Detection of Lead in the Carbon-Rich, Very Metal-Poor Star LP 625-44: A Strong Constraint on $s$-Process Nucleosynthesis at Low Metallicity

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ABSTRACT

We report the detection of the Pb I 4057.8Å line in the very metal-poor ([Fe/H]$=−2.7$), carbon-rich star, LP 625-44. We determine the abundance of Pb ([Pb/Fe] = 2.65) and 15 other neutron-capture elements. The abundance pattern between Ba and Pb agrees well with a scaled solar system $s$-process component, while the lighter elements (Sr-Zr) are less abundant than Ba. The enhancement of $s$-process elements is interpreted as a result of mass transfer in a binary system from a previous AGB companion, an interpretation strongly supported by radial velocity variations of this system.

The detection of Pb makes it possible, for the first time, to compare model predictions of $s$-process nucleosynthesis in AGB stars with observations of elements between Sr and Pb. The Pb abundance is significantly lower than the prediction of recent models (e.g., Gallino et al. 1998), which succeeded in explaining the metallicity dependence of the abundance ratios of light $s$-elements (Sr-Zr) to heavy ones (Ba-Dy) found in previously observed $s$-process-enhanced stars. This suggests that one should either (a) reconsider the underlying assumptions concerning the $^{13}$C-rich $s$-processing site ($^{13}$C-pocket) in the present models, or (b) investigate alternative sites of $s$-process nucleosynthesis in very metal-poor AGB stars.

Subject headings: nuclear reactions, nucleosynthesis – stars: abundances – stars: AGB and post-AGB – stars: carbon – stars: Population II

1. Introduction

The slow neutron-capture process ($s$-process) is considered one of the major pathways for the creation of nuclei heavier than iron, and the asymptotic giant-branch (AGB) phase of low-
and intermediate-mass stars has been studied as its most likely astrophysical site. One important component in understanding s-process nucleosynthesis is the correct identification of the neutron sources involved. Two reactions – \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\) and \(^{13}\text{C}(\alpha, n)^{16}\text{O}\) – have received most attention. Recent models of AGB stars prefer \(^{13}\text{C}\) as the main source, because the temperature of the He burning shell hardly reaches \(3 \times 10^8\) K required for the \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\) reaction (e.g., Gallino et al. 1998). This is supported by the observed metallicity dependence of the abundance ratios of heavier s-process elements (e.g., Ba, Nd) to lighter ones (e.g., Sr, Zr) found in s-process-enhanced objects such as MS- and S-type stars (Smith & Lambert 1990), barium stars (Luck & Bond 1991) and CH stars (Vanture 1992; Norris et al. 1997a). While the seed nuclei for the s-process, such as iron, are secondary (i.e., their abundances are proportional to metallicity), the production of \(^{13}\text{C}\) in AGB stars is primary, contrary to that of \(^{22}\text{Ne}\). Therefore, higher neutron exposure, and thus larger enhancement of the heavier elements, is expected from \(^{13}\text{C}\) in stars of lower metallicity. Models of nucleosynthesis in AGB stars by Gallino et al. (1998), followed by Busso et al. (1999), successfully reproduced the observed trend for lighter elements (Sr-Zr), as well as for heavier ones (Ba-Gd).

For stars of very low metallicity, according to these models, a large excess of lead (Pb) is expected. For instance, the enhancement of Pb by two or three orders of magnitude relative to that expected for solar-abundance stars is predicted for AGB stars with \([\text{Fe}/\text{H}] = -2.0\) \(^5\), while that of Ba is at most one order of magnitude (Busso et al. 1999). Thus Pb in metal-poor, s-process-enhanced, stars should provide an excellent diagnostic for models of s-process nucleosynthesis in AGB stars.

However, the abundance of Pb is difficult to measure in most stars.

