

NEAR-ULTRAVIOLET OBSERVATIONS OF CS 29497-030: NEW CONSTRAINTS ON NEUTRON-CAPTURE NUCLEOSYNTHESIS PROCESSES¹

INESE I. IVANS,^{2,3} CHRISTOPHER SNEDEN,⁴ ROBERTO GALLINO,⁵ JOHN J. COWAN,⁶ AND GEORGE W. PRESTON⁷

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ABSTRACT

Employing spectra obtained with the new Keck I HIRES near-UV-sensitive detector, we have performed a comprehensive chemical composition analysis of the binary blue metal-poor star CS 29497-030. Abundances for 29 elements and upper limits for an additional seven have been derived, concentrating on elements largely produced by means of neutron-capture nucleosynthesis. Included in our analysis are the two elements that define the termination point of the slow neutron-capture process, lead and bismuth. We determine an extremely high value of $[\text{Pb}/\text{Fe}] = +3.65 \pm 0.07$ ($\sigma = 0.13$) from three features, supporting the single-feature result obtained in previous studies. We detect Bi for the first time in a metal-poor star. Our derived Bi/Pb ratio is in accord with those predicted from the most recent FRANEC calculations of the slow neutron-capture process in low-mass asymptotic giant branch (AGB) stars. We find that the neutron-capture elemental abundances of CS 29497-030 are best explained by an AGB model that also includes very significant amounts of pre-enrichment of rapid neutron-capture process material in the protostellar cloud out of which the CS 29497-030 binary system formed. Mass transfer is consistent with the observed $[\text{Nb}/\text{Zr}] \sim 0$. Thus, CS 29497-030 is both an $r+s$ and “extrinsic AGB” star. Furthermore, we find that the mass of the AGB model can be further constrained by the abundance of the light odd-element Na.

Subject headings: binaries: spectroscopic — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: AGB and post-AGB — stars: individual (CS 29497-030) — stars: Population II

1. INTRODUCTION

The bulk of the “heavy elements,” those heavier than iron, are created by a combination of slow and rapid neutron-capture nucleosynthesis processes (s - and r -processes), with each responsible for $\sim 50\%$ of the solar system isotopes. In the s -process, successive neutron captures occur over sufficiently long timescales to permit unstable nuclei to β -decay, and in principle, the isotopic distribution of the s -process can be calculated from knowledge of stellar and nuclear physics (e.g., Busso et al. 1999; Straniero et al. 2005). Lead and bismuth are the last stable elements along the s -process path. All isotopes heavier than Bi are unstable and α -decay to Pb and Bi (Clayton & Rassbach 1967). In the Sun, the elemental abundances of Pb and Bi consist of significantly different combinations of r - and s -process isotope contributions, with $r:s$ ratios for Pb and Bi of 21:79 and 65:35, respectively (Travaglio et al. 1999; Simmerer et al. 2004; references therein). The solar system’s chemical composition is the integrated result of many generations of stars and depends upon the details of the formation history, initial mass functions, chemical yields, etc. The Pb and Bi abundances most useful for unraveling the sites and nuclear

parameters associated with the s - and r -process correspond to those in extremely metal-poor stars, formed from material with few prior generations of nucleosynthetic processing.

In the last 5 years, dozens of low-metallicity stars with $[\text{Pb}/\text{Fe}] > 1$ have been discovered⁸ (see, e.g., Sivarani et al. 2004; Barbuy et al. 2005; references therein). Such large values of heavy s -process enhancements in low-metallicity stars are thought to be the result of mass transfer in binary star systems in which the initially more massive star underwent an asymptotic giant branch (AGB) evolutionary phase and transferred material to the observed star. The Pb enhancements observed in metal-poor stars were predicted by Gallino et al. (1998), who noted that lower metallicity stars were expected to display increasingly higher abundances of heavier s -process elements relative to the abundances of lighter s -process elements. At lower metallicities, the number of neutrons captured per iron seed increases, allowing heavier elements to be produced in greater abundance. Enhancements of Pb have since been modeled by both phenomenological “classical” AGB models with parameterized neutron exposures and “stellar models” with stellar astrophysical constraints (e.g., Arlandini et al. 1999; Delaude et al. 2004; references therein).

