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LEADED METAL-POOR STARS

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RESUMEN

Se discuten los espectros de estrellas de baja metalicidad con abundancias altas de carbón y elementos de captura-n con especial atención a CS 29497-030, la estrella azul pobre en metales, que tiene una abundancia extremadamente alta de plomo. Este objeto, como casi todos los de su clase, muestra obvios realces de los productos de nucleosíntesis por captura lenta de neutrones, probablemente depositados en ésta por una compañera anteriormente en la rama asintótica. Sin embargo, su abundancia por captura de neutrones no puede ser enteramente explicada de esta manera; se requieren contribuciones previas importantes de procesos de captura rápida de neutrones.

ABSTRACT

The spectra of low metallicity stars with large abundances of carbon and neutron-capture elements are discussed, with special emphasis on the blue metal-poor star CS 29497-030, which has an extremely large abundance of lead. This object, like essentially all of its class, has obvious enhancements of the products of slow neutron-capture nucleosynthesis, probably delivered to it by a former asymptotic branch companion star. However, its neutron-capture abundance cannot be explained entirely in this fashion; significant prior contributions from rapid neutron-capture processes seem to be required.

Key Words: **NUCLEAR REACTIONS, NUCLEOSYNTHESIS, ABUNDANCES — STARS: ABUNDANCES — STARS: AGB AND POST-AGB — STARS: BINARIES — STARS: BLUE STRAGGLERS — STARS: INDIVIDUAL (CS29497-030) — STARS: POPULATION II**

1. INTRODUCTION

Very metal-poor stars of the Galactic halo display a rich variety of chemical compositions. Below metallicities[4] of [Fe/H] ~ -2, most stars have relatively similar overabundances of the α-elements (i.e., [Mg,Si,Ca,Ti/Fe] $\sim +0.3$), but a small number have been identified with (a) no enhancements or substantial deficiencies (e.g., Nissen & Schuster 1997, Ivans et al. 2003 and references therein), or (b) extreme overabundances ([α/Fe] $\sim +1$; Aoki et al. 2004 and references therein). The bulk relative abundances of the neutron-capture elements (n-capture, defined here as those with atomic numbers Z > 30) vary enormously, $-1 \lesssim$ [n-capture/Fe] $\lesssim +3$. Additionally, at least three flavors of n-capture element mixes exist in low metallicity stars. There are those stars that have sharply-defined abundance patterns that are consistent with rapid n-capture nucleosynthesis (the r-process), most notably CS 31082-001 (Hill et al. 2002) and CS 22892-052 (Sneden et al. 2003). There are stars whose n-capture abundances fit very well the predictions of slow n-capture nucleosynthesis (the s-process), such as LP 625-44 and LP 706-7 (Aoki et al. 2001). Then perhaps not surprisingly, there are very metal-poor stars displaying a mixture of r- and s-process origin in their n-capture abundances, notably HE 2148-1247 (Cohen et al. 2003).

The s-process-rich low metallicity stars have enjoyed much attention since the discovery of lead in many of their spectra (Van Eck et al. 2001, 2003; Aoki et al. 2002; Barbuy et al. 2005), just as predicted by Gallino et al. (1998). Their enhanced s-process abundances are typically accompanied by carbon overabundances. Discovery of such stars usually begins with the detection of strong CH or C_2 molecular bands, most easily noticed in cool giant stars at low spectral resolution. Many Pb-rich stars discovered to date have been such giants, which have very crowded spectra. The single available Pb I feature for most lead abundance studies lies at $\lambda =$ 4057.8 Å. This line is rarely both strong and little contaminated (see for example Figure 2 of Van Eck et al. 2003). Most other n-capture elements also present few features for analysis in the cool giants.

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[4]We adopt the usual spectroscopic notation that for elements A and B, $\log \epsilon(\mathrm{A}) \equiv \log_{10}(\mathrm{N_A/N_H}) + 12.0$, and $[\mathrm{A/B}] \equiv \log_{10}(\mathrm{N_A/N_B})_\star - \log_{10}(\mathrm{N_A/N_B})_\odot$. e.g., $[\mathrm{Pb/Fe}] = 3 \Rightarrow (\mathrm{N_{Pb}/N_{Fe}})_\star = 1000\times(\mathrm{N_{Pb}/N_{Fe}})_\odot$. Also, metallicity is defined as the stellar [Fe/H] value.

