HIGH-RESOLUTION INFRARED SPECTROSCOPY OF THE OLD OPEN CLUSTER NGC 6791

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ABSTRACT

We report abundance analysis for six M giant members of the old open cluster NGC 6791, based on infrared spectroscopy (1.5–1.8 μm) at R = 25,000, using the NIRSPEC spectrograph at the Keck II telescope. We find the iron abundance ([Fe/H]) = +0.35 ± 0.02, confirming the supersolar metallicity of this cluster as derived from optical medium-high resolution spectroscopy. We also measure C, O, and other α-element abundances, finding a roughly solar value of [α/Fe] and ([C/Fe]) = −0.35. Our approach constrains [O/Fe] especially well, on the basis of the measurement of a number of OH lines near 1.6 μm; we find [O/Fe] = −0.07 ± 0.03. The solar value of [α/Fe] is in contrast to the composition of similar stars in the Galactic bulge. We also find a low value of 12C/13C ≈ 10, confirming the presence of extramixing processes during the red giant phase of evolution, up to supersolar metallicities.

Subject headings: infrared: stars — open clusters and associations: individual (NGC 6791) — stars: abundances — stars: late-type — techniques: spectroscopic

1. INTRODUCTION

The open cluster NGC 6791 is currently believed to be one of the most massive, most metal-rich, and oldest stellar systems. For this reason it has been the subject of many photometric (Kinnman 1965; Harris & Cantera 1981; Demarque et al. 1992; Anthony-Twarog & Twarog 1985; Kaluzny 1990; Kaluzny & Udalski 1992; Garnavich et al. 1994; Meynet et al. 1993; Kaluzny & Rucinski 1993; Tripicco et al. 1995; Chaboyer et al. 1999; Stetson et al. 2003; Carney et al. 2005) and spectroscopic (Friel & Janes 1993; Peterson & Green 1998; Friel et al. 2002; Worthey & Jowett 2003) investigations. Its populous color-magnitude diagram (CMD) suggests a mass ≳4000 M☉ (Kaluzny & Udalski 1992) and an age in the 6–12 Gyr range, as inferred from both optical and IR photometry (see, e.g., Kaluzny & Udalski 1992; Tripicco et al. 1995; Chaboyer et al. 1999; Stetson et al. 2003; Carney et al. 2005), dependent on the adopted reddening and metallicity. Estimates of the cluster reddening also cover some range, from E(B − V) = 0.10 (Janes 1984) to E(B − V) = 0.22 (Kinnman 1965), with a mean value of E(B − V) = 0.16 that is in excellent agreement with the Schlegel et al. (1998) extinction maps, which give E(B − V) = 0.15 (see §2). NGC 6791 is a relatively distant cluster, with a suggested distance modulus (m − M)h ranging from 12.60 (Anthony-Twarog & Twarog 1985) to 13.6 (Harris & Cantera 1981). NGC 6791 has also a peculiar white dwarf luminosity function, and the metallicity of the cluster has some bearing on the explanation of the white dwarf properties (Bedin et al. 2005; Hansen 2005).

However, as reviewed by Stetson et al. (2003) and Carney et al. (2005), chemical abundances are difficult to measure in this moderately distant and reddened cluster. Its most luminous stars are relatively faint, and the combination of low effective temperature and high metallicity make high-resolution optical spectra difficult to analyze. Thus, metallicity estimates have been derived mainly using three different techniques, such as (1) photometric metallicity indicators (Janes 1984; Carney et al. 1986), (2) low- and moderate-resolution spectroscopy (Friel & Janes 1993; Peterson & Green 1998; Friel et al. 2002; Worthey & Jowett 2003), and (3) model isochrones (Stetson et al. 2003; Carney et al. 2005 and references therein). To summarize, the metallicity proposed for this cluster is in the range 0.11–0.44 dex. The first work at medium-high resolution is that of Peterson & Green (1998), who measured a sample of warm horizontal-branch stars at R = 20,000, finding an iron abundance [Fe/H] = +0.4 ± 0.1, a modest (if any) α-enhancement (within a factor of 2), and an approximately solar value of [C/Fe]. Very recently, two other spectroscopic studies on clump and red giant branch (RGB) stars have been performed by Carraro et al. (2006) and Gratton et al. (2006), finding [Fe/H] = +0.39 ± 0.01 and +0.47 ± 0.04, respectively. Carraro et al. (2006) also find an approximately solar value of [α/Fe], while Gratton et al. (2006) find the value of [O/Fe] to be depleted by a factor of 2 with respect to the solar value.

