INVESTIGATION OF THE PUZZLING ABUNDANCE PATTERN OF THE NEUTRON-CAPTURE ELEMENTS IN THE ULTRA–METAL-POOR STAR CS 30322-023

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ABSTRACT

The s-enhanced and very metal-poor star CS 30322-023 shows a puzzling abundance pattern of the neutron-capture elements. In particular, several neutron-capture elements, such as Ba and Pb, show enhancement, but other neutron-capture elements, such as Sr and Eu, exhibit deficiencies with respect to iron. The study of this sample star could provide a better understanding of s- and r-process nucleosynthesis at low metallicity. Using a parametric model, we find that the abundance pattern of neutron-capture elements could be best explained by a star that was polluted by an asymptotic giant branch (AGB) star, and if the CS 30322-023 binary system formed in a molecular cloud that had never been polluted by r-process material. The lack of r-process material also indicates that the AGB companion cannot have undergone a Type I.5 supernova, and thus must have had an initial mass below 4.0 $M_\odot$, while the strong N over-abundance and the absence of a strong C overabundance indicate that the companion’s initial mass was larger than 2.0 $M_\odot$. The smaller s-process–component coefficient of this star illustrates that there is less material accreted onto this star from the AGB companion and that the sample star should have formed in a binary system with a larger initial orbital separation, where the accretion-induced collapse (AIC) mechanism cannot work.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB

1. INTRODUCTION

The two neutron-capture processes, the (slow) s-process and the (rapid) r-process, occur under different physical conditions and are therefore likely to arise in different astrophysical sites. The dominant site of the s-process is thought to be the asymptotic giant branch (AGB) phase in low- and intermediate-mass stars (Busso et al. 1999). The site or sites of the r-process are not known, although suggestions include the v-driven wind of Type II supernovae (Woosley & Hoffman 1992; Woosley et al. 1994), the mergers of neutron stars (Lattimer & Schramm 1974; Rosswog et al. 2000), accretion-induced collapse (AIC; Qian & Wasserburg 1993), and Type 1.5 supernovae (Iben & Renzini 1983; Zijlstra 2004). The neutron-capture elements are composed of some pure r-process, some pure s-process, and some mixed-parentage isotopes. As a result, when the solar system’s total abundances ($A_s$) are separated into the contributions from the s-process ($A_{s,s}$) and the r-process ($A_{r,s}$), some elements are mostly contributed by the r-process, such as Eu, and some by the s-process, such as Ba. Therefore, Eu is commonly referred to as an “r-process element,” and Ba as an “s-process element.”

In an early systematic study of elemental abundances in halo stars, Spite & Spite (1978) found that the neutron-capture elements Ba and Y were overabundant with respect to iron and that the barium abundance increased almost as fast as iron at low metallicity, suggesting a common origin in massive stars. Based on this suggestion, Truran (1981) supposed that in the early Galaxy the neutron-capture elements were formed exclusively through the r-process. Observations of metal-poor stars with metallicities lower than [Fe/H] $\approx$ –2.5 enriched in neutron-capture elements have further supported this hypothesis (Sneden et al. 1996, 2003; Burris et al. 2000; Cayrel et al. 2001; Hill et al. 2002). Although the material from which Population II stars form is not expected to contain significant s-process contributions, some stars, including some subgiants, are greatly enriched in carbon and s-elements (hereafter referred to as s-rich stars; Norris et al. 1997; Hill et al. 2000). These are believed to be binary companions of initially more massive donor stars that have evolved through the thermally pulsing AGB phase and transferred material enriched in C and s-process elements onto the lower mass, longer lived secondary now observed.