Because Bi is the last stable element, knowledge of its abundance in metal-poor halo stars will help pin down the predictions of the abundances of heavier radioactive actinide elements such as Th and U (Kratz et al. 2004; Ratzel et al. 2004; references therein). Thus, abundance determinations of this element will also benefit nuclear-chronometer studies of the age of the Galaxy. With these multiple goals in mind, we observed the blue metal-poor (BMP; Preston et al. 1994) star CS 29497-030, a star that to date possesses the largest published $[\text{Pb}/\text{Fe}]$ abundance of any metal-poor star (Sneden et al. 2003, hereafter

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² Department of Astronomy, Mail Code 105-24, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125; iii@astro.caltech.edu.

³ Hubble Fellow.

⁴ Department of Astronomy, University of Texas, 1 University Station, C1400, Austin, TX 78712; chris@verdi.as.utexas.edu.

⁵ Dipartimento di Fisica Generale, Università di Torino, via Giuria 1, I-10125 Torino, Italy; gallino@ph.unito.it.

⁶ Department of Physics and Astronomy, University of Oklahoma, 440 West Brooks Street, Norman, OK 73019; cowan@nhn.ou.edu.

⁷ Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101; gwp@ociw.edu.

⁸ We adopt the usual spectroscopic notation that for elements A and B, $\log \epsilon(A) \equiv \log(N_A/N_H) + 12.0$ and $[A/B] \equiv \log(N_A/N_B)_* - \log(N_A/N_B)_\odot$. For example, $[\text{Pb}/\text{Fe}] = 3$ implies $(N_{\text{Pb}}/N_{\text{Fe}})_* = 1000(N_{\text{Pb}}/N_{\text{Fe}})_\odot$. Also, metallicity is defined as the stellar $[\text{Fe}/\text{H}]$ value.

SPC03; Van Eck et al. 2003; Sivarani et al. 2004; references therein), in order to derive its abundance of Bi and other neutron-capture elements.

2. OBSERVATIONS, REDUCTIONS, AND ANALYSIS

Spectra of CS 29497-030 were obtained from 2004 September 29 through October 1 with the blue configuration of the Keck I High Resolution Echelle Spectrometer (HIRESb; Vogt et al. 1994) and new three-chip CCD mosaic ($3 \times 2048 \times 4096 \times 15 \mu\text{m}$ pixels). The wavelength coverage is essentially continuous in the range $\sim 3050\text{--}5895 \text{ \AA}$. With 3×1 pixel on-chip binning and a slit width of $0''.861$, we obtained a resolving power $R \equiv \lambda/\Delta\lambda \approx 40,000$. Nine 1800 s exposures were taken, to attain a co-added signal-to-noise ratio (S/N) of 55:1 per resolution element in the center of the blaze of the bluest order. The S/N increases redward, with ~ 100 at 3680 \AA , ~ 250 at 4400 \AA , and ~ 300 at 5850 \AA . Data reduction was performed using standard tasks in IRAF,⁹ FIGARO,¹⁰ and SPECTRE (Fitzpatrick & Sneden 1987).

Our abundance analysis relied on the results of a combination of spectrum syntheses and equivalent width (EW) analyses measured with SPECTRE by fitting Gaussian profiles to the absorption lines. We employed stellar atmospheres without overshooting (Castelli & Kurucz 2004) and performed abundance calculations with a current version of MOOG (Sneden 1973). Adopting the stellar parameters of SPC03 as initial parameters, we then iterated on the Fe abundances to eliminate abundance trends with respect to the excitation potentials, EWs, and ionization states. We derive values of $T_{\text{eff}} = 7000 \text{ K}$, $\log g = 4.1$, $\xi_t = 1.9 \text{ km s}^{-1}$, and $[\text{Fe}/\text{H}] = -2.57$, all in good agreement with SPC03, with the exception of the lower metallicity derived from the higher quality data employed in this study. We also compared our abundances for CS 29497-030 with those of Sivarani et al. (2004). With 19 elements in common between the two studies (excluding those for which only an upper limit was derived), most of the abundances agree to within 1σ . The abundances in largest disagreement can be completely explained as the direct result of the differences in the adopted stellar parameters. As Sivarani et al. show (their Table 2), the photometry of CS 29497-030 leads to a wide range of T_{eff} values based on colors. In this Letter, we adopt the value of 7000 K , which satisfies both our spectroscopic constraints and is comparable to the estimate based on $V\text{--}K$ photometry. Further technical details regarding our reduction and analysis techniques will be reported in an expanded investigation currently under way (I. I. Ivans et al. 2005, in preparation).