Fortunately, warmer ($T_{eff} > 5000$ K) s-process-rich metal-poor stars have been discovered, such as the main-sequence turnoff star HE 0024-2523 (Lucatello et al. 2003) and the evolved (red horizontal or asymptotic giant branch) star CS 31062-050 (Johnson & Bolte 2003). Their spectra are much less dominated by CH, CN, and C_2 bands. Recently, Preston & Sneden (2000) carried out a large-sample survey of blue metal-poor (BMP) stars, which occupy the same color-magnitude domain as do the globular cluster blue stragglers. In that study it was discovered that nearly two-thirds of BMP stars are spectroscopic binaries, and that the most metal-poor BMP binaries often have elevated abundances of n-capture elements Sr and Ba. In a followup study of three binary and three constant-velocity BMP stars, Sneden, Preston, & Cowan (2003) demonstrated that all the binaries possess overabundances of C and all detectable n-capture elements. One of their program stars, CS 29497-030, had a detectable Pb I line. In this paper we will discuss the detailed abundance pattern of CS 29497-030, its connection to BMP stars and to other s-process-rich metal-poor stars, and its contrast with r-process-rich stars.

2. THE SPECTRUM OF THE EXTREME BMP BINARY CS 29497-030

Identification of binary s-process-enriched BMP stars is difficult to accomplish with low resolution spectra alone. The binary periods of BMP stars are usually long ($20\text{d} \lesssim P_{orbit} \lesssim 3000\text{d}$), hence the radial velocity variations are not large ($\sigma(v_R) < 20$ km s^{-1}), not easily noticed at low resolution. Additionally, the spectra of these warm ($6700 \text{ K} \lesssim T_{eff} \lesssim 7900$ K), high-gravity ($3.7 \lesssim \log g \lesssim 4.5$), metal-poor ([Fe/H] $\lesssim -2$) stars are relatively weak-lined. Abundance anomalies generally will not be apparent in BMP stars on spectra with resolving power $R \equiv \lambda/\Delta\lambda \lesssim 3000$. Low resolution surveys of photometrically-identified BMP candidates are useful mainly for overall estimation of metallicity.

At high spectral resolving power, $R \gtrsim 30{,}000$, anomalous chemical composition signatures are more apparent. In the blue-uv spectral region, the resonance lines of Sr II, and Yb II are prominent in s-process-rich BMP stars but barely detectable in their un-enhanced counterparts. However, most other n-capture spectral features are still fairly weak, and both high resolution and signal-to-noise are required for certain identification. Ivans et al. (2005) have recently used the new near-uv sensitive detector on the Keck I HIRESb instrument to survey CS 29497-030 in detail at resolving power R = 40,000 over the wavelength interval 3050 Å –– 5900 Å. In Figure 1 we reproduce a small spectral interval of this star and that of the well-known metal-poor subgiant HD 140283 observed with the same instrumental configuration. The absorption spectrum of Fe-peak and most lighter elements should be strongest in HD 140283, given the atmospheric parameters of the two stars: {T_{eff}, log g, [Fe/H]} = {5775 K, 3.75, –2.22} for HD 140283, and {7000 K, 4.10, –2.57} for CS 29497-030. This is clearly seen in the Mg I and Fe I features labeled in Figure 1. But CS 29497-030 exhibits strong features of Nd II (extremely weak in HD 140283) and Pb I (undetectably weak in HD 140283). Note that since the Mg and Pb lines are separated by only 0.3 Å, they would effectively blend together at low spectral resolution, at which the possible presence of Pb could well be missed.

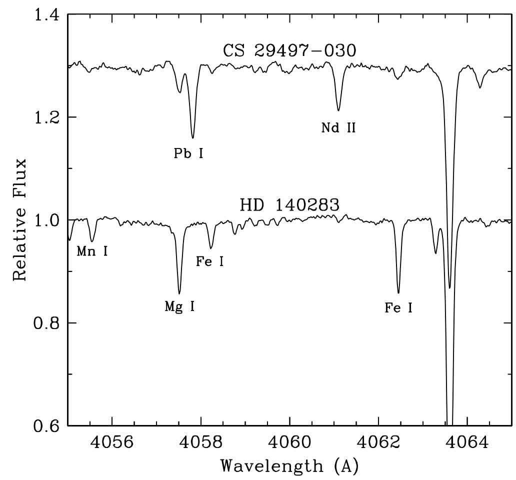

Fig. 1. The spectra of CS 29497-030 (n-capture, s-process rich) and HD 140283 (n-capture-poor) in a small spectral interval surrounding the prominent Pb I line at 4057.81 Å. The presence of Pb cannot be detected in most metal-poor stars such as HD 140283.