The currently generally favored s-process model is associated with the partial mixing of protons (PMP) into the radiative C-rich layers during thermal pulses (Gallino et al. 1998, 2003; Straniero et al. 1995, 2006). PMP activates the chain of reactions $^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta)^{13}\text{C}(\alpha,n)^{16}\text{O}$, which likely occurs in a narrow mass region of the He intershell (i.e., $^{13}\text{C}$ pocket) during the interpulse phases of an AGB star. Using the primary-like neutron source [$i.e.,^{13}\text{C}(\alpha,n)^{16}\text{O}$] and starting with a very low initial metallicity, most iron seeds are converted into $^{208}\text{Pb}$. So, when third dredge-up episodes mix the neutron-capture products into the envelope, the star appears s-enhanced and lead-rich. The nucleosynthesis of neutron-capture elements in the carbon-enhanced metal-poor stars (CEMP stars; Cohen et al. 2005) can be investigated by abundance studies of s-rich or r-rich stars. Recently, Masseron et al. (2006) analyzed the spectra of the lead-rich ultrametal-poor star CS 30322-023 and concluded that the observed abundances could not be well fit by a scaled solar system r-process ($A_{r,s}$) pattern or by the s-process pattern of an AGB model (0.8 $M_\odot$, $[\text{Fe/H}] = -3.8$). This star shows enhancement of the neutron-capture elements Ba and Pb, but the discovery that several neutron-capture elements, such as Sr and Eu, are deficient with respect to iron is puzzling. Masseron et al. (2006) estimated that CS 30322-023 is the most evolved CEMP star, probably in the AGB stage, possibly even in the thermally pulsing (helium-shell flashing) stage. However, there is another possibility for the s-enhancement
of CS 30322-023. Because of the strong N overabundance, the Na overabundance, and the absence of a strong C overabundance, Masseron et al. (2006) have also speculated that this star could be polluted by an AGB star that has a mass of at least 2.0 $M_\odot$, for the possible hot-bottom burning. Clearly, the close examination of elemental abundances in this object is still very important for a good understanding of the nucleosynthesis of neutron-capture elements in the early Galaxy.

There have been many theoretical studies of \( s \)-process nucleosynthesis in low-mass AGB stars. Unfortunately, the precise mechanism for chemical mixing of protons from the hydrogen-rich envelope into the \(^{12}\)C-rich layer to form a \(^{13}\)C pocket is still unknown (Busso et al. 2001). It is interesting to adopt the parametric model for metal-poor stars presented by Aoki et al. (2001) and developed by Zhang et al. (2006) to study the physical conditions that could reproduce the observed abundance pattern found in this star. In this paper, we investigate the characteristics of the nucleosynthesis pathway that produces the special abundance ratios of the \( s \)-rich object CS 30322-023 using the \( s \)-process parametric model (Zhang et al. 2006). The calculated results are presented in \( \S \) 2, where we also discuss the characteristics of the \( s \)-process nucleosynthesis at low metallicity. Conclusions are given in \( \S \) 3.

2. RESULTS AND DISCUSSION

We explore the origin of the neutron-capture elements in CS 30322-023 by comparing the observed abundances with the predicted \( s \)- and \( r \)-process contributions. For this purpose, we adopt the parametric model for metal-poor stars presented by Zhang et al. (2006). The \( i \)th element’s abundance in the envelope of the star can be calculated as follows:

\[
N_i(Z) = C_r N_{i,r} + C_s N_{i,s},
\]

\[1\]

where \( Z \) is the metallicity of the star, \( N_{i,s} \) is the abundance of the \( i \)th element produced by the \( s \)-process in the AGB star, and \( N_{i,r} \) is the abundance of the \( i \)th element produced by the \( r \)-process (per Si = 10\(^8\) at \( Z = Z_\odot \)). \( C_r \) and \( C_s \) are the component coefficients that correspond to contributions from the \( s \)-process and the \( r \)-process, respectively.

There are four parameters in the parametric model of \( s \)- and \( r \)-rich stars (\( s+r \) stars). They are the neutron exposure per thermal pulse, \( \Delta\tau \), the overlap factor \( r \), the component coefficient of the \( s \)-process \( C_s \), and the component coefficient of the \( r \)-process \( C_r \). The adopted initial abundances of seed nuclei lighter than the iron-peak elements were taken to be the solar system abundances, scaled to the value of [Fe/H] of the star. Because the neutron-capture–element component of the interstellar gas that formed very metal-deficient stars is expected to consist of mostly pure \( r \)-process elements, for the other, heavier nuclei we use the \( r \)-process abundances of the solar system (Arlandini et al. 1999), normalized to the value of [Fe/H]. The abundances of \( r \)-process nuclei in equation (1) are taken to be the solar system \( r \)-process abundances (Arlandini et al. 1999) for the elements heavier than Ba; for the other, lighter nuclei we use solar system \( r \)-process abundances multiplied by a factor of 0.4266 (Zhang et al. 2006). Using the observed data in the sample star CS 30322-023 (Masseron et al. 2006), the parameters in the model can be obtained from the parametric approach.

