THE HIGHLY UNUSUAL CHEMICAL COMPOSITION OF THE HERCULES DWARF SPHEROIDAL GALAXY

Andreas Koch\textsuperscript{1}, Andrew McWilliam\textsuperscript{2}, Eva K. Grebel\textsuperscript{3}, Daniel B. Zucker\textsuperscript{4}, & Vasily Belokurov\textsuperscript{1}

Accepted for publication in ApJ Letters

ABSTRACT

We report on the abundance analysis of two red giants in the faint Hercules dwarf spheroidal (dSph) galaxy. These stars show a remarkable deficiency in the neutron-capture elements, while the hydrostatic \(\alpha\)-elements (O, Mg) are strongly enhanced. Our data indicate [Ba/Fe] and [Mg/Fe] abundance ratios of \(\lesssim -2\) dex and \(\sim +0.8\) dex, respectively, with essentially no detection of other n-capture elements. In contrast to the only other dSph star with similar abundance patterns, Dra 119, which has a very low metallicity at [Fe/H]\(\sim -2.95\) dex, our objects, at [Fe/H]\(\sim -2.0\) dex, are only moderately metal poor. The measured ratio of hydrostatic/explosive \(\alpha\)-elements indicates that high-mass (\(\sim 35\, M_\odot\)) Type II supernovae progenitors are the main, if not only, contributors to the enrichment of this galaxy. This suggests that star formation and chemical enrichment in the ultrafaint dSphs proceeds stochastically and inhomogeneously on small scales, or that the IMF was strongly skewed to high mass stars. The neutron capture deficiencies and the [Co/Fe] and [Cr/Fe] abundance ratios in our stars are similar to those in the extremely low metallicity Galactic halo. This suggests that either our stars are composed mainly of the ejecta from the first, massive, population III stars (but at moderately high [Fe/H]), or that SN ejecta in the Hercules galaxy were diluted with \(\sim 30\) times less hydrogen than typical for extreme metal-poor stars.

Subject headings: Stars: abundances — Galaxies: dwarf — Galaxies: evolution — Galaxies: individual (Hercules) — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

Chemical abundance patterns in stars reflect the star formation (SF) histories of stellar systems: whatever mechanisms contributed to the enrichment of the interstellar medium will leave unique imprints in the resulting chemical abundance ratios. These allow one not only to trace the predominant modes of SF and reconstruct galactic enrichment histories, but also to place important constraints on the nucleosynthetic production sites of the elements. In particular, the \(\alpha\)-elements (e.g., O, Mg, Si, Ca, Ti), produced mainly by massive stars which end as Type II supernovae (SNe) on short time scales, and the neutron-capture elements (e.g., Y, Sr, Ba, La) from AGB stars, probe rapid and slow timescales, respectively.

Knowledge about chemical abundances and the evolutionary histories of the more luminous dwarf spheroidal (dSph) galaxies is constantly growing (e.g., Shetrone et al. 2003; Venn et al. 2004; Koch et al. 2008). However, only little is known about the metal-enrichment of the ultra-faint, presumably low-mass, systems recently discovered in the Sloan Digital Sky Survey (SDSS; Zucker et al. 2006a,b; Belokurov et al. 2006, 2007, 2008; Irwin et al. 2007; Walsh et al. 2007). Current low-resolution spectroscopy and photometric data indicate that these galaxies are predominantly metal poor (e.g., Muñoz et al. 2006; Belokurov et al. 2007; Kirby et al. 2008).

The discovery of only a couple of chemically peculiar stars in Galactic dSphs (Fulbright et al. 2004; Sadakane et al. 2004; Sbordone et al. 2007; Koch et al. 2008) and their similarity to a number of anomalous halo objects (Carney et al. 1997; Ivans et al. 2003) poses important questions for the general understanding of galaxy formation and chemical evolution: how common are chemically peculiar stars in the dSphs? What were the predominant enrichment processes that led to their abundance patterns? Are peculiar stars found in the Galactic halo related to those in dSphs?

Hercules (hereafter Her) is one of the faintest \((M_V \sim -6.6\) mag) and among the very metal poor \((\sim -2.3\) dex) dSph candidates discovered in the SDSS (Belokurov et al. 2007). Its \textit{stellar} mass is estimated to be \(4-7 \times 10^4\, M_\odot\) (Martin et al. 2008). Its extended morphology (Coleman et al. 2008) and a broad RGB render it an intrinsically peculiar galaxy that may have experienced interactions with the Milky Way. An investigation of its chemical properties is thus a natural endeavor.

