Observational Constraints on the 13C Neutron Source in Low-Mass AGB Stars (Postprint)

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Abstract

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Full Text

Preamble

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Constraints of Observational Evidences on the 13C Neutron Source in Low-mass AGB Stars

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Abstract

The 13C(α, n)16O reaction serves as the primary neutron source for the s-process (slow neutron capture process) in low-mass asymptotic giant branch (AGB) stars (M $\leq$ 3 M , where M and M denote the mass of AGB stars and solar mass, respectively). During the interpulse period, 13C within a reservoir (the so-called "13C pocket") burns under radiative conditions (at approximately 8 keV) and releases neutrons. To date, the physical formation mechanism of the 13C pocket remains poorly understood, and its structure has yet to be fully determined. In post-processing nucleosynthesis calculations, the 13C pocket is typically constrained through free parameterization based on observational data. This paper reviews how different observational constraints affect the 13C pocket from the perspectives of fundamental principles, main effects, and limitations, and concludes with an outlook on future research directions for constraining the 13C neutron source.

Keywords: AGB star; constraints; neutron source; s-process

1 Introduction

The slow neutron capture process (s-process) was proposed by Burbidge et al. in 1957 as a physical mechanism to explain the nucleosynthesis of elements heavier than the Fe group (A > 60). Since the mid-1990s, the widely accepted view has been that the main and strong components of the s-process found in the solar system (nuclei heavier than mass number A 90) were produced in relatively low-mass AGB stars (1.2 M < M $\leq$ 4 M) that died before the Sun' s birth. These stars consist of three layers: a degenerate C-O core, a thin He-rich intermediate shell, and a low-density, mostly convective H-rich envelope. They undergo periodic He-shell flashes known as thermal pulses (TPs). During the relatively long interpulse intervals, quiescent H-shell burning provides the radiative energy for the stellar surface.

According to current s-process nucleosynthesis models for low-mass (M $\leq$ 3 M) AGB stars, after the convective instability of the He shell subsides, the convective envelope penetrates into the He intershell region in a process called third dredge-up (TDU). At its deepest extent, this creates a thin transition zone containing a small amount of protons between the He-rich intershell and the H-rich envelope. When the H shell reignites, these protons are captured by the abundant 12C produced through the 3α reaction, forming a 13C reservoir via the chain 12C(p, γ)13N(β+)13C. This is the so-called "13C pocket." When this region contracts and heats up to (9–10) $\times$ 10^7 K, 13C burns via the 13C(α, n)16O reaction under radiative conditions during the long interpulse phase, releasing neutrons and initiating s-process nucleosynthesis. Although the resulting neutron density is low (Nn $< 10^8$ cm^{-3}), the long timescale of neutron irradiation (tens of thousands of years) ensures sufficient neutron exposure to synthesize the main s-process nuclei.

During TPs, when the temperature at the base of the He-flash-driven convective zone exceeds 3×10^8 K, a second neutron source, 22Ne(α, n)25Mg, becomes active. This process is faster than the first, with higher peak neutron densities but smaller neutron exposures, contributing only slightly to s-process nucleosynthesis and primarily affecting nuclei at s-process path branch points. The 22Ne neutron source dominates s-process nucleosynthesis in more massive AGB stars.

Although the 13C(α, n)16O reaction is considered the most efficient neutron source for the s-process in low-mass AGB stars, the detailed process of how H mixes from the convective envelope into the 12C-rich region to form the 13C reservoir remains unclear. Over the past two decades, various physical mechanisms have been proposed to reproduce the amount of 13C required by observations, including convective overshoot, gravity waves, rotation, and magnetic fields. Among these, convective overshoot has been repeatedly suggested, while the magnetic field mechanism has been systematically elaborated in recent years. The formation of the 13C pocket remains an open problem.

