High resolution infrared spectroscopy of the old open cluster NGC 6791

Livia Origlia

INAF – Osservatorio Astronomico di Bologna, Via Ranzani 1, I–40127 Bologna, Italy,
livia.origlia bo.astro.it

Elena Valenti

Dip. di Astronomia, Università degli Studi di Bologna, Via Ranzani 1, I–40127 Bologna, Italy,
INAF – Osservatorio Astronomico di Bologna,
elena.valenti3 unibo.it

R. Michael Rich

Physics and Astronomy Bldg, 430 Portola Plaza Box 951547 Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095-1547
rmr astro.ucla.edu

Francesco R. Ferraro

Dip. di Astronomia, Università degli Studi di Bologna, Via Ranzani 1, I–40127 Bologna, Italy,
francesco.ferraro3 unibo.it

ABSTRACT

We report abundance analysis for 6 M giant members of the old open cluster NGC 6791, based on infrared spectroscopy ($1.5-1.8\ \mu$m) at R=25,000, using the NIRSPEC spectrograph at the Keck II telescope. We find the iron abundance $\langle[\mathrm{Fe/H}]\rangle = +0.35 \pm 0.02$, confirming the super solar metallicity of this cluster derived from optical medium-high resolution spectroscopy. We also measure C, O and other alpha element abundances, finding roughly solar [alpha/Fe] and

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$\langle$[C/Fe]$\rangle = -0.35$. Our approach constrains [O/Fe] especially well, based on the measurement of a number of OH lines near 1.6 μm; we find [O/Fe]$=-0.07\pm0.03$. The Solar alpha enhancement is in contrast to the composition of similar stars in the Galactic bulge. We also find low ^{12}C/^{13}C ≈ 10, confirming the presence of extra-mixing processes during the red giant phase of evolution, up to super solar metallicities.

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

1. Introduction

The open cluster NGC 6791 is currently believed to be one of the most massive, metal-rich and oldest stellar system. For this reason it has been the subject of many photometric (Kinman 1965; Harris & Canterna 1981; Demarque, Green & Guenther 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, Green & Liebert 1999; Stetson, Bruntt & Grundhal 2003; Carney, Lee & Dodson 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 $\geq 4000 M_\odot$ (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, Green & Liebert 1999; Stetson, Bruntt & Grundhal 2003; Carney, Lee & Dodson 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 (Kinman 1965), with a mean value of E(B-V)=0.16 which is in excellent agreement with Schlegel, Finkbeiner, & Davis (1998) extinction maps, which gives E(B-V)=0.15 (see § 2). NGC 6791 is a relatively distant cluster, with a suggested distance modulus (m-M)$_0$ ranging from 12.60 (Anthony-Twarog & Twarog 1985) to 13.6 (Harris & Canterna 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 WD properties (Bedin et al. 2005; Hansen 2005).

However, as reviewed by (Stetson, Bruntt & Grundhal 2003; Carney, Lee & Dodson 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 technique such as *1)* photometric metallicity indicators (Janes 1984; Canterna 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, Bruntt & Grundhal 2003; Carney, Lee & Dodson 2005, and reference 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 the one by Peterson & Green (1998), who measured a sample of warm HB 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 about solar [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 [Fe/H]=+0.47±0.04, respectively. Carraro et al. (2006) also find about solar [α/Fe], while Gratton et al. (2006) find [O/Fe] 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 to study cool and metal rich stars than the optical spectral range. Our group has been undertaking a program using the NIRSPEC spectrograph (McLean 1998) at Keck to obtain spectra of old metal rich stars in the bulge field (Rich & Origlia 2005) and globular clusters (Origlia et al. 2003; Origlia & Rich 2004; Origlia, Valenti & Rich 2004; Origlia et al. 2005) 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 constrain better the age of this cluster, which deserves detailed investigations being 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, Lee & Dodson (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, Ferraro & Origlia 2004a,b). 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.

Table 1. Our sample of observed giant stars in NGC 6791.