Figure 1 shows our calculated best-fit result. For this star, the curves produced by the model are consistent with the observed abundances within the error limits. The agreement of the model results with the observations provides strong support for the validity of the parametric model. In the AGB model, the overlap factor \( r \) is a fundamental parameter. Gallino et al. (1998) have found an overlap factor of \( r \approx 0.4-0.7 \) in their standard evolution model of low-mass (1.5–3.0 $M_\odot$) AGB stars at solar metallicity. The overlap factor calculated for other \( s \)-enhanced metal-poor stars lies between 0.1 and 0.81 (Zhang et al. 2006). The overlap factor deduced for CS 30322-023 is about \( r = 0.65^{+0.10}_{-0.10} \), which lies in both of the above ranges.

The neutron exposure per pulse, \( \Delta\tau \), is another fundamental parameter in the AGB model. Zhang et al. (2006) have deduced a neutron exposure per pulse for other \( s \)-enhanced metal-poor stars that lies between 0.45 and 0.88 mbarn\(^{-1}\). The neutron exposure deduced for CS 30322-023 is about \( \Delta\tau = 0.55^{+0.13}_{-0.06} \) mbarn\(^{-1}\). In the case of multiple subsequent exposures, the mean neutron exposure is given by \( \tau_0 = -\Delta\tau/\ln r \). It is worth noting, however, that the value of \( \tau_0 = (2.38 \pm 0.7)(T_9/0.348)^{1/2} \) mbarn\(^{-1}\) (this work, \( T_9 = 0.1 \), in units of 10\(^9\) K) for CS 30322-023 is significantly larger than those that best fit solar system material, \( \tau_0 = (0.30 \pm 0.01)(T_9/0.348)^{1/2} \) mbarn\(^{-1}\) (Käppeler et al. 1989). In fact, the higher mean neutron exposure favors large amounts of production of the heavier elements, such as Pb and Ba, and smaller amounts of Sr, Y, etc. (Cui & Zhang 2006), which could be one reason for the puzzling abundance pattern of the \( s \)-process elements: i.e., Ba, Pb, etc., show enhancement, and Sr, Y, etc., exhibit deficiencies with respect to iron.

We explore the possibility that CS 30322-023 belongs to a binary system. In this case, the enhancement of the neutron-capture elements Ba and Pb suggests a mass-transfer episode from a former AGB star. One major goal of this work is to explore the astrophysical condition, associated with an AGB star in a binary system, in which several neutron-capture elements, such as Sr and Eu, are deficient with respect to iron. It should be noted that the \( s \)-process abundances in the envelope of the stars could be expected to be lower than the abundance produced by the \( s \)-process in the AGB star, because the material is mixed with the envelopes of the primary (former AGB star) and secondary stars. The component coefficient of the \( r \)-process calculated for CS 30322-023 is about \( C_r \sim 0 \), which means that the star and its AGB companion formed in a molecular cloud that had never been polluted by \( r \)-process material. This fact can directly lead to the special abundance pattern in which several neutron-capture elements, such
as Eu and Sr, are deficient with respect to iron. Zijlstra (2004) speculates that the strong metallicity dependence of mass loss during the AGB phase leads to a steeper initial-final mass relation for low-metallicity stars; that is, for a given initial mass, the final mass is higher for metal-poor stars. Therefore, the core of, e.g., a metal-poor star with [Fe/H] = −3.0 having an initial mass of 4.0 \text{M}_\odot would reach the Chandrasekhar mass, leading to a “Type 1.5” supernova. In such a supernova, r-process nucleosynthesis might have occurred, and the surface of the companion star observed today could have been polluted with the elements that were produced. Since the sample star had never been polluted by r-process material, a smaller initial mass (4 < M < 4.0 \text{M}_\odot) of the former AGB companion could be expected. In addition, based on the strong N overabundance, the Na overabundance, and the absence of a strong C overabundance, Masseron et al. (2006) have speculated that CS 30322-023 would have been polluted by an AGB star with a mass of at least 2.0 \text{M}_\odot.

