The r-Process and Chronometers

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1 Introduction

We have been examining the abundance distributions in metal-poor Galactic halo stars trying to identify, and understand, the signatures of the slow- and rapid-neutron capture processes (*i.e.*, the *s*- and the *r*-process). Detailed studies have been made of the stars CS 22892–052 [1, 2] and HD 115444 [3]. In our latest work we have added to this list the metal-poor ([Fe/H] = −2.0) halo star BD +17°3248 [4].

2 Observations and Abundance Trends in BD +17°3248

Using both ground-based (Keck and McDonald) and space-based (Hubble Space Telescope, HST) observations we have obtained high resolution, high signal-to-noise spectra of BD +17°3248. The element gold has been detected in BD +17°3248 as shown in Figure 1. This HST STIS observation shows a comparison between BD +17°3248 and HD 122563. While the spectra appear somewhat similar in this region, this is due to the complex set of absorption lines that contribute to the total feature near this wavelength. Specifically, there is an OH line near the 2675.94 Å gold line. This results in some blending of the gold feature for BD +17°3248. The OH absorption, however, is much stronger throughout the UV spectrum of HD 122563 and is solely repsonsible for the strong line at 2676.0 Å in this star. We note that the this gold detection in BD +17°3248 is the first in any metal-poor halo stars.

We show in Figure 2 the entire abundance distribution of BD +17°3248. This includes the element uranium. We have detected a weak line at 3859.60 Å in the spectrum of BD +17°3248 that we tentatively identify with this element. This would be only the second such detection, after Cayrel *et al.*[5], in any metal-poor halo stars.

We note in Figure 2 that the heavier neutron-capture elements, Z$\geq$ 56, including now the 3$^{\rm rd}$ *r*-process peak elements, all fall on the scaled solar system *r*-process distribution. This is the same pattern that was seen previously in CS 22892–052 and HD 115444 [6]. This strongly suggests a robust process for the production of these heavier neutron-capture elements. Very recently the europium isotopic abundance fractions have been determined for BD +17°3248, CS 22892–052 and HD 115444 [7]. Those fractions are all in excellent agreement with each other and with their values in the solar system. Thus, there appears to be a consistency in the production of the heavier neutron-capture elements and, at least for europium, the isotopes.

We also note the trend of the lighter neutron capture elements in Figure 2. Similarly to the case of CS 22892–052, the elements with Z = 40–50 in BD +17°3248 fall below the scaled solar system curve that fits the heavier neutron-capture elements. This might be explained by a single r-process site with two regimes or sets of conditions, or perhaps two different sites for the lighter and heavier neutron-capture elements (see [4]).

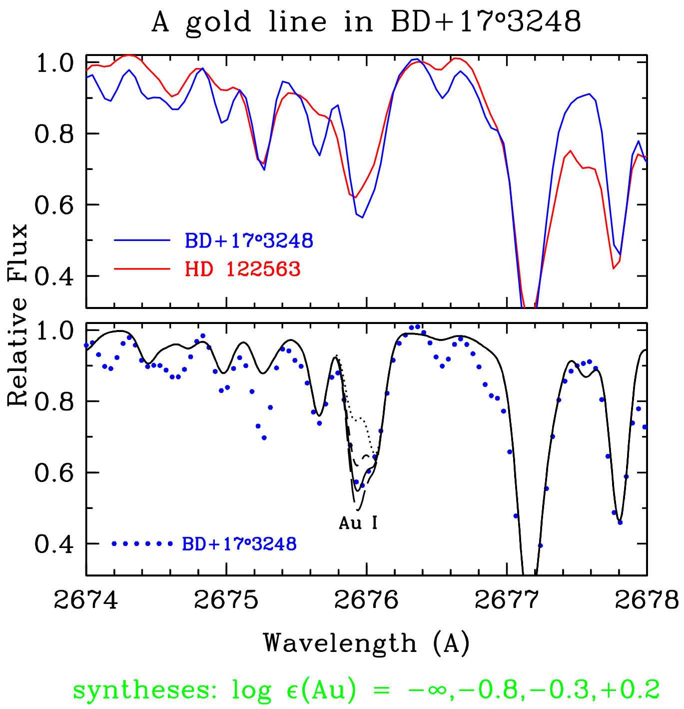

Figure 1: Observed HST-STIS and synthetic spectra in region surrounding the Au I 2675.94 Å line. In the top panel, the observed BD +17°3248 spectrum is compared to that of HD 122563. In the bottom panel, the observed BD +17°3248 spectrum is compared to four synthetic spectra, shown in order of increasing abundance by dotted, short dashed, solid, and long dashed lines computed for log ϵ(Au) $= -\infty$, -0.8, -0.3, $+0.2$.

