Footprints of the weak s-process in the carbon-enhanced metal-poor star ET0097

Guochao Yang, Hongjie Li, Nian Liu, Wenyuan Cui, Yanchun Liang and Bo Zhang

Abstract Historically, the weak s-process contribution to metal-poor stars is thought to be extremely small, due to the effect of the secondary-like nature of the neutron source $^{22}\text{Ne} (\alpha, n)^{25}\text{Mg}$ in massive stars, which means that metal-poor “weak s-process stars” could not be found. ET0097 is the first observed carbon-enhanced metal-poor (CEMP) star in the Sculptor dwarf spheroidal galaxy. Because C is enriched and the elements heavier than Ba are not overabundant, ET0097 can be classified as a CEMP-no star. However, this star shows overabundances of lighter n-capture elements (i.e., Sr, Y and Zr). In this work, having adopted the abundance decomposition approach, we investigate the astrophysical origins of the elements in ET0097. We find that the light elements and iron-peak elements (from O to Zn) of the star mainly originate from the primary process of massive stars and the heavier n-capture elements (heavier than Ba) mainly come from the main r-process. However, the lighter n-capture elements such as Sr, Y and Zr should mainly come from the primary weak s-process. The contributed fractions of the primary weak s-process to the Sr, Y and Zr abundances of ET0097 are about 82%, 84% and 58% respectively, suggesting that the CEMP star ET0097 should have the footprints of the weak s-process. The derived result should be a significant evidence that the weak s-process elements can be produced in metal-poor massive stars.

Keywords stars: abundances – stars: chemically peculiar – stars: individual (ET0097)

1 Introduction

Stellar chemical abundances reflect the accumulated results of various nucleosynthesis processes. Study of the stellar chemical abundance patterns is a vital task for understanding the different nucleosynthesis processes (Sneden et al. 2008). The light elements and iron-peak (Fe-peak) elements can be produced through charged-particle fusion reactions, whereas the heavier elements are produced through the neutron-capture (n-capture) process which includes the slow n-capture process (s-process) and the rapid n-capture process (r-process) (Burbidge et al. 1957). The s-process is further divided into two sub-processes: the main s-process and the weak s-process. The main s-process occurs in thermally pulsing asymptotic giant branch (TP-AGB) stars with low- and intermediate-mass and produces n-capture elements, especially the heavier n-capture elements with $Z \geq 56$ (Gallino et al. 1998, Busso et al. 1999, 2001). The helium-burning (He-burning) cores and the carbon-burning (C-burning) shells of massive stars are the sites of the weak s-process which mainly produce the lighter n-capture elements with $38 \leq Z \leq 47$ (Lamb et al. 1977, Raiteri et al. 1991, 1992, 1993).

On the other hand, the r-process can also be classified into two sub-processes: the main r-process and the weak r-process. Although the r-process nucleosynthesis mechanisms have been investigated by many pioneering works (e.g., Burbidge et al. 1957, Hillebrandt 1978, Mathews & Cowan 1990, Woosley et al. 1994).
Wheeler et al. (1998), different works gave different suggestions (Sneden et al. 2008). However, two possible sites for the r-process are commonly proposed. The first possible site relies on SNe II (Woosley et al. 1994; Qian & Woosley 1996). Travaglio et al. (1999) suggested that the main r-process should occur in SNe II with an initial mass range of 8 – 10 $M_\odot$ and dominantly generate heavier n-capture elements. While, Qian & Wasserburg (2007) proposed that the weak r-process (LEPP)” (or weak r-process) produces a uniform and unique abundance pattern. The second possible site refers to the mergers of binary neutron stars (NS-NS) or neutron star-black hole (NS-BH) systems (Lattimer & Schramm 1974, 1976; Eichler et al. 1989).

Freiburghaus et al. (1999) suggested that the neutron star mergers (NSMs) should be responsible for the heavier r-process elements $A \gtrsim 130$. Korobkin et al. (2012) further suggested that compact binary mergers (CBMs) can produce a robust r-process abundance pattern. Moreover, Matteucci et al. (2014) proposed that the theoretical production of the CBMs alone could entirely explain the observed Eu abundance in the Galaxy. Recently, Wanao et al. (2014) and Just et al. (2015) described that the NSMs can successfully generate not only heavy r-process elements but also light r-process elements. Although each of the two suggested sites above provides an important clue for understanding the nucleosynthetic mechanisms of the r-process, the actual astrophysical sites of the r-process remain under debate (Ishimaru et al. 2015; Goriely & Janka 2016).