Lead abundances for the metal-poor stars HD 115444 and HD 126238 were derived from Hubble Space Telescope ultraviolet spectra (Sneden et al. 1998), but Pb has not yet been detected in the optical spectra of these objects. The Sneden et al. (2000) analysis of a high-S/N Keck HIRES spectrum of the r-process-rich star CS 22892-052 detected Pb I lines in the visual spectrum of this star, and derived its abundance. We note that the Pb observed in all three of these stars is attributed primarily to the r-, rather than the s-process, due to the strong enhancements of other r-process-dominated nuclei, such as Eu. One study of the s-process for a solar metallicity star by Gonzalez et al. (1998) reports the Pb abundance of the post-AGB star FG-Sge, based on an analysis of the Pb I 7229Å line.

In this Letter we report the detection of Pb I 4057.8Å and derive a Pb abundance in the carbon-rich, very metal-poor star LP 625-44. This object was shown by Norris et al. (1997a) to exhibit very large excesses of carbon, nitrogen, and neutron-capture elements. Their interpretation was that the large excesses of heavy elements were likely to have originated from s-process nucleosynthesis in an AGB binary companion which provided LP 625-44 with carbon-rich material by mass transfer.

\(^5\)[A/B] = \log(N_A/N_B) - \log(N_A/N_B)_\odot, and \(\log \epsilon_A = \log(N_A/N_H) + 12\) for elements A and B.
The updated abundance pattern (see §3), and variation of radial velocity (see §2), reported in the present work make this interpretation quite convincing. The determination of a Pb abundance for this star (§3) provides the opportunity, for the first time, to test models of nucleosynthesis in AGB stars for s-process elements between Sr and Pb (§4).

2. Observations and Measurements

A high-resolution spectrum of LP 625-44 was obtained with the University College London coudé échelle spectrograph (UCLES) and Tektronix 1024×1024 CCD at the Anglo-Australian Telescope on August 5, 1996. The wavelength range 3700–4720 Å was covered with resolving power $R \sim 40,000$. We also obtained a red spectrum (5015–8500 Å) with the same instrument on June 16, 1994. The numbers of detected photons are 12000 per 0.04 Å pixel at 4300 Å ($S/N \sim 150$ per resolution element) and 2000 per 0.06 Å pixel at 6000 Å ($S/N \sim 60$ per resolution element).

Data reduction was performed in the standard way within the IRAF$^6$ environment. Equivalent widths were measured by fitting Gaussian profiles to the absorption lines, and will be reported in Aoki et al. (2000). The error for lines weaker than 60 mÅ, determined from the comparison of two measurements of lines which appear on adjacent échelle orders, was about 4 mÅ and 6 mÅ in the blue and red spectra, respectively. There is no systematic difference between the equivalent widths of Fe I lines measured in this work and those by Norris et al. (1996), even though our $S/N$ is substantially higher.

Additional spectra were obtained on 1998 August 11 and 2000 January 26, the former using UCLES, and the latter with the Utrecht échelle spectrograph (UES) on the William Herschel Telescope (WHT). Both have lower $S/N$ than is necessary for an abundance analysis, the sole aim being to measure radial velocities. In each case, HD 140283 was also observed to provide a template for cross-correlation. That star has a similar metallicity but is free of the CH blends that affect many lines in LP 625-44. Radial velocities for LP 625-44 were obtained relative to HD 140283 by cross-correlation, and by measuring the radial velocity of HD 140283 from the central wavelengths of 175 (1998) and 122 (2000) unblended lines. Error estimates were based on the variation in velocity from different échelle orders and from the standard error in the measurement of HD 140283. The heliocentric values, which extend those presented by Norris et al. (1997a), are: HJD 2451037.00: $v_{\text{rad}} = 33.5 \pm 0.2 (1\sigma)$ km s$^{-1}$; and HJD 2451569.80: $v_{\text{rad}} = 30.0 \pm 0.3 (1\sigma)$ km s$^{-1}$. Ryan et al. (1999) estimated external errors of 0.3 km s$^{-1}$ for a similar procedure; this has been added to the internal errors for Fig. 1. The data confirm that LP 625-44 is a binary with a period of at least 12 years.

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3. Abundance Analysis and Results

In the region near the Pb I line at 4058 Å, line-blending is so severe that the Pb abundance was derived by spectrum synthesis. This method was also applied to lines which are affected by blending and/or hyperfine splitting. The standard analysis, based on the equivalent widths, was applied to single (unblended) lines.

