THE METALLICITY OF THE OLD OPEN CLUSTER NGC 6791

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ABSTRACT

We have observed four red clump stars in the very old, metal-rich open cluster NGC 6791 to derive its metallicity using the high-resolution spectrograph SARG mounted on the Galileo National Telescope (TNG). Using a spectrum synthesis technique, we obtain an average value of [Fe/H] = +0.47 (± 0.04, rms = 0.08) dex. Our method was tested on μ Leo, a well-studied, metal-rich field giant. We also derive average oxygen and carbon abundances for NGC 6791 from synthesis of [O I] at 6300 Å and C II at 5086 Å, finding [O/Fe] ~ −0.3 and [C/Fe] ~ −0.2.

Subject headings: Galaxy: disk — open clusters and associations: general — open clusters and associations: individual (NGC 6791) — stars: abundances

1. INTRODUCTION

The determination of the abundances in stars of different ages and Galactic locations is one of the basic tools for interpreting the chemical evolution of the Milky Way disk. Galactic open clusters are particularly well suited to this purpose (e.g., Friel 1995), since they reach ages as old as the disk itself, cover a large range in metallicities and ages, and are observed in regions of the Galactic disk likely characterized by different star formation histories, and their distances and ages can be determined with a precision unreachable for all but the nearest field stars.

We are currently studying in an accurate and homogeneous way a significant sample of open clusters (Bragaglia & Tosi 2006 and references therein); reliable distances, reddenings, and ages are derived from photometry with the synthetic color-magnitude diagrams technique (Tosi et al. 1991) and will be combined with metal abundances from high-resolution spectroscopy to provide robust constraints on the current and past disk properties.

We have already presented the detailed chemical abundances of a few old open clusters (Bragaglia et al. 2001; Carretta et al. 2004, 2005). To our sample we now add NGC 6791, which, with an age of about 9–10 Gyr, is one of the oldest open clusters of our Galaxy and has supersolar metallicity (e.g., Peterson & Green 1998; Chaboyer et al. 1999; Stetson et al. 1999; Sietsjen et al. 2003; Carney et al. 2005; King et al. 2005). This cluster, almost as old as the Galactic disk, is of paramount importance to studying the time evolution of the disk properties. Apart from its age, NGC 6791 is interesting for its peculiar horizontal branch (HB), mostly composed of red stars, but with a (unusual) blue tail (Kaluzyński & Udalski 1992; Liebert et al. 1994). Its study could be relevant for a number of issues, e.g., the UV upturn in elliptical galaxies, the HB morphology, and its connection with mass loss in globular clusters.

Despite its peculiarities and its importance for Galactic formation studies, only one detailed work dealing with the chemical pattern in NGC 6791, based on modern fine abundance analysis and high-resolution spectroscopy, has been published so far; Peterson & Green (1998) analyzed the coolest and brightest (at V = 15.0, B − V = 0.48) blue HB star. Aside from this case, really high signal-to-noise ratio (S/N), high-resolution spectra can be obtained in acceptable exposure times for only the brightest, and hence cooler, giants in this cluster. At the very high metallicity of NGC 6791, these giants pose a great challenge to the observers (see § 2), and great care has to be taken to ensure the reliability of the analysis of their extremely crowded spectra.

This paper is organized as follows. Section 2 presents our data, atmospheric parameters and iron abundances from spectrum synthesis are described in § 3, § 4 provides the abundances of carbon and oxygen, and a discussion and summary are given in § 5.

2. OBSERVATIONAL MATERIAL

The spectra of the giants of NGC 6791 are extremely rich in lines, due to the rather cool temperature and the high metal content. To alleviate the analysis problems, we focused our attention on (fainter) stars on the red clump, which are warmer than the red giants. Even these spectra are actually at least as rich in lines as that of the canonical very metal-rich giant μ Leo (see Fig. 1). The long debate regarding the appropriate abundance to be attributed to this star (see, e.g., Gratton & Sneden 1990) emphasizes the difficulties of deriving correct abundances from the very line-rich spectra of cool giants.

We chose our targets among the stars listed as cluster members by Friel et al. (1989) on the basis of their radial velocities (RVs). They are all confirmed members by our own measurements. All spectra were obtained with the high-resolution spectrograph SARG mounted at the Italian Galileo National Telescope (TNG) in the Canary Islands. The resolution is R = 29,000, and the wavelength coverage is 4620–7920 Å. Individual spectra have been obtained (mostly in service mode) from 2001 November to 2005 September, with exposures ranging from 1 to 1.5 hr each. For each star, the total exposure time ranges from 4.5 to 8 hr. All spectra have been reduced using a standard IRAF 4 procedure for

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4 IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation.
bias and flat-field correction, spectra extraction, and wavelength calibration; the individual RVs were derived, and the spectra were shifted to zero RV and averaged. Table 1 lists the identifications, coordinates, and magnitudes for the stars, together with the heliocentric RVs, obtained by averaging the individual RVs for each star. Also shown is the S/N of the summed spectra measured near 6000 Å by comparing the spectrum of the stars with those of μ Leo (see below), which can be considered virtually noiseless for the purposes of this comparison.

