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HST/STIS abundances of the third-peak r-elements in the uranium star CS 31082-001

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The production site(s) of the r-process(es) remain(s) uncertain. The abundance patterns in r-process-enhanced extremely metal-poor stars are our best observational clues to the origin of the heaviest neutron-capture elements. If both U and Th are measurable, their age can also be determined by nucleo-chronology.

The extreme "r-process star" (r-II) CS 31082-001 ([Fe/H] ~ -2.9) is the most favourable case known for such analysis. The star is relatively bright, exhibits an extreme enhancement of neutron-capture elements, including U and Th, and shows no C or N enhancement. The insignificant blending by molecular lines therefore allows a more reliable abundance determination of these rare elements.

Most lines of the third-peak neutron-capture elements occur in the near-ultraviolet region, including the only available lines of such stable elements as Pt, Au, Bi, which are crucial for understanding the synthesis of the heaviest elements. To access their observable spectral features we have therefore observed CS 31082-001 with HST/STIS.

The resulting, more complete abundance pattern for the r-process elements provides an improved constraint on the nature of the r-process and the initial U/Th production ratio, which is required to deduce the star's age. From its extreme metal deficiency, CS 31082-001 should be one of the oldest stars in the Galaxy and hence a good indicator of the age of the Universe itself.

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1. Introduction

The production sites of the r-elements are still not known (e.g. Kratz et al. 2007; Thielemann et al. 2010). Models involve neutrino winds in which free seed nuclei are bombarded by a neutrino-driven wind of neutron-rich matter near the neutrino sphere of a core-collapse supernova (e.g. Wanajo et al. 2002), neutron star mergers (e.g. Freiburghaus et al. 1999), and neutron star formation during accretion-induced collapse (Wheeler et al. 1998).

Abundance patterns of the r-process elements in very metal-poor stars are our best observational guide to the true origin of these elements. The two very metal-poor stars with a strong enhancement of the r-process elements (including the actinides Th and U) that were first revealed were CS 22892-052 and CS 31082-001, found in the HK survey of Beers et al. (1992; Beers 1999). A third star, HE 1523-0901 was later identified in the Hamburg/ESO survey (Frebel et al. 2006, 2007).

In the Beers & Christlieb (2005) classification of metal-poor stars, r-element enriched stars that also show low Ba (s-element) abundances are designated as r-II, characterized by [Eu/Fe]>+1.0 and [Ba/Eu]<0. Thus far, 12 r-II stars are known (Hayek et al. 2009), among which 6 have well-determined Th abundances and two have U abundances as well: CS 31082-001 (Hill et al. 2002), HE 1523-0901 (Frebel et al. 2007).

CS 22892-052 (V=13.2, $T_{\rm eff}$=4760 K, log(g)=1.3, [Fe/H]= -3.1) was the first r-II star to be studied extensively from the ground (e.g., McWilliam et al. 1995; Sneden et al. 1996; Sneden et al. 2000, 2003; Cowan et al. 2005). The heavy neutron-capture elements only accessible from space were studied with HST/STIS by Cowan et al. (2005), who also analysed another 9 r-element-rich stars from UV spectra.

The second r-II star, CS 31082-001 (V=11.7, $T_{\rm eff}$=4825 K, log(g)=1.5, [Fe/H]=-2.9), has two important advantages over CS 22892-052: It is 1.5 magnitudes brighter and has much weaker CH and CN molecular bands, hence much less blending of the atomic lines by molecular lines. This, and a large U abundance, made it possible to reliably measure the UII line at 3859.6 Å (Cayrel et al. 2001; Hill et al. 2002). The third r-II star, HE 1523-0901 (Frebel et al. 2007), has the same favourable characteristics as CS 31082-001, while the more metal-rich BD+17°3248 (Cowan et al. 2002) only yields an upper limit for [U/Fe].