Star	2MASS	RA (2000)	DEC (2000)
#1	19211606+3746462	19h 21m 16s	+37d 46' 27"
#2	19204971+3743426	19h 20m 50s	+37d 43' 43"
#3	19213390+3750202	19h 21m 34s	+37d 50' 20"
#4	19204635+3750228	19h 20m 46s	+37d 50' 23"
#5	19205510+3747162	19h 20m 55s	+37d 47' 16"
#6	19205338+3748282	19h 20m 53s	+37d 48' 28"

2. Observations and abundance analysis

By using 2MASS photometry we constructed the K,(J–K) color magnitude diagram of NGC 6791 and selected 6 bright (H=9-11) giant stars (see Fig. 1). Table 1 reports their 2MASS name and coordinates. The program stars were observed at Keck on May 2005, with typical exposure times of 4min. We used NIRSPEC (McLean 1998) in the echelle mode, a slit width of $0\farcs43$ and a length of $12''$ giving an overall spectral resolution R=25,000, and the standard NIRSPEC-5 setting, which covers most of the 1.5-1.8 μm H-band have been selected.

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 flat-field corrected. Wavelength calibration has been performed using arc lamps and a 2-nd 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 $\geq$40 and Fig. 2 shows an example.

A grid of suitable synthetic spectra of giant stars has been computed by varying the photospheric parameters and the element abundances, using an updated version of the code described in Origlia, Moorwood & Oliva (1993). By combining full spectral synthesis analysis with equivalent widths measurements of selected lines, we derive abundances for Fe, C, O and other α-elements. The lines and 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. 2005; 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, being roto-vibrational 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 AlI lines in the Sun (see Baumueller & Gehren (1996), finding indeed 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 which can cause a deviation from LTE, namely over-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 $\geq$0.1 dex) are mainly observed in stars which are significantly hotter and more metal poor than those in our program. The code is based on the molecular blanketed model atmospheres of Johnson, Bernat & Krupp (1980) in the 3000-4000 K temperature range and the ATLAS9 models for temperatures above

