the RGB are investigated. In § 2 we present the cluster sample. In § 3 the observations and data reduction are described. The way in which the equivalent width of the CaT lines has been computed is described in § 4, where the behavior of the CaT with luminosity is also investigated. In § 5 we obtain the relationship between the equivalent width of the CaT lines and metallicity, and we discuss the influence of age and the [Ca/Fe] ratio on it. Finally, the derived relationships are used in § 6 to obtain the metallicities of the open clusters Berkeley 39, Trumpler 5, and Collinder 110.

2. Cluster Sample

To study the behavior of the CaT lines with metallicity, we have observed individual stars, with available $V$ magnitudes, in 29 stellar clusters (15 open and 14 globular). Of the 29 clusters in this sample, 27 also have $m - M$ magnitudes available. This sample covers the widest range of ages (0.25 Gyr $\leq \text{age} \leq 13$ Gyr) and metallicities ($2.2 \leq [\text{Fe/H}] \leq +0.47$) in which the CaT lines have been observed in a homogeneous way. The main parameters of the observed clusters are listed in Table I. Our sample covers most of the open clusters visible from the northern hemisphere with enough stars above the red clump to get a good sampling of the RGB, and with magnitudes easily reachable with the Isaac Newton Telescope

### References

- (1) Carretta & Gratton 1997; (2) Hubbs et al. 1990; (3) Gratton 2000; (4) Tautvaisiene et al. 2005; (5) Gonzalez & Wallerstein 2000; (6) Gratton et al. 2006; (7) Bragaglia et al. 2001; (8) Salaris & Weiss 2002; (9) Salaris et al. 2004; (10) Feltzing & Johnson 2002; (11) Sung et al. 1999; (12) Stetson et al. 2003; (13) Rosenberg et al. 1999; (14) Carraro et al. 2001; (15) Lee et al. 1999; (16) Marconi et al. 1997; (17) Sarajedini et al. 1999; (18) Ortolani et al. 1992; (19) Rosenberg et al. 2004; (20) Rosvick & Vandenverg 1998; (21) Gim et al. 1998; (22) Yong et al. 2005; (23) Kim & Sung 2003; (24) Bragaglia & Tosi 2003; (25) Richtler & Sagar 2001; (26) Kassis et al. 1997; (27) Layden & Sarajedini 1997; (28) Zoccali et al. 2004; (29) Origlia et al. 2005; (30) Fulsom 1996; (31) Carretta et al. 2004; (32) Sestito et al. 2006; (33) Shetrone & Kennicutt 2004; (34) Gratton & Ortolani 1989; (35) McWilliam et al. 1992; (36) Gratton 1987; (37) Carretta et al. 2001; (38) Sneden et al. 1997; (39) Brown et al. 1999; (40) Gratton & Contarini 1994.
(INT), the William Herschel Telescope (WHT), and the 2.2 m CAHA telescopes. In particular, the sample contains NGC 6705 (M11), a very young open cluster (0.25 Gyr) with a well-populated RGB, and NGC 6791, one of the oldest open clusters (~9 Gyr), which is among the most metal-rich clusters in our Galaxy ([Fe/H] ~ +0.47). From the south, using the VLT and the CTIO 4 m telescope, we observed four globular clusters, including NGC 5927 and NGC 6528, which are among the most metal-rich globular clusters in our Galaxy. The sample also includes observations of nine globular and three open clusters available at the ESO archive, whose observations were carried out with the same instrumental configurations as our own. With the purpose of investigating the behavior of the CaT lines with luminosity, we have observed stars along the RGB in five clusters spanning our whole range of metallicities.

Table 1 presents a list of all the clusters in our sample, together with their main characteristics: age, distance modulus, reddening, reference metallicities in three scales (see § 5), and [Ca/H]. In total, 26 of the 29 observed clusters have metallicities in at least one of the three scales. For the other three clusters (Cr 110, Tr 5, and Be 39), we calculate their metallicities with the relationships obtained here.

3. OBSERVATIONS AND DATA REDUCTION

About 500 stars have been observed in the 29 clusters of our sample in six different runs from 2002 to 2005, using the WHT and the INT, both at Roque de los Muchachos Observatory (La Palma, Spain); the 4 m telescope at CTIO (La Serena, Chile); the 2.2 m telescope at the Calar Alto Observatory (Almeria, Spain); and the VLT at Paranal Observatory (Chile). The dates, instrumental configurations, and spectral resolution for each run are listed in Table 2. The instrumental configurations have been chosen in order to ensure that the resolution is similar in each run. The exposure times were selected as a function of the magnitude of the stars in order to obtain a good signal-to-noise ratio (S/N), which in most cases was greater than 20. We have rejected from the analysis those stars with S/N lower than 20 (see below). In each run we have observed a few stars in common with other runs in order to ensure the homogeneity of our sample. Equivalent widths obtained for each star observed in two or more runs have been plotted in Figure 1. The differences between runs are <0.1 ± 0.1 Å. The calculated equivalent widths, together with the obtained radial velocity and the V and I magnitudes used, are listed in Table 3.

![Comparison between equivalent widths for stars observed with different telescopes. Small differences are within the uncertainties.](image-url)
The data taken with slit spectrographs, i.e., all except the observations with CTIO HYDRA and WHT WYFFOS, were reduced following the procedure described by Massey et al. (1992) using the IRAF packages but with some small differences described by Pont et al. (2004). We obtained two images of each object, with the star shifted along the slit. First, we subtracted the bias and overscan, and corrected by the flat-field. Then, since the star is in a different physical position in the two images, we subtracted one from the other, obtaining a positive and a negative spectrum in the same image. With this procedure the sky is subtracted in the same physical pixel in which the star was observed, thus minimizing the effects of pixel-to-pixel sensitivity variations. Of course, a time dependency remains, since the two spectra have not been taken simultaneously. These sky residuals are eliminated in the following step, in which the spectrum is extracted in the traditional way and the remaining sky background is subtracted from the information on both sides of the star aperture. As the next step, the spectrum is wavelength-calibrated. We then again subtracted the negative from the positive (so we added both spectra because one is negative) to obtain the final spectrum. Finally, each spectrum was normalized by fitting a polynomial, excluding the strongest lines in the wavelength range, such as those of the CaT. The order of the polynomial changes among runs in order to eliminate the response of each instrument. The wavelength calibration of the VLT data (both from the archive and from run 6) might be less accurate than the rest because arcs are not taken at the same time and with the same telescope pointing as the object. The effects of this on the wavelength calibration are discussed by Gallart et al. (2001), and we evaluate them in § 3. However, since we are not interested in obtaining precise radial velocities, this problem does not have an important impact on our project.

CTIO HYDRA and WHT WYFFOS are multifiber spectrographs. The data obtained with HYDRA have been extracted with the dohydra task within IRAF in the way described by Valdes (1992). This task was developed specially to extract data acquired with this instrument. The procedure is described in depth by Carrera et al. (2007). Basically, after bias, overscan subtraction, and trimming, dohydra traces the apertures, makes the flat-field correction, and calibrates in wavelength. We followed a similar procedure with the data obtained with WYFFOS, but in this case we used the general dofibers task, which works similarly to dohydra. Although both tasks allow for sky subtraction, the results were poor, and important residuals of sky lines remained. To remove the contribution of these sky lines, we have developed our own procedure to subtract them. Basically, it consists in obtaining an average sky spectrum from all fibers placed on the sky in a given configuration. Before subtracting this average, high-S/N sky from each star spectrum, we need to know the relation between the intensity of the sky in each fiber (which varies from fiber to fiber due to the different fiber responses) and the average sky. This relation is a weight (which may depend on wavelength) by which we must multiply the average sky spectra before subtracting it from each star. To calculate it, we have developed a task that finds the weight which minimizes the sky line residuals over the whole spectral region considered. As a result of this procedure, the sky emission lines are removed very accurately. Finally, the normalization was carried out in the same way as previously described.