The abundance analysis used model atmospheres in the ATLAS9 grid of Kurucz (1993a). We adopted an effective temperature $T_{\text{eff}} = 5500$K, determined by Norris et al. (1997a) from the $R-I$ color. This color is not severely affected by strong carbon and nitrogen features in stars of this temperature and abundance (Aoki et al. 2000). Surface gravity ($\log g$), metallicity, and microturbulent velocity ($\xi$), were re-determined in the present work. The surface gravity was obtained from the ionization balance between Fe I and Fe II, the metallicity was estimated from the abundance analysis of those lines, and $\xi$ was determined from the Fe I lines by demanding no dependence of the derived abundance on equivalent widths. The results are: $\log g = 2.8$, $\xi = 1.6$ km s$^{-1}$, and $[\text{Fe/H}] = -2.72$. The agreement with the results of Norris et al. (1997a) is good, with the exception of the microturbulent velocity, for which they derived 1.0 km s$^{-1}$.

Pb lines are difficult to measure in optical stellar spectra. Even for the sun, only four Pb I lines (3639 Å, 3683 Å, 3739 Å, and 4057 Å) have been studied in the visual region. From these, Youssef & Khalil (1989) determined the abundance $\log \epsilon_{\text{Pb}} = 2.0$, which agrees fairly well with meteoritic measurements ($\log \epsilon_{\text{Pb}} = 2.06$; Grevesse et al. 1996).

Our spectra covered the lines at 3739.9 Å and 4057.8 Å, listed in Table 1. They are expected to be weak, and no clear absorption appears in the solar spectrum. However, Pb I 4057.8 Å was clearly detected in LP 625-44, as shown in the upper panel of Fig. 2, where the synthetic spectra fitted to the observed data are also shown. In spite of the presence of other lines, the contribution of Pb I is remarkable. To check possible contamination of the Pb region by other elements, we examined the spectrum of HD 140283, a very metal-poor subgiant ($T_{\text{eff}} = 5750$ K, $\log g = 3.4$ and $[\text{Fe/H}] = -2.54$, Ryan et al. 1996). We found no distinct absorption feature at 4057.8 Å (see Fig. 1b in Norris et al. 1996). As a further check for contamination due to CH and CN, the observed and synthetic spectra of CS 22957-027 are shown in the lower panel of Fig. 2. Norris et al. (1997b) showed that this very metal-poor giant ($T_{\text{eff}} = 4850$K, $\log g = 1.9$ and $[\text{Fe/H}] = -3.38$) has very large excesses of $^{12}$C, $^{13}$C and N but no excess of heavy elements. This spectrum indicates that the absorption feature at 4057.8 Å in LP 625-44 is not due to CH and CN lines.

To check our procedure for the determination of the Pb abundance, we also analyzed the solar spectrum (Kurucz 1993b) using a solar photospheric model (Holweger & Müller 1974). Our result agrees very well with that of Youssef & Khalil (1989) for Pb I 3683Å, which is the clearest Pb I line in the optical range. This demonstrates the reliability of the basic data (e.g., partition functions) and the software used in our analysis. (Line contamination is so severe at 4057.8 Å in the solar spectrum that the exact abundance cannot be derived from this line.)
An abundance ratio $[\text{Pb}/\text{Fe}] = 2.65$ was derived for LP 625-44 from a comparison between the synthetic spectra and the observed one. The other Pb I line covered by our spectrum is at $3739.9\,\text{Å}$, but there is no distinct feature at this wavelength. Hence, we derive an upper limit on the abundance ratio $[\text{Pb}/\text{Fe}] < +3.2$ from this non-detection, which supports the Pb I $4057.8\,\text{Å}$ result ($[\text{Pb}/\text{Fe}] = 2.65$). This upper limit is important, as in the next section we show that this Pb abundance is lower than predicted by some models of s-process nucleosynthesis in very metal-poor AGB stars.

Our derived abundances for the heavy elements are similar to the results presented by Norris et al. (1997a). Abundances of Er, Tm and Hf, not previously known in this star, could also be determined due to the better quality of the new spectra. All new results are given in Table 2. The line data used in the analysis will be compiled in Aoki et al. (2000).

