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Chemical compositions of neutron-process elements in low-metallicity stars – tracers of r and $r+s$ nucleosynthesis processes

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Abstract. Employing spectra obtained with the near-UV sensitive detector on the Keck I HIRES, comprehensive chemical composition analyses have been performed on the neutron-capture-element-rich star, HD221170 ([Fe/H] = −2.2; Ivans et al 2006), and the binary blue metal-poor star, BPS CS29497-030 (−2.6; Ivans et al. 2005). The heavy element abundances of HD221170 are fit exquisitely well by a scaled-solar *r*-process abundance pattern with no contribution from the *s*-process. In contrast, the abundance pattern of CS29497-030 seems best fit by an AGB model with *s*-processing that also includes very significant amounts of pre-enrichment of *r*-process material in the protostellar cloud out of which the binary system formed.

Key words. nuclear reactions, nucleosynthesis, abundances – Galaxy: evolution – Galaxy: abundances – stars: abundances – stars: Population II – stars: individual (HD221170, BPS CS29497-030)

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*-process) with each responsible for approximately 50 percent of the solar system isotopes (see e.g., Cowan & Thielemann 2004, and references therein). In the *s*-process – the topic of a significant portion of the presentations at this Workshop – successive neutron captures occur over sufficiently long timescales to permit unstable nuclei to β-decay prior to neutron-capture 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; Cristallo et al. 2005).

The likeliest sites for the *r*-process are neutron-rich sites associated with massive star core collapse supernovae (SNeII), although the

Send offprint requests to: I. I. Ivans astrophysical site of the *r*-process has yet to be identified. Possible sites for the *r*-process include: supernovae winds/hot bubbles; disks and jets; neutron star mergers; and/or neutron star formation during accretion-induced collapse.

In the Sun, the abundances are the integrated result of many generations of stars, including millions of SNeII, and depend upon the details of the star formation history, initial mass function, chemical yields, etc. However, the heavy element abundances most useful for unravelling the origins of the *r*- and *s*-process correspond to those observed in stars which formed from material with few generations of prior nucleosynthetic processing, such as the relatively pristine material out of which extremely metal-poor stars were born.

2. Recent Observations of HD221170, an *r*-Process-Rich Star

Among the isotopes formed in the *r*-process are the radioactive group of elements known as the actinides, which include isotopes of Th and U. Due to their known radioactive decay rates, the abundances of Th (and U) in low-metallicity stars have been employed to derive the ages of presumably some of the oldest stars in the Galaxy, thereby setting a minimum for the age of the Universe. Critical assumptions in the analysis of the observations are that the production ratios of the elements are known, and that the elements under investigation arise from the same nucleosynthetic site. Following earlier work on the derivation of Th abundances and/or Th-based ages, Sneden et al. (1996) derived the first Th/Eu-based nucleocosmochronometric age for a very metal-poor star: CS22892-052, whose extreme *r*-process abundance enhancements were discovered by McWilliam et al. (1995). This was followed soon after by other Th/Eu-based age determinations of other metal-poor stars such as HD115444 (Westin et al. 2000) and BD+17 3248 (Cowan et al. 2002). The fundamental assumption built into the technique of applying these abundances to derive ages via nucleocosmochemistry is that the elements are created in the same processes, i.e. the same nucleosynthetic sites, and track the contributions of that process through Galactic chemical evolution, i.e. a production ratio can be specified.

There is no doubt that all of the Th and U is produced in the *r*-process: the termination point of the *s*-process occurs at ^{209}Bi. Isotopes heavier than ^{209}Bi decay too quickly to be built by the *s*-process. Pb and Bi are the last stable elements along the *s*-process path. And, Eu is predominantly an *r*-process element – over 90 % of the solar Eu was produced this way (Anders & Grevesse 1989; Käppeler, Beer & Wisshak 1989; Arlandini et al. 1999; Burris et al. 2000; Simmerer et al. 2004; Travaglio et al. 2004).

Included in the *n*-capture abundance study by Gilroy et al. (1988), HD 221170 has long been recognized as an *r*-process-rich star and has often been utilized as a template metal-poor star observation in other programs, including those of Burris et al. (2000), Fulbright (2000), Mishenina & Kovtyukh (2001), Mishenina et al. (2002), Yushchenko et al. (2002), Simmerer et al. (2004), and Barklem et al. (2005).