Examples of four stars with different metallicities are shown in Figure 2. Note how the strength of the CaT lines increases with metallicity.

The radial velocity of each star has been calculated in order to reject cluster nonmembers. We used the fxcor task in IRAF, which performs a cross-correlation between the target and template spectra of known radial velocity (Tonry & Davis 1979). We selected between 8 and 10 template stars in each run that had very high S/N and covered a wide range of radial velocities. The velocities were corrected to the heliocentric reference frame within fxcor. The final radial velocity for each star was obtained as the average of the velocities obtained from each template, weighted by the width of correlation peaks.

In the case of observations with slit spectrographs, the star might not be exactly positioned in the center of the slit. This error means a velocity uncertainty given by $\Delta v = c \Delta \Theta (p/\lambda_0)$, where $c$ is the speed of light, $p$ is the spectral resolution given in Å arcsec$^{-1}$, $\lambda_0$ is the wavelength of the lines (in this case $\sim 8600$ Å), and $\Delta \Theta$ is the angular offset of the star from the center of the slit in arcseconds. This effect has been described by Irwin & Tolstoy (2002) and Harris & Zaritsky (2006). In our case, it may only be significant in the case of the VLT observations. To estimate the offset in this case we used through-slit images obtained at the beginning of the observation of each configuration, taken to check that the stars were positioned in the slits. In this image we have measured the position of each stellar centroid, which is compared with the position of the slit given in the header of the image. The difference between both, $\Delta \Theta$, allows us to calculate the uncertainty in the measurement of the radial velocity. This value changes from one star to another, the error being about 15 km s$^{-1}$ on average.

The mean velocity for each cluster is listed in Table 4. Most of the values obtained agree, within the uncertainties, with previous measurements from the literature, even in the case of the clusters observed with the VLT, where the uncertainties are larger. In the case of NGC 2141, we found a mean velocity similar to the value obtained by Cole et al. (2004). Both values differ by 20 and 30 km s$^{-1}$, respectively, from the value found by Friel et al.
are other weaker bands at 8472, 8506, 8513, 8558, and 8569 oxide (VO) bands at 8521, 8538, 8574, 8597, 8605, 8624, 8649, near the bluest lines of the CaT. There are also several vanadium

near these bands complicates the definition of the continuum reference level. Cenarro et al. (2001) have presented a description of the previous CaT index definitions and a comparison among them. In Figure 3 we have plotted the line and continuum bandpasses used in several reference works, Cenarro et al. (2001; Fig. 3a), Rutledge et al. (1997b; Fig. 3b), and Armandroff & Zinn (1988; Fig. 3c), over a metal-poor (left) and a metal-rich (right) spectrum. The Armandroff & Zinn (1988) and Rutledge et al. (1997b) indices were defined for relatively metal-poor RGB stars where the influence of the molecular bands is not important. The index of Cenarro et al. (2001) was defined specifically to avoid the presence of molecular bands. Also, from Figure 3 we can easily see that the wings of the lines are larger than the line bandpasses defined by Armandroff & Zinn (1988) and Rutledge et al. (1997b) in the case of the metal-rich stars. Only the line bandpasses defined by Cenarro et al. (2001) completely cover the line wings. Although we have selected the bandpasses defined by Cenarro et al. (2001), which are listed in Table 5, the equivalent width of the line is measured in a different way, as described in § 4.2.

4. THE CALCULUM TRIPLET

We are interested in obtaining metallicities from red giant stars, and within this group from the brightest ones, which are of spectral types K and M. The main features in the infrared spectra of these stars are the CaT lines. But their spectra also contains other weak atomic lines. The Fe i (8514.1, 8674.8, 8688.6, and 8824.2 Å) and Ti i (8435.0 Å) lines are the most important. When within this range, we move to later spectral types, and hence to cooler stars, molecular bands begin to appear that change the slope of the local continuum. The main contribution are from the titanium oxide (TiO) bands, the strongest of which are the triplet situated at 8432, 8442, and 8452 Å and the doublet at 8595.6 and 8606.8 Å. There are other weaker bands at 8472, 8506, 8513, 8558, and 8569 Å, near the bluest lines of the CaT. There are also several vanadium oxide (VO) bands at 8521, 8538, 8574, 8597, 8605, 8624, 8649, and 8668 Å. The strength of these features increases when the temperature decreases, i.e., when we move to later spectral types. The presence of these bands complicates the definition of the continuum, which makes it difficult to obtain the equivalent widths of the CaT lines for stars with $T_{\text{eff}} \leq 3500$ K or $(V - I) > 2$, in the most metal-rich clusters. The description of the CaT region for other spectral types can be found in Cenarro et al. (2001).

4.1. Definition of Line and Continuum Bandpass Windows

In the literature we can find different prescriptions to measure the strength of the CaT lines. The classical definition of a spectral index consists of establishing a central bandpass covering a spectral feature and one or more bandpasses on both sides to trace the local continuum reference level. Cenarro et al. (2001) have

| Cluster | $V_r$ | $\sigma(V_r)$ | Stars | $V_r$(Ref.) | Ref. |
|---------|------|-------------|-------|------------|-----|
| NGC 104 (47 Tue) | −16 | 11 | 32 | −18.7 | 1 |
| NGC 188 | −44 | 20 | 8 | −45 | 2 |
| NGC 288 | −50 | 11 | 19 | −46.6 | 1 |
| NGC 362 | 213 | 7 | 16 | 223.5 | 1 |
| NGC 1851 | 321 | 9 | 14 | 320.5 | 1 |
| NGC 1904 (M79) | 227 | 5 | 16 | 206 | 1 |
| Be 20 | 80 | 7 | 4 | 70 | 2 |
| Be 2141 | 44 | 10 | 21 | 33/64 | 3, 4 |
| Cr 110 | 45 | 11 | 8 | 2 | |
| Tr 5 | 44 | 10 | 15 | 54 | 4 |
| NGC 2298 | 153 | 15 | 6 | 148.9 | 1 |
| Be 32 | 98 | 12 | 3 | 101 | 2 |
| Melote 66 | 18 | 10 | 11 | 23 | 5 |
| Be 39 | 59 | 6 | 5 | 55 | 2 |
| NGC 2420 | 69 | 5 | 5 | 67 | 2 |
| NGC 2506 | 76 | 5 | 3 | 84 | 6 |
| NGC 2682 (M67) | 36 | 6 | 9 | 33 | 2 |
| NGC 3201 | 491 | 3 | 10 | 494 | 1 |
| NGC 4590 (M68) | −89 | 7 | 19 | −93.4 | 1 |
| NGC 5927 | −84 | 5 | 20 | −107.5 | 1 |
| NGC 6352 | −114 | 8 | 23 | −121 | 1 |
| NGC 6528 | 220 | 7 | 5 | 206 | 1 |
| NGC 6681 (M70) | 199 | 7 | 4 | 220 | 1 |
| NGC 6705 (M11) | 28 | 7 | 10 | 34 | 7 |
| NGC 6715 (M54) | 156 | 8 | 23 | 142 | 1 |
| NGC 6791 | −46 | 10 | 10 | −57 | 2 |
| NGC 6819 | 2 | 5 | 7 | −5 | 2 |
| NGC 7078 (M15) | −108 | 10 | 33 | −107 | 1 |
| NGC 7789 | −58 | 6 | 20 | −64 | 2 |

References.—(1) Harris 1996; (2) Friel et al. 2002; (3) Friel 1989; (4) Cole et al. 2004; (5) Friel & Janes 1993; (6) Mathieu 1985; (7) Mathieu et al. 1986 (2002). For Cr 110, no previous measurement of its radial velocity could be found in the literature.