In this Letter we present the discovery of unusual chemical abundance patterns in two red giants in Hercules. The elemental abundances were identified in the course of a broader observational program dedicated to a high-resolution study of Hercules, and the comprehensive abundance analysis of the full sample will be presented elsewhere (Koch et al. 2008, in prep.)

2. OBSERVATIONS AND ABUNDANCE ANALYSIS

Targets were selected from the Sixth Data Release of the SDSS (Adelman-McCarthy et al. 2008). There is only a limited number of brighter red giants present in Her that are observable within reasonable integration times \((V \lesssim 19.2\) mag) and non-members were rejected from the sample in real time during the observing run, based on their highly discrepant velocities (cf. Simon & Geha 2007). Here we present the results for two of our red giants, which we label Her-2 and Her-3 accord-
ing to their brightness (V=18.7 and 19.0 mag). The observations were carried out over two nights on 2007 July 10–11 with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph at the 6.5-m Magellan2/Clay Telescope. A slit width of 1″ and a CCD binning of 2×1 pixel resulted in a spectral resolution of 20000, with a full spectral coverage using the blue and red echelles of 3350–9400˚.

The signal-to-noise (S/N) ratio of our spectra is the standard MIKE pipeline reduction package of Kelson (2003). The signal-to-noise (S/N) ratio of our spectra is 32 per pixel at ~6500˚, but it falls below 10 for the bluer orders. The radial velocities of the two target stars confirm their membership in Her (Simon & Geha 2007), but we note that Her-3 is probably a binary, based on its radial velocity curve (D. Adén 2008, private communication), although there is no secondary flux detected from the companion. Therefore, the companion is most likely very faint and will not affect the present analysis.

The chemical abundances were determined from an equivalent width (EW) analysis, where we employed gf-values from the literature. Typically, 15–25 Fe I lines of sufficient strength could be measured. For most of the other species, only a few absorption features were distinguishable (see Table 1), which, coupled with the slightly low S/N led to large scatter in some abundance ratios. Many absorption lines of the heavy elements are too weak to be reliably measured in our spectra, yielding only upper abundance limits.

Stellar abundances were computed with the program MOOG (Sneden 1973) using stellar atmospheres generated from the Kurucz LTE models\(^5\). Given the strong enhancements in the α-elements O and Mg in our Her stars (Sect. 3), we chose to use the α-enhanced Kurucz model atmospheres, AODFNEW, in our analysis. Furthermore, we adopted photometric (V−I) effective temperatures for our stellar atmospheres, where colors were transformed from the SDSS g,r,i system using the prescriptions of Jordi et al. (2006). A reddening of E(B−V)= 0.06 (Schlegel 1998) and the according extinction laws of Rieke & Lebovsky (1985) were adopted throughout this work. We note that the photometric values agree well with the temperatures derived from excitation equilibrium. The physical gravities were derived from the photometric data, adopting a distance to Her of 140 kpc (Belokurov et al. 2007) and a stellar mass of 0.8 M\(\odot\), representative of the red giants (see also Koch & McWilliam 2008). The Fe abundances from the ionized and neutral lines agree marginally within the uncertainties so that ionization equilibrium holds with the adopted surface gravities. As a result, we derive stellar atmosphere parameters (\(T_{\text{eff}}, \log g, \xi\)) of (4270 K, 0.69, 2.5 km s\(^{-1}\)) for Her-2 and (4340 K, 0.91, 2.5 km s\(^{-1}\)) for Her-3, with typical uncertainties of (±50 K, ±0.15, ±0.1 km s\(^{-1}\)). Our adopted microturbulent velocity values are higher than typical red giant stars with similar parameters. This is likely an artifact of the relatively low S/N of our spectra, due to asymmetry in abundance errors on strong lines (Magain 1984); however, we stress that these high microturbulent velocity values are appropriate for our spectra. Hyperfine splitting was included for the even-Z elements Sc, Mn, Co, and Ba, but is usually negligible for the Na lines we used in our stars.