In Figure 1, we illustrate three 4 \AA swaths of spectrum syntheses surrounding regions of selected near-UV features of platinum, bismuth, lead, erbium, and ytterbium. In Table 1, we list our abundances for CS 29497-030, including formal uncertainties of their means, and the adopted 1σ , which includes an allowance for any uncertainty in the spectroscopically derived stellar parameters. Abundances derived from a single feature have been assigned $\sigma = 0.3 \text{ dex}$. For some elements with additional useful features at wavelengths redward of our HIRESb setup, we made new abundance determinations of the 2D-FRUTTI data employed by SPC03.

⁹ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the NSF.

¹⁰ FIGARO is provided by the Starlink Project, which is run by CCLRC on behalf of PPARC (UK).

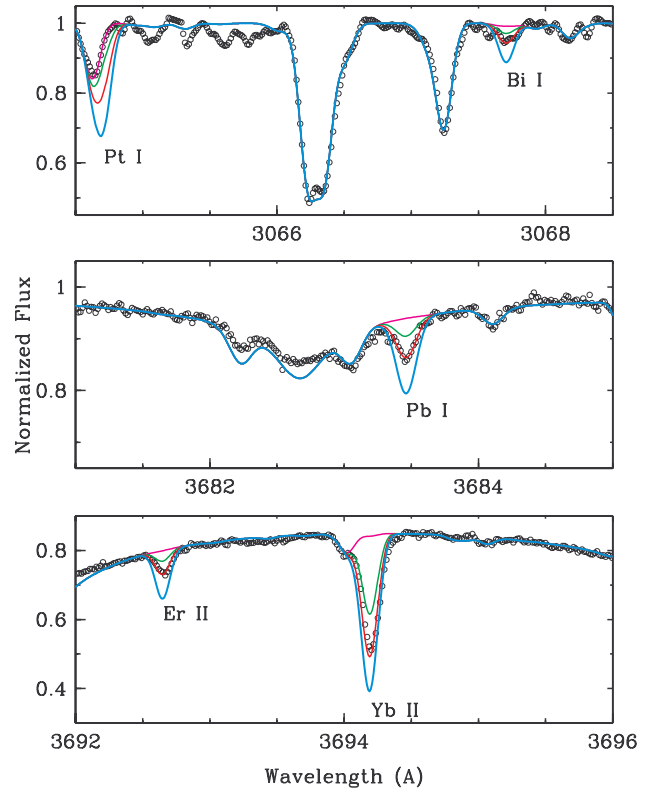


FIG. 1.—Spectra surrounding platinum, bismuth, lead, erbium, and ytterbium features in the near-UV. Circles represent the observed spectrum, and the solid lines the spectrum syntheses. The magenta line represents a synthesis with no detectable contribution of the named element (e.g., only an upper limit is derived for Pt). The green and blue syntheses otherwise bracket the derived abundances (presented in Table 1 and displayed here in red) by $\pm 0.4 \text{ dex}$.

The derived abundances of O, Na, Al, and K shown in Table 1 have not been corrected for non-LTE (NLTE) effects, which are known to exist for these elements. The available literature on this issue in *warm* low-metallicity stars is both sparse and in poor agreement. For the elemental abundances of O, Na, Al, and K, we suggest that the following values be considered with greater confidence: upper limits of $[\text{O}/\text{Fe}] \leq +1.59$, $[\text{Na}/\text{Fe}] \leq +0.88$, $[\text{Al}/\text{Fe}] \leq +0.58$, and $[\text{K}/\text{Fe}] \leq +1.07$, which include our estimated NLTE corrections.