Errors in our estimated abundances were obtained as follows. Errors arising from uncertainties in the atmospheric parameters were evaluated by adding in quadrature the individual errors on the parameters $-\Delta T_{\text{eff}} = 100\,\text{K}, \Delta \log g = 0.3$, and $\Delta \xi = 0.5\,\text{km}\,\text{s}^{-1}$. The internal errors were estimated by assuming the random error in the equivalent width measurements to be $4\,\text{mA}$ (and $6\,\text{mA}$ for Ba II in the red region; see §2), and taking the random error in less-certain $gf$ values to be 0.1 dex.

4. Discussion and Concluding Remarks

Fig. 3 presents derived abundances as a function of atomic species for LP 625-44. The thick solid line indicates the abundance pattern of the main s-process component determined by Arlandini et al. (1999), while the thin line indicates the r-process component. The dotted line is the total solar abundance adopted by Arlandini et al. (1999). We see good agreement between the observed abundances of elements heavier than Ba with the scaled s-process component. This fact, found by Norris et al. (1997a) for Ba to Dy, is now extended to heavier elements and made even more compelling. The excesses of these elements, and their s-process nature, are interpreted as a result of the transfer of material rich in s-process elements across a binary system including an AGB star. Our new radial velocity measurements confirm the binarity and strengthen this interpretation. Since the excess of heavy elements is very large (e.g., $[\text{Ba}/\text{Fe}] = 2.7$), the material from the AGB star should dominate the surface abundances of LP 625-44. Thus, the relative abundances of the heavy elements in this star should provide an almost pure representation of the nucleosynthesis products of the previously existing very metal-poor ([Fe/H] = $-2.7$) AGB companion.

With the adoption of this interpretation the abundances in LP 625-44 can be compared with theoretical predictions of nucleosynthesis in AGB stars. Gallino et al. (1998) and Busso et al. (1999) showed that, at low abundance, the metallicity effect on s-process yields favors the production of heavier elements. As found in Fig. 3, the Sr-Zr enhancement relative to the solar s-component is much smaller than that of heavy elements (Ba-Hf) in LP 625-44, a result in qualitative agreement with the expected metallicity dependence.
The metallicity effect is essentially due to the level of neutron exposure, which is expected to be higher at lower metallicity (see §1). Higher neutron exposure necessarily requires larger production of the heaviest s-process element, Pb, in very metal-poor stars. Busso et al. (1999) explicitly showed the metallicity effect on the enhancement factors of s-process elements relative to solar abundances for $-3.2 < \frac{[\text{Fe}/\text{H}]}{} < 0.4$ in their Figure 12, where the enhancement factor of Pb is larger by about two orders of magnitude than that of Ba at $[\text{Fe}/\text{H}] = -2.7$. However, the enhancement of Pb in LP 625-44 ($[\text{Pb}/\text{Fe}] = 2.65$) is nearly the same as that of Ba ($[\text{Ba}/\text{Fe}] = 2.74$). If the observed Pb abundance of LP 625-44 generally represents the yields from very metal-poor AGB stars, their models of nucleosynthesis in AGB stars may overestimate its production by about two orders of magnitude at very low metallicity.

This conflict might be resolved by tuning the models of Gallino et al. (1998) or Busso et al. (1999). For instance, the neutron flux can be changed by modifying the extension or chemical profile of the $^{13}$C-pocket, which is a free parameter in their models. Another parameter is the mass of the AGB star, upon which the number of thermal pulses (and hence episodes of neutron exposure) is strongly dependent.

Another possibility is that the s-process production mechanism in very metal-poor (e.g., $[\text{Fe}/\text{H}] < -2.5$) AGB stars is quite different from that in more metal-rich stars. The calculation of low-mass stellar evolution in metal-deficient stars by Fujimoto et al. (2000) showed that hydrogen mixing occurs during the helium shell flash for $1-3.5 \, M_\odot$ stars with $[\text{Fe}/\text{H}] < -2.5$ (their case II'), contrary to the situation for stars with higher metallicity (their case IV). Their result suggests that the production of $^{13}$C, and subsequent s-process nucleosynthesis, is possible in the helium convective region during thermal pulses in these very metal-poor stars.