Carbon-enhanced metal-poor (CEMP) stars are an interesting stellar class which is composed of stars with low metallicities and overabundant C. Based on the abundance patterns of n-capture elements, CEMP stars can be further divided into four sub-classes (Beers & Christlieb 2005): (1) CEMP-r stars: [Eu/Fe] > 1.0. Stars of this sub-class are rare. CS22892-052 has been classified as an example of CEMP-r star and shows no sign of binarity (Sneden et al. 2003; Hansen et al. 2011), (2) CEMP-s stars: [Ba/Fe] > 1.0 & [Ba/Eu] > 0.5. These stars are suggested to be in binary systems. The overabundant s-process elements of one CEMP-s star are thought to originate from its former-AGB companion (Lucatello et al. 2003). (3) CEMP-r/s stars: 0.0 < [Ba/Eu] < 0.5. The astrophysical origins of CEMP-r/s stars are in debate, as these stars show overabundances of both s-process and r-process elements. Jonsell et al. (2006) summarized 9 possible formation scenarios to explain the peculiar abundance pattern. They found that each of the scenarios alone was not enough to explain the enrichment of both s-process and r-process elements. (4) CEMP-no stars: [Ba/Fe] < 0.0. The origins of CEMP-no stars have been studied by many works (e.g., Bromm & Loeb 2003; Ryan et al. 2005; Frebel et al. 2007; Masseron et al. 2010; Gilmore et al. 2013; Norris et al. 2013). Based on the radial velocity analysis for the CEMP-no stars, Starkenburg et al. (2014) found that only two of the 15 CEMP-no sample stars show signatures of binarity. On the other hand, relied on the abundance analysis of the bright CEMP-no star BD+44°493, Placco et al. (2014) and Roederer et al. (2016) suggested that this CEMP-no star could well be a second-generation star. Recently, with much improved statistics, Hansen et al. (2016) concluded that CEMP-no stars may indeed be bona-fide second-generation stars, formed from natal gas clouds polluted by the very first (massive) stars. Furthermore, they also suggested that these stars are not consistent with any mass-transfer mechanism.

ET0097 ([Fe/H] = −2.03) is the first observed CEMP star in the Sculptor dwarf spheroidal galaxy. Skúladóttir et al. (2015) found that this star can be classified as a CEMP-no star, since the C abundance is high and the elements heavier than Ba are not overabundant. For lighter n-capture elements (i.e., Sr, Y and Zr), the abundances of this star are higher than the average abundances of other stars in Sculptor and C-normal stars in the Galactic halo. They proposed that, (1) the reason for C enhancement may be that the gas cloud in which ET0097 formed contains the material from faint SNe; (2) the lighter n-capture elements should come from the weak r-process or the weak s-process, while there were not enough evidences to determine which process is the main contributor. Because ET0097 is the first observed CEMP-no star in Sculptor, it is important to investigate the astrophysical origins of its elements, especially the lighter n-capture elements Sr, Y and Zr.

In this work, we adopt the abundance decomposition approach presented by Li et al. (2013a) to investigate the astrophysical origins of the elements of ET0097. The abundance decomposition approach of the sample star is described in § 2. The results and discussions are provided in § 3. The conclusions are presented in § 4.

2 Abundance decomposition approach of the sample star

The metal-poor stars CS 22892-052 and CS 31082-001 are deemed as the prototypes of “main r-process stars”,

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as their abundance pattern of heavier n-capture elements matches the r-process abundance pattern of the solar system closely (Cowan et al. 1991, Truran et al. 2002, Wanajo et al. 2006, Sneden et al. 2008), whereas their abundances of lighter n-capture elements are deficient relative to the r-process abundances of the solar system. On the other hand, the metal-poor stars HD 122563 and HD 88609 are called as “weak r-process stars”, because their abundances of lighter n-capture elements are excessive and their abundances of heavier n-capture elements are deficient (Westin et al. 2006, Honda et al. 2004). Based on the abundances of the main r-process stars and the weak r-process stars, Li et al. (2013a) derived the abundances of the main r- and weak r-process with iterative approach and found that almost all the metal-poor stars have been polluted by both main r- and weak r-process material.