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with poorer S/N have been rejected. The equivalent width of each line is the area limited by the fitted profile of the line and the continuum level, defined as the linear fit to the mean values of the flux in each window chosen to determine the continuum. Formal errors of the fit are estimated as the difference between the equivalent width measurement for continuum displacements of $C_6(S/N)^{-1}$.

4.3. The CaT Index

The equivalent widths of the three CaT lines are combined to form the global index $\Sigma \text{Ca}$ (Armandroff & Da Costa 1991). Some authors excluded the weakest line at 8498 Å on the basis of its poor S/N (e.g., Suntzeff et al. 1993; Cole et al. 2000). Others have used all three lines, either weighted (e.g., Rutledge et al. 1997b) or unweighted (e.g., Olszewski et al. 1991). As our spectra have high S/Ns, we used the unweighted sum of the three lines, $\Sigma \text{Ca} = W_{8498} + W_{8542} + W_{8662}$, and we calculated its error as the square root of the quadratic sum of the errors of each line. As we have some stars in common with previous works, we can compare the $\Sigma \text{Ca}$ calculated by us with values obtained in previous papers. Rutledge et al. (1997b) compared their $\Sigma \text{Ca}$ with previous index definitions until 1997. Here, for simplicity, we only compare our index with three reference works. Stars in common with Armandroff & Da Costa (1991), Rutledge et al. (1997b), and Cole et al. (2004) are plotted in Figure 4. As mentioned before, the works of Armandroff & Da Costa (1991) and Rutledge et al. (1997b) were focused on old and metal-poor stars. However, Olszewski et al. (1991) and Suntzeff et al. (1993), using the same index that Armandroff & Da Costa (1991) defined for globular cluster stars, measured the equivalent width of the CaT lines in stars of two open clusters, M11 and M67, respectively. We use these values to complete the measurements of Armandroff & Da Costa (1991).

We find a quasilinear relation up to $\Sigma \text{Ca} \sim 7$ among the $\Sigma \text{Ca}$ values in this paper and those obtained by Armandroff & Da Costa

| TABLE 5 |
|-----------------------------------------|
| Line Bandpasses (Å) | Continuum Bandpasses (Å) |
|---------------------|--------------------------|
| 8484–8513           | 8474–8484                |
| 8522–8562           | 8563–8577                |
| 8642–8682           | 8619–8642                |
| ...                 | 8799–8725                |
| ...                 | 8776–8792                |

Fig. 3.—Continuum (clear) and line (dark) bandpasses defined by (a) Cenarro et al. (2001), (b) Rutledge et al. (1997b), and (c) Armandroff & Zinn (1988). They have been overplotted onto metal-poor (left) and metal-rich (right) stars. The bands of Cenarro et al. (2001) are wider in the lines to cover the wings fully and narrower in the continuum in order to avoid the most prominent molecular features for metal-rich stars. [See the electronic edition of the Journal for a color version of this figure.]
The next step is to relate the CaT index with metallicity. The strength of the absorption lines mainly depends on the chemical abundance, stellar effective temperature ($T_{\text{eff}}$), and surface gravity ($\log g$). Therefore, to relate the equivalent width of the CaT lines with metallicity it is necessary to remove the $T_{\text{eff}}$ and $\log g$ dependence. Armandroff & Da Costa (1991) and Olszewski et al. (1991) demonstrated that the cluster stars define a sequence in the luminosity-$\Sigma\text{Ca}$ plane, using luminosity measures from indicators like $M_I$ or $(V - V_{\text{HB}})$. These sequences are separated as a function of the cluster metallicity. The theoretical explanation of this can be found in Pont et al. (2004) using Jørgensen et al. (1992) models, which describe the behavior of the CaT lines as a function of $T_{\text{eff}}$, $\log g$, and metallicity.

It is necessary to study the morphology of the sequence defined by each cluster in the luminosity-$\Sigma\text{Ca}$ plane. From a theoretical point of view, the increment of luminosity along the RGB comes with a drop in $T_{\text{eff}}$ and $\log g$ that decreases and increases the strength of the lines, respectively. The result is a modest increment in $\Sigma\text{Ca}$ with luminosity ($\delta\Sigma\text{Ca}/\delta M_I \sim 0.5$). Moreover, the models predict that $\Sigma\text{Ca}$ increases more rapidly with luminosity in the upper part of the RGB (above the HB) than in the lower part. In other words, the sequence defined by each cluster might not be linear and might be best described by adding a quadratic component. The Jørgensen et al. (1992) models also predict that $\Sigma\text{Ca}$ increases more rapidly when $\log g$ decreases, or when the luminosity increases, for the more metal-rich clusters than for the more metal-poor ones. Therefore, the linear and quadratic terms, which characterize the sequence defined for each cluster in the...
luminosity-$\Sigma$Ca plane, increase with metallicity, as can be seen in Figure 15 of Pont et al. (2004).

Observationally, the variation in $\Sigma$Ca with metallicity has traditionally been studied from $(V - V_{\text{HB}})$, which removes any dependence on distance and reddening (e.g., Armandroff & Da Costa 1991; Rutledge et al. 1997b; Cole et al. 2004). In this context, it is found that clusters define linear sequences in the $(V - V_{\text{HB}})$-$\Sigma$Ca plane, where the reduced equivalent width, $W'$, is defined as $\Sigma$Ca = $W'_{\text{HB}} + \beta (V - V_{\text{HB}})$. Rutledge et al. (1997b) found that the slopes of these sequences were the same for all clusters in their sample, independent of their metallicity. Therefore, only $W'_{\text{HB}}$ changes from one cluster to another, and its variation is directly related to metallicity. Other studies have reached the same conclusion using open and globular clusters (e.g., Olszewski et al. 1991). Pont et al. (2004; see also Armandroff & Da Costa 1991) have demonstrated that this also occurs in the $M_V$-$\Sigma$Ca and $M_V$-$\Sigma$Ca planes. However, no studies have observed the theoretical predictions that cluster sequences are not exactly linear with luminosity, or that their shape depends on metallicity. The main objective of this study is to apply the relationships obtained to derive metallicities of individual stars in Local Group galaxies, which in general have had multiple star formation epochs and do not always have a well-defined HB (e.g., LMC: Carrera et al. 2007; SMC: Noël et al. 2007; Leo A: Cole et al. 2007).