New high resolution, high signal-to-noise spectra of HD221170 were gathered with the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I telescope at the W. M. Keck Observatory and with the 2d-coudé échelle spectrograph (Tull et al. 1995) on the 2.7-m H. J. Smith telescope at McDonald Observatory. Details of the observations and analysis are described in Ivans et al. (2006).

The abundance analysis relied on the results of a combination of spectrum syntheses and equivalent width (EW) analyses. Stellar atmospheres without overshooting (Castelli & Kurucz 2004) were employed and the abundance calculations were performed with a current version of the LTE stellar line analysis code, MOOG (Sneden 1973). Employing spectroscopic constraints, final parameter values of $T_{\rm eff}$/log g/ξ_t/[Fe/H] = 4510/1.00/1.8/−2.19 were derived.

Prior to now, the most comprehensive abundance studies of HD221170 have been those of Yushchenko et al. (2002, 2005), and Gopka et al. (2004). However, in contrast to the results of Yushchenko et al. (2005), Ivans et al. find good agreement between the abundances they derived for the heavy elements and the predicted scaled solar r-process values. Many of the abundance differences between the studies appear to arise from differences in the quality of the spectra employed. We refer to Ivans et al. for further discussion regarding this issue.

In Fig. 1 are displayed the abundances derived for HD221170 in Ivans et al. (2006) shown in the context of predictions of the scaled solar r-process abundances by Simmerer et al. (2004) and Arlandini et al. (1999; with most values taken from Table 10 of Simmerer et al).

For some elements, there is a disagreement between the derived solar photospheric and chondritic/meteoritic abundances. For instance, Lodders (2003) notes discrepancies of −0.07, +0.11 and +0.08 dex for Pr (Z = 59), Hf (Z = 72) and Os (Z = 76), respectively. Incorporating additional uncertainties such as these in the *solar* abundance scale is sufficient to push the observed HD221170 and predicted scaled-solar abundances into good agreement.

The resulting n-capture abundance pattern distribution for $Z \geq 56$ is fit well by the predicted scaled solar system r-process abundances, as has been seen in other r-process-rich stars such as CS22892-052, BD+17 3248, and HD 15444. The derived ratios of the heavy elements are in excellent agreement with those previously derived for other r-process-rich metal-poor stars, including the giant stars of globular cluster M15 (Sneden et al. 2000). Also comparable is the inferred age, based upon the Th/Eu chronometer, of 11.7 ± 2.8 Gyr (which includes the estimated uncertainty arising from both the measured abundances and the predicted Th/Eu production ratio) and in accord with the cosmic age derived from the measurements made by the WMAP experiment, both those combined with results from the Sloan Digital Sky Survey ($14.1^{+1.0}_{-1.9}$ Gyr; Tegmark et al. 2004), as well as those combined with earlier cosmic microwave background (CMB) and large-scale structure data (13.7 ± 0.2 Gyr; Spergel et al. 2003). Thus, the heavy element abundances in HD221170 appear to be a good match to the scaled-solar r-process predictions, and the abundance ratio of Th/Eu is indeed usable as a chronometer in this star.

3. Recent Observations of CS29497-030, an r+s Star

In the last five years, dozens of low-metallicity stars with [Pb/Fe] > 1 have been discovered (e.g. Lucatello, 2003; Sivarani et al. 2004; Barbuy et al. 2005; and references therein). Such large values of heavy s-process enhancements in low metallicity stars are typically the result of mass transfer in binary star systems where the initially more massive star underwent an 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 would be 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.

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; and references therein). Thus, abundance determinations of this element will also benefit nuclear chronometer studies of the age of the Galaxy. Accordingly, observations were made by Ivans et al. (2005) of the blue metal-poor star (BMP; Preston et al. 1994) CS29497-030, the star possessing the largest [Pb/Fe] abundance of any metal-poor star published to date (Sneden et al. 2003; Van Eck et al. 2003, Sivarani et al. 2004; and references therein), in order to derive its abundance of Bi and other neutron-capture elements.