Since the specific structure of the 13C pocket cannot be determined, its 13C mass fraction (concentration of 13C nuclei), size (mass of the pocket), and shape (distribution of 13C nuclei) are typically constrained through free parameterization using observational data in Torino post-processing AGB models. Observational constraints on the 13C pocket fall into four main categories: the solar system s-process abundance pattern, spectroscopic observations of [hs/ls] and [Pb/hs] in stars of different metallicities (where ls denotes light s-elements and hs denotes heavy s-elements, with [hs/ls] = [hs/Fe] -[ls/Fe]), s-process enhancements observed in stars younger than the Sun, and high-precision isotopic ratio measurements in presolar SiC grains. These constraints provide insights into the structure of the 13C pocket in AGB stars from different perspectives and to varying degrees. A deeper understanding of the structural characteristics of the pocket helps reveal its formation mechanism.

Three main models are used in the literature to simulate s-process nucleosynthesis in AGB stars. The first is the Torino post-processing AGB model, which performs complete nucleosynthesis calculations through post-processing. In this approach, the main physical parameters are obtained from stellar models calculated with a restricted nuclear network containing key isotopes and reactions, upon which an ad hoc 13C pocket is imposed. The Torino post-processing AGB model is the traditional and most widely used model for s-process nucleosynthesis via radiative 13C burning in AGB stars, and most post-processing nucleosynthesis calculations fitting stellar elemental abundance observations employ this model. The second is the FRANEC Repository of Updated Isotopic Tables and Yields (FRUITY) model, which directly couples a complete nuclear reaction network (from H to Bi) to stellar evolution, with the 13C pocket forming self-consistently after TDU and its mass decreasing as the intershell He region naturally contracts. Based on infrared observations of AGB stars, FRUITY models predict fewer thermal pulses. Over the past decade, when discussing assumptions for post-processing nucleosynthesis calculations of the 13C pocket, the more modern approach has been to use Torino post-processing AGB models updated with the FRUITY repository. The third is the Monash post-processing AGB model, where proton penetration is "assumed" without invoking a specific physical formation mechanism. This model assumes that at the deepest extent of each TDU event, protons from the envelope are mixed into the He intershell, forming a partial mixing zone (PMZ). Buntain et al. studied the effects of different types of PMZs on the resulting 13C pocket and subsequent nucleosynthesis, finding that changing the mixing function profile of the PMZ generally produces the same results as changing its extent. The Monash post-processing AGB model has also been used to calculate stellar yields for low- and intermediate-mass metal-rich AGB stars (1 M –8 M), investigate the metallicity of AGB parent stars of meteoritic SiC grains, and study the galactic chemical evolution of radioactive isotopes produced by the s-process. This paper focuses on how observational data constrain the structural parameters of the 13C pocket, primarily involving Torino AGB models or Torino post-processing AGB models updated with the FRUITY repository.

The structure of this paper is organized as follows: Section 2 reviews how four types of observational data constrain the 13C pocket, including the solar system s-process abundance pattern, s-process abundance patterns in stars of different metallicities, s-process elemental abundance observations of young stars in the Milky Way, and heavy element isotopic ratios in presolar SiC grains. Section 3 provides a brief summary and outlook.

2.1 Solar System s-Process Element Abundance Pattern

The s-process is responsible for producing about half of the nuclei heavier than Fe up to ^{209}Bi, including approximately 30 s-only nuclei that can only be formed via the s-process, such as ^{100}Ru, ^{110}Cd, ^{116}Sn, ^{122},^{123},^{124}Te, ^{150}Sm, and ^{160}Dy (unaffected by branching), as well as ^{142}Nd, ^{86},^{87}Sr, ^{152},^{154}Gd, and ^{134},^{136}Ba (affected by branching). Compared to other stars, the solar system elemental abundance distribution obtained from solar spectroscopy or meteoritic materials is the most precise and detailed, making it a common observational constraint in s-process theoretical studies.