For example, the Magellanic Clouds do not have a measurable HB in the color-magnitude diagram, and in studies which define the reduced equivalent width as a function of $(V - V_{\text{HB}})$ (e.g., Cole et al. 2005), the HB position has been taken as that of the red clump. However, in the Magellanic Clouds the position of the red clump is about 0.4 mag brighter than the HB. This only implies an underestimation of the metallicity by $\approx 0.15$ dex, which is similar to the uncertainty on the metallicity determination itself. Distances to Local Group galaxies are, in general, determined with an accuracy greater than 0.4 mag, and so, even if the error on the derived metallicity due to the uncertainty in the position of the HB is not large, it can be minimized by defining the reduced equivalent width as a function of absolute magnitude. This point is also important in the case of open clusters, which hardly ever have a HB or, if they do, it is usually not well defined. For this reason, like Pont et al. (2004) we redefine $W'$ as the value of $\Sigma$Ca at $M_V = 0$ (hereafter $W'_0$) or $M_V = 0$ (hereafter $W'_0$).

First we study in detail the morphology of the cluster sequences in the luminosity-$\Sigma$Ca plane. As discussed above, from a theoretical point of view we expect that these sequences are not exactly linear. We have observed stars along the RGB in five clusters covering the whole metallicity range. In Figure 5 we have plotted stars observed in these clusters in the $M_V$-$\Sigma$Ca and $M_V$-$\Sigma$Ca planes. These stars have magnitudes in the ranges $-2 < M_V < 2$ and $-3 < M_V < 2$ or $-2.3 < V - V_{\text{HB}} < 1.8$. These ranges contain stars both brighter and fainter than previous works (e.g., Rutledge et al. 1997b; Cole et al. 2004). Note that the strength of the CaT lines increases more rapidly in the upper part of the RGB, as predicted by Pont et al. (2004) using Jørgensen et al. (1992) models. These observations can be used to obtain a new relationship between $\Sigma$Ca, absolute magnitude, and metallicity that is valid for all the stars in the RGB and takes into account the curvature in the luminosity-$\Sigma$Ca plane. The sequence of each cluster has been fitted with a quadratic function such that $\Sigma$Ca = $W'_0$ + $\beta M_V$ + $\gamma M_V^2$. We have plotted the result when the stars of each cluster are fitted independently in Figure 5. The coefficients of the fit are shown in Table 6. From this, it seems that $\beta$ tends to increase with metallicity, as predicted theoretically. In the case of $\gamma$ this increment is not observed, i.e., its variation does not show a significant dependence on metallicity, except for the most metal-rich cluster, which also has a large uncertainty.

Using the Jørgensen et al. (1992) empirical relations and the BaSTI stellar evolution models (Pietrinferni et al. 2004), we have calculated theoretical sequences for clusters with $[\text{Fe/H}] \geq -1$, which are plotted in Figure 6 as dashed lines. These sequences were obtained for $[\text{Fe/H}] = +0.5, 0, -0.5$, and $-1$, while the cluster metallicities are $[\text{Fe/H}] = +0.47, -0.14, -0.67$, and $-1.07$, respectively. Jørgensen et al. (1992) did not compute relationships for more metal-poor clusters. We used BaSTI isochrones with metallicities of $+0.32$, $-0.28$, $-0.58$, and $-0.98$, respectively, in order to estimate $T_{\text{eff}}$ and $\log g$ along the RGB. The Jørgensen et al.
(1992) relationships were calculated for the two strongest CaT lines. To compare the theoretical predictions with the observational sequences we computed, using our own data, an empirical relation between $\Sigma C_{4844.2-8662}$ obtained from these two lines and the $\Sigma C_{6}$ used in this work, computed from the three CaT lines. We found $\Sigma C_{6} = 0.13 + 1.21 \Sigma C_{4844.2-8662}$. Applying this correction, we find that the theoretical and observed cluster sequences still do not match. There is a zero point that changes from one cluster to another, which is not surprising because the cluster metallicities are not exactly the same as those used to compute the theoretical relationships. Therefore, the theoretical sequences have been shifted in order to superimpose them on the cluster ones. It can be seen that models do not exactly reproduce the behavior of the observed cluster sequences. However, the prediction that the shape changes from the metal-poor clusters to the metal-rich ones is observed, although, as was mentioned before, these variations are similar to the uncertainties.

We can simplify the problem if we assume that all clusters have the same tendency, i.e., if we calculate a single slope and quadratic term for the whole sample. So only the zero point changes among clusters. To obtain these coefficients, we have performed an iterative least-squares fit as described by Rutledge et al. (1997b). From a set of reference values, we obtained the quadratic and linear terms of the fit in iterative steps, until they converged to a single value within the errors and allow only the zero point to change among clusters. The values are $\beta_V = -0.647 \pm 0.005$ and $\gamma_V = 0.085 \pm 0.006$. In the same way, for $M_V$ we obtained $\beta_V = -0.618 \pm 0.005$ and $\gamma_V = 0.046 \pm 0.001$. In Figure 6 we have plotted the individual fit for each cluster (solid line) and that when the linear and quadratic terms do not change among clusters (dashed lines). In both cases, the dotted lines represent the region where there are no cluster stars and the fits have therefore been extrapolated. As we can see in Figure 6, in the magnitude interval covered by cluster stars both fits are similar and give very similar values of $W'$ within the uncertainties. For example, for NGC 7078, where the discrepancy is larger, we obtained $2.79 \pm 0.06$ and $2.79 \pm 0.01$ in $I'$ and $2.64 \pm 0.08$ and $2.31 \pm 0.01$ in $I$, when the linear and quadratic terms change among clusters or are fixed, respectively. Larger differences between both fits are found in the regions where the relationships are extrapolated.

Moreover, in our case we are interested in measuring the strength of the CaT lines in galaxies where we can observe only the upper part of the RGB with a good S/N. The quadratic behavior of the cluster sequences in the luminosity-$\Sigma C_{6}$ plane is not significant when we observe stars with $M_V \leq 0$ only (or $M_V \leq 1.25$; this magnitude limit has been selected in order to sample in both filters the same number of stars in each cluster). For example, when we repeat the previous procedure, but only for stars with $M_V \leq 1.25$, we find that the quadratic term is $\gamma_V = 0.004 \pm 0.003$, which is negligible within the uncertainty. In the same way, when we only observe stars with $M_V \geq 1.25$ we obtain a similar result: $\gamma_V = 0.002 \pm 0.01$. The same happens in the $M_V-\Sigma C_{6}$ plane, but here the quadratic terms are even smaller. According to this, the cluster sequence can be considered linear above and below $M_V = 1.25$ and $M_V = 0$, and we can fit it as $\Sigma C_{6} = W'_V + \beta_V M_V$ or $\Sigma C_{6} = W'_V + \beta_V M_V$ on each side of this point. Following the same iterative procedure as in the case of the quadratic fit, we calculated the values of the slope $\beta$ for $M_V \leq 1.25$ and $M_V \leq 0$, obtaining $\beta_V = -0.74 \pm 0.01$ and $\beta_V = -0.60 \pm 0.01$, respectively. The linear fits for $M_V \leq 1.25$ and $M_V \leq 0$ are represented in Figure 6 by dot-dashed lines. In all cases, within the ranges covered by the cluster stars the linear fit to the bright stars is equivalent, within the uncertainties, to the quadratic ones.

