ON THE IRON CONTENT OF NGC 1978 IN THE LMC: A METAL-RICH, CHEMICALLY HOMOGENEOUS CLUSTER

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ABSTRACT

We present a detailed abundance analysis of giant stars in NGC 1978, a massive, intermediate-age stellar cluster in the Large Magellanic Cloud, characterized by a high ellipticity and suspected to have a metallicity spread. We analyzed 11 giants, all cluster members, by using high-resolution spectra acquired with UVES/FLAMES at the ESO Very Large Telescope. We find an iron content of [Fe/H] = −0.38 dex with very low σ[Fe/H] = 0.07 dex dispersion, a mean heliocentric radial velocity $v_r = 293.1 \pm 0.9$ km s$^{-1}$, and a velocity dispersion σ = 3.1 km s$^{-1}$, thus excluding the presence of a significant metallicity, as well as velocity, spread within the cluster.

Subject headings: globular clusters: individual (NGC 1978) — Magellanic Clouds — stars: abundances — techniques: spectroscopic

1. INTRODUCTION

The Large Magellanic Cloud (LMC) is the nearest galaxy of the Local Group with a very populous system of globular clusters (GCs) that cover a wide range of metallicity and age. At least three main populations can be distinguished, namely, an old population, coeval with the Galactic GC system, an intermediate population (1–3 Gyr), and a young population (<1 Gyr).

Despite its importance, there is still a lack of systematic and homogeneous work aimed at determining the accurate chemical abundances and abundance patterns of the LMC GC system. Starting from the first compilation of metallicity by Sagar & Pandey (1989), the most systematic analysis still remains to be done by Olszewski et al. (1991), who estimated the metallicity of 70 LMC clusters using the Ca ii triplet. Other metallicity determinations are based on the Lick spectral indices (de Freitas Pacheco et al. 1998) or integrated infrared (IR) spectroscopy (Oliva & Origlia 1998), or are derived from Strömgren (Dirsch et al. 2000; Larsen et al. 2000) and Washington (Bica et al. 1998) photometry.

Detailed chemical abundances of LMC GCs from medium-to high-resolution spectroscopy are still scarce. Hill et al. (2000, hereafter H00) measured Fe, O, Al, Ca, and Ti abundances of a few giants in four GCs (namely, NGC 1866, NGC 1978, ESO 121, and NGC 2257) by using high-resolution UVES (UV-Visual Echelle Spectrograph) spectra. Korn et al. (2000, 2002) measured a few B stars in four young LMC clusters and inferred chemical abundances of Fe, C, N, O, and other α-elements (see also Rich- tler et al. 1989). Smith et al. (2002) measured four giants in NGC 1898 and NGC 2203 and obtained accurate abundances of Fe, C, O, Na, Al, and Sc. Results concerning the chemical composition of four old LMC GCs (namely, NGC 1989, NGC 2005, NGC 2019, and Hodge 11) are presented by Johnson et al. (2006), based on high-resolution spectra taken with MIKE (Magellan Inamori Kyocera Echelle) at the Magellan telescope.

In this Letter we present the first results of an ongoing project aimed at screening the chemical composition of a complete sample of LMC GCs and their surrounding field populations, by using UVES/FLAMES (Fiber Large Array Multi-Element Spectrograph). The major goal of our work is to derive a new homogeneous metallicity scale based on high-resolution spectroscopy together with a detailed description of the abundance patterns of key metals such as α, iron-group, and neutron-capture elements.

