From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
Proceedings IAU Symposium No. 228, 2005
V. Hill, P. François & F. Primas, eds.

doi:10.1017/S1743921305006228

CS29497-030 Abundance Constraints on Neutron-Capture Nucleosynthesis

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Abstract. Chemical abundances and upper limits of three dozen elements have been derived for the binary blue metal-poor, extremely lead-rich star CS29497-030. The findings include a large contribution of *s*-process material (e.g., [Pb/Fe] > 3.5) and a large contribution of *r*-process material (e.g, [Eu/Fe] ∼2), abundances which place it in the class of objects known as *r*+*s* stars. The ratio of [Zr/Nb] ∼0, along with its stellar parameters, indicates that it is not an intrinsic AGB star. Modelling the abundance distribution (which includes the first Bi abundance determination for any metal-poor star) with *s*-process calculations employing FRANEC models, there is excellent agreement with the observations by adopting a 1.3 $M_\odot$ AGB model with an enhanced ^{13}C-pocket and a pre-enrichment of *r*-process material. In this scenario, the initial abundances of CS29497-030 and its binary partner arose from a parent cloud with an extreme *r*-process abundance, in which star formation was triggered by a core-collapse supernova which polluted, snowplowed, and clumped a nearby molecular cloud. Pollution from the former AGB star's dredged-up material subsequently enriched the envelope composition of CS29497-030 (Ivans *et al.* 2005). Critical tests of this model and scenario include the dependence of abundance ratios on systematics due to non-LTE effects, the choice of stellar parameters and model atmospheres, and the assumed abundance pattern of the protostellar cloud out of which the CS29497-030 binary system formed.

Keywords. Nuclear reactions, nucleosynthesis, abundances, stars: abundances, stars: AGB, stars: binaries, stars: blue stragglers, stars: individual (CS29497-030), stars: Population II

1. Background

Employing high resolution spectra acquired with the new near-UV-sensitive detector on the Keck I HIRESb, and focusing largely on elements created in neutron-capture nucleosynthesis processes, Ivans *et al.* (2005; Bi-I05 hereafter), report the first detection of Bi in a metal-poor star. In addition, their derived abundance distribution pattern is matched-well by *s*-process calculations that are based on a pre-enrichment of *r*-process material. In these Proceedings, we focus our attention on some of the outstanding issues related to the findings of Bi-I05.

CS29497-030 is a blue metal-poor star (BMP) originally discovered as part of the Preston programme (1994). Employing the Bi-I05 data, we derive a radial velocity, $v_{\rm r}$ = 43.2 ± 0.6 km/s on HJD = 2453278.89055, consistent with both the binary star orbit derived by Preston & Sneden (2000) and additional $v_{\rm r}$ observations by Sivarani *et al.*

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Table 1. Stellar Parameters Employed Previous Spectroscopic Analyses

$T_{\rm eff}$	log g	v_t	[Fe/H]	Obs./Tel./Inst.	Reference
7150	4.28	1.85	−2.41	ESO VLT UVES	Bragaglia *et al.* (these Proceedings)
7000	4.10	1.90	−2.57	Keck HIRESb	Ivans *et al.* (2005)
6650	3.50	2.00	−2.70	ESO VLT UVES	Sivarani *et al.* (2004)
7050	4.20	1.75	−2.16	LCO 2D-FRUTTI	Preston & Sneden (2000), Sneden *et al.* (2003)
7426	3.90	···	−2.50	ESO LSO B&C	Wilhelm *et al.* (1999)

(2004). Combining the mean $v_{\rm r}$ with the available proper motion information from SIMBAD, we deduce an apogalactic orbital distance of ∼10 kpc and a maximum distance above the Galactic plane of ∼2 kpc – orbital characteristics of a halo star possessing no unusual kinematics.