Finally, for clusters where we have observed a wide range of magnitudes we find that the slope ($\beta$) increases, although within the uncertainties, with metallicity. We can check this point, using now all clusters in our sample. A total of 27 clusters in $I$ and 29 in $V$ have stars brighter than $M_V = 0$ and $M_V = 1.25$. We have fitted the sequence to each cluster independently in the linear form $\Sigma C_{6} = W'_V + \beta_V M_V$. The values obtained from the slope have been plotted against $W'$, which is directly correlated with metallicity, for each cluster in Figure 7. From this figure it is seen that there is no significant relation between the cluster slope and $W'$ (or [Fe/H]). Therefore, from here on we consider the slope of the fit to be the same for the whole range of [Fe/H] and, hence, for all objects.

In summary, as we are specially interested in obtaining metallicities for stars in the upper part of the RGB with the CaT, where the quadratic term is not significant and the slope can be fixed independently of metallicity, we are going to use a linear fit with a single slope for the calibration using the whole cluster sample. This is what has been done in all previous calibrations of the CaT.

Figures 8 and 9 represent the clusters in our sample in the $M_V-\Sigma C_{6}$ and $M_V-\Sigma C_{20}$ planes, respectively, together with the linear fit to each of them. Using the same procedure as in the case of the quadratic fit discussed above, we have obtained $\beta_V = -0.677 \pm 0.004$ A mag$^{-1}$ and $\beta_V = -0.611 \pm 0.002$ A mag$^{-1}$ in the $M_V-\Sigma C_{6}$ and $M_V-\Sigma C_{20}$ planes, respectively. The value found in the $M_V-\Sigma C_{6}$ plane is slightly larger than that obtained by Pont et al. (2004), $\beta_V = -0.48 \pm 0.02$ A mag$^{-1}$. Although these authors used a different method to calculate the metallicity (they fitted each cluster individually and obtained the mean of the slopes of all of them), this is not the reason for the discrepancy, because if we follow the same procedure with our own data, again we find...
Fig. 7.—Values of the slopes obtained from the individual fit for each cluster vs. $W'$. Solid lines are the linear fit, which is given at the bottom. Note that there is no correlation between slope and $W'$ (and therefore $[\text{Fe/H}]$) in any of the filters. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 8.—Cluster sample in the $M_V$-$\Sigma\text{Ca}$ plane. Solid lines are the linear fit to the stars in each cluster when we assume that the slope is the same for all of them. The typical error is shown in the lower right corner. [See the electronic edition of the Journal for a color version of this figure.]
5. THE Ca ii TRIPLET METALLICITY SCALE

An important point in this study is the reference metallicities. It would be ideal to use the same metallicity scale for both open and globular clusters, and that this would have been obtained from high-resolution spectroscopy. In the literature we can find two globular cluster metallicity scales obtained from high-resolution spectroscopy: Carretta & Gratton (1997, hereafter CG97) and Kraft & Ivans (2003, hereafter KI03). There is a third metallicity scale obtained from low-resolution data: Zinn & West (1984, hereafter ZW84). There are systematic differences among these three scales, but there is no reason to prefer any particular one of them. For this reason, here we study the behavior of the CaT lines with metallicity in these three scales. Lamentably, there is not a homogeneous metallicity scale obtained from high-resolution spectroscopy for open clusters. However, the metallicities of some of them have been obtained directly in the CG97 scale by some authors: NGC 6819 (Bragaglia et al. 2001), NGC 2506 (Carretta et al. 2004), NGC 6791 (Gratton et al. 2006), and Be 32 (Sestito et al. 2006). These metallicities were obtained using Fe i and Fe ii lines. For the other eight open clusters in our sample there are also metallicities obtained from high-resolution spectroscopy in RGB stars and using Fe i and Fe ii lines in a similar way to CG97. Even though some discrepancies could exist because the procedures are not exactly the same, we consider these metallicities also to be on the CG97 scale. The reference values in this scale are listed in column (2) of Table 1, and the sources for each of them are listed in column (3). The reference metallicities in ZW84 and KI03 are listed in columns (4) and (5), respectively. In both cases, we have used only values obtained directly by these authors.

5.1. Calibration in the CG97 Metallicity Scale

Figures 10 and 11 show the run of $W_0^V$ and $W_0^I$ with metallicity. In most cases, the errors are smaller than the size of the points. The circles indicate clusters younger than 4 Gyr. The solid line shows the best fit to the data. The dashed lines represent the 90% confidence level. Note that in both cases there is a linear correlation. The bottom panels show the residuals of the linear fit. We have used 22 clusters for the calibration in $V$ and 20 for that in $I$. There are three clusters that differ from the fit by more than 0.2 dex in both filters. These clusters are NGC 2420, NGC 2506, and Ber 32. They have been excluded from the analysis. In the case

\[ \beta_I = -0.61. \] There are no previous determinations of $\beta_V$. The values obtained for $W_0^V$ and $W_0^I$ are listed in Table 7.
TABLE 7
DERIVED $W_V^I$ AND $W_V^O$ AND THE NUMBER OF STARS USED

| Cluster   | $W_V^I$     | No. of Stars | $W_V^O$     | No. of Stars |
|-----------|-------------|--------------|-------------|--------------|
| NGC 104   | 6.94 ± 0.01 | 34           | 6.23 ± 0.01 | 14           |
| NGC 188   | 8.17 ± 0.07 | 6            | 7.27 ± 0.08 | 5            |
| NGC 288   | 5.51 ± 0.01 | 19           | 5.04 ± 0.03 | 14           |
| NGC 362   | 6.01 ± 0.01 | 16           | ...         | ...          |
| NGC 1851  | 5.94 ± 0.03 | 14           | 5.24 ± 0.04 | 8            |
| NGC 1904  | 4.91 ± 0.03 | 16           | ...         | ...          |
| Be 20      | 6.86 ± 0.03 | 4            | 6.39 ± 0.03 | 3            |
| NGC 2141  | 8.33 ± 0.01 | 18           | 7.67 ± 0.02 | 15           |
| Cr 110     | 8.21 ± 0.04 | 11           | 7.74 ± 0.06 | 6            |
| Tr 5       | 7.52 ± 0.04 | 16           | 6.97 ± 0.04 | 15           |
| NGC 2288   | 3.75 ± 0.03 | 6            | 3.09 ± 0.03 | 5            |
| Be 32      | 5.90 ± 0.08 | 4            | 5.27 ± 0.08 | 4            |
| Melote 66  | 7.69 ± 0.03 | 11           | 6.90 ± 0.03 | 11           |
| Be 39      | 8.21 ± 0.04 | 5            | 7.27 ± 0.06 | 3            |
| NGC 2420   | 6.26 ± 0.09 | 6            | 6.15 ± 0.08 | 4            |
| NGC 2506   | 6.96 ± 0.09 | 4            | 6.37 ± 0.09 | 3            |
| NGC 2682   | 8.24 ± 0.01 | 6            | 7.48 ± 0.01 | 8            |
| NGC 3201   | 5.46 ± 0.03 | 9            | 4.76 ± 0.02 | 6            |
| NGC 4590   | 2.84 ± 0.02 | 19           | 2.19 ± 0.06 | 12           |
| NGC 5927   | 7.81 ± 0.01 | 21           | 6.92 ± 0.01 | 13           |
| NGC 6352   | 7.10 ± 0.01 | 19           | 6.31 ± 0.01 | 19           |
| NGC 6528   | 8.28 ± 0.04 | 5            | 7.58 ± 0.04 | 5            |
| NGC 6681   | 5.05 ± 0.03 | 4            | 4.49 ± 0.07 | 3            |
| NGC 6705   | 8.95 ± 0.07 | 7            | 8.28 ± 0.12 | 6            |
| NGC 6715   | 4.86 ± 0.03 | 23           | 4.30 ± 0.03 | 24           |
| NGC 6791   | 9.78 ± 0.09 | 9            | 8.77 ± 0.09 | 8            |
| NGC 6819   | 8.41 ± 0.04 | 7            | 7.64 ± 0.04 | 7            |
| NGC 7078   | 2.78 ± 0.01 | 38           | 2.18 ± 0.01 | 14           |
| NGC 7789   | 8.47 ± 0.02 | 20           | 7.61 ± 0.02 | 20           |