| Ion     | [X/Fe] | σ    | N | [X/Fe] | σ    | N |
|---------|--------|------|---|--------|------|---|
| [Fe/H]Ca T \(^a\) | −2.39 | 0.13 | ⋯ | −1.72 | 0.15 | ⋯ |
| Fe I/H | −2.02 | 0.20 | 24 | −2.04 | 0.43 | 15 |
| [O I]  | −1.78 | 0.21 | 3 | −1.84 | 0.41 | 2 |
| Na I   | 1.12  | 0.18 | 2 | <0.89 | 0.08 | 2 |
| Mg I   | 0.78  | 0.11 | 2 | 0.62  | 0.09 | 2 |
| Al I   | 0.81  | ⋯   | 1 | 0.77  | ⋯   | 1 |
| Si I   | <0.58 | ⋯   | 1 | <0.63 | ⋯   | 1 |
| Cr I   | −0.05 | 0.32 | 3 | −0.14 | 0.04 | 2 |
| Mn I   | 0.23  | 0.08 | 2 | <0.06 | 0.33 | 3 |
| Co I   | 0.53  | 0.10 | 2 | 0.42  | ⋯   | 1 |
| Ni I   | 0.30  | 0.10 | 10 | 0.12  | 0.15 | 5 |

\(^a\) Metallicity estimate based on the calcium triplet calibration of Ruchridge et al. (1997a,b), on the metallicity scale of Carretta & Gratton (1997).

3. ABUNDANCE RESULTS

The final chemical abundance ratios derived for the red giants are listed in Table 1, relative to Fe I for the neutral species and to Fe II for ionized species and for the [O I] lines. Solar abundances were taken from Asplund et al. (2005). Listed in Table 1 are 1σ scatter of our measurements from individual lines and the numbers of lines employed to derive these abundances. The above uncertainties on the atmospheric parameters translate into typical total systematic errors of less than 0.1 dex, based on the formalism of Koch & McWilliam (2008; their Table 8). Details on the full data set and a thorough treatment of all systematic errors will be presented in a forthcoming paper.

3.1. Iron

At an [Fe/H] of −2.02 and −2.04 dex, both stars are slightly more metal rich than the sample mean found from comparison with globular cluster fiducials (Belokurov et al. 2007) and from low-resolution data, which yield a mean metallicity of −2.3 or −2.5 dex (Simon & Geha 2007; Kirby et al. 2008). The latter work finds an intrinsic metallicity spread of at least 0.5 dex (r.m.s.), which would indicate that our stars are well within the Her metal-rich tail. In particular, almost all of the ultra-faint dSphs studied to date show broad metallicity ranges of this order of magnitude. In general, a zero-point difference between the CaT “metallicities” and our [Fe/H] values can be expected due to the low [Ca/F e] (−0.15) found here. Naively, we expect a zero-point correction to the CaT metallicities based on halo [Ca/F e] calibrations of +0.50 dex (see also Koch et al. 2008). This would suggest [Fe/H] = −1.8 from correcting the Simon & Geha (2007) metallicities. We can check this result using our MIKE spectra, which contain the CaT lines; accordingly, we find CaT-based metallicities of [Fe/H]_{CaT} = −2.39 and −1.72 for Her-2 and 3. Moreover, our high-resolution [Fe/H] for Her-2 agrees well to within the uncertainties with the low-dispersion value derived by Kirby et al. (2008) and with the value based on Strömgren photom-

\[ \text{http://kurucz.harvard.edu} \]
etry (D. Adén; private communication).

3.2. **Alpha- and light elements**

As a glance at Table 1 shows, the [Ca/Fe] and [Ti/Fe] ratios of the Her stars are at most slightly to moderately enhanced, which is compatible with the abundance ratios found in the more luminous dSphs (Fig. 1; Shetrone et al. 2001, 2003; Venn et al. 2004; Sadakane et al. 2004; Sbordone et al. 2007; Koch et al. 2008).

At [Si/Fe] \(\lesssim 0.6\) dex, the Her stars have abundance ratios similar to other metal poor dSph stars from the literature (yet consistent with the typical Galactic halo pattern). One has to keep in mind, however, that these values are upper limits based on only one line. Furthermore, the production of Si in massive stars, which are required to contribute to peculiar abundance patterns in metal-poor stars, is not yet fully understood (e.g., Cohen et al. 2007).