To cross-check our method of abundance derivation, we also analyzed a spectrum of μ Leo with the same procedure. This star was selected because it has stellar parameters and iron abundances similar to those expected in the NGC 6791 sample. The spectrum of μ Leo was acquired using the FEROS spectrograph at the ESO 1.5 m telescope at La Silla. The original spectrum has a resolution of R ~ 48,000; however, in order to make the analysis as similar as possible to that of the stars of NGC 6791, this spectrum was degraded at the same resolution as our SARG spectra. As evident from Figure 1, at this resolution the spectrum of μ Leo is indeed very similar to those of the stars of NGC 6791, except for the higher S/N, and very subtle differences in the line strengths. The fact that we are dealing with a different, lower resolution spectrum than that analyzed by Gratton & Sneden (1990) and adopt a different solar model explains the slight differences between our results and theirs (see § 3.4).

3. ABUNDANCES IN NGC 6791 FROM SYNTHESIS OF Fe LINES

In NGC 6791, even the spectra of red clump stars are so crowded that we deemed the traditional analysis, based on equivalent width measurements, not entirely reliable, due to the large inherent uncertainties in both the location of the continuum level and the presence of blends (see Gratton & Sneden [1990] and Smith & Ruck [2000] for a similar approach in the case of spectra of much higher resolution and S/N than presented here for μ Leo).

We then derived iron abundances for our program stars by comparing the observed profiles for a number of Fe lines to syntheses of small spectral regions (typical width ~2.5 Å) around the chosen lines. This procedure allows us to take fully into account the presence of blends. Furthermore, the correct positioning of the continuum level is much less a problem, since we can directly compare the highest points of the spectrum in the observed regions with those present in the synthetic spectra, insofar as we trust the line lists used in our analysis. These lists were built taking appropriately into account the inclusion of all relevant lines and the quality of the gf values, carefully discussed in Gratton et al. (2003).

These (extensive) line lists were obtained after careful comparisons with both the spectrum of the Sun and of HR 3627. This is a cool (~4200 K), very metal-rich ([Fe/H] ~ +0.3) star. With this combination of parameters, the strength of lines in HR 3627 is typically similar to (or even stronger than) that of the red clump stars of NGC 6791. We are fully confident that a line list that closely matches the spectrum of this star will also provide reasonable results for our program stars. This lengthy preparatory work on HR 3627 was based on excellent observational material; its spectrum, acquired with SARG, has both very high S/N (~400) and high resolution (R ~ 150,000), so that even extremely faint possible contaminants could be detected and included in the line lists. We selected a number of Fe I and Fe II lines that were free from nearby strong features. We restricted the spectral range from about 5500 to 7000 Å, to avoid the low response of the spectrograph in the blue region and fringe or severe telluric contamination redward of the upper wavelength limit. Around each line (within ±2 Å) we extracted lines of neutral and singly ionized atomic species from the Kurucz database (Kurucz 1995). We also included molecular lines, in particular of contaminant CN and hydrides. Lines unaccounted for in the Kurucz database and/or in the solar tables (Moore et al. 1966) were assumed to be Fe I lines with an excitation potential of 3.5 eV. The transition probabilities of the Fe lines we wanted to synthesize were left untouched with respect to the line list we used by Friel et al. (1989); BDA: Mermilliod (1995). V and B − V are from Montgomery et al. (1994); K from Skrutskie et al. (2006). RV from this paper.

![Figure 1](image-url) Small portion of the spectra of our target stars compared with μ Leo, degraded to the same resolution.
used in the EW analysis; the $gf$ values of the nearby lines were adjusted one by one, by matching the high-resolution spectrum of HR 3627. For more details about HR 3627 and these line lists, see Carretta et al. (2004).

The synthetic spectra were obtained using model atmospheres extracted from the grid of Kurucz (1993). For consistency with other papers analyzing stars in open clusters (see, e.g., Carretta et al. 2004), the models considered in this paper are those with the overshooting option included.

The fitting of the synthetic spectra to those observed was done by eye. There is of course some arbitrariness in the eye fitting, since different weights can be attributed to the line cores or wings. However, we found that our by-eye fitting gives the same average abundances but much less line-to-line scatter than a fitting based on more objective criterions, such as a least-square fitting to the data. The reason for the smaller scatter likely reflects a better estimate of the appropriate level of the local continuum, which is a free parameter in the fitting and is a critical issue when determining abundances.