Fig. 10.—Top: [Fe/H] vs. $W_V^I$. The solid lines are the best linear fit to the data. Dashed lines define the confidence band of the fit. Open circles are clusters younger than 4 Gyr. The residuals of the linear fit are shown in the bottom panel. Note that the $W_V^I$ errors are smaller that the size of points in most cases. The clusters excluded from the analysis (NGC 2420, NGC 2506, and Be 32) have not been plotted. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 11.—Same as Fig. 10, but with $W_V^O$. [See the electronic edition of the Journal for a color version of this figure.]

of NGC 2420, only six stars in $V$ and four in $I$ are radial velocity members. This, together with a relatively large uncertainty in its metallicity (Gratton 2000), contributes to its large error bar. In the case of NGC 2506 and Be 32, there are only three and four stars, respectively, with membership confirmed by their radial velocities. Thus, slight differences in the $\Sigma$Ca value of one of them could change the derived $W_V^O$ significantly. Two of the three very deviant clusters (NGC 2420 and NGC 2506) have ages less than 4 Gyr, but five other young clusters fit the mean relationships in Figures 10 and 11 to better than 0.2 dex. We doubt, therefore, that cluster age is the major cause of the large deviations.

The best linear fits, shown in Figures 10 and 11, are

$$[Fe/H]_{CG97}^{V} = -3.12 \pm 0.06 + 0.36 \pm 0.01W_V^I, \quad \sigma_V = 0.08,$$

(4)

$$[Fe/H]_{CG97}^{I} = -2.95 \pm 0.06 + 0.38 \pm 0.01W_I^O, \quad \sigma_I = 0.09.$$

(5)

Some studies have predicted that this relationship may present a curvature due to the loss of CaT index sensitivity at high metallicities (e.g., Diaz et al. 1989). Cole et al. (2004) investigated this point, adding a quadratic term. They found that the coefficient of this term is insignificant and does not improve the quality of the fit. We performed the same analysis in our sample, which covers a wider range of ages and metallicities, finding a similarly insignificant influence of a quadratic term.

5.2. Calibration on Other Metallicity Scales

In this section we study the behavior of the CaT on the ZW84 and KI03 scales. In Figure 12 we have plotted the metallicities in ZW84 (bottom) and KI03 (top) listed in Table 1 versus $W_V^I$ (left) and $W_I^O$ (right).

In the case of the KI03 metallicity scale (Fig. 12, top), the behavior of $W$ with metallicity is linear, as for the CG97 scale.
These authors used three stellar atmosphere models to obtain metallicities. For simplicity, in Figure 12 we have plotted only the metallicity values obtained using MARCS models. However, a linear behavior is also found when we use the metallicities computed from the Kurucz models with or without convective overshooting. The linear fits for each of the three models are

\[
[\text{Fe/H}]_{\text{KI03}}^{(W')} = -3.42 \pm 0.03 + 0.37 \pm 0.01 W', \quad \sigma = 0.10, \tag{6a}
\]

\[
[\text{Fe/H}]_{\text{KI03}}^{(W')} = -3.43 \pm 0.03 + 0.38 \pm 0.01 W', \quad \sigma = 0.10, \tag{6b}
\]

\[
[\text{Fe/H}]_{\text{KI03}}^{(W')} = -3.51 \pm 0.03 + 0.40 \pm 0.01 W', \quad \sigma = 0.10, \tag{6c}
\]

\[
[\text{Fe/H}]_{\text{KI03}}^{(W')} = -3.29 \pm 0.03 + 0.40 \pm 0.01 W', \quad \sigma = 0.09, \tag{7a}
\]

\[
[\text{Fe/H}]_{\text{KI03}}^{(W')} = -3.24 \pm 0.03 + 0.40 \pm 0.01 W', \quad \sigma = 0.09, \tag{7b}
\]

\[
[\text{Fe/H}]_{\text{KI03}}^{(W')} = -3.31 \pm 0.03 + 0.41 \pm 0.01 W', \quad \sigma = 0.09, \tag{7c}
\]

where equations (6a) and (7a) are for the MARCS model, equations (6b) and (7b) are for the Kurucz model with convective overshooting, and equations (6c) and (7c) are for the Kurucz model without convective overshooting.

Differences between metallicities derived with the MARCS model and the models of Kurucz with or without overshooting are negligible.

This linear behavior is not surprising because, as KI03 demonstrated, their metallicities are linearly correlated with the CG97 values, which are, at the same time, linearly correlated with our \( W' \). However, the metallicities calculated by KI03 are systematically lower than the CG97 ones. KI03 studied this point and concluded that the difference could be explained because they used different \( T_{\text{eff}} \) and \( \log g \) values, as well as different atmosphere models. The combination of all these can easily introduce systematic differences into the globular cluster abundance scales.

In the case of ZW84, we have found that the data are best fitted by a second-degree polynomial (Fig. 12, solid line):

\[
[\text{Fe/H}]_{\text{ZW84}}^{(W')} = -1.98 \pm 0.07 - 0.18 \pm 0.02 W'^2, \quad \sigma = 0.10, \tag{8a}
\]

\[
[\text{Fe/H}]_{\text{ZW84}}^{(W')} = -2.07 \pm 0.07 - 0.12 \pm 0.03 W'^2, \quad \sigma = 0.09. \tag{8b}
\]

In §4.3 we discussed several previous definitions and measurement procedures of the CaT lines, and noted the loss of sensitivity to the CaT lines strength in some cases (e.g., Armandroff & Da Costa 1991) which also found a nonlinear relationship between the CaT index and metallicity. We mentioned that this non-linearity was probably the result of the combination of an inaccurate measurement of the CaT on strong-line stars and the particular metallicity scale in use. In order to assess the relative importance each factor, we now compare the effects on the derived abundances of alternatively (1) assuming a linear relationship between \( W' \) and metallicity on the ZW84 metallicity scale and (2) adopting a Gaussian to fit the CaT lines, which provides a poorer fit. When a linear relationship between \( W' \) and \([\text{Fe/H}]_{\text{ZW84}} \) is assumed, the derived metallicity of a strong-line star, \( W'_f = 8.5, \) is underestimated in 0.3 dex. In the case of a weak-line star, \( W'_f = 2, \) again the metallicity is underestimated in 0.2 dex. Similar results are obtained when lines are not properly fitted. For example, as we saw in §4.3, Armandroff & Da Costa (1991) fitted the line profile with a Gaussian, resulting in their index being saturated for strong-line stars. The relation between the reduced equivalent width obtained from their index and metallicities in the CG97 scale is a second-degree polynomial. If we then assume a linear relationship between this index and \([\text{Fe/H}]_{\text{CG97}} \) for a strong-line star, its metallicity would be underestimated in 0.3 dex. A similar result is obtained for a weak-line star. We conclude, therefore, that the effects on the derived metallicity due to a poor fit to the line or the nonlinearity of the metallicity scale are comparable.