Details of the observations, reductions, and analyses are described in Ivans et al. (2005). The origin of the neutron-capture elements in CS29497-030 was explored by comparing the observed abundances with predicted r- and s-process contributions. In Fig. 2, the observed abundances are displayed in the context of

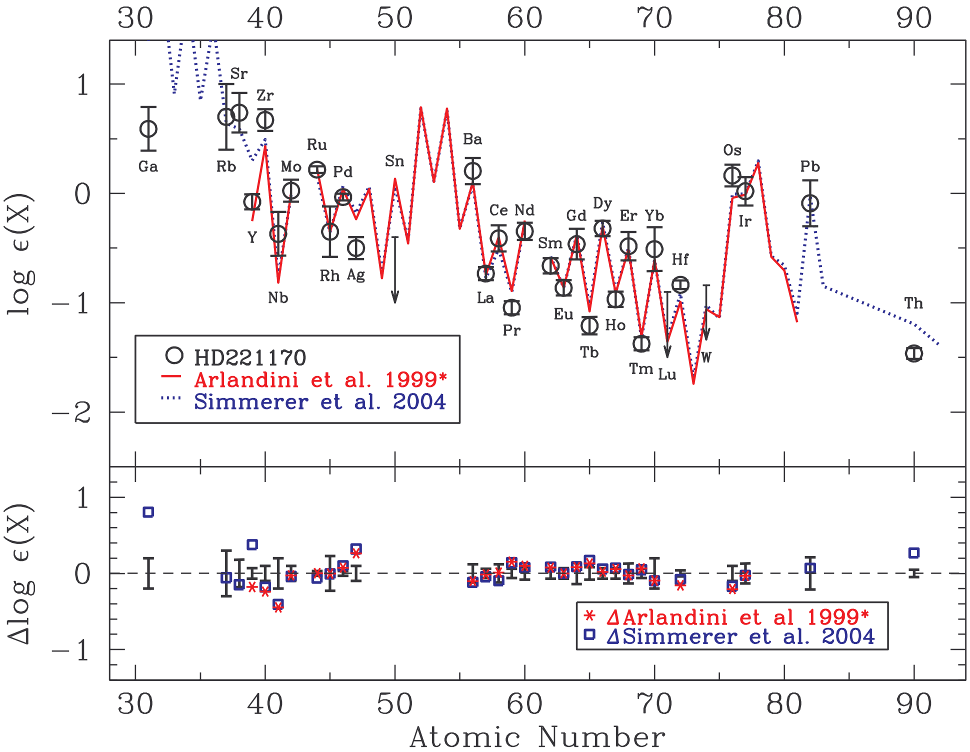

Fig. 1. Comparison of the log ϵ(X) abundances for $Z > 30$ in HD221170 with the scaled-solar r-process predictions from Simmerer et al. (2004; dashed blue line) and those based on Arlandini* et al. (largely 1999; solid red line). Both sets of predictions have been normalized to the value derived for log ϵ(Eu) in HD221170. In the top panel, the upper limits and open circles with error bars denote the stellar abundances. The bottom panel displays the difference defined as $\Delta \log \epsilon(\mathrm{X}) \equiv \log \epsilon(\mathrm{X})_{\mathrm{pred}} - \log \epsilon(\mathrm{X})_{\mathrm{obs}}$ where the error bars are those adopted for the abundances derived for each element by Ivans et al. (2005). Upper limits are not displayed in the bottom panel.

recent s-process FRANEC calculations (see Bisterzo et al., These Proceedings). Predictions from two sets of initial abundance assumptions are shown, with and without pre-enrichment of the initial abundances.

The pre-enrichment treatment employed in the s-process calculations permits an exploration of the scenario that the initial abundances of CS29497-030 and its binary companion arose from a parent cloud pre-enriched with an extreme r-process abundance. In our picture, the formation of this pair of low mass stars was triggered by a SNe which polluted, snowplowed, and clumped a nearby molecular cloud. In the associated s-process calculation, all of the initial r-process isotopes have been enhanced (according to their r-process contribution to the solar system abundances and normalized to Eu – in accord with the findings of r-process-rich stars such as HD221170) 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 [Fe/H] ~ –2.6 for an AGB star of $1.3M_{\odot}$ with an enhanced ^{13}C "pocket" abundance (Case ST×2; see Bisterzo et al., These Proceedings), in which all heavy-element abundance predictions are from the s-process. Also illustrated in Fig. 2 are s-process calculations based on the r-process pre-enrichment scenario.