2. Stellar Parameters and Abundance Effects

The chemical composition of CS29497-030 is unusual. Its Pb abundance, the result of intense *s*-processing, puts it in the class of extremely lead-rich stars (see Lucatello, these Proceedings). As a result of the *s*-process, one would expect to observe [La/Eu] ∼0.7. However, in CS29497-030, [La/Eu] = 0.23, which puts it in the class of objects known as r+s stars (see Bisterzo *et al.*, these Proceedings). As noted by Bi-I05 and Goriely (these Proceedings), some of the abundances derived by Sivarani *et al.* (2004) and Bi-I05 are in less than good agreement. Adopting one set over another could lead to differing views of its nucleosynthetic history. Bi-I05 find that the abundances in largest disagreement between the two studies (including the abundance of Eu) are completely accounted for as the direct result of the differences in the adopted stellar parameters.

In Table 1, we present the stellar parameters derived in previous and current analyses. In addition, we refer the reader to Sivarani *et al.* (2004; their Table 2) who derive photometric $T_{\rm eff}$ values for CS29497-030 and who show that they are a function of the colour index, with redder colours generally yielding warmer temperatures. Possible causes due to molecular band effects, incorrect reddening values, and anomalous values of the ratio of total-to-selective extinction have been ruled out. Further exploration of the stellar parameter issue is currently underway employing all four high resolution data sets.

3. Abundance Results

The abundance distribution pattern of CS29497-030, based on the Bi-I05 results, is shown in Figure 1. The abundances of the 3$^{\rm rd}$ *s*-process peak elements Pb and Bi are both in accord with the r+s calculations, as are the abundances of elements in the 2$^{\rm nd}$ peak. In addition to the neutron-capture element abundances, the best-fit determination made by Bi-I05 included the abundances of Mg and Na, which are very sensitive to primary neutron production (see Bi-I05 for details). We refer the reader to Bisterzo *et al.* (these Proceedings) for additional stellar examples of r+s abundance pattern calculations.

The abundance of Na is also sensitive to non-LTE effects. However, the available literature in *warm* low metallicity stars is both sparse and in poor agreement. For the resonance feature at λ5889.97Å, Baumüller *et al.* (1998) suggest that a correction of $-0.55 < \Delta < -0.11$ dex would need to be applied to the Na I abundance of a star of $T_{\rm eff}$/log g = 6500/4.0 (their hottest example) in the metallicity range $-2 <$ [Fe/H] < -3. For the same stellar parameters, Takeda *et al.* (2003) find corrections in the range of $-0.19 < \Delta < -0.13$ dex. For a star of $T_{\rm eff}$/log g = 7000/4.5 in the same metallicity range,

https://doi.org/10.1017/S1743921305006228 Published online by Cambridge University Press