Qian & Wasserburg (2003) proposed a theory for the creation of s+r stars. They suggest that a s+r star is a member of a binary system in which the former primary went through the AGB phase. In this stage, carbon and s-process elements were dumped onto the surface of the companion via mass transfer. The former primary then evolved into a white dwarf. Mass transfer then occurred in the reverse direction, i.e., from the companion to the white dwarf, leading in turn to an accretion-induced collapse (AIC) of the white dwarf into a neutron star. Subsequent r-process nucleosynthesis is then presumed to occur in a neutrino-driven wind of the neutron star, and the nucleosynthesis products contaminate the surface layers of the star that is observed today.

The binary system with lower mass AGB stars (M < 4.0 \text{M}_\odot) and larger initial orbital separation could not cause AIC, because the white dwarf accretes matter insufficiently from the polluted star, and the star is polluted only by the AGB companion, which can explain the formation of s-only stars. The r-process component coefficient of CS 30322-023 is about 0, which implies that this star is a s-only star. Zhang et al. (2006) have calculated the s-process component coefficient for two other s-only stars with C_s = 0.0005 and 0.0006 and 10 s+r stars with 0.0017 \leq C_s \leq 0.0060. The s-process component coefficient of CS 30322-023 is about 0.0002, which is smaller than the other s-rich stars. This fact illustrates that there is less material accreted onto CS 30322-023 from the AGB companion, and the sample star should have formed in the binary system with a larger initial orbital separation, which could not cause AIC. This could be another reason leading to the special abundance pattern in which several neutron-capture elements are deficient with respect to iron, such as Sr and Y.

In addition, the s-process pattern of this star is matched by a model with r = 0.65, which is large enough to be consistent with the idea that the AGB star polluting the sample star was of low mass (M < 4.0 \text{M}_\odot; Cui & Zhang 2006).

As a star evolves off the main sequence, its convective envelope penetrates deeper and deeper, reaching into regions where there was previous H burning, and thus undergoes the so-called first dredge-up. Later on, when a star evolves off the red giant branch (RGB), a further mixing episode can take place (usually referred to as “extra mixing”). Masseron et al. (2006) have estimated that CS 30322-023 is an evolved CEMP star. As such, it would be expected to have passed through the deepest convective envelope stage, i.e., the amount of accreted material from the former AGB star, including C and s-elements, such as Sr and Ba, is further diluted by the material of the stellar convective envelope, thus decreasing both [C/Fe] and [s/Fe] (where “s” represents a species of s-process element). Although the mixing processes (first dredge-up and extra mixing) should have occurred in the sample star, the effect of orbital separation of the binary system mentioned above is also expected to be important.

It is interesting to estimate quantitatively the dilution effect brought by the orbital separation for CS 30322-023 with C_s = 0.0002. The s-process abundances of the sample star are a result of pollution from the dredged-up material of the former AGB star. The measured [s/Fe] refers to the average s-process material of the AGB star after dilution by mixing with the envelope of the little companion that is now the extrinsic star. At some time on the AGB, the convective He shell and the envelope of the giant will be overabundant in heavy elements by factors of, respectively, f_{shell} and f_{env,1} with respect to solar system abundances normalized to the value of [Fe/H]. The approximate relation between f_{env,1} and f_{shell} is

\[
f_{\text{env},1} \approx \frac{\Delta M_{\text{dr}}}{M_1 f_{\text{shell}}},
\]

where \(\Delta M_{\text{dr}}\) is the total mass dredged up from the He shell into the envelope of the AGB star and \(M_1^*\) is the envelope mass of the AGB star. For a given s-process element, the overabundance factor \(f_{\text{env},2}\) in the future s-enhanced star can be approximated relatively to the overabundance factor \(f_{\text{env},1}\) by