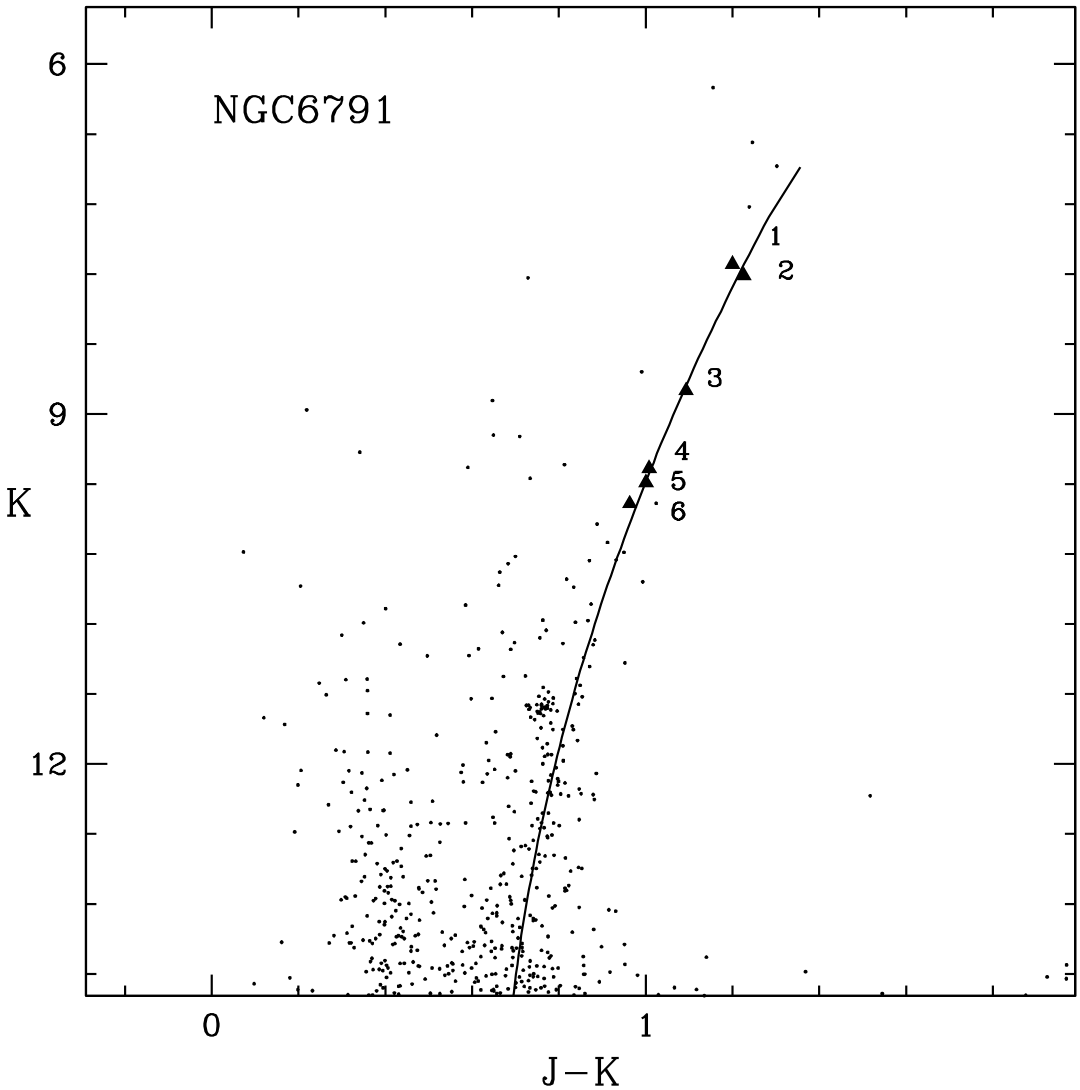

Fig. 1.— K,(J–K) color magnitude diagram of NGC 6791 as obtained from 2MASS photometry. The giant stars observed with NIRSPEC are plotted as filled triangles and the derived RGB fiducial ridge line is superimposed as a solid line.