The primary light elements and primary Fe-peak elements are generated in the massive stars \( M > 10 M_\odot \) through charged-particle reactions (Heger & Woosley 2010). The ratios \( \text{[Sr/Fe]} \approx 1 \) in weak r-process stars mean that weak r-process elements and Fe-peak elements are ejected together from the massive stars. Li et al. (2013a) combined the primary-like abundances (i.e., the yields have no correlation with the initial metallicity) of light elements and Fe-peak elements with those of weak r-process elements as “primary component”. In this case, the primary process abundances include the abundances of the primary light elements, the primary Fe-peak elements and the weak r-process elements.

The stellar chemical abundances reveal the contributions of various nucleosynthesis processes and could not be explained by only one process (Allen & Barbuy 2006). Therefore the decomposition of the total abundance of each observed element in a star is meaningful to research the relative contribution of individual nucleosynthesis process. One of our goals is to investigate the astrophysical origins of the elements, especially the lighter n-capture elements in ET0097. For this purpose, having adopted the abundance decomposition approach presented by Li et al. (2013a), we explore the astrophysical origins of the elements of this sample star. Because the contribution of the main s-process is effective when \( [\text{Fe/H}] \geq -1.5 \) and the weak s-process is deemed as a secondary process (i.e., the yields increase with increasing metallicity) (Travaglio et al. 1994, 2004), in the first step, we neglect the contributions of the s-process to ET0097. The i-th element abundance of ET0097 could be expressed as follows:

\[
N_i = (C_{r,m}N_{i,r,m} + C_{pri}N_{i,pri}) \times 10^{[\text{Fe/H}]},
\]

where \( N_{i,r,m} \) and \( N_{i,pri} \) are the main r-process and primary process abundances which are adopted from Li et al. (2013a) \( \text{(per H} = 10^{12} \text{ at } \text{[Fe/H]} = [\text{Fe/H}]) \). \( C_{r,m} \) and \( C_{pri} \) are the corresponding component coefficients.

We obtain the best component coefficients by seeking for the minimum \( \chi^2 \). The reduced \( \chi^2 \) is defined as follows:

\[
\chi^2 = \sum_{i=1}^{K} \frac{(\log N_{i,obs} - \log N_{i,cal})^2}{(\Delta \log N_{i,obs})^2(K - K_{free})},
\]

where \( \log N_{i,obs} \) is the observed abundance of the \( i \)-th element, \( \Delta \log N_{i,obs} \) is the observed error, \( N_{i,cal} \) is the calculated abundance, \( K \) is the number of the elements used by the corresponding fit, and \( K_{free} \) is the number of the free parameters. With the best component coefficients, we can derive the calculated abundances of ET0097. If each observed elemental abundance can fit into the corresponding calculated abundance within the observed error, the relative contribution of individual process to the elemental abundance of the star can then be determined.

3 Results and discussions

In this work, we aim to determine the astrophysical origins of the elements, especially the lighter n-capture elements in ET0097 and explore the relative contribution of individual nucleosynthesis process to the elements of this CEMP star. Based on equations (1, 2) and the observed abundances adopted from Skáladóttir et al. (2015), we start to explore the origins of the elements for the metal-poor star ET0097 \( ([\text{Fe/H}]) = -2.03 \) with the main r-process and primary process. The best fit results are shown in Figure 4. In the upper panel, the observed abundances are plotted by the filled circles and the calculated abundances are indicated by the solid line. The lower panel shows the relative offsets, \( \Delta \log \varepsilon(x) \equiv \log \varepsilon(x)_{cal} - \log \varepsilon(x)_{obs} \). Because the component coefficients are constrained by the observed abundances, the calculated errors are estimated from the average observed errors \( \approx 0.18 \text{ dex} \) of ET0097, which are shown by the dashed lines. From Figure 4 we can see that, for most light elements, Fe-peak elements and heavier n-capture elements, the observed abundances can fit into the calculated abundances within the observed errors, whereas the calculated abundances of the lighter n-capture elements are lower than the corresponding observed abundances. The discrepancy between the calculated abundances and the observed abundances means that the contributions of the main
r-process and primary (or weak r-) process are not sufficient to explain the abundances of the lighter n-capture elements of ET0097 and the contribution of another process is required. Note that the overabundances of lighter n-capture elements should not be ascribed to the main s-process, because of the low observed ratio \([\text{Ba/Fe}] = -0.44\) in ET0097 (Skúladóttir et al. 2013).