The atmospheric conditions of CS 29497-030 (high T_{eff} and log g, low [Fe/H], and large [n-capture/Fe]) combine to yield enhanced detectability of some n-capture transitions. Figure 6 of Sneden et al. (2003) demonstrates the contrast in the Ba II 4554 Å line strength between this star and the mean of three constant radial velocity BMP stars. Figure 1 of Ivans et al. (2005) shows the spectra of Pb I 3683 Å, Yb II 3694 Å, and even Bi I (detected for the first time in a metal-poor star). Unfortunately, for many of the rare earths, the n-capture abundances are not large enough to overcome the effects of the other three parameters, so that features of Pr, Sm, Tb, and Tm for example are not yet detected in CS 29497-030.

3. ELEMENTAL ABUNDANCES IN CS 29497-030

Three detailed analyses have been conducted for CS 29497-030: Sneden et al. (2003; 6 n-capture elemental abundances), Sivarani et al. (2004; 9 n-capture elements), and Ivans et al. (2005; 17 elements; 4 more with significant upper limits). The abundance ratios among the n-capture elements derived in all of these studies agree to well within the stated errors. Our discussion will concentrate on the Ivans et al. results. In Figure 2 we show part of Figure 2 from that paper, here limiting the atomic number range to just the n-capture domain. Both observed abundances and theoretical predictions are included in this figure, but some basic comments should be made on the observations. First, Ba and La have larger overabundances than does Eu. Since Ba and La are most easily manufactured in the s-process while Eu usually is synthesized in the r-process, the larger overabundance of Ba and La signals a dominant s-process contribution to CS 29497-030. The Pb and Bi abundances point strongly in the same direction: these two elements are ∼1 dex more enhanced than are Ba and La, a situation that only can be achieved in an s-process synthesis event in a metal-poor stellar progenitor.

In Figure 2 the observed abundances and upper limits are compared to predictions for two sets of calculations. The dotted line denoted by "s" is from an s-process calculation for a metal-poor $1.3M_{\odot}$ AGB stellar model without any prior r-process enrichment. These comparisons suggest that a simple assumption of purely s-process synthesis of these elements cannot totally explain the n-capture abundances of CS 29497-030. A significantly better fit occurs with the addition of a significant r-process abundance component (from a previous-generation supernova) prior to the onset of the s-process (in the former AGB companion to CS 29497-030).

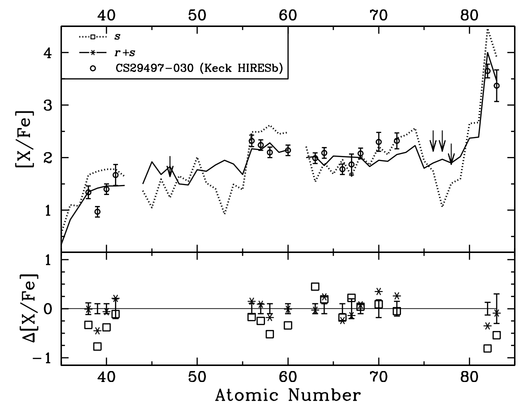

Fig. 2. Abundances of n-capture elements in CS 29497-030, compared with n-capture theoretical predictions. This figure is adapted from Figure 2 of Ivans et al. (2005). In the top panel, open circles with error bars denote the stellar abundances, and downward-pointing arrows indicate upper limits. The dotted line represents predictions from an s-process calculation for a metal-poor $1.3M_{\odot}$ AGB stellar model without any prior r-process enrichment. The solid line represents the best fit s-process calculation for the same AGB model but with the addition of an r-process abundance pre-enrichment. In the bottom panel, differences defined as Δ[X/Fe] $\equiv$ $[\mathrm{Fe/H}]_{\mathrm{obs}}$ – $[\mathrm{Fe/H}]_{\mathrm{calc}}$ are shown. Open box symbols represent differences with respect to the s-process-only model predictions, and star symbols represent differences with respect to the r+s predictions. The error bars from the top panel are repeated in the bottom panel, and are centered at Δ[X/Fe] = 0 for all elements. Upper limits from the top panel are not shown in the bottom panel.