\[
f_{\text{env},2} \approx \frac{\Delta M_2}{M_2^* f_{\text{env},1}} = \frac{\Delta M_2}{\Delta M_{\text{dr}}} \frac{M_1^*}{f_{\text{shell}}},
\]

where \(\Delta M_2\) is the amount of matter accreted by the future s-enhanced star and \(M_2^*\) is the envelope mass of the star. The component coefficient \(C_s\) is computed from the relation

\[
C_s = \frac{f_{\text{env},2}}{f_{\text{shell}}} \approx \frac{\Delta M_2}{\Delta M_{\text{dr}}} \frac{M_{1}^*}{M_2^*}.
\]

For wide binary systems, mass transfer operates through stellar winds, rather than by Roche-Lobe overflow (Boffin & Jorissen 1988). We use the Bondi-Hoyle accretion rate to calculate the mass being accreted by the sample star (Theuns et al. 1996; Jorissen et al. 1998),

\[
\Delta M_2 = -\frac{\alpha}{A^2} \left( \frac{GM_2}{r_{\text{eq}}^3} \right)^2 \left[ \frac{1}{1 + \left( v_{\text{orb}} / v_{\text{eq}} \right)^2} \right]^{3/2} \Delta M_1,
\]

where \(A\) is the semimajor axis of the orbit of the binary system and \(\alpha\) is a constant expressing the accretion efficiency, with \(\alpha = 0.1\) in the situation of interest here, according to the detailed hydrodynamic simulations (Theuns et al. 1996; Jorissen et al. 1998). Here \(v_{\text{eq}}\) is the wind velocity and \(v_{\text{orb}}\) is the orbital mean velocity. \(\Delta M_1\) is the wind mass-loss of the former AGB star in a binary system, i.e., the present white dwarf star.

For the evolved sample star (∼0.8 \text{M}_\odot; Masseron et al. 2006), the mass of the convective envelope, \(M_{2}^*\), is larger than the main-sequence stars with similar stellar masses. As a result, the dilution of the accreted material is relatively large, and we take \(M_{2}^* \approx 0.5 \text{M}_\odot\) (Boffin & Jorissen 1988). Adopting formulas (4) and (5) and taking \(\Delta M_{\text{dr}} \approx 0.03\)–0.05 \text{M}_\odot (Gallino et al. 1998) and \(\Delta M_1 \approx M_1^*\), we can estimate the fraction of the mass captured by the little companion (∼0.8 \text{M}_\odot) to be from ∼0.2% to 0.3% of the mass lost by the wind (15 km s\(^{-1}\)) from the former AGB star (∼3.0 \text{M}_\odot) over a period of ∼10–20 yr. This implies that the sample star, CS 30322-023, should belong to a long-period system, consistent with the expectation that the accretion rate be smaller in wider systems. Because of the uncertainties of mass-loss rates and our poor knowledge of how and when mass transfer
phenomena occur, we do not claim that this is the only or even the best understanding of the s-process component coefficient. Obviously, long-term radial velocity monitoring is advisable, possibly leading to the determination of orbital elements for CS 30322-023, which could allow for a further test of our results.

It was also possible to isolate the contributions corresponding to the s- and r-processes by our parametric model. In the Sun, the elemental abundances of Ba and Eu consist of significantly different combinations of s- and r-process isotope contributions, with s/r ratios for Ba and Eu of 81:19 and 6:94, respectively (Arlandini et al. 1999). The Ba and Eu abundances are most useful for unraveling the sites and nuclear parameters associated with the s- and r-processes, corresponding to those in extremely metal-poor stars polluted by material having undergone nucleosynthetic processing a few times. We explored the contributions of the s- and r-processes for these two elements in the sample star. From equation (1), we obtained s/r ratios for Ba and Eu of 99.6:0.4 and 74.2:25.8, which are obviously larger than the ratios in the solar system. The abundances of r-elements, such as Eu, in the sample star are lower than those in normal stars, so the sample star seemed to be an “extremely” s-only star.