It is striking that both the hydrostatic \(\alpha\)-elements Mg and O are strongly enhanced by a factor of about 10 relative to the Solar abundance ratios found in the majority of the Local Group dSphs. The light element Na is strongly enhanced in the Her stars, with typical [Na/Fe] ratios of 0.6–0.8 dex. For stars with similar atmosphere parameters to Her-2 and 3, the calculations of Takeda et al. (2003) show downward non-LTE corrections that become more severe with increasing EW for our Na I lines at 8183 and 8195 Å. Given the large EWs of our 8183/8195 Å Na I lines, near 160–190 mÅ, the Takeda et al. results suggest abundance corrections that reduce our LTE values by 0.3 to 0.4 dex. Thus, if non-LTE effects on Fe are ignored, the [Na/Fe] ratios in our Her stars are probably close to +0.3 dex, rather than \(\sim 0.7\) dex indicated in Table 1. The weak Al lines are not detectable in Her-3, but Al appears to be enhanced in Her-2. This is well consistent with Al and Na production in massive SNe II, similar to the \(\alpha\)-elements Mg and O (e.g., Woosley & Weaver 1995).

3.3. **Neutron-capture elements**

Fig. 2 shows the spectral regions around the Ba II line at 6496 Å. For comparison, we overplot a spectrum of a red giant in the Carina dSph, with similar atmospheric parameters as the Her stars and with a low [Fe/H] of \(-2.72\) dex (Koch et al. 2008). The Carina giant has [Ba/Fe] of \(-0.63\) dex and is thus Ba-depleted like the metal poor halo stars. Yet, a weak Ba absorption feature is discernible. Neither of the Her stars, however, shows any Ba absorption above the noise level. As a secondary test we synthesized the spectral regions around the Ba 6141 and 6496 lines and verified that essentially all of the visible absorption is due to noise and/or a blend with an Fe line. As a result, the [Ba/Fe] ratio is compatible with upper limits from the spectral S/N of \(\sim 2\) dex in both stars (Fig. 3).

The same holds for every other heavy n-capture element. We do not detect the usually prominent Sr II line at 4077 Å above noise, nor are Y, La, and Eu measurable above the noise, indicating an extraordinary level of depletion.

4. **INHOMOGENEOUS CHEMICAL ENRICHMENT IN HERCULES**

The only other red giant in a dSph known to date to have strong enhancements in the light elements O,
Mg, Na and Al, and a complete n-capture deficiency is Dra 119 (Shetrone et al. 1998; Fulbright et al. 2004). Similar to our Her stars, Dra 119 is characterized by no significant occurrence of elements heavier than Ni. Fulbright et al. (2004) argue that the chemical patterns seen in Dra 119 are explicable with SNe II enrichment by high-mass progenitors of at least 20 M⊙. Theoretical yields (e.g., Woosley & Weaver 1995) indicate that the high ratio of hydrostatic to explosive α elements (O and Mg, relative to Ca, Ti) found in our Her stars (at [Mg/Ca]= 0.94 and 0.58 dex, respectively), requires nucleosynthesis by relatively high mass Type II SNe (∼35 M⊙). Moreover, given the strong depletion of Ba in the two Her stars, SNe events in this mass regime apparently do not produce any significant amount of n-capture elements.

Given the low luminosity of the Her dSph, we consider an incomplete sampling of the high-mass end of the IMF as the most likely reason for the dominance of material from ∼35 M⊙ SNe II (e.g., Carigi & Hernandez 2008). Accordingly, we have performed stochastic chemical evolution experiments to investigate the [O/Mg], [Mg/Ca] and [Mg/Fe] ratios, similar to McWilliam & Searle (1999). Our calculations employed a Miller-Scalo (1979) IMF with slope of −2.56 and element yields from Woosley & Weaver (1995) for low-metallicity (Z = 10−4 Z⊙) SNe II progenitors in the mass range 12 to 40 M⊙. Our calculations indicate that the observed [Mg/Ca] and [Mg/Fe] ratios in Her are found in less than 1% of systems with 7 to 12 SNe II events; approximately 10% of systems possess the observed [Mg/Ca] and [Mg/Fe] ratios after 1–3, and ∼5 SN II events respectively. About 10% of systems show the observed [O/Mg] ratios after 11 SNe II; this reduced to 1% of systems after 32 SNe II. Thus, our experiment suggests that the abundance ratios can only be reasonably obtained in systems which experienced fewer than ∼11 SNe II enrichment events, although it is more likely that only 1–3 events were responsible for the chemical composition of our stars.

