SODIUM AND OXYGEN ABUNDANCES IN THE OPEN CLUSTER NGC 6791 FROM APOGEE H-BAND SPECTROSCOPY

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ABSTRACT

The open cluster NGC 6791 is among the oldest, most massive, and metal-rich open clusters in the Galaxy. High-resolution H-band spectra from the Apache Point Observatory Galactic Evolution Experiment (APOGEE) of 11 red giants in NGC 6791 are analyzed for their chemical abundances of iron, oxygen, and sodium. The abundances of these three elements are found to be homogeneous (with abundance dispersions at the level of ≲0.05–0.07 dex) in these cluster red giants, which span much of the red-giant branch ($T_{\text{eff}} \sim 3500–4600$ K), and include two red clump giants. From the infrared spectra, this cluster is confirmed to be among the most metal-rich clusters in the Galaxy ($[\text{Fe/H}] = 0.34 \pm 0.06$) and is found to have a roughly solar value of $[\text{O/Fe}]$ and slightly enhanced $[\text{Na/Fe}]$. Our non-LTE calculations for the studied Na lines in the APOGEE spectral region ($16373.86$ Å and $16388.85$ Å) indicate only small departures from LTE ($\lesssim 0.04$ dex) for the parameter range and metallicity of the studied stars. The previously reported double population of cluster members with different Na abundances is not found among the studied sample.

Key words: infrared; stars – open clusters and associations: general – stars: abundances

1. INTRODUCTION

The open cluster NGC 6791 is a notable object, being one of the oldest (∼8 Gyr old; e.g., Harris & Canterna 1981; King et al. 2005; Brogaard et al. 2012) and most metal-rich open clusters in the Galaxy ($[\text{Fe/H}] \sim +0.4$; e.g., Peterson & Green 1998; Gratton et al. 2006; Carraro et al. 2006; Origlia et al. 2006; Carretta et al. 2007; Boesgaard et al. 2009). This cluster’s $[X/Q] = (A(X)_{\text{Star}} - A(X)_{\odot}) - (A(Q)_{\text{Star}} - A(Q)_{\odot})$. 

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color–magnitude diagram displays a few unusual features that heighten interest in this object, including a well-defined binary sequence falling above the main sequence, several alleged blue horizontal branch stars (Platais et al. 2011), which is unusual for a metal-rich stellar population (Brogaard et al. 2012), along with a white-dwarf cooling sequence that exhibits two luminosity peaks (Bedin et al. 2008a, 2008b).

Other unusual aspects of NGC 6791 are the color width of the red giant branch (RGB; Kinman 1965) and color variations of the main-sequence turn-off stars (Twarog et al. 2011). These features could be explained as either extended star formation (over ∼1 Gyr), a process not identified in any other open cluster, or spatial variations in the reddening (Twarog et al. 2011; Platais et al. 2011; Brogaard et al. 2012). A recent result that relates to the possibility of extended star formation in NGC 6791 is from Geisler et al. (2012), who found two distinct groups differing in their respective sodium abundances. These two Na-abundance groups were proposed to be two separate stellar populations within NGC 6791; this would be the first time such distinct stellar populations were identified in an open cluster, although this is now commonly found in most globular clusters (Gratton et al. 2012). These distinct populations are responsible for the Na and O abundance anti-correlations, which are the signature of a globular cluster. As NGC 6791 is among the most massive open clusters (Gratton et al. 2014) found that the Na abundances in a sample of NGC 6791 members can be described by a single Na abundance to within ~0.1 dex.

Due to its high metallicity (as well as location within the Kepler field of view), NGC 6791 was targeted as a calibration cluster by the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski 2012; Zasowski et al. 2013), one of four experiments that are part of the Sloan Digital Sky Survey III (SDSS-III; Eisenstein et al. 2011). APOGEE obtained H-band high-resolution spectra of red giants with the goal of measuring radial velocities and chemical abundances of up to 15 elements in over 100,000 stars in the Galactic bulge, disk, and halo. NGC 6791 was selected for the present analysis due to both its high metallicity, which places it at the high end of the APOGEE target metallicities, and the possibility that it contains more than one stellar generation. In this Letter, abundance results for iron, oxygen, and sodium are presented to investigate whether the selected sample reveals two sodium populations.
elements for our targets, will be presented in a future paper (K. Cunha et al., in preparation).

Sodium abundances were obtained from the two well-defined Na I lines falling in the middle APOGEE detector, with this doublet arising from the $2p^6 3d^2 \Sigma_u^+ - 2p^6 3s^2 \Pi_u$ level with $\chi_{\text{low}} = 3.753$ eV, to the $2p^6 3s^2 \Pi_u$ level with $\chi_{\text{hi}} = 4.510$ eV. The air wavelengths are 16373.86 Å and 16388.85 Å, with values of $\log g_f = -1.318$ and $-1.018$, respectively (M. D. Shetrone et al., in preparation). One of the observed Na I lines is illustrated in Figure 1 (bottom panel; solid circles). Synthetic spectra with three different sodium abundances are also displayed as the solid curves.