3. DISCUSSION

We explored the origin of the neutron-capture elements in CS 29497-030 by comparing the observed abundances with predicted r - and s -process contributions. In Figure 2, we display our abundances in the context of FRANEC models and s -process calculations performed by Gallino et al. (1998, 2005 [in preparation]; see also Straniero et al. 2005 and references therein). Predictions from two sets of initial abundance assumptions are shown: with and without pre-enrichment of the initial abundances. $[\text{La}/\text{Eu}]$ ratios produced in the s -process at this low metallicity are typically $+0.7 \text{ dex}$. In CS 29497-030 the $[\text{La}/\text{Eu}]$ ratio is ~ 0.2 , clearly indicating a strong r -process contribution. The pre-enrichment treatment employed in the s -process calculations here permits an exploration of the possibility that the initial abundances of CS 29497-030 and its binary partner arose from a parent cloud with an extreme r -process abundance. In our picture, the formation of this pair of low-mass stars was triggered by a supernova that polluted,

TABLE 1
CS 29497-030: DERIVED ABUNDANCES

Species	$\log \epsilon(X)$	\pm	n	[X/Fe]	σ
C	8.29	0.03	9	+2.30	0.10
C (CH)	8.46	+2.47	0.10
N (CN)	7.60	+2.12	0.35
O ^a	7.84	0.11	3	+1.48	0.11
Na ^a	4.34	...	1	+0.58	0.30
Mg	5.45	0.07	4	+0.44	0.14
Si	5.01	...	1	+0.03	0.30
K ^a	3.62	...	1	+1.07	0.30
Ca	4.26	0.04	6	+0.47	0.10
Sc	1.20	0.01	3	+0.67	0.10
Ti	3.06	0.03	17	+0.64	0.11
Cr	3.13	0.04	5	+0.03	0.10
Mn	2.47	0.07	4	-0.35	0.13
Ni	3.72	0.02	2	+0.04	0.10
Sr	1.67	0.07	3	+1.34	0.12
Y	0.64	0.02	13	+0.97	0.10
Zr	1.43	0.03	11	+1.40	0.10
Nb	0.52	0.04	3	+1.67	0.20
Ba	1.88	0.06	3	+2.32	0.11
La	0.80	0.01	15	+2.22	0.10
Ce	1.08	0.02	20	+2.10	0.10
Nd	1.02	0.02	17	+2.14	0.10
Eu	-0.07	0.03	6	+1.99	0.10
Gd	0.64	0.02	5	+2.09	0.10
Dy	0.31	0.02	7	+1.78	0.10
Ho	-0.19	0.05	4	+1.87	0.20
Er	0.44	0.04	4	+2.08	0.10
Yb	0.81	0.13	2	+2.30	0.18
Hf	0.63	0.07	5	+2.32	0.15
Pb	2.93	0.07	3	+3.65	0.13
Bi	1.51	...	1	+3.37	0.30

Upper Limits					
Al ^a	3.83	...	1	-0.07	...
Co	4.02	...	1	+1.67	...
Ga	1.63	...	1	+1.32	...
Ag	0.7:	...	1	+2.03	...
Os	1.4:	...	1	+2.52	...
Ir	1.3:	...	1	+2.52	...
Pt	1.5:	...	1	+2.27	...

^a Derived abundance does not take into account NLTE correction, which would revise abundance. See § 2 for discussion and recommended upper limits.

snowplowed, and clumped a nearby molecular cloud. In the associated s -process calculation, all the initial r -process isotopes have been enhanced (according to their r -process contribution to the solar system abundances and normalized to Eu), and this in turn affects the seed abundances available to the subsequent s -processing.

In the case of no pre-enrichment, the displayed result represents the most recent FRANEC calculations of the s -process at $[\text{Fe}/\text{H}] \sim -2.6$ for an AGB star of $1.3 M_{\odot}$ with an enhanced ^{13}C abundance, in which all heavy-element abundance predictions are from the s -process. Also illustrated in Figure 2 are s -process calculations based on the r -process pre-enrichment scenario. Calculations for $\pm 0.05 M_{\odot}$ produce abundances that bracket those shown in the figure.

