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AN ABUNDANCE ANALYSIS OF BRIGHT GIANTS IN THE GLOBULAR CLUSTER NGC 1851[1]

David Yong
Research School of Astronomy and Astrophysics, Australian National University, Weston, ACT 2611, Australia; yong@mso.anu.edu.au
and
Frank Grundahl
Department of Physics and Astronomy, University of Aarhus, Denmark; fgj@phys.au.dk
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ABSTRACT

We present the chemical compositions for eight bright giants in the globular cluster NGC 1851. Our analysis reveals large star-to-star abundance variations and correlations of the light elements O, Na, and Al, a feature found in every well-studied globular cluster. However, NGC 1851 also exhibits large star-to-star abundance variations of the *s*-process elements Zr and La. These *s*-process elements are correlated with Al and anticorrelated with O. Furthermore, the Zr and La abundances appear to cluster around two distinct values. A recent study revealed a double subgiant branch in NGC 1851. Our data reinforce the notion that there are two stellar populations in NGC 1851 and indicate that this cluster has experienced a complicated formation history with similarities to ω Centauri.

Subject headings: globular clusters: individual (NGC 1851) — stars: abundances

Online material: color figure

1. INTRODUCTION

Recent studies have revealed that the Galactic globular clusters ω Centauri (Bedin et al. 2004), NGC 2808 (D'Antona et al. 2005; Piotto et al. 2007), and M54 (Siegel et al. 2007) contain multiple stellar populations. The evidence consists of *Hubble Space Telescope* color-magnitude diagrams (CMDs) in which multiple main sequences have been identified. In all cases, the most plausible explanation is that these globular clusters contain populations with distinct compositions and/or ages, in contrast to the classical concept that globular clusters are monometallic, coeval, simple stellar populations. The most recent addition to this intriguing collection is NGC 1851, a globular cluster with a bimodal horizontal branch (HB), whose CMD displays a double subgiant branch (Milone et al. 2007).

Both ω Centauri and M54 possess a large metallicity spread and are the two most massive Galactic globular clusters. ω Centauri is widely regarded as the nucleus of an accreted dwarf galaxy (e.g., Smith et al. 2000), and M54 is suspected to be the nucleus of the Sagittarius dwarf spheroidal galaxy (e.g., Layden & Sarajedini 2000). However, not all clusters with multiple main sequences show a metallicity spread, and although there is speculation that all globular clusters may have been the nuclei of ancient dwarf galaxies (Bekki 2006), currently there is little direct observational evidence. For NGC 2808, the multiple main sequences and complex HB morphology can be attributed to a large He abundance variation (D'Antona & Caloi 2004; D'Antona et al. 2005; Piotto et al. 2007), but the Fe abundances and ages show little, if any, variation among the populations. Although there are large star-to-star abundance variations of O, Na, and Al in NGC 2808 (Carretta 2006), such patterns are ubiquitous in Galactic globular clusters (e.g., Kraft 1994; Gratton et al. 2004).

The situation regarding the chemical compositions for stars in the globular cluster NGC 1851 is less clear owing to the lack of data. The sole spectroscopic abundance analysis was conducted by Hesser et al. (1982). Low-resolution spectra revealed extremely strong CN bands for three out of eight bright red giants. Hesser et al. (1982) also found that the Sr and Ba lines may be enhanced in CN-strong stars relative to other giants in this cluster. Such abundance patterns, if confirmed, would bear a striking resemblance to ω Centauri. A study of the stellar chemical compositions in NGC 1851 is of great interest in order to provide constraints on the interpretation of the double subgiant branch and to explore the chemical evolution of this cluster.