The use of IR spectroscopy offers an interesting alternative to optical spectroscopy, as it is less sensitive to the blanketing effects and more suitable for the study of cool and metal-rich stars than the optical spectral range. Our group has been undertaking a program using the NIRSPEC spectrograph (McLean et al. 1998).
at the Keck telescope to obtain spectra of old metal-rich stars in the bulge field (Rich & Origlia 2005) and in globular clusters (Origlia et al. 2003; Origlia & Rich 2004; Origlia et al. 2005a, 2005b) with the aim of studying the composition and chemical evolution of the bulge and globular clusters. Precise chemical abundances of NGC 6791 are crucial to better constrain the age of this cluster, which deserves detailed investigations, since it is one of the few examples in which we can study stars that formed very early in the evolution of the Galactic disk. As underlined by Carney et al. (2005), because NGC 6791 is both old and metal-rich, it also plays a fundamental role in calibrating several “secondary” metallicity indicators, such as the low- to moderate-resolution spectroscopy or photometry (see, e.g., Valenti et al. 2004a, 2004b). In this context, we present high-resolution IR spectra and the abundance analysis of six bright giants in the open cluster NGC 6791. Our observations, data reduction, and abundance analysis follow in §2, while §3 discusses our results.

### 2. OBSERVATIONS AND ABUNDANCE ANALYSIS

By using Two Micron All Sky Survey (2MASS) photometry, we constructed the \((K, J - K)\) CMD of NGC 6791 and selected six bright \((H = 9–11)\) giant stars (see Fig. 1). Table 1 reports their 2MASS names and coordinates. The program stars were observed at the Keck telescope in 2005 May, with typical exposure times of 4 minutes. We used NIRSPEC (McLean et al. 1998) in the echelle mode, with a slit width of 0′′43 and a length of 12″, giving an overall spectral resolution of \(R = 25,000\), and with the standard NIRSPEC 5 setting, which covers most of the 1.5–1.8 \(\mu\)m \(H\) band.

The raw stellar spectra have been reduced using the REDSPEC IDL-based package written at the UCLA IR Laboratory. Each order has been sky-subtracted by using nodding pairs and has been flat-field corrected. Wavelength calibration has been performed using arc lamps and a second-order polynomial solution, while telluric features have been removed by using a O-star featureless spectrum. The signal-to-noise ratio of the final spectra is \(\geq40\), and Figure 2 shows an example.

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**Figure 1.** \((K, J - K)\) color-magnitude diagram of NGC 6791 as obtained from 2MASS photometry. The giant stars observed with NIRSPEC are plotted as filled triangles, and the derived RGB fiducial ridge line is superimposed as a solid line.

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### Table 1: Our Sample of Observed Giant Stars in NGC 6791

| Star | 2MASS        | R.A. (J2000.0) | Decl. (J2000.0) |
|------|--------------|----------------|-----------------|
| 1.   | J19211606+3746462 | 19 21 16        | +37 46 46       |
| 2.   | J19204971+3743426 | 19 20 50        | +37 43 43       |
| 3.   | J19213390+3750202 | 19 21 34        | +37 50 20       |
| 4.   | J19204635+3750228 | 19 20 46        | +37 50 23       |
| 5.   | J19205510+3747162 | 19 20 55        | +37 47 16       |
| 6.   | J19205338+3748282 | 19 20 53        | +37 48 28       |

*Note:* Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

A grid of suitable synthetic spectra of giant stars has been computed by using the photospheric parameters and the element abundances, using an updated version of the code described in Origlia et al. (1993). By combining full spectral synthesis analysis with equivalent width measurements of selected lines, we derive abundances for Fe, C, O, and other \(\alpha\)-elements. The lines and the analysis method have been detailed and subjected to rigorous tests in our previous studies of Galactic bulge field and cluster giants (see Origlia et al. 2005b; Rich & Origlia 2005 and references therein). Here we summarize the major issues. The code uses the LTE approximation. In the \(H\) band, most of the OH and CO molecular lines are not saturated and can be safely treated under the LTE approximation, since they are rovibrational transitions in the ground electronic state, providing accurate C and O abundances (Merrill & Ridgway 1979; Lambert et al. 1984; Smith et al. 2000). Detailed computations of possible NLTE effects for atomic lines in the \(H\) band have been performed only for Al lines in the Sun (see Baumüller & Gehren 1996), who indeed find negligible corrections. However, most of the near-IR atomic lines are of high excitation potential, indicating that they form deep in the atmosphere, where the LTE approximation should hold even in giants of low gravity. Moreover, one of the major mechanisms that can cause a deviation from LTE, namely, ionization by UV radiation, is less efficient in cool giants, while photon suction can have some relevance. According to NLTE computations on Fe and Mg lines (see, e.g., Gratton et al. 1999; Zhao & Gehren 2000), deviations from LTE (at a level of \(\geq0.1\) dex) are mainly observed in stars that are significantly hotter and more metal-poor than those in our program. The code is based on the molecular blanketed model atmospheres of Johnson et al. (1980) in the 3000–4000 K temperature range and on the ATLAS9 models for temperatures above 4000 K. Since in the near-IR the major source of continuum opacity is H\(^{-}\), with its minimum near 1.6 \(\mu\)m, the dependence of the results on the choice of reasonable model atmospheres should not be critical. However, as a check, we also computed synthetic spectra using the more updated NextGen model atmospheres by Hauschildt et al. (1999) and compared them with those obtained using Johnson et al. (1980) models, finding minor differences (Rich & Origlia 2005). Three main compilations of atomic oscillator strengths are used: the Kurucz database,\(^2\) Bémont & Grevesse (1973), and Meléndez & Barbuy (1999). Reference solar abundances are from Grevesse & Sauval (1998). In the first iteration, we estimate the stellar temperature from the \((J - K)_{0}\) colors (see Table 2) and the color-temperature transformation of Montgeotribe et al. (1998), which was specifically calibrated on globular cluster giants. Gravity has