The line parameters (oscillator strengths and damping broadening) were obtained using the same precepts adopted in Gratton et al. (2003). The same line parameters and microturbulent velocity were adopted for all stars.

### 3.1. Atmospheric Parameters

Effective temperatures ($T_{\text{eff}}$) and surface gravities ($\log g$) were obtained from the photometry, using $B$ and $V$ values from Montgomery et al. (1994) and $K$ magnitudes from 2MASS (Skrutskie et al. 2006). We derived the $T_{\text{eff}}$ from the $V-K$ colors, assuming the calibration by Alonso et al. (1999) and a reddening of $E(B-V) = 0.15$, the median value from the literature. We prefer not to use temperatures from the $B-V$ colors because of their strong dependence on metal abundance. We have found a posteriori that the values of the effective temperatures corresponding to the $B-V$ colors agree well with those from the $V-K$ colors for the metal abundance of NGC 6791, determined in the present analysis. We also prefer not to use temperatures derived from line extinction, because for the lines considered here there is a quite strong degeneracy between effective temperatures and microturbulent velocities (see below).

The calibration of the color-temperature relations of Alonso et al. (1999) is used for consistency with the analyses we are conducting of several other open clusters. It should be noted that their calibration only extends up to [Fe/H] = +0.2, and application to the stars of NGC 6791 requires an extrapolation. However, the $V-K$ color index used in this paper is only very marginally sensitive to metal abundance, so errors in our temperatures cannot be large. Errors in our effective temperatures are mainly due to uncertainties in the assumed reddening, e.g., an error of $\Delta E(B-V) = 0.04$ mag, a reasonable upper limit in the case of NGC 6791, implies an error of $\sim 100$ K in the assumed temperatures. For consistency, a similar approach was adopted for $\mu$ Leo, with the $V-K$ color from Johnson (1966) photometry. Note that this $T_{\text{eff}}$ for $\mu$ Leo is slightly cooler (by 50 K) than that derived by Gratton & Sneden (1990) using the infrared flux method.

Surface gravities were obtained from the location of the stars in the color-magnitude diagram, assuming a distance modulus of $(m-M)_V = 13.45$ (the median value from the literature), bolometric corrections from Alonso et al. (1999), and a mass of 0.9 $M_\odot$. Most of the errors in the surface gravities stem from uncertainties in the distance modulus, e.g., an error of $(m-M)_V = 0.5$ mag, a reasonable upper limit, implies an error of 0.2 dex in the surface gravities. For $\mu$ Leo, we adopted the value of the gravity given by Gratton & Sneden (1990), using a variety of methods (equilibrium of ionization for Fe, dissociation equilibrium for MgH, and pressure-broadened lines); this value is in fact almost identical to that of the NGC 6791 stars.

Microturbulent velocities ($v_t$) were obtained by eliminating trends of abundances with respect to the expected line strength (Magain 1984) $X = \log gf - EP \times \Theta_{\text{exc}}$, where $\log gf$ is the oscillator strength of the lines, $EP$ is the excitation potential (in eV), and $\Theta_{\text{exc}} = 5040/(0.86 T_{\text{eff}})$ represents the approximate temperature of the layers where most of the lines form. This implies that abundances are roughly independent of line strength. We considered here the average values of the abundances derived for the individual lines of all the stars of NGC 6791, in order to reduce the scatter and better demonstrate possible trends. This means that the same value of the microturbulent velocity was adopted for all stars. The same value was also adopted in the analysis of $\mu$ Leo, and it is slightly smaller (by 0.15 km s$^{-1}$) than what Gratton & Sneden (1990) and Smith & Ruck (2000) adopted. Uncertainties in these microturbulent velocities are approximately 0.08 km s$^{-1}$ for a given effective temperature; this is obtained by modifying $v_t$ from its best value until the slope becomes equal to its statistical error. Note, however, that there is a strong correlation between microturbulent velocities and effective temperatures, e.g., adopting temperatures 100 K higher, we would have derived microturbulent velocities $\sim 0.13$ km s$^{-1}$ larger. Final metallicities are obtained by interpolating in the Kurucz (1993) grid of model atmospheres (with the overshooting option) on the model with the proper atmospheric parameters whose abundance matches that derived from Fe i lines.
3.2. **Abundances from Individual Lines**

Figure 2 shows an example of the quality of the fit of three of the observed iron lines with synthetic spectra. The synthetic spectra have been computed with atmospheric parameters appropriate for the star and Fe abundances of $\log n(\text{Fe}) = 7.6$, 7.8, 8.0, 8.2, 8.4, 8.6, and 8.8. The lines considered in the analysis are marked with a tick mark in Figure 2. From these three comparisons we concluded that a best value for the Fe abundance was $\log n(\text{Fe}) = 8.00$. Note that other Fe I lines falling in the same spectral ranges of the program lines generally give Fe abundances in good agreement with those indicated by the lines selected in our analysis, although they were not actually used in the estimate of the best value for each star.