2. OBSERVATIONS AND ABUNDANCE ANALYSIS

The spectra for eight bright giants in NGC 1851 were retrieved from the ESO archive. The observations were obtained using UVES (Dekker et al. 2000). Each star was observed for 900 s using the 0.70″ slit, which provided a spectral resolution of $R \simeq 55{,}000$ per 4 pixel resolution element. The data were reduced using standard procedures in IRAF. The wavelength coverage ranged from 5950 to 9750 Å with a typical signal-to-noise ratio of 60 per pixel near 6500 Å. All stars are radial velocity members with v_r ranging from +316 km s^{-1} to +332 km s^{-1}. One star, 333, was also observed by Hesser et al. (1982).

The stellar parameters were determined using the same tools and techniques described in Grundahl et al. (2002) and Yong et al. (2006). While the agreement between the photometric and spectroscopic stellar parameters was excellent, we adopted the spectroscopic parameters. (Photometric estimates were based on data from Grundahl et al. [1999] and 2MASS [Skrutskie et al. 2006]. The results and conclusions would not change had we adopted photometric stellar parameters.)

Abundances were measured from an equivalent-width analysis. For O, La, and Eu, synthetic spectra were generated to account for blends, hyperfine structure, and/or isotopic splitting. We used the LTE line analysis and spectrum synthesis program MOOG (Sneden 1973), Kurucz (1993) model atmospheres, and the same line lists employed by Yong et al. (2005). While many lines of interest lie below 6000 Å and were not observed, there were a sufficient number of lines from which the abundances of O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Mn, Fe,

[1] Based on observations made with ESO Telescopes at the Paranal Observatories under programme 70.B-0361(A)

TABLE 1
STELLAR PARAMETERS AND ABUNDANCES

Star[a]	$T_{\rm eff}$ (K)	log g (cgs)	v_t (km s^{-1})	[Fe/H]	[O/Fe]	[Na/Fe]	[Mg/Fe]	[Al/Fe]	[Zr/Fe]	[La/Fe]	[Eu/Fe]
003 ……	4075	0.60	1.80	−1.28	0.52	0.13	0.25	0.32	0.02	0.28	0.83
095 ……	4025	0.15	1.95	−1.40	0.44	0.23	0.50	0.46	0.14	0.30	0.75
112 ……	4025	0.25	1.85	−1.34	0.13	0.74	0.42	0.76	0.38	0.69	0.69
151 ……	4175	0.65	1.80	−1.32	0.61	−0.14	0.35	0.26	0.09	0.27	0.82
209 ……	4400	1.15	1.75	−1.20	0.49	−0.27	0.40	0.21	0.35	0.30	0.70
329 ……	3875	0.10	1.55	−1.20	0.39	0.34	0.33	0.49	0.58	0.60	0.65
333 ……	4225	0.75	1.70	−1.25	0.44	−0.21	0.36	0.18	0.10	0.20	0.65
395 ……	3975	0.45	1.65	−1.15	−0.01	0.62	0.39	0.63	0.40	0.55	0.60

[a] Star names taken from Stetson (1981).

Co, Ni, Zr, La, and Eu could be measured. We focus on the most fascinating results, which come from the light elements (O, Na, and Al), Fe, and the neutron-capture elements (Zr, La, and Eu). The stellar parameters and abundances are presented in Table 1.

3. RESULTS

Even within our small sample of stars, NGC 1851 exhibits large star-to-star abundance variations of the light elements O, Na, and Al (see Fig. 1). The amplitude of the variation is 0.62, 1.02, and 0.58 dex for [O/Fe], [Na/Fe], and [Al/Fe] respectively. O and Na are anticorrelated, Na and Al are correlated, and there does not appear to be an anticorrelation between Mg and Al. We note that the correlations remain evident regardless of whether we plot [X/Fe] or log ϵ(X). Such abundance patterns have been found in all globular clusters, including those with and without multiple main sequences.

We find a mean abundance [Fe/H] $= -1.27 \pm 0.03$ ($\sigma = 0.09$) with values spanning 0.25 dex. The ratio [Fe/H] appears to exhibit a range that may be larger than that expected from observational uncertainties. It is not clear whether this is a real (though small) spread in the Fe abundance or merely an artifact of small number statistics or the limited set of Fe lines available given the restricted wavelength coverage. Figure 1 shows that the Fe abundance is not correlated with the Al abundance.