The first target observed in our survey is NGC 1978. This intermediate-age (≈3.5 Gyr; Girardi et al. 1995) cluster is very massive (≈2 × 105 $M_\odot$; Westerlund 1997, p. 72) and is located in a high-density stellar region, about 3.5 north of the bar field. It also shows a peculiar, very high ellipticity ($e = 0.3$; Geisler & Hodge 1980; Fischer et al. 1992). The multicolor BVR photometry by Alcaino et al. (1999) has shown a broad red giant branch (RGB), consistent with a metallicity spread [Fe/H] ≈ 0.2 dex. On the basis of this evidence, the authors suggested the possible existence of two different subpopulations as the result of a merging. This scenario was further supported by H00, who analyzed the high-resolution spectra of two giant stars located in the southeast region of the cluster. They found [Fe/H] = −1.1 and −0.82 dex, with a significant star-to-star difference (Δ[Fe/H] ≈ 0.3 dex). However, the same stars were previously observed by Olszewski et al. (1991), who found [Fe/H] = −0.46 and −0.38, i.e., a much higher (by a factor of ≈3) metallicity and a much smaller (Δ[Fe/H] ≈ 0.08 dex) star-to-star difference.

In order to better understand the formation and evolution of NGC 1978, a detailed high-resolution spectroscopic study of a significant sample of cluster stars is needed. Here we present the detailed abundance of iron for 11 giants in NGC 1978.

2. OBSERVATIONS AND SPECTRAL ANALYSIS

In order to establish whether or not a metallicity spread is present throughout NGC 1978, 11 RGB stars were observed in two different runs on 2003 October [ESO program 072.D-0342(A)] and 2005 February [as a backup program within the ESO program 074.D-0369(A)]. We used the multiobject spectrograph UVES/FLAMES (Pasquini et al. 2002), mounted at the Kueyen 8 m unit telescope (UT2) of the ESO Very Large Telescope (VLT). The UVES setup (red arm, centered at 5800 Å) provides a wavelength coverage of 4800–6800 Å and a resolution $R \approx 40,000$. The spectra have been acquired in series of 4–6 exposures of ≈45 minutes each, flat-field–corrected and average-combined together for a total exposure time of 3–5 hr. The final spectra have typical signal-to-noise ratio S/N ≥ 40. The selection of the target stars is based on our high-quality near-IR photom-
Fig. 1.—IR $(K, J - K)$ color-magnitude diagram of NGC 1978 from Mucciarelli et al. (2006). The 11 program stars (filled circles) are labeled according to their identification number in Table 1.

Fig. 2.—Location of the 11 program stars (filled circles) within the cluster area. The $(X, Y)$-coordinates are in pixels. The two filled triangles mark the position of the two stars measured by Olszewski et al. (1991) and H00.

Fig. 3.—Spectra of four program stars (the typical signal-to-noise ratio is $35–40$). A few reference lines are indicated.

The analysis of the chemical abundances was performed using the ROSA package (Gratton 1988). The line equivalent widths (EWs) of the observed spectra have been measured by Gaussian-fitting the line profiles, adopting a relationship between EW and FWHM (see, e.g., Bragaglia et al. 2001); an iterative clipping average over a fraction of the highest spectral points around each line has been applied to derive a local continuum. The details of the line list and the corresponding atomic parameters are given in Gratton et al. (2003). The stellar temperatures ($T_{\text{eff}}$) have been estimated using the IR $(J - K)$ color and the transformations by Alonso et al. (1999, 2001) and Montegriffo et al. (1998). Since the difference between the two temperature scales in the cool regime is always $<50$ K, we adopted the average of the two values.

Gravity has been estimated according to the location of the stars in the CMD and using a theoretical isochrone of $\sim3$ Gyr and $Z = 0.008$ from Carullo et al. (2004), by assuming a stellar mass of $1.37 M_{\odot}$, a distance modulus of $(m - M)_0 = 18.5$ (van den Bergh 1998), a reddening of $E(B - V) = 0.1$ (Persson et al. 1983), and the interstellar extinction law defined by Rieke & Lebofsky (1985). For the bolometric corrections, we used those computed by Montegriffo et al. (1998). Note that a slightly different choice of the isochrone metallicity has a negligible impact on the inferred stellar gravity; indeed, by varying the former by a factor of 2, the mass changes by $\approx 0.03 M_{\odot}$, which translates into a gravity variation of $\approx 0.01$ dex. Conversely, a different assumption for the cluster age can have some impact; we find that a 1 Gyr age variation implies a 0.05 dex gravity variation. According to the prescriptions in Magain (1984), the microturbulence velocity $v_t$ (see Table 1) is obtained by removing the residual trend of the derived Fe i abundances with the predicted line strengths $X$ (defined as $\log gf - \theta_X$), using a large number (typically 70–80) of Fe i lines for each star. ATLAS model atmospheres with convective overshooting by Kurucz (1993) are used to perform the abundance analysis.