Table 2 gives abundances for Fe lines\(^7\) as obtained from the comparison of observations with spectral synthesis. Lines with expected line strength $X > -5.6$ were not used in the analysis, because there is a tendency for these lines to give abundances that are too low. This is likely a reflection of the weight we gave in our abundance estimates to the cores of these lines. These form at very tiny optical depths, where the adopted model atmospheres are probably not adequate and deviations from LTE become important. Such lines are strongly saturated, so they would not be good abundance indicators. Since the four target stars are very similar to each other, it is meaningful to average the results for the individual stars and derive the average abundance provided by each line. This is given in the last column of the table; the associated error bar is simply the dispersion of the mean. Figure 3 shows the lack of trends in the average Fe abundances with wavelength, EP, and line intensity parameter $X$, thus reinforcing the reliability of the derived abundances.

Table 3 summarizes the abundances obtained for each star. Columns (2), (3), and (4) give the values adopted for the atmospheric parameters ($T_{\text{eff}}$, $g$, and [$A$/H]), while the microturbulent velocity is the same for all stars ($v_t = 1.05$ km s\(^{-1}\)). In columns (5)–(10) we give the average values of the abundances.

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\(^7\) These abundances are by number; we use the usual spectroscopic notations. $\log n(A)$ is the abundance (by number) of the element A in the scale, where $\log n(\text{H}) = 12$. [$A$/H] is the logarithmic ratio of the abundances of elements A and H in the star, minus the same quantity in the Sun.
of Fe from neutral and singly ionized lines, along with the number of lines used in the analysis and the rms scatter of individual abundances. Finally, in columns (11) and (12) we give the [Fe/H] values. The reference solar abundances adopted here are log $n(Fe) = 7.54$ and 7.49 from neutral and singly ionized lines, respectively; those are the values we obtained from a solar analysis compatible with the present analysis (see Gratton et al. 2003).

The last row of Table 3 gives the average abundance for the cluster. The average Fe abundance from neutral lines is [Fe/H] = +0.47 ± 0.04 (rms of individual stars equal to 0.07 dex). The line-to-line scatter for each individual star is in the range 0.11–0.18 dex. This is dominated by uncertainties still present in the location of the continuum level within the small spectral windows considered in this analysis.

If we consider the average abundances for each line derived from the four spectra, the line-to-line scatter is 0.08 dex, as expected by assuming that the four results are independent of each other. For these average abundances, there is a small, insignificant trend with line excitation, $\Delta[Fe/H]/\Delta E_P = 0.009 \pm 0.012$ dex eV$^{-1}$. This implies that temperatures from line excitation are 38 ± 50 K higher than those adopted here. We deem this agreement as fully satisfying.

There is also a small, but again insignificant, difference between the abundances of Fe i and Fe ii, [Fe/H] i − [Fe/H] ii = 0.04 ± 0.07 dex. This small difference would have canceled had we chosen temperatures about 50 K lower than adopted or gravities about 0.15 dex larger.

### 3.3. Errors on the Derived Abundances

Table 4 gives the sensitivity of the derived abundances on the assumptions on the atmospheric parameters of the program stars (listed in col. [1]). Column (2) gives the considered parameter variation, and columns (3) and (4) the resulting variation in the abundances derived from Fe i and Fe ii lines respectively. Column (5) lists the estimated value for the systematic error in our analysis for each of the parameters, and columns (6) and (7) the corresponding uncertainties in the abundances from Fe i and ii lines, respectively.

The total errors listed in the bottom row of Table 4 are obtained by summing the contribution of each source of error, including the fitting error, quadratically. This estimate of the total error is computed assuming zero covariance between the effects of errors in the atmospheric parameters. In principle, this assumption is not strictly valid, since there are correlations between different parameters. In practice, the Fe abundance is mainly a function of the adopted effective temperatures. In fact, adopting $T_{eff}$ values, e.g., 200 K higher, we would have obtained higher microturbulent velocities (by 0.26 km s$^{-1}$) and Fe abundances smaller by about 0.15 dex. Note that since the effect on microturbulent velocity is larger than the direct effect of temperature variations, the abundances decrease with increasing model temperatures, at variance with the usual dependence for late type stars. Unfortunately, given the correlation between effective temperature and microturbulent velocity, we could not derive reliable effective temperatures from the excitation equilibrium.