The most striking result of our analysis is that NGC 1851 has a significant star-to-star abundance variation of the light *s*-process element Zr and the heavy *s*-process element La. Figure 2 shows two pairs of stars with essentially identical stellar parameters. Therefore, any difference in line strengths must be due to differences in abundances between the pairs of stars. In this figure, the strengths of Fe and other atomic lines are very

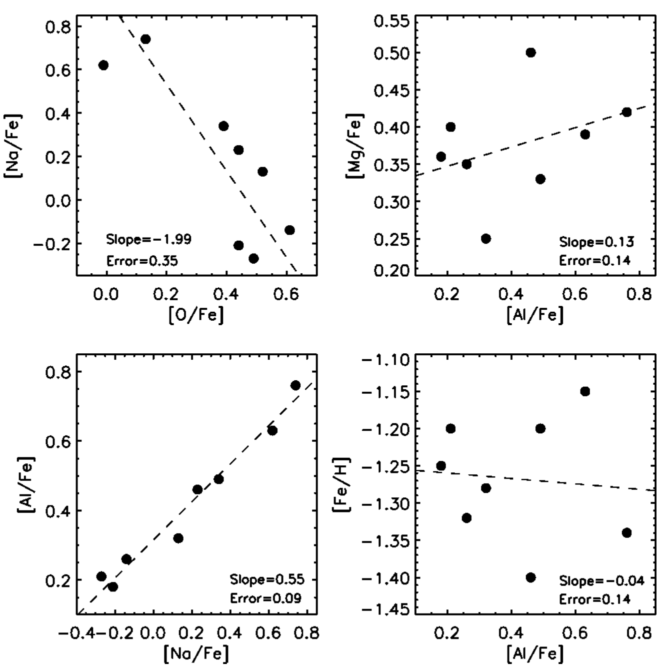

FIG. 1.—Clockwise from upper left, [Na/Fe] vs. [O/Fe], [Mg/Fe] vs. [Al/Fe], [Fe/H] vs. [Al/Fe], and [Al/Fe] vs. [Na/Fe]. Linear least-squares fits to the data are shown (slope and associated error are included). O and Na are anticorrelated, and Al and Na are correlated. Mg and Al do not appear to be correlated, nor are Fe and Al.