5. ABUNDANCE RESULTS

The mean Fe, O, and Na abundances, as well as the microturbulent velocities adopted for the target stars, are found in Table 1. In most instances, the line-to-line abundance scatter (standard deviations) is less than 0.1 dex. The sensitivities of the oxygen and iron abundances to uncertainties in the adopted stellar parameters are discussed in our previous study (Smith et al. 2013). Smith et al. (2013) did not include sodium, so the abundance sensitivities of the two studied Na I lines to stellar parameters are presented here. The procedure used is the same as Smith et al. (2013), and involves perturbing the stellar parameters of $T_{\text{eff}}, \log g, \xi$, and overall model metallicity ($[\text{m/H}]$) and determining how much these parameter perturbations change the derived Na abundances. The relevant covariant terms between primary stellar parameters are included with perturbations of $\Delta T_{\text{eff}} = \pm 50$ K, $\Delta \log g = \pm 0.2$ dex, $\Delta \xi = \pm 0.2$ km s$^{-1}$, $\Delta [\text{m/H}] = \pm 0.1$ dex. Two representative model atmospheres were perturbed, with one a “hot” model ($T_{\text{eff}} = 4500$ K, $\log g = 2.50$, $\xi = 1.3$ km s$^{-1}$, $[\text{m/H}] = +0.4$) and the other a “cool” model ($T_{\text{eff}} = 3530$ K, $\log g = 0.8$, $\xi = 1.8$ km s$^{-1}$, $[\text{m/H}] = +0.4$). Given these two models and perturbations, the respective Na abundance changes are $\Delta A(\text{Na}) = \pm 0.06$ dex for the hot model and $\Delta A(\text{Na}) = \pm 0.09$ dex for the cool model. These variations are similar to the abundance differences found between the two individual Na I lines as listed in Table 1.

Non-LTE abundance corrections for Na lines were computed using the statistical equilibrium and line formation codes described in Bergemann et al. (2012a, 2012b, 2013) and the model atom described in Gehren et al. (2004). In this previous work, the model was applied to the analysis of optical Na I lines in solar-type stars, and indicated a significant negative correction relative to LTE at low metallicity, typically [Fe/H] $< -1$. Here, we extend these calculations to the $H$-band Na I lines, and derive non-LTE corrections for the transitions 16373.86 Å and 16388.85 Å. To our knowledge, these are the first non-LTE results for the sodium spectral lines in the $H$ band; we find that the two IR Na I lines are largely free from departures from LTE over the $T_{\text{eff}}$ and log g ranges covered by the high-metallicity red giants analyzed here. The individual lines have non-LTE corrections ($A(\text{Na})_{\text{non-LTE}} - A(\text{Na})_{\text{LTE}}$) that range from $-0.01$ to $-0.04$ dex; corrections of this size have no significant impact on our conclusions.

6. DISCUSSION

The sample of 11 RGB and RC stars studied in the open cluster NGC 6791 have Fe abundances that are quite homogeneous: the mean value is $A(\text{Fe}) = 7.84 \pm 0.06$. The abundance dispersion is consistent with the expected errors in the derivation of $A(\text{Fe})$. The mean iron abundance for the target stars is quite
enhanced relative to solar, confirming previous results in the literature that NGC 6791, although very old, is among the most metal-rich populations in the Galaxy. The oxygen and sodium abundances are also found to be homogeneous, with mean values and standard deviations of $A(O) = 9.10 \pm 0.06$ and $A(Na) = 6.75 \pm 0.07$, which yield a near-solar $[O/Fe] = +0.01$ and a slightly enhanced $[Na/Fe] = +0.17$.

Very few studies in the literature have derived both Na and O abundances for NGC 6791 members. As discussed previously, Geisler et al. (2012) obtained the unexpected result of two populations in sodium in this open cluster from an analysis of optical spectra obtained with Keck/HIRES and WIYN/Hydra. Figure 2 shows the $[Na/Fe]$ versus $[O/Fe]$ abundances for our 11 stars (blue circles), in comparison with the bracket abundances taken directly from Geisler et al. (2012; red triangles). The two studies adopted slightly different solar reference values; the solar abundances adopted here are: $A_{\odot}(Fe) = 7.50$; $A_{\odot}(O) = 8.75$; $A_{\odot}(Na) = 6.24$ (Caffau et al. 2008; Asplund et al. 2009). If the Geisler et al. (2012) results were put on this scale, their $[Na/Fe]$ and $[O/Fe]$ values would increase by $+0.08$ and $+0.05$ dex, respectively. Although the $[O/Fe]$ abundances in the two studies are in reasonable agreement, it is clear that the Na abundance distribution of NGC 6791 members obtained here does not overlap with the behavior of Na found in the Geisler et al. (2012) sample. The two studies have six stars in common (the green lines in Figure 2 connect these results) and the $[Na/Fe]$ abundances for these six stars are systematically lower in this study relative to Geisler et al., with an average difference of $\Delta[Na/Fe] = -0.20$ dex. In addition, Geisler et al. (2012) find a population of stars with lower Na abundances that is not matched by the results obtained for our sample.