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\(^2\) Available at [http://cfa-www.harvard.edu/amdata/ampdata/kurucz 23/sekur.html](http://cfa-www.harvard.edu/amdata/ampdata/kurucz 23/sekur.html).
NGC 6791: #1 + #2

Fig. 2.—Selected portions of the $H$-band spectrum obtained with NIRSPEC for stars 1 and 2. Some features of interest are also marked.

**TABLE 2**

| Star | $(J-K)_0$ | $T_{\text{eff}}$ | log $g$ | $v_r$ | [Fe/H] | [O/Fe] | [Si/Fe] | [Mg/Fe] | [Ca/Fe] | [Ti/Fe] | [Al/Fe] | [C/Fe] |
|------|-----------|-------------------|--------|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1.... | 1.13      | 3600              | 1.0    | $-49$ | $+0.36 \pm 0.09$ | $-0.04 \pm 0.13$ | $-0.06 \pm 0.18$ | $-0.03 \pm 0.10$ | $+0.04 \pm 0.14$ | $+0.06 \pm 0.16$ | $+0.04 \pm 0.16$ | $-0.36 \pm 0.12$ |
| 2.... | 1.15      | 3600              | 1.0    | $-52$ | $+0.33 \pm 0.09$ | $-0.05 \pm 0.13$ | $-0.03 \pm 0.18$ | $-0.03 \pm 0.10$ | $+0.07 \pm 0.14$ | $-0.03 \pm 0.16$ | $+0.07 \pm 0.16$ | $-0.33 \pm 0.12$ |
| 3.... | 1.02      | 3800              | 1.5    | $-50$ | $+0.32 \pm 0.08$ | $-0.06 \pm 0.11$ | $+0.08 \pm 0.17$ | $-0.02 \pm 0.09$ | $+0.08 \pm 0.13$ | $+0.08 \pm 0.16$ | $+0.08 \pm 0.14$ | $-0.32 \pm 0.11$ |
| 4.... | 0.93      | 4000              | 1.5    | $-50$ | $+0.38 \pm 0.08$ | $-0.08 \pm 0.09$ | $+0.08 \pm 0.21$ | $-0.05 \pm 0.08$ | $+0.02 \pm 0.13$ | $+0.02 \pm 0.14$ | $+0.02 \pm 0.14$ | $-0.38 \pm 0.11$ |
| 5.... | 0.92      | 4000              | 1.5    | $-51$ | $+0.37 \pm 0.08$ | $-0.09 \pm 0.09$ | $+0.03 \pm 0.21$ | $-0.02 \pm 0.08$ | $+0.03 \pm 0.13$ | $+0.03 \pm 0.14$ | $+0.03 \pm 0.14$ | $-0.37 \pm 0.11$ |
| 6.... | 0.89      | 4000              | 1.5    | $-52$ | $+0.36 \pm 0.07$ | $-0.11 \pm 0.09$ | $-0.01 \pm 0.21$ | $+0.00 \pm 0.08$ | $+0.04 \pm 0.12$ | $+0.04 \pm 0.14$ | $+0.04 \pm 0.13$ | $-0.36 \pm 0.10$ |

Notes.—The $J - K$ colors are from 2MASS and have been corrected for reddening using Schlegel et al. (1998) extinction maps. The heliocentric radial velocity is given in units of km s$^{-1}$. 
been estimated from theoretical evolutionary tracks, according to the location of the stars on the RGB (see Origlia et al. 1997 and references therein for a more detailed discussion). For the microturbulence velocity, an average value of $\xi = 2.0 \text{ km s}^{-1}$ has been adopted. More stringent constraints on the stellar parameters are obtained by the simultaneous spectral fitting of the several CO and OH molecular bands, which are very sensitive to temperature, gravity, and microturbulence variations (see Figs. 6 and 7 of Origlia et al. 2002). The adopted values are listed in Table 2.