The main component of the s -process is produced in an AGB star undergoing a series of He shell flashes via the triple- α reaction just below the H-burning shell. In these He-shell flashes (pulses), proton mixing leads to $^{12}\text{C}(p, \gamma)^{13}\text{N}(e^+, \nu)^{13}\text{C}(\alpha, n)^{16}\text{O}$ reactions, releasing neutrons in radiative conditions in the interpulse period that can then be captured by Fe and heavy-element seeds (Iben & Renzini 1982; Busso et al. 1999; Straniero et al. 2005). The next thermal pulse injects the energy required to dredge up the nucleosynthesis products into the envelope while mixing more protons with the products of fur-

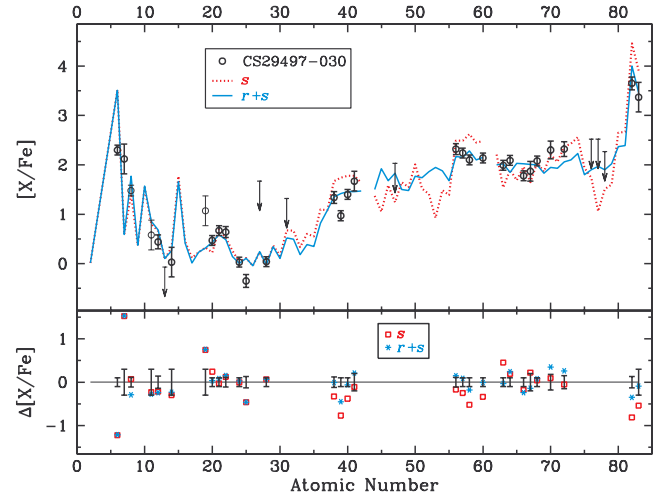


FIG. 2.—Comparison of the $[\text{X}/\text{Fe}]$ abundances in CS 29497-030 with predictions from s -process calculations of a $1.3 M_{\odot}$ AGB star model. In the top panel, the upper limits and open circles with error bars denote the stellar abundances. Thin symbols denote the four light-element abundances that may suffer from uncorrected NLTE systematics (see § 2). The solid blue line represents the best-fit s -process calculations based on an extreme r -process abundance pre-enrichment ($r+s$); the dotted red line represents predictions from s -process calculations without r -process enrichment. The bottom panel displays the difference, defined as $\Delta[\text{X}/\text{Fe}] \equiv [\text{Fe}/\text{H}]_{\text{obs}} - [\text{Fe}/\text{H}]_{\text{calc}}$, and upper limits are not shown.

ther triple- α reactions. Thus, the photospheric abundance ratios of neutron-rich elements created in the s -process are a function of the histories of the envelope and core masses and the number of thermal pulses.

The number of thermal pulses affects the number of free neutrons for subsequent neutron-capture processing, and the abundance of Na places a stringent limit upon the assumed AGB star progenitor mass. The Na abundance results from $^{22}\text{Ne}(n, \gamma)^{23}\text{Na}$ reactions, where ^{22}Ne is largely of primary origin, only slightly affected by α -captures during the thermal pulses. ^{22}Ne derives its abundance from CNO nuclei ashes (^{14}N) capturing α -particles in the convective thermal pulse, with primary ^{12}C produced and mixed to the surface by previous dredge-up episodes. More massive AGB models produce higher $[\text{Na}/\text{Fe}]$ abundances (e.g., a $1.5 M_{\odot}$ model undergoes ~ 20 thermal pulses, implying $[\text{Na}/\text{Fe}] \sim 2$). The best fit to our recommended upper limit of $[\text{Na}/\text{Fe}]$, as well as the overall abundances of CS 29497-030, was found to be from a $1.3 M_{\odot}$ AGB model that had undergone only six thermal pulses.

Among the light neutron-capture elements, the s -process model with pre-enrichment predicts abundances in good agreement with those derived for Sr and Zr. An “intrinsic AGB” (i.e., high luminosity and low $\log g$) is expected to be Tc-rich, ^{93}Zr -rich, and ^{93}Nb -poor (Wallerstein & Dominy 1988). An “extrinsic AGB” is on or near the main sequence and was once the lower mass star in a binary system. The s -process abundances of the extrinsic AGB star are a result of pollution from the former AGB star’s dredged-up material, at an epoch sufficiently remote for the ^{93}Zr to have now decayed to ^{93}Nb . Our $[\text{Nb}/\text{Zr}]$ ratio and stellar parameters for CS 29497-030 are both in accord with those of an extrinsic AGB.