As a further comparison, Figure 3 shows $[Na/Fe]$ versus $T_{\text{eff}}$ for this study and Geisler et al. (2012). It is not expected that there would be a dependence of the Na abundance with $T_{\text{eff}}$, which maps stellar evolution along the RGB. The values of $[Na/Fe]$ derived here exhibit a small increase with decreasing temperature, but the change is rather small, at about 0.15 dex over $\sim 1100$ K. The two hottest stars in our sample are clump giants, and have already evolved up the RGB, to low values of $T_{\text{eff}}$, and then moved to the higher-temperature RC after having undergone the He-core flash. In contrast, the results by Geisler et al. (2012) exhibit a discontinuity in $[Na/Fe]$ abundance at around $T_{\text{eff}} \sim 4500$ K. The NGC 6791 members from Geisler et al. (2012) that have elevated values of $[Na/Fe]$, representing the Na-rich population, are only found for red giants with $T_{\text{eff}} \leq 4435$ K.
4500 K, with the lower Na abundance giants falling at higher $T_{\text{eff}}$'s. Geisler et al. (2012) argue, however, that the most direct evidence for an Na spread in their sample is among the RC stars, where half of their sample of RC stars showed significant Na enhancement. The Na and O abundances obtained here, and their respective abundance dispersions, agree well with those of the recent study by Bragaglia et al. (2014), who analyzed optical spectra of 35 stars in NGC 6791 from Keck/HIRES and WIYN/Hydra. Bragaglia et al. (2014) find average abundances (and abundance dispersions) of $A(\text{Fe}) = 7.87 \pm 0.06$ (Δ(this study—Bragaglia) = −0.03), $A(\text{O}) = 9.00 \pm 0.09$ (Δ(this study—Bragaglia) = +0.10) and $A(\text{Na}) = 6.70 \pm 0.10$ (Δ(this study—Bragaglia) = +0.05). The comparison between the results from their optical and our $H$-band abundance analyses are very good, with differences of less than 0.1 dex and similar dispersions ($\sigma \sim 0.06$—0.10 dex). Earlier results from the optical for two RC stars by Carretta et al. (2007) were much lower (they found $[\text{O/Fe}] = −0.35$ for the two stars analyzed). The Na abundances for their two studied stars differed by 0.3 dex ($[\text{Na/Fe}] = +0.28$ and −0.02), possibly indicating an intrinsic abundance scatter for Na, but this scatter is not confirmed in the much larger sample by Bragaglia et al. (2014). Within the sample of 11 stars analyzed in this study, we do not find evidence of two distinct populations in sodium in NGC 6791. On the contrary, our results are well represented by a single population, with an abundance scatter of the order of the expected abundance analysis errors. We note that we have not analyzed any of the stars that Geisler et al. (2012) found to be Na-poor. It is not impossible that only stars from one population, from an underlying two-population distribution, were selected for this study, as well as in the sample of Bragaglia et al. (2014). However, this is unlikely given that roughly 40% of the stars in Geisler et al. (2012) were from the low-Na population, while 60% from the high-Na population.

7. CONCLUSIONS

Based on $H$-band high-resolution APOGEE spectra of 11 red-giant members of NGC 6791, this old open cluster is found to be quite metal-rich and chemically homogeneous, with a mean and standard deviation of $[\text{Fe/H}] = +0.34 \pm 0.06$. We also find that both oxygen and sodium are enhanced along with iron, as well as being chemically homogenous, with $[\text{O/Fe}] = +0.35 \pm 0.06$ and $[\text{Na/H}] = +0.51 \pm 0.07$.

We do not find evidence of two populations in sodium in this cluster. Although the sample observed here with APOGEE is relatively small, it does cover the temperature range from 3500 K (well up the luminous part of the RGB) to roughly 4500 K (for stars near the base of the RGB, as well as two stars in the RC). This sample is well-represented by a single Na abundance, with a star-to-star abundance scatter consistent with the expected uncertainties in the analysis.

Our results from non-LTE calculations indicate that the two Na I lines used in this analysis (16373.86 Å and 16388.85 Å) are largely free from departures from LTE over the $T_{\text{eff}}$ and log g ranges covered by the high-metallicity red giants analyzed here (with all corrections being at most 0.04 dex) and so non-LTE corrections have no significant impact on our conclusions.

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