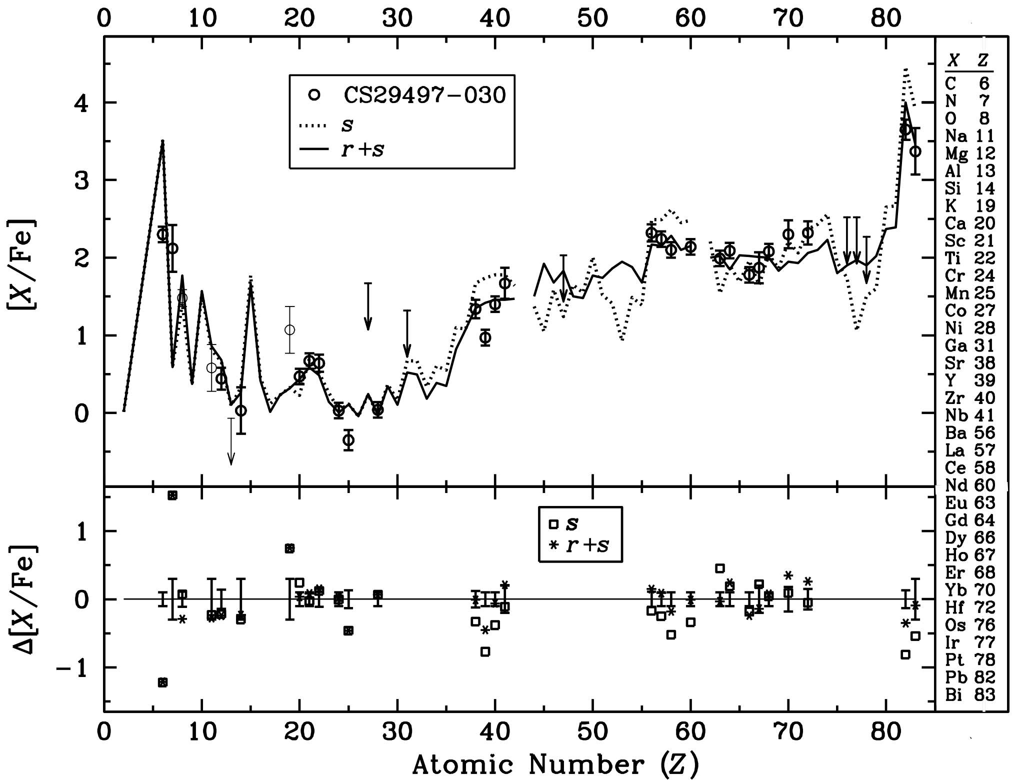

Figure 1. A comparison of the [X/Fe] abundances in CS29497-030 with predictions from s-process calculations with and without pre-enrichment of r-process material. In the top panel, open circles and upper limits denote the stellar abundances. Thinner symbols denote light elements which may suffer from unaccounted-for non-LTE effects. The solid and dotted lines represent best-fit s-process calculations with and without r-process pre-enrichment. The bottom panel displays the difference of the calculated abundances with respect to those observed by Bi-I05 (adapted from Figure 2 of Ivans *et al.* 2005).

Gratton *et al.* (1999) derive a correction of $-0.13 < \Delta < -0.11$ whereas Mashonkina *et al.* (2000) derive $\Delta = -0.43$ for a star of $T_{\rm eff}/\log g = 7000/4.0$ and [Fe/H] = –2. It is clear that the knowledge of the non-LTE behaviour of Na is qualitatively well understood. However, there exists some disagreement in the resulting values of the corrections to be applied to the observations. Extending the non-LTE investigations to lower metallicities and warmer temperatures than have so far been published would be extremely useful in studies of stars such as CS29497-030.

In CS29497-030, the predicted values for C and N are discrepant with respect to the observations. This may be due to CNO processing – the former AGB star companion to CS29497-030 may have undergone extra mixing below the bottom of the convective envelope, bringing elements from this region down to layers where additional CNO processing could occur. This cool bottom processing (CBP) would diminish ^{12}C and produce ^{14}N enhancement with concomitant production of ^{13}C (Wasserburg *et al.* 1995). We refer the reader to Bisterzo *et al.* (these Proceedings) for further discussion.

The r+s calculations apparently overpredict the abundance of Gd and underpredict those of Yb and Hf. Pb is also apparently overpredicted by the r+s model but far less so than in the s-only calculations. Of all 36 elements analysed by Bi-I05, these four – Gd,

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Yb, Hf, and Pb – possess the *largest* uncertainties in their solar system abundances, with differences of $\sim$0.1 – 0.2 dex between the photospheric and meteoritic values (Lodders 2003). Incorporating this additional uncertainty in the *solar* abundance scale is sufficient to push the observed and predicted abundances of *all four* elements into reasonably good agreement.

4. The Source of the r-process Material in CS29497-030

The abundances of CS29497-030 seem to be best explained by pre-enrichment of r-process material out of which the original binary system formed, followed by r+s-process pollution from its former AGB companion as described by Bi-I05. Other r+s stars have been reported and discussed in the literature. A variety of scenarios have been proposed as to how those objects became r+s stars. We do not review the scenarios here but instead refer the reader to the original studies of Aoki *et al.* (2002), Cohen *et al.* (2003), Johnson & Bolte (2004), Zijlstra (2004), Barbuy *et al.* (2005), and references therein, as well as to Goriely (these Proceedings). Here, we look to the observed chemical composition of CS29497-030 to provide us with clues about the supernova supposed to be responsible for the protostellar cloud pre-enrichment.