Seemingly at odds with the idea of small numbers of massive SNe II is the metallicity, at [Fe/H]=−2.0 dex; comparable abundance patterns in the Galactic halo stars are only found towards the very metal poor regime (e.g., McWilliam & Searle 1999; Cohen et al. 2007. Dra 119, with a comparably high [Mg/Ca] ratio has a very low [Fe/H] of almost −3 dex. Since Audouze & Silk (1995) argue that most individual SNe produce [Fe/H]∼−4.0 dex, we might statistically expect that ~100 SNe contributed to the composition of our Her stars. Other notable abundance anomalies in our Her stars include the extremely low [Ba/Fe] and enhanced [Co/Fe] ratios. Remarkably, low [Ba/Fe], high [Co/Fe] and low [Cr/Fe] ratios are typical of halo stars with [Fe/H]∼−3.5 (McWilliam et al. 1995). It is, however, possible, that unusual [Co/Cr] abundance ratios may be partly due to NLTE effects. Overall, it is as if the processes typical of the extremely low metallicity Galactic halo occurred in the Her dwarf at [Fe/H]=−2.0 dex. We note, however, that the high [Mg/Ca] ratios are inherent to the Her stars and not found in the metal poor halo stars.

It is conceivable that our Her stars formed from SN ejecta diluted with a much smaller amount of pristine gas than typically occurred in the Galactic halo. If the Her stars in fact resemble more the very metal poor Galactic halo stars, then their unusual composition could reasonably be due to one, or at most a few, SN events. This scenario requires that high mass SNe II produce the enhanced [Co/Fe] and deficient [Cr/Fe] values seen in our Her stars (typical at extremely low metallicity). While this scenario might explain our observed Her abundances, it leaves unanswered the origin of the enhanced [Co/Cr] ratios found in extremely metal-poor stars of the Galactic halo.

A viable interpretation is that our Her stars have an unusually high abundance of nearly pure population III material, produced and ejected by the first stars. These first stars are thought to be dominated by zerometallicity high mass SNe II (e.g. Yoshida et al. 2008), which would naturally explain the high [O,Mg/Fe] ratios. This scenario would also easily explain the high [Co/Fe] and low [Cr/Fe] values, if the unusual trends of these two ratios at low [Fe/H] are due to population III SN ejecta, as suggested by McWilliam (1997). While this idea removes the aforementioned difficulties associated with the Co and Cr abundances, the [Mg/Ca] ratios are unlike halo stars near [Fe/H]=−4. This scenario leads to the question of why the Her dwarf has a concentration of primordial material ~30 times that of the low-metallicity halo. Perhaps it is related to Her’s presumably low baryonic mass, which may have formed only one relatively low-mass population III star that ejected a large amount of population III Fe-peak material.

Whatever the cause, it appears that stochastic chemical evolution might reasonably explain the unusual abundance patterns in the Her dwarf galaxy (see also Marcolini et al. 2006, 2008). If true, this would indicate that the chemical enrichment proceeds very differently in very low-mass environments (see also Koch et al. 2008), and that low luminosity dwarf galaxies would be useful for directly measuring the abundance yields of low-metallicity Type II SNe.

We gratefully acknowledge Mark Wilkinson for help with preparing the observations and Andrea Marcolini and Daisuke Kawata for very helpful comments on an early version of this Letter.

REFERENCES

Adelman-McCarthy, J.K. et al. 2008, ApJS, 175, 297
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in “Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis”, ASP Conf. Ser., 336, 25
Audouze, J., & Silk, J. 1995, ApJ, 451, L49
Belokurov, V., et al. 2006, ApJ, 647, L111
Belokurov, V., et al. 2007, ApJ, 654, 897
Belokurov, V., et al. 2008, Astron. and Astrophys., 807, arXiv: 0807.2831
Coleman, M. G., et al. 2007, ApJ, 668, L43
Carney, B. W., Wright, J. S., Snedden, C., Laird, J. B., Aguilar, L. A., & Latham, D. W. 1997, AJ, 114, 363
Carigi, L., & Hernandez, X. 2008, ArXiv e-prints, 802, [arXiv:0807.1203]
Carretta, E., & Gratton, R. 1997, A&AS, 121, 95
Cohen, J. G., McWilliam, A., Christlieb, N., Shectman, S., Thompson, I., Moe, R. M., Wisotzki, L., & Reimers, D. 2007, ApJ, 659, L161
Daisuke, K., & Kawanoto, Y. 2008, ArXiv e-prints, 807, arXiv: 0807.2831