Table 1 shows the adopted atmospheric parameters and the
values of [Fe/H], and [Fe/H] for all the program stars. The $N_{\text{Fe}},$ and $N_{\text{Fe}}$ numbers of lines used to derive the abundance are also listed. We adopt reference solar log n(Fe i) = 7.54 and n(Fe ii) = 7.49 for neutral and ionized Fe, respectively (see Gratton et al. 2003). Given the low temperature of the observed stars, and in order to avoid spurious effects due to line blending, only a few safe lines were used to derive the Fe ii abundance. In particular, for three stars (namely, NGC 1978-21, NGC 1978-22, and NGC 1978-23) no good lines are available.

The plots shown in Figure 4 represent a test for the validity of our analysis. In particular, the absence of any trend of $\Delta$Fe/\DeltaT (where $\chi$ is the excitation potential) with respect to $T_{\text{eff}}$ (the middle panel of Fig. 4) supports the reliability of our temperature scale. Similarly, the absence of a trend in the top panel is good proof of the correctness of our microturbulent velocities. We underline this point because H00 estimated (for similar stars in this cluster) a larger value (typically $v_t \sim 1.9$ km s$^{-1}$). This difference is clearly due to the different methodology used to calculate this parameter: H00 used the observed EWs and not, as we do, the expected line strengths.

3. RESULTS AND DISCUSSION

Our spectroscopic analysis based on 11 cluster member stars provides an average iron abundance from neutral Fe i lines of [Fe/H]$_{\text{i}}$ = $-0.38 \pm 0.02$ dex and [Fe/H]$_{\text{ii}}$ = $-0.26 \pm 0.02$ dex from singly ionized lines. The overall metallicity dispersion is $\sigma = 0.07$ dex. The overall error budget in [Fe/H] has been computed according to the uncertainties in the adopted atmospheric parameters and in the measured EWs. Uncertainties in temperatures (typically $\pm 60$ K) are estimated by taking into account the errors of the infrared colors [typically $\delta(A - V)$ $\sim 0.02$ mag] and reddening [$\delta(E(B-V))$ $\sim 0.02$ mag]. The uncertainty in gravity ($\pm 0.08$ dex) is obtained by quadratically summing uncertainties in the temperature, in the distance modulus, and in the bolometric correction. A 1 $\sigma$ random error ($\pm 0.11$ km s$^{-1}$) in microturbulent velocity has been estimated from the slope of the abundance/line strength relation. The internal errors in [A/H] are typically less than 0.10 dex. Finally, the contribution of the EW measurement uncertainties to the abundance error budget was estimated by dividing the average rms scatter of Fe i lines (assumed to represent the error of each individual line) by the square root of the number of lines. Considering all these error sources, we obtain a total uncertainty of $\pm 0.07$ dex for [Fe/H]$_{\text{i}}$ and of $\pm 0.17$ dex for [Fe/H]$_{\text{ii}}$, fully consistent with the (low) cluster metallicity dispersion. This confirms the high homogeneity level in the iron content of this cluster.