There are quite strong arguments favoring the solution adopted throughout this paper. In fact, had we adopted the hypothetical 200 K warmer mentioned above [which would be obtained assuming a reddening of $E(B − V) = 0.23$, a value near the upper limit in the analyses of NGC 6791], abundances from Fe ii lines would have resulted that are much lower than those derived from Fe i lines, with an offset of 0.24 dex, rather than 0.04 dex. In principle, it should be possible to compensate for such an offset by increasing the surface gravities by 0.5 dex.

### Table 3

**Summary of Atmospheric Parameters and Abundance Derivations**

| Star   | $T_{eff}$ (K) | log g | $[A/H]$ | $n$ mean | $n$ rms | $[Fe/H]$ i | $[Fe/H]$ ii |
|--------|---------------|-------|---------|---------|---------|-----------|-----------|
| $\mu$ Leo                        | 4490 | 2.30 | 0.47    | 29 | 7.92 | 0.15 | 6 | 7.79 | 0.10 | +0.38 | +0.30 |
| 2014                           | 4463 | 2.30 | 0.50    | 26 | 7.94 | 0.12 | 6 | 7.90 | 0.11 | +0.40 | +0.41 |
| 3009                           | 4473 | 2.33 | 0.50    | 29 | 8.10 | 0.14 | 6 | 7.87 | 0.24 | +0.56 | +0.38 |
| 3019                           | 4468 | 2.35 | 0.50    | 28 | 7.99 | 0.11 | 5 | 7.80 | 0.21 | +0.45 | +0.36 |
| SE49                           | 4512 | 2.32 | 0.50    | 29 | 8.01 | 0.18 | 6 | 8.09 | 0.33 | +0.47 | +0.60 |
| Cluster Mean                   |       |       |         | 8.01 | 0.07 | 7.92 | 0.08 | 6 | 8.09 | 0.47 | +0.43 |

**Notes.** $v_t$ is 1.05 km s$^{-1}$ for all stars. Bottom row gives the cluster mean iron abundance.
(up to values of $\log g \sim 2.8$). However, this would require a distance modulus of $(m - M)_V \sim 12.15$, incompatible with the distances derived from the color-magnitude diagrams in the literature. The absolute magnitude of core He-burning stars (i.e., the clump stars we are observing) is expected to be $M_V \sim 1.2$, according to the models by Girardi & Salaris (2001). This corresponds to a distance modulus of $(m - M)_V \sim 13.4\pm1.3$, in agreement with the value used in our analysis. Hence, an upper limit for the effective temperatures of the program stars in NGC 6791 is about 100 K higher than the adopted values [corresponding to a reddening of $(E(B - V) < 0.18$ and a microturbulent velocity of $v_t < 1.18$ km s$^{-1}$]. This implies that the lower limit of the Fe abundance is [Fe/H] $> +0.39$ dex. Similar arguments can be used to define a robust upper limit of [Fe/H] $< +0.55$.

Summarizing, the Fe abundance we derive for NGC 6791 is [Fe/H] $= +0.47 \pm 0.04 \pm 0.08$, where the first error value represents the random term, as derived from the star-to-star scatter, and the second error value represents the systematic errors, due to the assumptions on reddening, distance modulus, mass, temperature scales, etc.

### 3.4. A Comparison with $\mu$ Leo

To further assess the soundness of the results of our spectrum synthesis analysis, we also analyzed the well-known, metal-rich field star $\mu$ Leo, strictly using the same criteria. The average Fe abundance we derived is $\log n(\text{Fe}) = 7.92 \pm 0.03$ (29 lines, rms $= 0.15$ dex) from neutral lines, and $\log n(\text{Fe}) = 7.79 \pm 0.04$ (6 lines, rms $= 0.10$ dex) from singly ionized lines. These values correspond to [Fe/H] = $+0.38 \pm 0.03$ and [Fe/H] = $+0.30 \pm 0.04$, respectively. The difference in the abundances provided by neutral and singly ionized lines is only marginally larger than the internal error and is similar to the corresponding difference found for the stars in NGC 6791.