The [Ti/Si] value derived by Bi-I05 for CS29497-030 is on the order of +0.5, where the average abundance for stars of comparable metallicities is $<$[Ti/Si]$> \simeq -0.1$ ($\sigma \sim 0.4$; based on the 14 abundance studies cited in Figures 9 and 10 of Ivans *et al.* 2003). Taking this abundance at face value, the [Ti/Si] abundance may be a result of pre-enrichment of the protostellar cloud by a low-mass supernova. Relative to massive SNe, low-mass SNe are predicted to produce higher values of [Ti/Si] (Woosley & Weaver 1995; Nomoto *et al.* 1997). Is there additional evidence from the ratios of other elements that the r-process pre-enrichment in CS29497-030 also results from a low-mass SNe?

In investigations of the astrophysical site of low [Eu/Fe] abundances in the context of models of Galactic chemical evolution, Ishimaru & Wanajo (1999), Travaglio *et al.* (1999, 2001), and Ishimaru *et al.* (2004) find that only the less massive SNe in a tiny mass range are responsible for origin of Eu (the heavy r-process material). The Travaglio *et al.* studies adopt the Woosley & Weaver (1995) SNe model yields, where their lowest mass SNe also yield the smallest contribution of Fe, and the Ishimaru *et al.* studies assume that their lowest mass SNe (8–10$M_\odot$) produce no iron. Thus, most, if not all, of the iron abundance in the material out of which the subsequent r-enriched stars form in these models is the result of prior Galactic enrichment.

5. Summary and Concluding Remarks

The abundance distribution pattern of CS29497-030 is fit well by s-process calculations employing an AGB model that incorporates an enhanced ^{13}C pocket and pre-enrichment of r-process material (out of which the original binary system formed). The abundances of Si, Ti, and Eu are in accord with the view that their contributions in the pre-enriched material result from an object near the low-mass limit of core collapse SNe progenitors.

In addition to the elemental abundances in the 1$^{\rm st}$, 2$^{\rm nd}$, and 3$^{\rm rd}$ s-process peaks, abundances of light elements that are very sensitive to primary neutron production (such as Na and Mg) can help constrain the mass of the AGB model. We encourage future studies of s-process abundance patterns to include the abundances of these light elements.

Some elemental abundances, such as Na, however, require non-LTE corrections before the abundances can be used as a check against the calculations. Extending non-LTE

https://doi.org/10.1017/S1743921305006228 Published online by Cambridge University Press

investigations to lower metallicities and warmer temperatures than have so far been published would be extremely useful in studies of stars such as CS29497-030.

Other light elements, such as C and N, do not seem to fit the predicted abundance pattern. This may be the result of CBP. Abundances of C, N, and $^{12}C/^{13}C$ are all critical tracers of CBP, which may play an important role in our understanding of the neutron sources and sinks in astrophysical *s*-process calculations, and should be included in the abundance studies performed on other $r+s$ and/or lead-rich stars.

In addition, the solar photospheric and meteoritic abundances of Gd, Yb, Hf, and Pb are in poor agreement, inducing more uncertainties to studies attempting to reconcile predictions from models and observed abundances. Our stellar spectroscopic abundance "gold standard" – the chemical composition of our solar system – still needs work.

Further details regarding the extended analysis of CS29497-030 will be reported in a paper currently in preparation.

Acknowledgements

It is a pleasure to thank the organizers of this Symposium for making this meeting such an interesting and fruitful one. We also thank the following agencies for providing funding support: NASA through Hubble Fellowship grant HST-HF-01151.01-A from the Space Telescope Science Inst., operated by AURA, under NASA contract NAS5-26555 to III; AAS (US) through an Int. Travel Grant to III; NSF (US) through grants AST03-07495 to CS and AST03-07279 to JJC; and MIUR-FIRB (Italy) "The astrophysical origin of heavy elements beyond Fe" to RG and SB. We acknowledge and appreciate the use of NASA's Astrophysics Data System Bibliographic Services, the SIMBAD database operated by CDS (France) and the achievement of the HIRES CCD upgrade group.

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