The main component of the s-process is produced in an AGB star undergoing a series

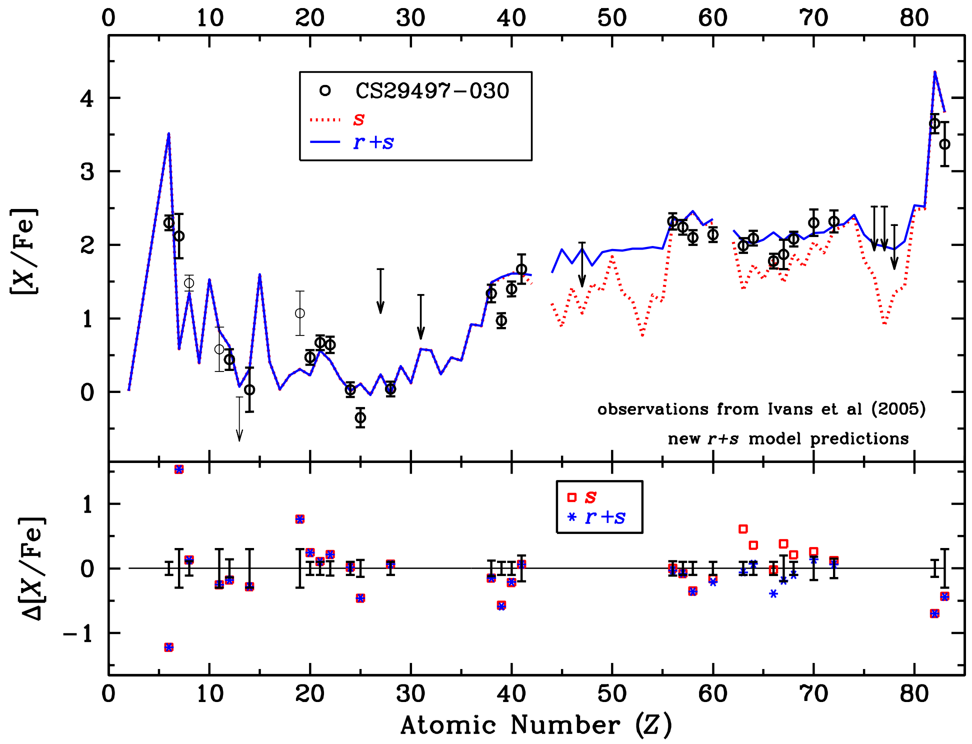

Fig. 2. Comparison of the [X/Fe] abundances in CS29497-030 with predictions from *s*-process calculations of a $1.3 M_{\odot}$ AGB star model. In the top panel, the upper limits and open circles with error bars denote the stellar abundances. Thinned symbols denote four light element abundances which may suffer from uncorrected NLTE systematics (O, Na, Al, and K; see Ivans et al. 2005). The solid blue line represents the best fit *s*-process calculations based on an extreme *r*-process abundance pre-enrichment ($r+s$); the red dotted line represents predictions from *s*-process calculations without *r*-process enrichment. The bottom panel displays the difference defined as Δ[X/Fe] $\equiv$ $[\mathrm{X/Fe}]_{\mathrm{obs}} - [\mathrm{X/Fe}]_{\mathrm{calc}}$ and upper limits are not shown.

of He shell flashes via the triple-α reaction just below the H-burning shell. 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. More massive AGB models produce higher [Na/Fe] abundances.

Among the light neutron-capture elements, where no *r*-process enrichment was assumed, 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; 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 or a a low luminosity red giant phase, but 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. The [Nb/Zr] ratio and stellar parameters for CS29497-030 are both in accord with those of an extrinsic AGB.

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;

Bisterzo et al., These Proceedings; and references therein). Numerous scenarios have been proposed for their origins. However, the scenario described by Ivans et al. (2005) not only produces a good fit to the abundances observed in CS29497-030 but also possesses predictive power. We refer the reader to Bisterzo et al. (These Proceedings) for numerous examples of the application of these calculations to the abundances of other *r*+*s* stars.

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