This value of the Fe abundance of $\mu$ Leo can be compared with literature estimates. We consider only abundances based on very high quality spectra ($R \sim 100,000$, S/N > 200) and comparisons with synthetic spectra, since use of equivalent widths is not reliable for such line-rich spectra. Gratton & Sneden (1990) derived $\log n(\text{Fe}) = 7.97 \pm 0.02 \pm 0.15$ (36 lines, rms $= 0.12$ dex). Within the internal errors, the present estimate of the abundance agrees with that of Gratton & Sneden (1990). The [Fe/H] value given by Gratton & Sneden (1990) is slightly lower than that estimated in this paper ([Fe/H] = $+0.34 \pm 0.03$), due to their use of a different solar abundance, derived using the Holweger & Mueller (1974) model atmosphere, rather than the abundance obtained from the same grid considered for red giants. More recently, Smith & Ruck (2000) used a very similar technique and set of atmospheric parameters, and obtained a lower value of $\log n(\text{Fe}) = 7.79 \pm 0.03$ (internal error). This value is about 0.13 dex lower than the present one, and the difference can be ascribed to the larger value of the microturbulent velocity adopted by Smith & Ruck (2000; 1.22 km s$^{-1}$ rather than 1.05 km s$^{-1}$; see also Table 3). These comparisons show that systematic errors in our analysis are within the adopted error bar.

By comparing the abundances in NGC 6791 with those of $\mu$ Leo, we conclude that the former has an Fe abundance larger than the latter by 0.09 $\pm$ 0.05, where the error here is simply the quadratic sum of the internal errors, since the other uncertainties should cancel out in the differential abundance analysis. This small positive difference agrees well with the visual impression from Figure 1.

### 4. ABUNDANCES OF OXYGEN AND CARBON

We estimated the abundance of oxygen from the [O i] line at 6300.31 Å. The second, weaker [O i] line at 6363.79 Å is barely measurable in our spectra, and the three O lines near 7775 Å (which are not the best suited for this kind of star) fall in a region where strong interference fringes make it difficult to extract accurate information from spectra.

The 6300.31 Å line often happens to be strongly affected by telluric contamination. However, in the case of NGC 6791, the cluster RV relative to Earth motion keeps the [O i] line from being contaminated by telluric absorptions in the majority of our spectra. Compromising between a slightly lower S/N and a lower data manipulation, we decided to average only the un-disturbed spectra for each star and measure the O abundance from them.

In order to derive reliable O abundances, a careful synthesis of the [O i] lines is necessary, including not only the contribution of the nearby Ni line but also the relevant coupling with C abundances and the contamination by CN lines. While a full discussion of CNO abundances is deferred to a forthcoming paper, here we preliminarily estimate the C abundances from the spectral synthesis of the C$_2$ molecular features at 5086 Å. Figure 4 shows an example of matching of synthetic spectra for star 3019 in the forbidden [O i] line and in the C$_2$ regions. The synthetic spectra were computed assuming $[\text{Ni/Fe}] = -0.2$ and $^{13}$C/^{12}$C = 8. The latter value is adequate for low-mass evolved giants, while the former one provides CN features in reasonable agreement with observations for the best C abundance.

Combining the C and O abundances provided by these two abundance indicators, we find average abundance ratios of $[\text{C/Fe}] = -0.23$ dex (a rather normal value for clump stars) and...
thetic spectra were computed assuming $[\text{Fe}/\text{H}] = +0.320 \pm 0.023 \pm \sigma_{\text{sys}}$, where $\sigma_{\text{sys}}$ the systematic error attached to their metallicity scale, is unknown. We have only one star in common (3019, their R25), for which the quoted abundance is $[\text{Fe}/\text{H}] = +0.341$.

All the four stars analyzed here were observed at low resolution by Friel et al. (1989), where we adopted identification and membership status from. The same group (Friel & Janes 1993) later published their metallicities; $[\text{Fe}/\text{H}]$ values are $+0.32 \pm 0.28$ (for star 2014), $+0.23 \pm 0.33$ (3009), $+0.39 \pm 0.15$ (3019), and $+0.41 \pm 0.21$ (SE49). These values, which would give an average metallicity of about $+0.34$, do not differ much from our new ones, considering that the scale used by Friel & Janes (1993) gives on average metal-poorer values than others. The final result of their analysis depends on the calibration of indices using standard stars with metallicity derived by several different sources. Because of a recent revision of their abundance scale (Friel et al. 2002), these abundances were lowered to $+0.12 \pm 0.13$, $+0.11 \pm 0.13$, $+0.15 \pm 0.11$, and $+0.16 \pm 0.11$ for the same stars; for their total sample of 39 stars, they derived an average metallicity of $+0.11$, $\sigma = 0.10$ dex.