5.3. The Role of Age in the \( W'_f \) (\( W'_i \)) Versus \([\text{Fe/H}] \) Relationship

Pont et al. (2004) investigated the influence of age in the \( W'_f \) (\( W'_i \)) versus \([\text{Fe/H}] \) relationship from a theoretical point of view. They used the theoretical calculations of CaT equivalent widths for different values of \( g, T_{\text{eff}} \), and metallicity calculated by Jørgensen et al. (1992) together with the Padova stellar evolution models (Girardi et al. 2002). They concluded that the variation of \( W' \) with age for a fixed metallicity would be negligible for clusters older than 4 Gyr. However, this was not the case for the younger clusters. This is observed clearly in Figure 15 of Pont et al. (2004). For a given metallicity, the sequences in the \( M_T - \Sigma \text{Ca} \) and \( M_T - \Sigma \text{ECa} \) planes are separated as a function of their ages for clusters younger than ~4 Gyr. According to this calculation, for the same metallicity, \( W' \) decreases with age. Thus, metallicities for clusters younger than 4 Gyr, calculated from calibrations computed from old stars, will be underestimated. This age dependence is more important in the \( M_T - \Sigma \text{Ca} \) plane than in the
This means that \( W'_I \) would be less sensitive to age than \( W'_V \).

Using the Jørgensen et al. (1992) models and the BaSTI stellar evolution models (Pietrinferni et al. 2004), we have estimated the expected \( W' \) differences as a function of age. From these calculations, for two clusters with the same metallicity and age 10.5 and 0.6 Gyr, the youngest cluster \( W'_V \) would be approximately 0.7 \( \AA \) lower than that of the oldest one. This implies that the metallicity obtained for young clusters using this calibration would be 0.25 dex more metal-poor than the actual metallicity. In the case of \( W'_I \), the difference would be 0.4 \( \AA \), so the metallicity obtained for young clusters would be 0.15 dex more metal-poor than the actual one. As we can see in Figure 15 of Pont et al. (2004), the difference would be similar for different metallicities.

From our data, we confirm that the influence of age is weak. In Figure 13 we plot \( W'_I \) versus age for clusters with \(-0.17 \leq [\text{Fe/H}] \leq +0.07\). Independently of their ages, all clusters have similar \( W'_I \), with the exception of the youngest cluster, NGC 6705 (0.25 Gyr).

In general, the relationship between the reduced equivalent width of an atomic line and the chemical abundance of the corresponding element is described by the curve of growth. This is only linear for very weak and unsaturated lines. This is not the case for the CaT. As we can find the [Ca/Fe] ratio for most of the clusters in our sample from the literature, in Figure 15 we have plotted \( W'_V \) and \( W'_I \) versus [Ca/H]. The relationship between the CaT lines strength should also be sensitive to the Ca abundances. In fact, the relationships obtained in this work and those found in the literature have been obtained assuming implicitly the specific relationship between Ca and Fe followed by clusters used in the calibration (see Fig. 14 for the relationship of the clusters used in this work). Using these relationships to derive Fe abundances in stellar systems with a different chemical evolution than the Milky Way, reflected in the calibrating cluster sample, could give wrong results.

5.4. The Influence of [Ca/Fe] Abundance

The CaT has traditionally been used to infer iron abundances from Ca lines, and we also do so in this paper. However, the CaT lines strength should also be sensitive to the Ca abundances. In
both is equivalent to the curve of growth. The relations obtained are
\[
[\text{Ca/H}]^V = -2.51 \pm 0.08 + 0.30 \pm 0.01 W', \quad \sigma = 0.11, \quad (9)
\]
\[
[\text{Ca/H}]^I = -2.36 \pm 0.08 + 0.31 \pm 0.01 W', \quad \sigma = 0.11. \quad (10)
\]

As in the case of the [Fe/H] relationship, we obtain a linear dependence. However, note that in this case the errors of the fit are larger. This may be related to the inhomogeneity of the [Ca/H] abundances, which were obtained from different sources.

In any case, even though [Ca/H] changes linearly with \(W'\), [Fe/H] does not have to do likewise. However, as we see in Figures 10 and 11, the relationship between [Fe/H] and \(W'\) is also linear. On the other hand, since the [Ca/H] and [Ca/Fe] abundances are related according to \([\text{Fe/H}] = [\text{Ca/H}] - [\text{Ca/Fe}]\), we can expect that [Ca/Fe] also changes linearly with \(W'\) (and with [Fe/H]) if the relation with [Ca/H] is linear. In fact, in Figure 14 we can check that this is the case over the whole range of [Fe/H] except for the most metal-poor clusters. Note however that the linear behavior of \(W'\) with [Ca/H] and [Ca/Fe] is a characteristic of our particular sample, but this would not have to be the rule.

The problem of the relation between the CaT, [Ca/H], and [Fe/H] has been addressed by Idriat et al. (1997) from an empirical point of view. For their sample of late-type stars (G and K), they found that the dominant stellar parameter controlling the behavior of the CaT lines is metallicity, and contrary to what would be expected, the [Ca/Fe] ratio has practically no effect on the CaT index. However, all the stars in their sample follow the same relationship between Ca and Fe, so they cannot check in a general way the influence of the [Ca/Fe] ratio.

To properly investigate the influence of the [Ca/Fe] ratio, it is necessary to have objects with the same metallicities and different [Ca/H] ratios. In our sample, most of the metal-poor clusters have high \(\alpha\)-element abundances relative to Fe, as is the case for Ca. On the other hand, open clusters are metal-rich and have low \(\alpha\)-element abundances. To study the influence of the [Ca/Fe] ratio on the CaT calibration as a function of metallicity it would be necessary to include metal-rich objects with high \(\alpha\)-element abundances (i.e., stars in the Milky Way bulge) and metal-poor objects with low \(\alpha\)-element abundances (i.e., perhaps stars in dwarf galaxies). This sort of work would need a huge observational effort, which explains why it has not been done until now.

6. DERIVED CLUSTER METALLICITIES

We use the relationships derived in previous sections to estimate the metallicities in the three observed clusters without previous determinations. In fact, we have observed Cr 110, a poorly studied cluster with no previous spectroscopic metallicity determinations. For Be 39, only Friel et al. (2002) have determined its metallicity from low-resolution spectroscopy. The sequences of these clusters in the \(M_I-\Sigma\text{Ca}\) plane have been plotted in Figure 16.

6.1. Berkeley 39

The first color-magnitude diagram of this open cluster was published by Kaluzny & Richtler (1989). These authors calculated a distance modulus of \((m-M)_0 = 13.44\) and \(E(B-V) = 0.12\). These values agree with the determinations of Carraro et al. (1994), who also used color-magnitude diagrams. The age of this cluster is \(7 \pm 1\) Gyr (Salaris et al. 2004).