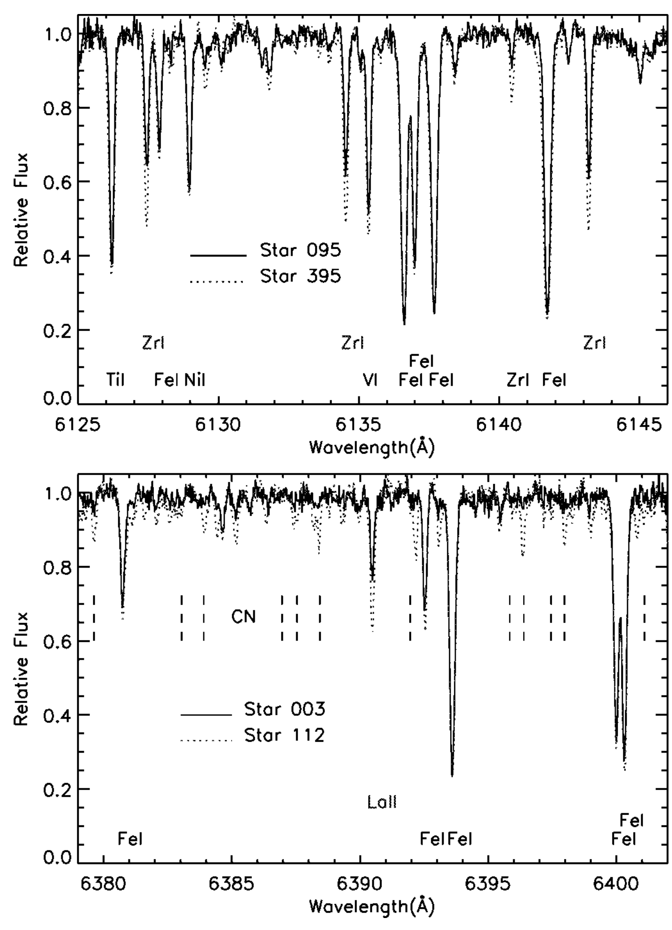

FIG. 2.—The upper panel shows stars 095 and 395 centered on the Zr II lines. The stellar parameters are very similar, as confirmed by the atomic lines of similar strength. However, the Zr lines differ considerably. The lower panel shows stars 003 and 112 centered on the La II line. The stellar parameters are very similar, as are the strengths of atomic lines. However, the La line differs considerably, as do the CN molecular lines. [*See the electronic edition of the Journal for a color version of this figure.*]

similar between the pairs of stars, as expected. However, the Zr and La lines show large differences, and therefore the Zr and La abundances must differ considerably. From a quantitative analysis, the amplitude of the variation is 0.56 and 0.49 dex for [Zr/Fe] and [La/Fe], respectively. This figure also shows that star 112 is CN-strong (and La-rich) relative to star 003. Recall that Hesser et al. (1982) found extremely CN-strong stars in this cluster and that the Sr and Ba lines were enhanced in these stars. Unfortunately, Zr and La are the only *s*-process elements that we could measure owing to the wavelength coverage, and we were also unable to measure C or N abundances. We note that the strengths of the 6141.71 and 6496.90 Å Ba II lines differ from star to star, with the Zr- and La-rich stars exhibiting stronger Ba lines. However, the Ba lines are saturated (>190 mÅ) such that reliable abundances cannot be readily measured, and therefore we cannot quantify the star-to-star Ba abundance dispersion. According to Hesser et al. (1982), star 333 is CN-normal, and we find no enhancement of Zr or La.

In Figure 3, the *s*-process elements Zr and La are correlated with Al and anticorrelated with O. Once again, the correlations are present regardless of whether we plot [X/Fe] or log ϵ(X). The abundances of Zr and La cluster around two distinct values. The three La-rich stars have a mean value [La/Fe] $=$ 0.61, while the five La-normal stars have a mean value [La/Fe] $=$ 0.27. The three La-rich stars are also Zr-rich with a mean value [Zr/Fe] $=$ 0.45, and the five La-normal stars are also Zr-normal with a mean value [Zr/Fe] $=$ 0.14. Curiously, one of the La-normal stars (star 209) appears to be relatively Zr-rich, [Zr/Fe] $=$ 0.35. Setting aside this star, the four remaining Zr-normal stars have a mean value [Zr/Fe] $=$ 0.09. The mean ratio of heavy to light *s*-process elements is very similar for the three La-rich, Zr-rich stars and for the five La-normal, Zr-normal stars, [La/Zr] $=$ 0.16 and 0.13, respectively.

Finally, we draw attention to the abundance of the *r*-process element Eu. The average ratio, [Eu/Fe] $= +0.71$, is rather high compared with other globular clusters and field stars at the metallicity of NGC 1851 (e.g., Pritzl et al. 2005). We do not find any evidence for a star-to-star Eu abundance dispersion or bimodality. Eu is not correlated with the light elements O or Al nor with the *s*-process elements Zr and La.