To date, the only published analysis based on high-resolution spectroscopy remains that by Peterson & Green (1998). They obtained 4 hr of integration at the 4 m Mayall telescope at Kitt Peak on a blue HB star that is a cluster member, both by proper motion and RV. The summed spectrum has S/N and resolution lower than ours (S/N ~ 30 pixel$^{-1}$, $R = 20,000$), but is less affected by blends because of the much higher temperature (about 7300 K). They employed both EWS (for Fe and atmospheric parameters determination) and spectrum synthesis (for all the other measured elements). They discussed the use of different scales, e.g., for log gf values and solar reference abundances. On the scale they chose to adopt, their star has $[\text{Fe}/\text{H}] = +0.37 (\pm 0.10)$ dex; since their solar Fe is log $n = 7.67$ and ours is 7.54, their value corresponds to $[\text{Fe}/\text{H}] = +0.50$ on our scale.

Taken at face value, the agreement with our results appears excellent, but it does not take into account many differences, e.g., log gf, model atmospheres, and the like. For instance, we have four Fe lines in common with Peterson & Green (1998), one of Fe i and three of Fe ii (see our Table 2 and their Table 1), and the average difference in log gf is about 0.29 (our values minus theirs). They also measured the abundances of several elements by means of extensive spectrum synthesis, finding strong overabundances with respect to the solar ratio for N and Na (+0.5 or +0.4) and slightly lower ones for Mg and Si (+0.2) and Eu (+0.1). All the other elements, including C and O, display solar-scaled abundances. In our analysis we have so far measured only C and O abundances, finding for them subsolar ratios. A complete comparison between the two analyses is beyond the purpose of the present paper, and the chosen targets are also quite different in properties, but the comparison will be done once we have measured all other elements.

Summarizing, we have derived the metallicity of NGC 6791 by analyzing the high-resolution, high S/N spectra of four red clump stars, finding an average $[\text{Fe}/\text{H}] = +0.47 \pm 0.04 \pm 0.08$, where the two error values represent the random and systematic terms, respectively. This result has been obtained using spectrum synthesis of Fe i and Fe ii lines, and adopting atmospheric

\[ [\text{O}/\text{Fe}] = -0.32 \text{ dex}. \] The comparisons with synthetic spectra clearly show that the O abundance cannot be much larger than this value. It cannot be much lower either, otherwise the features due to C-bearing molecules would be much stronger (the spectra of the stars clearly shows that O \( \gg \) C).

As a comparison, Gratton & Sneden (1990) derived for $\mu$ Leo $[\text{C}/\text{Fe}] = [\text{O}/\text{Fe}] = -0.15$ dex. NGC 6791 is then slightly more deficient in both O and C with respect to $\mu$ Leo, along the standard trend of more pronounced deficiency of these elements with increasing metal abundance (see Bensby et al. 2005; Andersson & Edvardsson 1994).

5. DISCUSSION AND SUMMARY

The first detailed study of NGC 6791 of which we are aware is that of Kinman (1965), who published a photographic color-magnitude diagram and derived information on membership and intrinsic colors (i.e., reddening) from low-resolution spectra. There is a general agreement that this cluster is at about the same galactocentric distance as the Sun, is about twice as old, and about twice as metal-rich. Nevertheless, there are significant differences between properties derived by different authors, $(m - M)_0 \sim 12.6 - 13.6$, $E(B - V) \sim 0.09 - 0.23$, age \( \sim \) 7-12 Gyr, and $[\text{Fe}/\text{H}] \sim 0.1 - 0.4$ (for a recent review see Stetson et al. 2003). NGC 6791 has also been observed with the ACS on board the Hubble Space Telescope (King et al. 2005; Bedin et al. 2005), reaching almost the hydrogen-burning limit on the main sequence and defining the white dwarfs’ cooling sequence.

Spectroscopic studies of NGC 6791 are fewer, but present interesting results. Since the pioneering work by Spinrad & Taylor (1971), the cluster has been recognized to be more metal-rich than the Sun; they found $[\text{M}/\text{H}] = +0.75$, but with a method that attributes $[\text{M}/\text{H}] \approx +0.6$ to NGC 188 and M67, both of which are currently known to have near-solar metallicity.

More recently, the red HB (the “red clump”) has been studied by low-resolution spectroscopy by Hufnagel et al. (1995); they wanted to investigate possible correlations between CH and CN band strengths and found none, at variance with similar studies on globular clusters.

Worthey & Jowett (2003) took low-resolution spectra of 23 K giants in NGC 6791 and derived, using Lick IDS indices, $[\text{Fe}/\text{H}] = +0.320 \pm 0.023 \pm \sigma_{\text{sys}}$, where $\sigma_{\text{sys}}$ the systematic error attached to their metallicity scale, is unknown. We have only one star in common (3019, their R25), for which the quoted abundance is $[\text{Fe}/\text{H}] = +0.341$.