Historically, because of the secondary-like nature of the neutron source \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\), the contribution of the weak s-process of normal massive stars to metal-poor stars is neglected. However, considering the rapid rotation of massive stars, Frischknecht et al. (2012) found that low-metallicity massive stars should produce primary weak s-process elements effectively. Following this nucleosynthetic theory, Cescutti et al. (2013) suggested that metal-poor stars with high \([\text{Sr/Ba}]\) should contain the s-process material from rapidly rotating massive stars. Recently, Jablonka et al. (2015) carried out a detailed analysis of the elemental abundances for five extremely metal-poor stars in Sculptor. They found that the contributions of the main r- and weak r-process are not enough to explain the observed abundances of the metal-poor star ET0381 \((\text{Fe/H}) = -2.44\), because of the high ratio \([\text{Sr/Ba}] = 0.36\) of this star. They considered that the abundances of some n-capture elements in ET0381 should have the contribution of the s-process of massive stars. The results of these works imply that the contribution of the weak s-process to the abundances of lighter n-capture elements of some metal-poor stars, especially the metal-poor stars with high \([\text{Sr/Ba}]\) such as ET0097 \((\text{Sr/Ba} = 1.15)\), should not be neglected.

Adding the contribution of the weak s-process, we use the combined abundances of the main r-process, weak r-process and weak s-process to fit the observed abundances of ET0097:

\[
N_i = (C_{\text{r},i}N_{i,r,m} + C_{\text{pri},i}N_{i,pri} + C_{s,w,i}N_{i,s,w}) \times 10^{[\text{Fe/H}]},
\]

where \(N_{i,s,w}\) is the primary weak s-process abundance which has been normalized to the weak s-process abundance of Sr presented by Raiteri et al. (1993). \(C_{s,w}\) is the corresponding component coefficient. The abundance \(N_{i,s,w}\) is adopted from Frischknecht et al. (2012) (model B3, \(v_{\text{ini}}/v_{\text{crit}} = 0.5\)), as the calculated abundance ratio \([\text{Sr/Ba}] = 0.94\) is close to the observed abundance ratio \([\text{Sr/Ba}] = 1.15\) of ET0097. The component coefficients \(C_{\text{r},i}\) and \(C_{\text{r},i}\) could reveal the relative contributions from the main r-, primary and weak s-process, respectively, so the relative contribution of individual process to the observed abundances can be derived by applying these component coefficients.

Considering the contribution from the primary weak s-process, we investigate the origins of the elements for ET0097 using equations (2) and (3). The new fitted results are shown in Figure 2. The symbols are the same as in Figure 1. It is obvious that all the calculated values are in excellent agreement with the observed abundances within the observed errors. The results mean that, although the contributions of the main r- and weak r-process to the abundances of lighter n-capture elements are significant, the observed overabundances of lighter n-capture elements of ET0097 could be ascribed to the contribution of the primary weak s-process of massive stars, i.e., the CEMP star ET0097 should have the footprints of the weak s-process.

The observed abundances of Sr, Y and Zr can fit successfully in the combined contributions of the main r-process, the weak r-process and the primary weak s-process. Obviously, the relative contributions of the three processes to the abundances of lighter n-capture elements are important for us to understand the elemental origins of this star. The component abundances of the three processes for Sr, Y and Zr of ET0097 are presented in Figure 3. The filled circles with error bars refer to the calculated abundances and the corresponding errors. The abundances of the main r-process, the weak r-process and the primary weak s-process are plotted by the filled up triangles, filled down triangles and filled diamonds, respectively. From Figure 3, we can see that for Sr, Y and Zr, the abundances of the primary weak s-process are apparently higher than those of the main r- and weak r-process, which means that the primary weak s-process is the main contributor to the abundances of Sr, Y and Zr of ET0097. The contributed fractions of the primary weak s-process to Sr, Y and Zr abundances of ET0097 are about 82%, 84% and 58%, respectively. On the other hand, the contributed fractions of the weak r-process to Sr, Y and Zr abundances are about 14%, 13% and 35%, respectively. Furthermore, the contributed fractions of the main r-process to Sr, Y and Zr abundances are about 4%, 3% and 7%, respectively. Obviously, the astrophysical reason of the overabundances of the lighter n-capture elements in ET0097 can be ascribed to the additional contribution of the primary weak s-process.