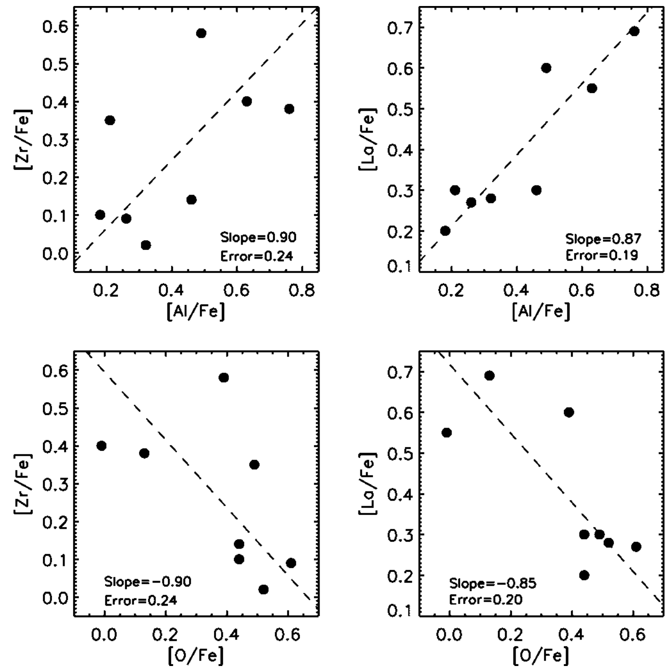

FIG. 3.—Clockwise from upper left, [Zr/Fe] vs. [Al/Fe], [La/Fe] vs. [Al/Fe], [La/Fe] vs. [O/Fe], and [Zr/Fe] vs. [O/Fe]. Linear least-squares fits to the data are shown (slope and associated error are included). Zr and La increase with increasing Al and decrease with increasing O.

4. DISCUSSION

Milone et al. (2007) explored various possibilities for explaining the double subgiant branch in NGC 1851. If age is the sole parameter, a difference of 1 Gyr would be required. If composition is the sole parameter, any abundance variation invoked to account for the double subgiant branch is heavily constrained by the width of the main sequence (and giant branch). Milone et al. (2007) estimate that the maximum possible abundance variation on the main sequence would be Δ[Fe/H] $=$ 0.1 dex or a helium abundance $\Delta Y = 0.026$. They argue that the He abundance alone cannot explain the observed subgiant branch. They suggest that a population with a 0.2 dex metallicity increase could explain the subgiant branch, but that such an abundance spread is precluded by the width of the main sequence and giant branch. However, a combination of increased [Fe/H] by 0.2 dex and helium from $Y = 0.247$ to $Y = 0.30$ could reproduce the observed subgiant branch behavior as well as ensure a sufficiently narrow main sequence and giant branch.

Available measurements indicate that the abundances of Fe, O, Na, Al, and neutron-capture elements do not change as a function of evolutionary status from the main sequence to the giant branch in globular clusters (e.g., Gratton et al. 2001; James et al. 2004; Cohen & Meléndez 2005). If we assume that the abundances for giant stars are representative of subgiant stars in NGC 1851, then our measured abundances eliminate the possibility that the subgiant branch split is due to an abundance difference of 0.2 dex for Fe and a shift of Y from 0.247 to 0.30. Although our sample size is limited, there is no hint of a bimodal distribution of Fe abundances separated by 0.2 dex, as required for the chemical composition explanation for the double subgiant branch. Indeed, Milone et al. (2007) noted that such a possibility is also precluded by the magnitudes of blue HB stars. Interestingly, the dispersion in our Fe abundances ($\sigma = 0.09$ dex) is within the 0.1 dex "limit" imposed by the width of the main sequence.