Fig. 4.—Comparison between the observed spectrum for star 3019 in NGC 6791 (thick line) and synthetic spectra (thin lines) for the [O i] line at 6300 Å (top panel) and the C$_2$ molecular feature at 5086 Å (bottom panel). The synthetic spectra were computed assuming $[\text{N}/\text{Fe}] = -0.2$, and $^{12}\text{C}/^{13}\text{C} = 8$. In the top panel we adopted $[\text{C}/\text{Fe}] = -0.25$, and $[\text{O}/\text{Fe}] = -0.65, -0.55, -0.45, -0.35, -0.25, -0.15$, and $-0.05$. In the bottom panel we adopted $[\text{O}/\text{Fe}] = -0.35$, and $[\text{C}/\text{Fe}] = -0.40, -0.35, -0.30, -0.25, -0.20, -0.15$, and $-0.10$. 

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parameters from the photometry. The soundness of our analysis has also been checked relative to a well-studied, metal-rich field giant star, $\mu$ Leo.

We have measured O and C abundances using the syntheses of the [O i] line at 6300.31 Å and $C_2$ molecular feature at 5086 Å, finding $[O/Fe] = -0.32$ and $[C/Fe] = -0.23$ dex, on average, for NGC 6791.

NGC 6791 represents a challenge to any model for the formation of the Galactic disk, a possible missing link between globular and open clusters, a genuine puzzle that modern abundance analysis based on high-resolution spectroscopy will help to solve.

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REFERENCES

Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261
Andersson, H., & Edvardsson, B. 1994, A&A, 290, 590
Bedin, L. R., Salaris, M., Piotto, G., King, I. R., Anderson, J., Cassisi, S., & Monnary, Y. 2005, ApJ, 624, L45
Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, A&A, 433, 185
Bragaglia, A., & Tosi, M. 2006, AJ, 131, 1544
Bragaglia, A., et al. 2001, AJ, 121, 327
Carney, B. W., Lee, J.-W., & Dodson, B. 2005, AJ, 129, 656
Carretta, E., Bragaglia, A., Gratton, R. G., & Tosi, M. 2004, A&A, 422, 951
———. 2005, A&A, 441, 131
Chaboyer, B., Green, E. M., & Liebert, J. 1999, AJ, 117, 1360
Friel, E. D. 1995, ARA&A, 33, 381
Friel, E. D., & Janes, K. A. 1993, A&A, 267, 75
Friel, E. D., Janes, K. A., Tavarez, M., Scott, J., Katsanis, R., Lotz, J., Hong, L., & Miller, N. 2002, AJ, 124, 2693
Friel, E. D., Liu, T., & Janes, K. A. 1989, PASP, 101, 1105
Girardi, L., & Salaris, M. 2001, MNRAS, 323, 109
Gratton, R. G., Carretta, E., Claudi, R., Lucatello, S., & Barbieri, M. 2003, A&A, 404, 187
Gratton, R. G., & Sneden, C. 1990, A&A, 234, 366
Holweger, H., & Mueller, E. A. 1974, Sol. Phys., 39, 19
Hufnagel, B., Smith, G. H., & Janes, K. A. 1995, AJ, 110, 693
Johnson, H. L. 1966, ARA&A, 4, 193
Kajzner, J., & Udalski, A. 1992, Acta Astron., 42, 29
King, I. R., Bedin, L. R., Piotto, G., Cassisi, S., & Anderson, J. 2005, AJ, 130, 626
Kinnman, T. D. 1965, ApJ, 142, 655
Kurucz, R. L. 1993, Kurucz CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s grid (Cambridge: SAO)
———. 1995, Kurucz CD-ROM 23, Atomic Line Data (Cambridge: SAO)
Liebert, J., Saffer, R. A., & Green, E. M. 1994, AJ, 107, 1408
Magain, P. 1984, A&A, 134, 189
Mermilliod, J.-C. 1995, in Information and Online Data in Astronomy, ed. D. Egret & M. A. Albrecht (Dordrecht: Kluwer), 127
Montgomery, K. A., Janes, K. A., & Phelps, R. L. 1994, AJ, 108, 585
Moore, C. E., Minnaert, M. G. J., & Houtgast, J. 1966, The Solar Spectrum 2935 Å to 8770 Å (Washington: USGPO)
Peterson, R. C., & Green, E. M. 1998, ApJ, 502, L39
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Smith, G., & Ruck, M. J. 2000, A&A, 356, 570
Spinrad, H., & Taylor, B. J. 1971, ApJ, 163, 303
Stetson, P. B., Bruntt, H, & Grundahl, F. 2003, PASP, 115, 413
Tosi, M., Greggio, L., Marconi, G., & Focardi, P. 1991, AJ, 102, 951
Worthey, G., & Jowett, K. J. 2003, PASP, 115, 96