3. RESULTS

From our spectral analysis we find all six stars that are likely members of the cluster, showing an average heliocentric radial velocity $\langle v_r \rangle = -52 \pm 1 \text{ km s}^{-1}$. This value is in good agreement with previous estimates (Friel & Janes 1993; Friel et al. 2002). We derive abundances for Fe, C, O, Ca, Si, Mg, Ti, and Al. The final values of our best-fit models, together with random 1 $\sigma$ errors, are listed in Table 2. We find an average [$\text{Fe/H}$] = $+0.35 \pm 0.02$ dex, a roughly solar value of [$\alpha$/Fe] = $-0.35 \pm 0.03$ dex, and a low value of $^{12}\text{C}/^{13}\text{C} \approx 10 \pm 2$.

We also explored the results using models with $\Delta [\text{X/H}] = \pm 0.2$ dex, $\Delta T_{\text{eff}} = \pm 200$ K, $\Delta \xi = \mp 0.5$ km s$^{-1}$, and $\Delta \log g = \pm 0.5$ dex with respect to the best-fit parameters. Figure 3 shows an example for star 3. It is clearly seen that models with $\pm 0.2$ dex abundance variations give remarkably different molecular line profiles. Temperature variations of $\pm 200$ K and microturbulence variations of $\pm 0.5$ km s$^{-1}$ mainly affect the OH lines, while gravity mainly affects the CO lines. As a further check of the statistical significance of our best-fit solution, we also compute synthetic spectra with $T_{\text{eff}} = 3600$ K, $\log g = 1.0$, $\xi = 2$ km s$^{-1}$, [$\text{Fe/H}$] = $+0.3$, [O/Fe] = $+0.0$, and [$\text{C/Fe}$] = $-0.3$ as reference stellar parameters (see also Table 2). For comparison, we also plot synthetic spectra with different abundances and stellar parameters with respect to the best-fit solution. Bottom left: $\Delta [\text{X/H}] = \pm 0.2$ dex; bottom right: $\Delta T_{\text{eff}} = \pm 200$ K; top left: $\Delta \xi = \mp 0.5$ km s$^{-1}$; top right: $\Delta \log g = \pm 0.5$ dex.

Fig. 3.—Section of the H-band spectrum of star 3 and our best fit (solid line), using $T_{\text{eff}} = 3600$ K, $\log g = 1.0$, $\xi = 2$ km s$^{-1}$, [$\text{Fe/H}$] = $+0.3$, [O/Fe] = $+0.0$, and [$\text{C/Fe}$] = $-0.3$ as reference stellar parameters (see also Table 2). For comparison, we also plot synthetic spectra with different abundances and stellar parameters with respect to the best-fit solution. Bottom left: $\Delta [\text{X/H}] = \pm 0.2$ dex; bottom right: $\Delta T_{\text{eff}} = \pm 200$ K; top left: $\Delta \xi = \mp 0.5$ km s$^{-1}$; top right: $\Delta \log g = \pm 0.5$ dex.
bulge M giants observed with IR echelle spectroscopy (Rich & Origlia 2005), we find values of [Fe/H] between solar and of solar and enhanced [α/Fe] abundance ratios, as for K giants. The processes that enrich the bulge rapidly and at early times evidently require a star formation rate high enough to retain an α-enhanced composition to nearly the solar metallicity; this does not appear to have been the case for NGC 6791. The age of the Galactic bulge has been debated over the years, and ages as young as 8–9 Gyr have been discussed seriously, especially when the luminous OH/IR stars are considered (cf. van Loon et al. 2003). In terms of chemistry, there does appear to be a distinct difference between NGC 6791 and the bulge. The solar value of [α/Fe] does not prove that NGC 6791 is younger than the bulge, but it does point to the cluster having formed well after SNe Ia were able to contribute substantial iron to the interstellar medium. Yet another population of disk stars with similarly high abundances are the metal-rich dwarfs found in the disk (Castro et al. 1997; Pompéia et al. 2003). These dwarfs appear to have an inner disk origin and exhibit some α-enhancement and are therefore different from NGC 6791. Our results would appear to indicate that the enrichment of metals is not a monotonic process in galaxies. A proto–Milky Way 4–5 Gyr after the big bang had some disk regions with twice solar metallicity. Our low value of $^{12}$C/$^{13}$C indicates that extramixing processes due to cool bottom burning are also at work during the RGB evolution at very high metallicity, confirming our findings for the metal-rich giants in the Galactic bulge (Origlia et al. 2005b and references therein).

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