3 r-Process Chronometers

The long-lived radioactive nuclei, such as ^{232}Th and ^{238}U, can be used as chronometers (or clocks) to determine the ages of stars. Thus, the detection of thorium in a number of halo stars has led to stellar radioactive age estimates. To minimize observational errors the ratio of the radioactive element thorium (formed entirely in the r-process) is normally compared to the stable (r-process) element europium. The detection of 3$^{\rm rd}$ r-process peak elements such as Pt provides additional chronometric pairs, with the advantage that these elements are closer in atomic mass (than Eu) to Th. Furthermore, new stellar detections of U can provide a second chronometer and help constrain age determinations. Employing the newly detected

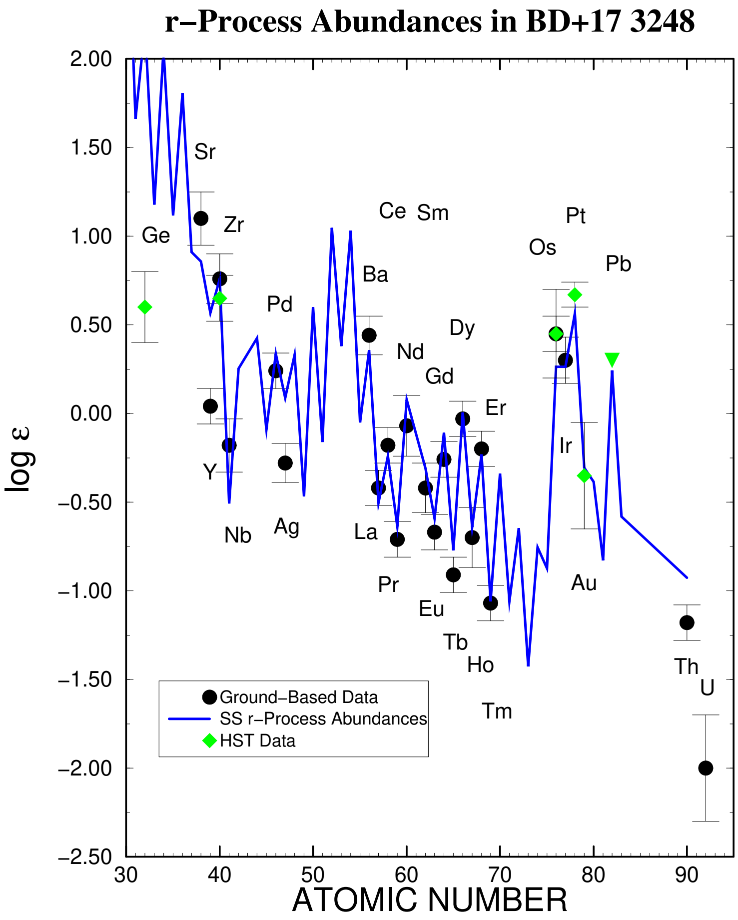

Figure 2: Neutron-capture element abundances in BD +17°3248, obtained by ground-based and HST observations, compared to a scaled solar system r-process abundance curve. The upper limit on the lead abundance is denoted by an inverted triangle. Note also the thorium and uranium detections.

Th, U and 3rd r-process peak element abundances Cowan *et al.*[4] made chronometric age estimates for BD +17°3248. The average value of the various chronometric pairs suggests an age of 13.8 ± 4 Gyr for this star. This age estimate is consistent, within error limits, with other chronometric age determinations for metal-poor Galactic halo stars.

The still relatively large uncertainties reflect the sensitivity of the age estimates to both the observed and predicted (initial) abundance ratios. Additional stellar observations will help to reduce observational uncertainties. Even in cases where only upper limits on uranium may be avaialable (perhaps the norm for most stars), the upper limits to the U/Th ratio can already provide lower limits on the age estimates for the most metal-poor stars and hence constrain age determinations for the Galaxy [8]. Additional theoretical studies, see [8, 9], will also help to reduce the errors in the theoretical predictions for the initial abundances of the radioactive elements produced in the r-process. Despite any current uncertainties, this radioactive dating technique offers promise. It is independent of chemical evolution or cosmological models. It offers an alternative means of placing lower lmits on the ages of the Galaxy and the Universe.

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