An important issue is the abundance of the actinides with respect to the other r-process elements. CS 31082-001 exhibits enhanced Th (and U) relative to the Solar r-process abundance pattern – the so-called actinide boost – as do three other very metal-poor r-II stars ([Fe/H]< -2.9): CS 30306-132 (Honda et al. 2004), CS 31078-018 (Lai et al. 2008) and HE 1219-0312 (Hayek et al. 2009). The relative abundances of all other r-elements in these stars, from the rare earths to the third r-process peak, are identical to those in all other known r-process enhanced stars (Roederer et al. 2009), so in these four stars a different nucleosynthesis process appears to have affected only the radioactive elements beyond the third r-process peak.

Many of the key neutron-capture elements in these stars are observable from the ground, such as Eu, Gd, Dy, Th, and more recently many others were measured, such as U, Os, Ir, Pb (Cayrel et al. 2001; Hill et al. 2002; Plez et al. 2004). However, HST/STIS observations are crucial to obtain abundances of those neutron-capture elements that have no or only extremely weak lines in the visible domain. These elements include Bi, Pt, and Au – the heaviest r-process elements, which populate the so-called third r-process peak. We present here a preliminary abundance determination of the third r-process elements Os, Ir, Pt, Au, Bi, as well as Pb.

Our observing Program ID 9359 (PI: R. Cayrel), aiming to observe CS 31082-001 with HST/STIS, was approved in 2002. Achieving S/N $\sim$ 40 required 45 orbits with STIS in spectroscopic mode E230M and the NUV-MAMA detector, operating in the wavelength range 1575-3100 Å at a resolution of R=30,000. Reductions were carried out by F. Primas with the STIS pipeline, which includes the most up-to-date scattered light correction routines. The spectra have S/N$\sim$40 in the range 2600 – 3070 Å, comprising orders 2 to 13.

2. Heavy element abundance derivation in CS 31082-001 from STIS spectra

Element abundances in CS 31082-001 were determined with the spectrum synthesis code Turbospectrum (Alvarez & Plez 1998) and are presented in Table 1.

Table 1: r-process and s-process fractions of the observed elements, solar r-fraction abundances (Simmerer et al. 2004), abundances from previous work (Hill et al. 2002; Plez et al. 2004) using VLT-UVES observations, and present results correspond to abundances derived from HST/STIS observations.

Element	Z	r-fraction	s-fraction	log $\varepsilon(X)_{\odot}^{r-fraction}$	log $\varepsilon(X)_{previous}$	log $\varepsilon(X)_{present}$	log [X/Fe]
Os	76	0.916	0.084	1.353	+0.43	+0.43	+1.30
Ir	77	0.988	0.012	1.353	+0.20	+0.20	+1.75
Pt	78	0.949	0.051	1.654	− − −	+0.65	+1.93
Au	79	0.944	0.056	0.785	− − −	−0.40	+1.58
Pb	82	0.214	0.786	1.334	−0.55	−0.65	+0.50
Bi	83	0.647	0.353	0.508	− − −	−0.50	+1.55
Th	90	1.000	0.000	0.163	−0.98	− − −	+1.86
U	92	1.000	0.000	−0.033	−1.92	− − −	+1.52

Improved abundances of the elements of the third peak could yield precious information about the elusive conditions that built this peak, better knowledge of the r-process as a whole, and therefore a better determination of the production ratio of U/Th. In particular, in CS 31082-001 it remains to be understood the Pb deficiency, the U and Th boost, and to check these with respect to the newly obtained abundances. This work is in progress. When final abundances are reached, we will be able to compare the age of the star as derived with different production ratios from the literature. Three types of chronometers involving U and Th can be used: Th/r-element, U/r-element and U/Th. The main uncertainty is due to the theoretical production ratios. Among calculations available (Goriely & Arnould 2001; Kratz et al. 2007; Schatz et al. 2002; Wanajo et al. 2002, 2007), none of them permits derivation of consistent ages using all available ratios U/Th, U/Os, U/Ir, U/Pt, U/Au, U/Bi. U/Th gives 13.95 Gyr adopting Goriely & Arnould (2001), whereas U/Bi gives 13.8 Gyr adopting Wanajo (2007). Consistent production ratio values for all the elemental ratios are still missing.