We discuss the uncertainty of the parameters using the method presented by Aoki et al. (2001). We choose Sr as the representative for the first peak elements, Ba as the representative for the second peak elements, Pb as the representative for the third peak elements, and Eu as the representative for the r-process elements. In Figure 2, region II shows $\Delta r = 0.55^{+0.18}_{-0.06}$ mbar$^{-1}$ and $r = 0.68^{+0.10}_{-0.09}$ with $\chi^2 = 0.556$, and region I shows $\Delta r = 0.19^{+0.09}_{-0.12}$ mbar$^{-1}$ and $r = 0.87^{+0.10}_{-0.08}$ with $\chi^2 = 0.846$. In both regions, all the observed ratios of the four representative elements can be accounted for within the error limits. The corresponding mean neutron exposures for regions I and II are $\tau_0 = 1.36^{+0.03}_{-0.02}$ mbar$^{-1}$ and $\tau_0 = 1.28^{+0.01}_{-0.007}$ mbar$^{-1}$, respectively. Since the final abundance distributions of the s-process nucleosynthesis depend mainly on the mean neutron exposure $\tau_0$, we investigate the relation between $\tau_0$ and the overlap factor $r$. It is worth noting that although the values of the overlap factor and the neutron exposure are obviously different for the two regions, the value of the mean neutron exposure for region I is indeed close to that of region II. The uncertainties of the parameters for the star CS 30322-023 are similar to those for other metal-poor stars, obtained by Zhang et al. (2006).

3. CONCLUSIONS

The star CS 30322-023 is an ultra–metal-poor lead star that has a special abundance pattern of the neutron-capture elements. In particular, this star shows enhancement of the neutron-capture elements Sr and Eu, are deficient with respect to iron. The neutron-capture elemental abundance pattern could be explained by a binary system formed in a molecular cloud that had never been polluted by r-process material. This fact can explain the several neutron-capture elements that are deficient with respect to iron, such as Eu and Sr. The initial mass of the AGB companion should be smaller than 4.0 $M_\odot$, which excludes the possibility of forming a Type I supernova, and larger than 2.0 $M_\odot$ because of the strong N over-abundance and the absence of a strong C over-abundance. The r-process component coefficient of CS 30322-023 is very small, which implies that this star is an “extreme” s-only star. The s-process component coefficient of this star is smaller than the other s-rich stars. Although the mixing processes (first dredge-up and extra mixing) should have occurred in the sample star, the effect of orbital separation of the binary system is also important. The sample star CS 30322-023 should belong to a wide binary system where the AIC mechanism cannot work. This could be an important reason for the special abundance pattern in which several neutron-capture elements are deficient with respect to iron, such as Sr, Y, and Eu. Certainly, the possibility that CS 30322-023 could be a thermally pulsing AGB star (Masseron et al. 2006) is also existent. In this case, the operation of the s-process is associated with thermal pulses occurring on the AGB. As a result of the so-called “third dredge-up,” s-process enriched material is brought to the surface of the AGB star. Obviously, large uncertainties still remain in this topic, and a full understanding of the abundance pattern and evolutionary state of CS 30322-023 will depend on future high-resolution studies and long-term radial-velocity monitoring. More in-depth theoretical and observational studies of s-rich stars will reveal the characteristics of the s-process at low metallicity and the history of enrichment of s- and r-elements in the early Galaxy.

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REFERENCES

Aoki, W., et al. 2001, ApJ, 561, 346
Arlandini, C., Käppeler, F., Wisshak, K., Gallino, R., Lugaro, M., Busso, M., & Straniero, O. 1999, ApJ, 525, 886
Boffin, H. M. J., & Jurissen, A. 1988, A&A, 205, 155
Burrus, D. L., Pilachowski, C. A., Armandroff, T. E., Sneden, C., Cowan, J. J., & Roe, H. 2000, ApJ, 544, 302
Buß, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. 2001, ApJ, 557, 802
Buß, M., Gallino, R., & Wasserburg, G. J. 1999, ARA&A, 37, 239
Cayrel, R., et al. 2001, Nature, 409, 691
Cohen, J. G., et al. 2005, ApJ, 633, 1109
Cui, W. Y., & Zhang, B. 2006, MNRAS, 368, 305