Our detection of Pb in the very metal-poor, carbon- and s-process-rich star, LP 625-44 provides a strong constraint on models of nucleosynthesis in AGB stars. The observed abundance patterns for heavier elements (Ba-Pb) agree well with the solar main s-process component, rather than with nucleosynthesis models for very metal-poor AGB stars. Further observation of s-process elements, including Pb, for objects similar to LP 625-44, and revisions of the theoretical approach to the nucleosynthesis in very metal-poor environments, will impact on our understanding of the evolution of low- and intermediate-mass stars, as well as of the enrichment of heavy elements in the early Galaxy. In this context, we note that we have also measured Pb in the star LP 706-7, which is similar to LP 625-44 in many respects (Norris et al. 1997a). That object, whose s-process abundances nevertheless differ from those of LP 625-44, will be discussed separately in a future paper.

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Table 1: Pb I lines and Results for LP 625-44

| Wavelength (Å) | χ (eV) | log gf | [Pb/Fe] |
|----------------|--------|--------|---------|
| 3739.940       | 2.66   | −0.12  | < +3.2  |
| 4057.815       | 1.32   | −0.20  | +2.7    |

Table 2: Heavy Element Abundances for LP 625-44

| Element        | [X/Fe] | log ε_{el} | n | σ  |
|----------------|--------|------------|---|----|
| Fe I ([Fe/H])  | −2.71  | 4.78       | 34| 0.13|
| Fe II ([Fe/H]) | −2.70  | 4.79       | 3 | 0.18|
| Sr II          | +1.15  | 1.37       | 3 | 0.16|
| Y II           | +0.92  | 0.45       | 2 | 0.12|
| Zr II          | +1.31  | 1.22       | 4 | 0.12|
| Ba II          | +2.74  | 2.26       | 3 | 0.20|
| La II          | +2.50  | 1.02       | 5 | 0.13|
| Ce II          | +2.27  | 1.20       | 26| 0.12|
| Pr II          | +2.45  | 0.55       | 5 | 0.12|
| Nd II          | +2.22  | 1.00       | 16| 0.12|
| Sm II          | +2.20  | 0.48       | 16| 0.12|
| Eu II          | +1.97  | −0.2       | 2 | 0.20|
| Gd II          | +2.31  | 0.70       | 6 | 0.13|
| Dy II          | +1.98  | 0.1        | 4 | 0.2 |
| Er II          | +2.04  | 0.3        | 2 | 0.2 |
| Tm II          | +1.96  | −0.6       | 1 | 0.2 |
| Hf II          | +2.76  | 0.8        | 2 | 0.2 |
| Pb I           | +2.65  | 2.0        | 1 | 0.2 |

Fig. 1.— Radial velocity as a function of Julian Day for LP 625-44.

Fig. 2.— Comparison of the observed (dots) and synthetic (lines) spectra near Pb I 4057.8Å. In the upper panel, LP 625-44 is shown along with the four synthetic spectra for [Pb/Fe] = 0.0, 2.35, 2.65 and 2.95. The atomic and molecular species that strongly contribute to the absorption are also labelled. For comparison, and for a check on possible contamination from molecular lines, the spectrum of CS 22957-027, and the synthetic spectrum for [Pb/Fe] = 0.0 are shown in the lower panel.
Fig. 3.— The abundances of heavy elements as a function of atomic species for LP 625-44. The thick solid line indicates the main $s$-process component determined by Arlandini et al. (1999) using models of 1.5 $M_\odot$ and 3 $M_\odot$ AGB stars at $Z = \frac{1}{2}Z_\odot$, while the thin line indicates the $r$-process component derived by subtraction of the $s$-process component from the solar abundances. The exception is the $r$-process component of Pb, for which the value determined by Käppeler et al. (1989) is adopted. The dotted line represents the total solar abundance adopted in Arlandini et al. (1999). All abundance patterns are normalized to the observed Ba abundance of LP 625-44.