The abundances of elements in CS 29497-030 with large s -process contributions in the solar system are predicted to have lower abundances in the $r+s$ results than those predicted from the s -process operating without r -process pre-enrichment. The pre-enrichment of the additional heavy elements affects the

s-processing within the He intershell of the AGB star, both in the ^{13}C pocket and the convective thermal pulse. Because the heavy-element isotopes in the pre-enrichment case are so numerous, they strongly compete with Fe as seeds for neutron capture. In addition, this competition takes a global role of leaving fewer neutrons available for the *s*-process isotopes, which further decreases *s*-process efficiency.

Other *r+s* stars have recently been reported and discussed in the literature (e.g., Aoki et al. 2002; Cohen et al. 2003; Johnson & Bolte 2004; Zijlstra 2004; Barbuy et al. 2005; references therein). In some of the previous efforts to model the abundances of *r+s* stars, *s*-process material has been added to the assumed *r*-process abundance enhancements (e.g., Delaude et al. 2004). However, those modeling attempts were performed with fewer abundances than employed here for CS 29497-030, and the previous attempts neither required nor included *s*-processing of the *r*-enhanced material within the He intershell of the AGB star as has been done in the present study. As noted, CS 29497-030 possesses the largest [Pb/Fe] abundance of any metal-poor star published to date. Its *s*-process contribution to Bi disguises its initial *r*-process contribution. However, we predict that *r+s* stars with *less s*-processing (and a relatively higher amount of *r*-processed material) will provide third *s*-peak abundance ratios more useful in the effort to pin down the abundance predictions—and production sites—for the production of the *r*-process actinide elements such as Th and U.

4. CONCLUSIONS

The chemical abundances of the extremely Pb-rich BMP star CS 29497-030 are an excellent test bed to set new constraints on models of neutron-capture processes at low metallicity. We find CS 29497-030 to be an *r+s* star and that the abundance ratios are best fitted by a pre-enrichment of *r*-process material out of which the binary system formed. The more massive companion underwent an AGB phase, and heavy elements from the pre-enrichment competed with Fe as seeds for neutron capture, leaving fewer neutrons available for *s*-process isotopes and diminishing the *s*-process efficiency. Pollution from the former AGB star's dredged-up material subsequently enriched the envelope composition of CS 29497-030. Based on the fit to the low number of AGB model thermal pulses to match the observed abundance pattern, including the abundances of Na and Mg, we deduce that the progenitor mass of the AGB star

was $1.3 M_{\odot}$. The relative abundances we derive for Nb and Zr, as well as the stellar parameters corresponding to an evolutionary stage near the main sequence, confirm that CS 29497-030 is an extrinsic AGB star.

We encourage future studies of *s*-process abundance patterns to include the abundance of light elements sensitive to the neutron excess, such as Na and Mg. We find that these elements are useful constraints on the mass of the AGB progenitor. However, some light elements are affected by NLTE effects, and studies to date of those effects are sparse and in poor agreement. It would be useful to extend the knowledge to lower metallicity and warmer temperatures than have so far been investigated.

Overall, the predicted abundances from the (*r+s*)-process fit well the observed abundance patterns of CS 29497-030, from the first (Sr and Zr) and second peaks of the *s*-process (Ba and La), as well as the third peak (Pb and Bi). Our abundance determination for Bi is the first such in any metal-poor star. In addition, the value derived for Bi is in accord with the Pb abundance. We find that the *s*-process contribution to the pre-enrichment of *r*-process material in CS 29497-030 swamps the *r*-process signature in the abundance of Bi. We recommend that additional *r+s* stars (but with relatively less *s*-processing than is found in CS 29497-030) be observed in order to derive Pb and Bi abundances that may further illuminate the issues regarding the production of actinide elements, Th and U, and the other neutron-capture processes at work at early times in our Galaxy.

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