Our average metallicity is in good agreement with the previous estimate by Olszewski et al. (1991), who obtained [Fe/H] = $-0.42 \pm 0.04$, but both these estimates disagree with the significantly lower abundance ([Fe/H]$_{\text{III}}$ = $-0.96 \pm 0.15$) found by H00. Unfortunately, we did not reobserve the two stars measured by H00; hence, no direct comparison can be made. However, the relatively large number of giants mea-

![Fig. 4.—$\Delta$Fe/\DeltaT (top panel), $\Delta$Fe/\DeltaT (middle panel), and derived [Fe/H] (bottom panel), as a function of $T_{\text{eff}}$. The size of the typical error bar is shown in the bottom panel.](image-url)
sured in this work and the accurate tests we performed on the abundance analysis suggest that our result is quite solid. It is also worth noting that the high-metallicity estimate for this intermediate-age cluster is in agreement with the recent finding (see, e.g., Cole et al. 2000, Smith et al. 2002, and Cole et al. 2005) that the metallicity distribution of intermediate-age LMC field stars shows a remarkable peak in the abundance distribution at [Fe/H] \( \approx -0.4 \pm 0.2 \) dex.

Although the discussion of the overall age-metallicity relation in the LMC is beyond the scope of this Letter, the result obtained here deserves a few considerations. It is interesting to note that NGC 1978 is in the age range where different star formation (SF) models provide significantly different predictions in the age-metallicity relation. For example, the predictions of the two models discussed by Pagel & Tautvaisiene (1998; see their Fig. 4) show significant differences for clusters in the 2–10 Gyr age range. The two models are also discussed in H00 and compared with some observations (see their Fig. 4a). Here we just note that the current age estimate for NGC 1978 \( (\approx 3.5 \, \text{Gyr}; \text{Girardi et al. 1995}) \) and our metallicity determination place the cluster in a position within the age-metallicity diagram that is more consistent with a smooth SF model rather than with a bursting model. Of course, no firm conclusion can be reached on the basis of only one cluster; however, we strongly emphasize that only the combination of accurate metallicities and age determinations could significantly improve our knowledge of the star formation history of the LMC. Hence, an accurate determination of the age of NGC 1978 based on a highly accurate CMD is urgently needed to properly locate the cluster in the age-metallicity diagram.

NGC 1978 is one of the most massive stellar clusters in the LMC, and it has been suspected of harboring a chemically inhomogeneous stellar population (see § 1). Note that both the most massive stellar systems in the halos of our Galaxy (\( \omega \, \text{Cen}, \ M_\odot \approx 3 \times 10^6 \); Merritt et al. 1997) and M31 (G1, \( M_\odot \approx 7 \times 10^6 \); Meylan et al. 2001) show evidence of a metallicity spread and a complex star formation history (Ferraro et al. 2004b; Sollima et al. 2005). Curiously, both of these massive stellar systems show a relatively large ellipticity \( (e \approx 0.2) \), similar to NGC 1978. These properties have been interpreted as possible signatures of a merging event. Hence, our findings deserve a few additional comments in the context of cluster formation. The fact that our targets are well distributed within the entire cluster area (see Fig. 2) and the fact that they show an high level of homogeneity in their iron abundance allow us to safely conclude that NGC 1978 does not show any signature of metallicity spread. Also, the IR CMDs presented by Mucciarelli et al. (2006) do not confirm the presence of a significant spread along the RGB (contrary to the claim of Alcaino et al. 1999). Of course, our finding makes the merging hypothesis very unconvincing since it would require either that the two subunits had similar metallicity or that the two gas clouds with different metallicities efficiently mixed at better than \( \delta [\text{Fe}/\text{H}] = 0.07 \) dex before star formation started. Both these occurrences are quite unlikely; hence, we can safely conclude that there is no signature pointing at a merging event in the formation history of this cluster. Moreover, previous dynamical studies of this cluster (Fischer et al. 1992) already found no evidence of merging. Finally, it is also worth noting that ellipticity is a common feature of many LMC and Galactic clusters (see, e.g., Goodwin 1997), with no evidence of a metallicity spread. A few explanations for a large ellipticity, other than merging, can be advocated, with the two most likely being cluster rapid rotation and/or strong tidal interactions with the parent galaxy.

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