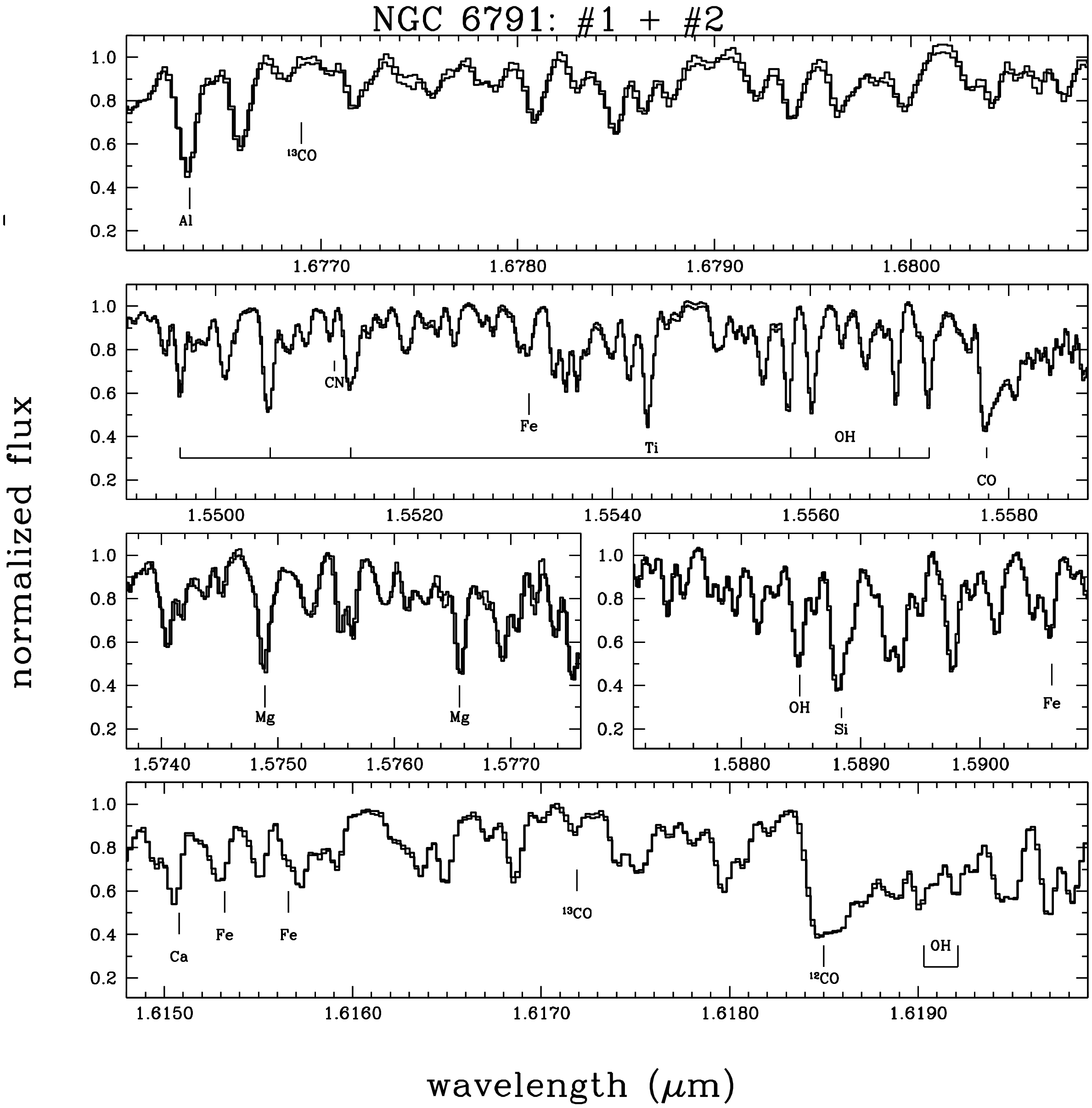

Fig. 2.— Selected portions of the H band spectrum obtained with NIRSPEC for stars #1 and #2. Some features of interest are also marked.

4000 K. Since in the near IR the major source of continuum opacity is H^- with its minimum near 1.6 μm, 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 we compare them with those obtained using Johnson, Bernat & Krupp (1980) models, finding minor differences (Rich & Origlia 2005). Three main compilations of atomic oscillator strengths are used: the Kurucz database (c.f. *http://cfa-www.harward.edu/amdata/ampdata/kurucz23/-sekur.html*), Bièmont & Grevesse (1973) and Meléndez & Barbuy (1999). Reference solar abundances are from Grevesse & Sauval (1998). In the first iteration, we estimate stellar temperature from the $(J-K)_0$ colors (see Table 2) and the color-temperature transformation of Montegriffo et al. (1998) specifically calibrated on globular cluster giants. Gravity has 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 microturbulence velocity an average value ξ=2.0 km/s 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. 6,7 of Origlia, Rich & Castro (2002)). The adopted values are listed in Table 2.

3. Results

From our spectral analysis we find all the 6 stars likely members of the cluster, showing an average heliocentric radial velocity $\langle v_r \rangle = -52 \pm 1$ Km/s. 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 1σ errors are listed in Table 2. We find an average [Fe/H] = $+0.35 \pm 0.02$ dex, roughly solar [α/Fe], [C/Fe] = -0.35 ± 0.03 dex and low $^{12}C/^{13}C \approx 10 \pm 2$.

We also explored the results using models with Δ[X/H] = ±0.2 dex, $\Delta T_{\rm eff} = \pm 200$ K, $\Delta\xi = \mp 0.5$ km s^{-1}, and $\Delta\log g = \pm 0.5$ dex, with respect to the best-fit parameters. Fig. 3 shows an example for star #3. It is clearly seen that models with ±0.2 dex abundance variations give remarkably different molecular line profiles. Temperature variations of ±200 K and microturbulence variation of ±0.5 km/s mainly affects 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 $\Delta T_{\rm eff} = \pm 200$ K, $\Delta\log g = \pm 0.5$ dex and $\Delta\xi = \mp 0.5$ km s^{-1}, and with corresponding simultaneous variations of the C and O abundances (on average, ±0.2 dex) to reproduce the depth of the molecular features. As a figure of merit of the statistical test we adopt the difference between the model and the observed spectrum (hereafter δ). In order to quantify systematic discrepancies, this parameter is more powerful than the classical χ^2 test, which is instead equally sensitive to *random* and *systematic* errors (see also Origlia et al. 2003; Origlia & Rich 2004). Our best fit solutions always show >99% probability to be representative of the observed spectra, while spectral fitting solutions with abundance variations of ±0.2 dex, due to possible systematic uncertainties of ±200 K in temperature, ±0.5 dex in gravity or ∓0.5 km/s in microturbulence are statistical significant at 1-2σ level, only. Hence, as a conservative estimate of the systematic error in the derived best-fit abundances, due to the residual uncertainty in the adopted stellar parameters, one can assume a value of $\leq \pm0.1$ dex. However, it must be noted that since the stellar features under consideration show a similar trend with variations in the stellar parameters, although with different sensitivities, *relative* abundances are less dependent on the adopted stellar parameters (i.e. on the systematic errors) and their values are well constrained down to $\approx \pm0.1$ dex (see also Table 1).