Gallino et al. (hereafter G98) provided a detailed description of the Torino post-processing AGB model and performed extensive nucleosynthesis calculations. G98 proposed that the 13C pocket forms through diffusion of protons at the envelope boundary, making it relatively small. They defined a standard case 13C pocket (hereafter ST case), illustrated schematically in Figure 1 [Figure 1: see original paper] (from Figure 1 in G98). The vertical axis X represents the mass fraction of nuclide i (where i denotes H, 13C, or 14N), while the horizontal axis M represents the shell mass (in solar masses M) from the bottom to the top of the 13C shell region. Based on characteristic neutron exposure intensity, the 13C pocket is subdivided into three distinct zones. Following updates by Bisterzo et al., the total mass of the ST 13C pocket is about 10^{-3} M , approximately 1/20 of a typical convective TP mass in low-mass AGB stars, containing about 5×10^{-6} M of 13C and 2×10^{-7} M of 14N (produced through CNO cycling during H-shell burning), with an exponential distribution of 13C nuclei mass fractions. According to Straniero et al., these parameters are derived from past calculations (primarily based on convective models) and from calculations allowing a star with initial solar metallicity to reproduce the main s-process component of the solar system. Using the ST 13C pocket, G98 showed that a model with half-solar metallicity ($Z = 1/2$ Z) and initial mass of 2 M can reproduce the main s-process component of the solar system well. To better align with Galactic chemical evolution mechanisms, Arlandini et al. further calibrated the best-fit results to the arithmetic mean of nucleosynthetic yields from 1.5 M and 3 M models at half-solar metallicity. Subsequent studies found that similar s-process elemental abundance distributions could be obtained using either a zone-dependent or constant 13C distribution.

However, Palmerini et al. noted that reproducing solar system s-only nuclide abundances is only a basic test of validity for any slow neutron capture model—a necessary but not sufficient condition. This is because the parameters controlling the s-process essentially depend only on neutron exposure (or the average number of neutrons captured per Fe seed nucleus) and neutron density, and most existing models can be tuned to explain solar system abundances. Additionally, using the solar system s-process abundance pattern as a constraint on AGB star 13C pockets has another limitation: this pattern actually represents the integrated result of nucleosynthesis from multiple generations of AGB stars before solar system formation and cannot reflect the characteristics of a single AGB star. Reproducing the solar system s-process abundance pattern requires coupling Galactic Chemical Evolution (GCE) with AGB stellar models.

Bisterzo et al. investigated how uncertainties in the internal structure of the 13C pocket—by varying 13C and 14N abundances and pocket mass—affect GCE predictions. They found that once different weighted ranges of 13C pocket strength are assumed, GCE predictions at the time of solar system formation are only mildly affected by the pocket’ s size and shape. GCE predictions may also be influenced by uncertainties related to GCE assumptions. Nevertheless, these studies did not provide new constraints on the 13C pocket.

2.2 s-Process Element Abundance Patterns in Stars with Different Metallicities

The primary observational targets for s-process elemental abundances are: (1) planetary nebulae around AGB or post-AGB stars and white dwarfs; (2) binary companions that have accreted material from primary AGB stars. Stellar surface elemental abundances can be obtained from high-resolution spectroscopic observations in the ultraviolet, optical, and infrared ranges, with spectral features typically arising from absorption lines formed in the stellar photosphere. AGB stars are objects where the s-process is currently active (or was recently active), providing direct information about s-process nucleosynthesis in these stars. However, AGB stellar surfaces are very cool, and their spectra contain numerous molecular lines, making abundance analysis extremely difficult and limiting the number of measurable elements. Excess heavy s-process elements have also been found in post-AGB stars, which rapidly lose their residual envelopes as they evolve from AGB stars to planetary nebulae. However, their atmospheric structures are as unstable and complex as supergiants, complicating spectroscopic analysis. In contrast, in suitably separated binary systems, material from the primary AGB star’ s surface begins to accumulate onto the secondary companion when the primary evolves into an AGB star. The secondary is typically an unevolved main-sequence star or red giant, distinguished from normal stars by excess C and heavy s-process elements (such as Ba). Compared to the primary AGB star, it has a longer evolutionary timescale. After the primary evolves into a low-luminosity white dwarf, only the companion preserving the material provided by the AGB primary remains observable. In this case, s-process yields are easily measured on the secondary companion’ s surface because the object remains relatively warm with less severe molecular absorption. Additionally, abundances of noble gases (such as Ne, Ar) can be observed from emission lines in planetary nebulae, providing complementary information to chemical yields obtained from stellar observations. Generally, analysis of these spectral lines can only determine elemental abundances, and the variety of measurable elements is relatively limited compared to solar system material analysis. Through detailed analysis of special spectral lines, isotopic ratios of important elements such as Ba and Eu can also be measured.