The abundances of additional elements add further complexity to NGC 1851. The star-to-star abundance variation of O, Na, and Al and the anticorrelation of O and Na exist in NGC 1851 and indeed in all globular clusters. Although our sample size is small, the amplitude of these abundance variations is comparable to clusters at a similar metallicity. However, the light *s*-process element Zr and the heavy *s*-process element La exhibit a large star-to-star abundance variation. (Our spectra also indicate a large range in Ba line strengths, and presumably Ba abundance, but we are unable to quantify the range.) Furthermore, the Zr and La abundances appear to have a bimodal distribution and reinforce the idea that there are two stellar populations in this cluster. (The ratio of heavy to light *s*-elements, [La/Zr] is similar for the "two populations.") La and Al (and Zr and Al) are correlated, and so the source of the Al variation is likely to be the source of the La variation. The hint of a correlation between Al and Zr has also been found in NGC 6752 (Yong et al. 2005). Asymptotic giant branch (AGB) stars may produce large enhancements of Al and La, albeit via different processes in AGB stars of different masses (e.g., Busso et al. 1999; Karakas & Lattanzio 2003). The He, C, N, and O produced by such AGB stars may play a role in the age differences for the subgiant branch populations.

Milone et al. (2007) raise the tantalizing prospect that the relative frequency of stars on the fainter/brighter subgiant branches (45% vs. 55%) roughly matches the relative frequency of HB stars bluer/redder than the instability strip (37% vs. 63%). The fraction of CN-strong, Ba-strong, Sr-strong stars found by Hesser et al. (1982) was ∼40%. In this study, the fraction of Zr-strong, La-strong stars was also ∼40%. On the basis of the relative numbers, we speculate that the brighter subgiant branch stars have "normal" CN, Sr, Zr, Ba, and La abundances and populate the red HB. We also speculate that the fainter subgiant branch stars are CN-strong, enriched in Sr, Zr, Ba, and La, and populate the blue HB. Indeed if the CN-, Zr-, and La-enriched stars are also He-rich, they are expected to populate the blue HB (Sweigart 1997). However, we caution that the relative numbers of the two populations will not be the same at all evolutionary phases. Nevertheless, the abundances in subgiant branch, giant, and red HB stars can test this hypothesis.

Since the fainter subgiant branch stars are older than the brighter subgiant branch stars (assuming age is the only parameter controlling the double subgiant branch), then our tentative speculation would require that the Zr-rich, La-rich stars are younger than the Zr-normal, La-normal stars. While this unpalatable scenario would be a challenge to explain, Villanova et al. (2007) find that the most metal-rich subgiant stars in ω Centauri are among the oldest stars in the cluster. Clearly, the sequence of events that led to the formation of the different stellar populations in NGC 1851 and ω Centauri requires some imagination. On the other hand, an analysis of a larger sample of giant stars may reveal that the CN-strong, Zr-rich, La-rich stars are associated with the majority population of brighter subgiant branch stars. In this case, if the CN-strong, Zr-rich, La-rich stars are the progeny of the CN-normal, Zr-normal, La-normal stars, the assumed 1 Gyr age difference would then place constraints on the mass range of the AGB stars that produced the CN, Zr, and La excess. At the metallicity of NGC 1851, A. Karakas (2007, private communication) suggests that the minimum mass (zero-age main sequence) of the AGB stars would be approximately 2 $M_{\odot}$. Further, the AGB stars that produce La have $M \gtrsim 1\ M_{\odot}$, and the AGB stars that produce Al have $M \gtrsim 4\ M_{\odot}$.

Finally, we note that the only other globular cluster that exhibits a large range in C, N, O, Na, Al, Sr, Zr, Ba, and La abundances is ω Centauri. Both NGC 1851 and ω Centauri display multiple subgiant branches that are presumably due to stellar populations with different ages and compositions. Further, NGC 1851 and ω Centauri are the only clusters that display a large variation in the Strömgren m_1 index, traditionally used as a metallicity indicator. NGC 1851 appears to exhibit a bimodal m_1 distribution on the giant branch, which suggests an extreme variation in C and/or N abundances (F. Grundahl 2007, in preparation). In the context of the formation of the Galactic globular cluster system, we speculate that NGC 1851 may represent a "bridge" between ω Centauri (large variation of all elements) and NGC 6752–like clusters (constant Fe but large variations of light elements C–Al). A more detailed analysis of additional elements and additional stars in NGC 1851 is of great interest.

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