4. Discussion and Conclusions

Our derived iron abundance for NGC 6791 is in excellent agreement with the results of Peterson & Green (1998) and Carraro et al. (2006) and only slightly lower than the Gratton et al. (2006) ones. All these works suggest about 0.2 dex higher iron abundances than those obtained by Friel & Janes (1993); Friel et al. (2002) from low-resolution spectroscopy ([Fe/H]=+0.19 dex and [Fe/H]=+0.11 dex, respectively). Hence, the high (2-3 times solar) metallicity of NGC 6791, now confirmed by 4 independent surveys at medium-high resolution in the optical and in the IR, strongly supports a 8-9 Gyr age as derived from the Main Sequence *Turn-Off* (Carraro et al. 2006).

Our solar [α/Fe] abundance ratio is in good agreement with the finding by Peterson & Green (1998) for O, Ca, Ti, while their Si and Mg abundances are slightly higher. Our [C/Fe] abundance is a factor of 2 lower than the one by Peterson & Green (1998) but in good agreement with the Gratton et al. (2006) value of [C/Fe]=-0.2. Our and Peterson & Green (1998) solar [O/Fe] is twice the value found by Gratton et al. (2006). An overall Solar [α/Fe] is consistent with a standard disk chemical enrichment scenario where both SN II and SN Ia contributed to the enrichment of the interstellar medium. However, it is interesting that the iron abundance of NGC 6791 reached +0.35 dex, more than a factor of two greater than Solar, only a few Gyrs after the first stars were formed, relatively early in the history of the Galaxy.

In comparison with the Galactic bulge, NGC 6791 stars reach [Fe/H]=+0.35, only 0.15