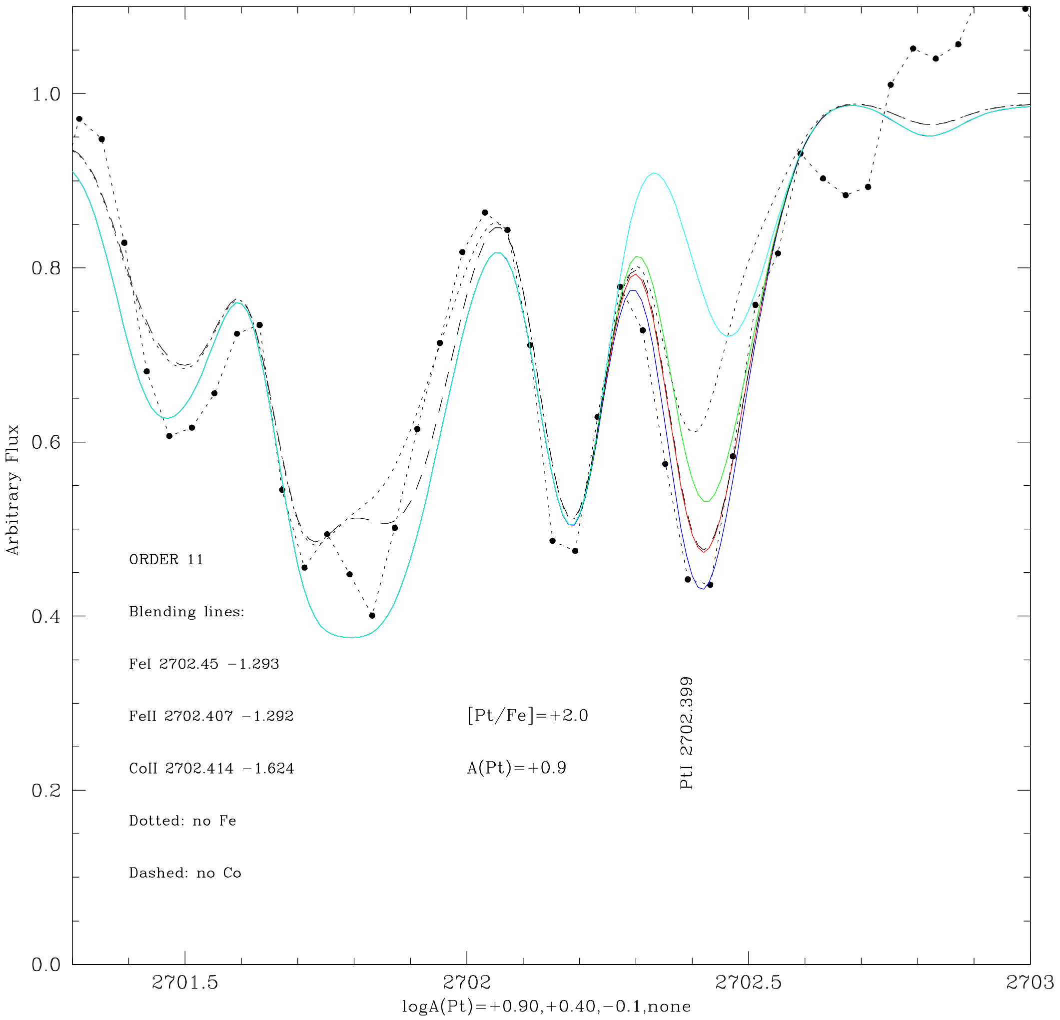

Figure 1: The Platinum line at 2702.399 Å is only weakly blended, hence a good Pt indicator.

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