There are few determinations of its metallicity. From photometric data Twarog et al. (1997) estimated \([\text{Fe/H}] = -0.18 \pm 0.03\), while from low-resolution spectroscopy Friel & Janes (1993) and Friel et al. (2002) obtained \([\text{Fe/H}] = -0.32 \pm 0.08\) and \(-0.26 \pm 0.09\), respectively. In our case we have 10 RGB stars which are cluster members from their radial velocity, although only five stars have \(I\) magnitudes available. Moreover, only two are brighter than \(M_I = 0\); nevertheless, the other three have magnitudes close to this value. We therefore used all five stars. From equation (5) we obtain \([\text{Fe/H}]_{\text{K907}} = -0.14 \pm 0.02\). We have used the relationship as a function of \(M_I\) because the RGB is more resolved in the \(I\) filter, and this relation is less sensitive to age. The calculated value is slightly more metal-rich than previous spectroscopic determinations. In the KI03 and ZW84 scales we obtain \([\text{Fe/H}]_{\text{KI03}} = -0.33 \pm 0.14\) and \([\text{Fe/H}]_{\text{ZW84}} = -0.23 \pm 0.25\), respectively, from equations (7a) and (8b). On these scales we have no young and/or metal-rich reference clusters, but, as we have checked before, the influence of age is weak.

We have also calculated the radial velocity of this cluster. We find \(V_r = 59 \pm 5\) km s\(^{-1}\), which is similar to values found previously (i.e., Friel et al. 2002; \(V_r = 55 \pm 7\) km s\(^{-1}\)).

6.2. Trumpler 5

Trumpler 5, also named Cr 105, is also a poorly studied cluster, even though it was discovered about 75 yr ago. It is located toward the Galactic anticenter in a rich star field in Monoceros, and in a region of variable interstellar reddening. This has complicated the studies of this cluster. In fact, only photometric studies could be found in the literature (e.g., Kaluzny 1998; Kim & Sung 2003; Piatti et al. 2004), with the exception of the work by Cole et al. (2004), who observed the CaT lines in a few stars on the RGB and derived the first spectroscopic determination of its metallicity. The distance modulus and reddening of this cluster have been derived from isochrone fitting. Most studies converge on a reddening of \(E(B-V) = 0.6\) (e.g., Kim & Sung 2003). However, this does not happen in the case of the distance, where the values lie between \((m-M)_0 = 12.25\) (Piatti et al. 2004) and \((m-M)_0 = 12.64\) (Kim & Sung 2003), corresponding to a distance from the Sun of 2.4 or 3.4 kpc, respectively. Also, the age
and metallicity have traditionally been estimated from isochrones. The age of this cluster is estimated between 2.4 ± 0.2 Gyr (Kim & Sung 2003) and 5.0 ± 0.5 Gyr (Piatti et al. 2004), while the derived metallicity is [Fe/H] = −0.30 ± 0.15 dex (e.g., Kim & Sung 2003; Piatti et al. 2004).

We have observed 21 stars in the field of Tr5, 17 of which are radial velocity members (Table 3). The metallicity derived from equation (5) is [Fe/H]_{CG97} = −0.36 ± 0.05, which is more metallic (although within the error) than the previous spectroscopic determination, [Fe/H] = −0.56 ± 0.11, by Cole et al. (2004). The alternative determination of the metallicity on the KI03 and ZW84 scales gives [Fe/H]_{K103} = −0.56 ± 0.09 and [Fe/H]_{ZW84} = −0.48 ± 0.20, respectively, from equations (7a) and (8b).

From our data we have also calculated the radial velocity of this cluster, $V_r = 44 ± 10$ km s$^{-1}$, which is similar to the value derived by Cole et al. (2004). $V_r = 54 ± 5$ km s$^{-1}$.

6.3. Collinder 110

Collinder 110 is a poorly populated cluster, and even less studied than Tr5. Only two photometric studies can be found in the literature for the last three decades. Using synthetic color-magnitude diagrams, Bragaglia & Tosi (2003) have estimated a reddening of 0.38 ≤ E(B−V) ≤ 0.45 and a distance modulus (m−M)$_0$ between 11.8 and 11.9. From these values they derived an age between 1.1 and 1.5 Gyr. Similar values were found by Dawson & Ianna (1998). There are no metallicity determinations for this cluster in the literature. Bragaglia & Tosi (2003) tried to derive the metallicity of this cluster from different stellar evolution models, but concluded that the final result varies widely depending on the models.

The metallicity derived from equation (5) is [Fe/H]_{CG97} = −0.01 ± 0.07. If we use equations (7a) and (8b) on the KI03 and ZW84 metallicity scales we find [Fe/H]_{K103} = −0.19 ± 0.21 and [Fe/H]_{ZW84} = 0.00 ± 0.30. From our data we can also provide the first determination of its radial velocity, $V_r = 45 ± 8$ km s$^{-1}$.

7. SUMMARY

We have observed the CaT lines in RGB stars in a sample of 29 clusters of the Milky Way. This sample covers an age range of (13 Gyr ≤ age ≤ 0.25 Gyr) and a metallicity range of (−2.2 ≤ [Fe/H] ≤ +0.47). These are the widest ranges of ages and metallicities in which the behavior of the CaT has been investigated in a homogeneous way until now. We have obtained relationships between the CaT equivalent widths and metallicities on the scales of Zinn & West (1984), Carretta & Gratton (1997), and Kraft & Ivans (2003). The influence of other parameters, such as age and [Ca/Fe] ratio, has been investigated. Moreover, for the first time, the behavior of the CaT lines as a function of luminosity along the RGB has been studied for the whole range of metallicities in our sample.

The main results of this work are the following:

1. Theoretically, it has been predicted that the sequences of clusters in the luminosity-ΣCa plane may not be linear, and that the slope should change with metallicity. In this article we have demonstrated that the nonlinear tendency and the change of the slope can be (marginally) detected if a wide range of magnitudes in the RGB is observed.

2. However, this behavior is not significant if only the usual range of 3–4 mag below the tip of the RGB is observed. For this reason, for stars with $M_V ≤ 1.25$ or $M_V ≤ 0$ we have considered that the sequences of the clusters in the $M_V$-ΣCa and $M_V$-ΣCa planes are linear and share a common slope, independent of metallicity.

3. We have obtained relationships between the reduced equivalent width ($W'_V$ and $W'_I$) and metallicity on the Zinn & West (1984), Carretta & Gratton (1997), and Kraft & Ivans (2003) scales. While on the Carretta & Gratton (1997) and Kraft & Ivans (2003) scales these relationships are linear, in the case of the Zinn & West (1984) scale it is quadratic.

4. Theory predicts that the relationship between the CaT line equivalent widths and metallicity might be dependent on age, mainly for clusters younger than 4 Gyr. We have studied the influence of age and found that the expected differences due to age are similar to the metallicity resolution of our work.

5. We have also investigated the influence of Ca abundances on the relationships between $W'_V$ and $W'_I$ and metallicity. We have found that [Ca/H] also changes linearly with $W'_V$ and $W'_I$.

6. Finally, the relationships obtained have been used to compute the metallicity of three clusters in our sample: Berkeley 39, Trumpler 5, and Collinder 110. For Collinder 110, there are no previous determinations of its metallicity in the literature.

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