Frischknecht et al. (2012) have predicted that rapidly rotating massive stars with low metallicity should facilitate the primary weak s-process. The derived footprints of the weak s-process in ET0097 should be a significant evidence that the weak s-process elements can be produced in metal-poor massive stars.

For the CEMP-no star ET0097, the abundance ratios \([\text{Sr, Y, Zr}/\text{Fe}] = 0.47 (\pm 0.11)\) and \([\text{Sr/Ba}] = 1.15 (\pm 0.22)\), which means that the lighter n-capture elements are enhanced relative to Fe and heavier n-capture
Based on the discussions above, the astrophysical reason of enhanced lighter n-capture elements should be the contributions of the primary weak s-process occurred in the rapidly rotating massive stars with low metallicity. ET0097 should not be a particular object and the similar abundance characteristics have also been revealed in some CEMP-no stars of the Galactic halo. For the CEMP-no star BS 16929-005, the observed abundance ratios \[ \frac{\text{Sr}, \text{Y}}{\text{Fe}} = 0.22 \pm 0.16 \] and \[ \frac{\text{Sr}, \text{Ba}}{\text{Fe}} = 0.87 \pm 0.23 \] (Honda et al. 2004). In addition, for the CEMP-no star CS 22949-037, the abundance ratios \[ \frac{\text{Sr}, \text{Y}}{\text{Fe}} = 0.15 \pm 0.24 \] and \[ \frac{\text{Sr}, \text{Ba}}{\text{Fe}} = 0.94 \pm 0.39 \] (Norris et al. 2001). Overall, the number of CEMP-no stars is still small, especially for the stars with excessive abundances of lighter n-capture elements and deficient abundances of heavier n-capture elements. Obviously, further abundance studies of CEMP-no stars are needed.

4 Conclusions

The observations of n-capture elements for the metal-poor stars provide an excellent chance to determine the abundance patterns synthesized by various n-capture processes. ET0097 is the first observed CEMP star in the Sculptor dwarf spheroidal galaxy. The elemental abundances of this star should contain significant nucleosynthetic information. In this work, having adopted the abundance decomposition approach, we investigate the astrophysical origins of the elements in ET0097. We find that the light elements and the Fe-peak elements (from O to Zn) of this star mainly originate from the primary process of massive stars and the heavier n-capture elements (heavier than Ba) mainly come from the main r-process. However, the lighter n-capture elements (i.e., Sr, Y and Zr) should mainly come from the primary weak s-process. The contributed fractions of the primary weak s-process to the Sr, Y and Zr abundances of ET0097 are about 82%, 84% and 58%, respectively.

Historically, the weak s-process contribution to metal-poor stars is thought to be extremely small, due to the effect of the secondary-like nature of the neutron source \( ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \) in massive stars (Travaglio et al. 2004). If this is the case, metal-poor “weak s-process stars” could not be found. Recently, Frischknecht et al. (2012) predicted that rapidly rotating massive stars with low metallicity should facilitate the primary weak s-process. Our calculated results mean that the abundances of Sr, Y and Zr in ET0097 mainly come from the weak s-process, i.e., the CEMP star ET0097 should have the footprints of the weak s-process. The derived result should be a significant evidence that the weak s-process elements can be produced in metal-poor massive stars. We wish the derived results in this work can provide more information and more constraints on the n-capture nucleosynthesis for low metallicity. Clearly, more observational data for metal-poor stars, particularly for the ones in which lighter n-capture elements are enhanced, would be important for future works.

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Fig. 1  Best fitted results in the first step for the sample star. In the upper panel, the filled circles are the observed abundances and the solid line is the calculated abundances. In the lower panel, the filled circles refer to the relative offsets, $\Delta \log \varepsilon(x) \equiv \log \varepsilon(x)_{\text{cal}} - \log \varepsilon(x)_{\text{obs}}$. The dashed lines are the calculated errors.

Fig. 2  New fitted results for the sample star. Symbols are the same as in Figure 1.
Fig. 3  Component abundances of the individual process for Sr, Y and Zr of the sample star. The filled squares with error bars refer to the observed abundances and the corresponding errors. The filled circles with error bars refer to the calculated abundances and the corresponding errors. The filled up triangles, filled down triangles and filled diamonds refer to the abundances of the main r-process, weak r-process and primary weak s-process, respectively. See the electronic edition of the Journal for a color version of this figure.