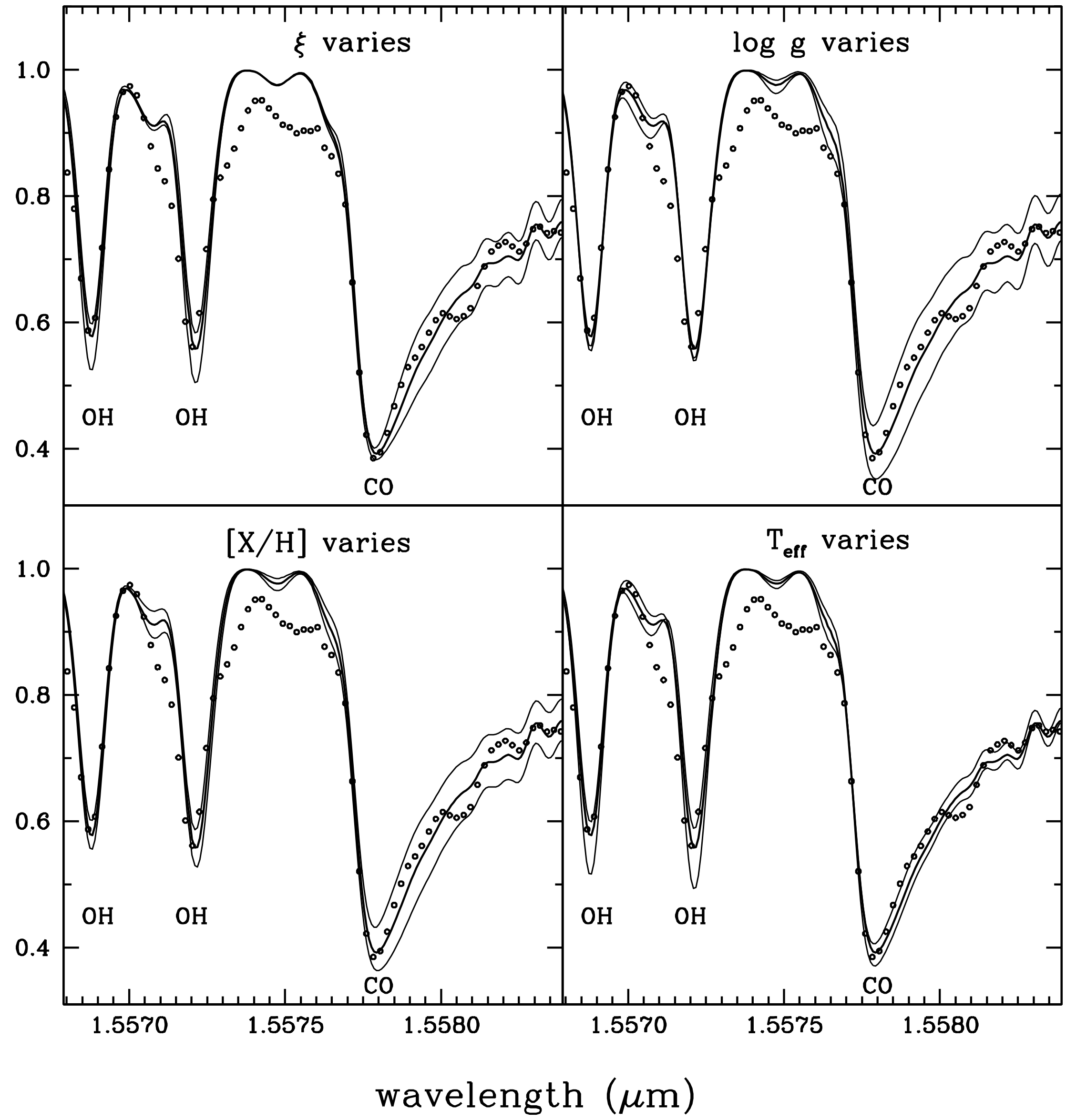

Fig. 3.— Section of the H band spectrum of star #3 and our best fit (solid line), using $T_{\rm eff}$=3600 K, log g=1.0, ξ=2 km s^{-1}, [Fe/H]=+0.3, [O/Fe]=+0.0, [C/Fe]=–0.3 as reference stellar parameters (see also Table 2). For comparison we also plot synthetic spectra with different abundances and stellar parameters with respect to the best-fit solution. Bottom-left: Δ[X/H] = $\pm$0.2 dex; bottom-right: $\Delta T_{\rm eff}$ = $\mp$200 K; top-left: $\Delta\xi$ = $\pm$0.5 km s^{-1}; top-right: Δlog g = $\mp$0.5 dex.

dex lower than the most metal rich bulge K giants reported by Fulbright, McWilliam, & Rich (2005). The α-element abundances are distinctly lower than those seen in the bulge giants (McWilliam & Rich 1994). In our sample of 11 bulge M giants observed with IR echelle spectroscopy (Rich & Origlia 2005) we find [Fe/H] between 1/3 and Solar and enhanced [α/Fe] abundance ratios as for K giants. The processes that enrich the bulge rapidly and early evidently require a star formation rate high enough to retain an alpha 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 [alpha/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 alpha 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 ^{12}C/^{13}C indicates that extra-mixing processes due to *cool bottom burning* are at work during the RGB evolution also at very high metallicity, confirming our findings for the metal rich giants in the Galactic bulge (Origlia et al. 2005, and references therein).

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Table 2. Stellar parameters and chemical abundances for our sample of stars in NGC 6791.

Star	$(J\text{-}K)_0^a$	$T_{\rm eff}$	log g	v_r^b	[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	-0.04	-0.06	-0.03	+0.04	+0.06	+0.04	-0.36
					±0.09	±0.13	±0.18	±0.10	±0.14	±0.16	±0.16	±0.12
#2	1.15	3600	1.0	-52	+0.33	-0.05	-0.03	-0.03	+0.07	-0.03	+0.07	-0.33
					±0.09	±0.13	±0.18	±0.10	±0.14	±0.16	±0.16	±0.12
#3	1.02	3800	1.5	-50	+0.32	-0.06	+0.08	-0.02	+0.08	+0.08	+0.08	-0.32
					±0.08	±0.11	±0.17	±0.09	±0.13	±0.16	±0.14	±0.11
#4	0.93	4000	1.5	-50	+0.38	-0.08	+0.08	-0.05	+0.02	+0.02	+0.02	-0.38
					±0.08	±0.09	±0.21	±0.08	±0.13	±0.14	±0.14	±0.11
#5	0.92	4000	1.5	-51	+0.37	-0.09	+0.03	-0.02	+0.03	+0.03	+0.03	-0.37
					±0.08	±0.09	±0.21	±0.08	±0.13	±0.14	±0.14	±0.11
#6	0.89	4000	1.5	-52	+0.36	-0.11	-0.01	+0.00	+0.04	+0.04	+0.04	-0.36
					±0.07	±0.09	±0.21	±0.08	±0.12	±0.14	±0.13	±0.10

[a] (J–K) colors are from 2MASS and have been corrected for reddening using Schlegel, Finkbeiner, & Davis (1998) extinction maps.

[b] Heliocentric radial velocity in km s^{-1}.