4. COMPARISON TO OTHER N-CAPTURE-RICH HALO STARS

In Figure 3 we plot the n-capture abundance sets of CS 29497-030 and the warm evolved star CS 31062-050 (Johnson & Bolte 2004). Obviously CS 29497-030 has somewhat larger abundances of the lighter elements shown here as well as Pb. The overall message of this picture, however, is that the qualitative patterns are nearly identical, as appears to be the case for other Pb-rich stars (Figure 8 of Sneden et al. 2003). This distribution seems to be as characteristic of the s-process in very metal-poor stars as is the r-process pattern. A useful contrast between s- and r-process-rich stars can now be made. One such a comparison is shown in Figure 4. The s-process abundances are the means of those from the two stars of Figure 3. The r-process abundances are those of CS 22892-052 (Sneden et al. 2003), shifted as a group so that its La abundance matches that of the s-process-rich average. The two chemical composition sets are not similar, and for individual stars it is clear that assignment of s- or r-process-richness may be confidently made with just the abundances of a few key elements.

The "Texas-Mexico" conferences have often emphasized the astrophysics of gaseous nebulae. What connection do Pb-rich stars have here? Péquignot & Baluteau (1994) first suggested that n-capture species could be present in planetary nebulae, and more recently Dinerstein (2001) and Sterling et al. (2002) have demonstrated that Se (Z = 34) and Kr (Z = 36) are both present and sometimes enhanced

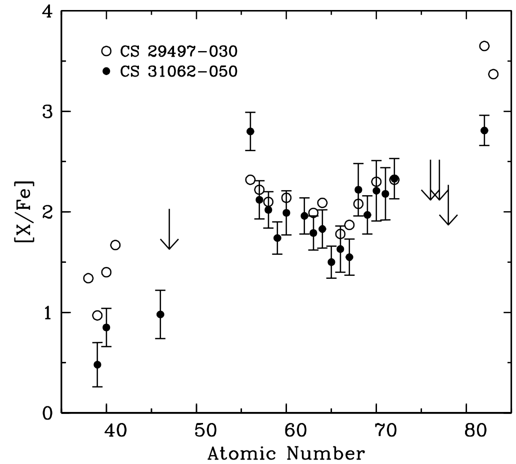

Fig. 3. Abundances of n-capture elements in metal-poor, s-process-rich stars CS 29497-030 and CS 31062-050 (Johnson & Bolte 2004). The abundances for CS 29497-030 are those of the previous figure, but for clarity the error bars are not plotted here.

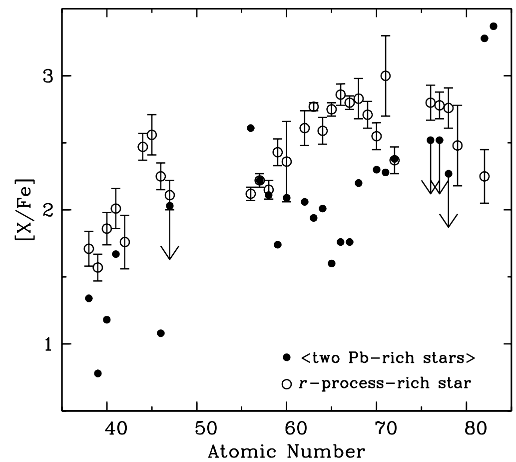

Fig. 4. Abundances of n-capture elements in the metal-poor, r-process-rich star CS 22892-052 (filled circles), and the mean of abundances in the comparably metal-poor s-process-rich stars CS 31062-050 and CS 29497-030. Prior to forming the mean of the two s-process abundance sets, +0.10 dex has been added to the data for CS 31062-050 (Johnson & Bolte 2004) to normalize the abundance distributions in these two stars such that their [X/Fe] values agree.

in many of these objects. Now Ge (Z = 32) has been identified in two white dwarf stars (Vennes et al. 2005). Production of s-process elements in AGB stars must be transferred to the outside world as the AGB stars die, and in metal-poor Pb-rich stars, in planetary nebulae, and in white dwarfs we see this transfer in action. And the prospect of observing even heavier elements in the nebulae and white dwarfs is exciting to contemplate.

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