Measuring heavy element abundance patterns in AGB stars or objects affected by AGB nucleosynthesis and comparing them with model predictions is crucial for understanding the s-process mechanism. Theoretical models predict that s-process element formation in AGB stars depends on the star’ s initial mass, metallicity, 13C pocket properties, and mass-loss rate. Elemental abundances at the three s-process peaks located at magic neutron numbers N = 50, 82, and 126 can provide observational constraints on AGB models. These peaks occur because Sr, Y, Zr (light s-process elements, ls), Ba, La, Ce, Nd, Sm (heavy s-process elements, hs), and Pb have low neutron capture cross-sections that act as bottlenecks in the s-process reaction path. AGB model nucleosynthesis calculations show that [hs/ls] is quite low at high metallicity (Z) because the limited number of neutrons per seed restricts heavy s-process element production. As Z decreases, [hs/ls] first increases, reaches a maximum at some Z value (which depends on 13C pocket efficiency), and then begins to decrease. [Pb/hs] follows a similar pattern. It is particularly important to emphasize that since these ratios are essentially frozen after a few dredge-up episodes, they are almost independent of mass-loss rate and TDU efficiency—the two most uncertain quantities in AGB modeling. Consequently, [hs/ls] and [Pb/hs] are commonly used as indicators of s-process efficiency to test AGB star s-process nucleosynthesis models and infer neutron exposure or the total amount of 13C within the pocket.

Torino post-processing nucleosynthesis calculations based on the G98 ST 13C pocket show that the observed variations of [hs/ls] and [Pb/hs] with metallicity in stars can be well reproduced by adopting a range of 13C pocket strengths (also called 13C pocket efficiencies) k × ST (i.e., multiplying the 13C mass fraction of the ST case by a factor k while keeping the pocket mass constant). For example, Husti et al. used 13C pockets ranging from ST = 4.5 to 2ST to simulate the s-element abundance patterns of 34 Ba stars ($-1.19 \leq$ [Fe/H] $\leq$ -0.04), while Bisterzo et al. used 13C pockets ranging from ST = 55 to ST to explain observational data for 94 carbon-enhanced metal-poor stars enriched in s-process elements (CEMP(s) stars) (89 of which have $-3.5 \leq$ [Fe/H] ≤ -1.7; see their Tables 10 and 11).

Bisterzo et al. noted that 2ST represents an upper limit because further proton ingestion leads to 14N formation, which consumes neutrons via 14N(n, p)14C (earning 14N the designation "neutron poison"). The minimum 13C pocket that significantly affects the s-process distribution depends on the star' s initial Fe content because the number of available neutrons per Fe seed increases with decreasing metallicity. As the smallest 13C pocket, they assumed 0.1ST for disk metallicities ([Fe/H] < -1) and 0.03ST for halo metallicities ([Fe/H] > -1). These fitting parameters constrain the range of total 13C amount within AGB star 13C pockets.

AGB stars are typically divided into two classes based on the C/O abundance ratio in their envelopes: MS and S stars with C/O < 1, and C(N) stars with C/O ≥ 1. For a given metallicity, observations reveal dispersions in the three s-process peaks among MS, S, C(N) stars, and Ba stars in the Galactic disk. At low metallicities, even larger dispersions are observed in CEMP(s) stars based on high-resolution spectroscopic measurements. The physical reasons for these phenomena remain unclear but may be due to variations in 13C pocket parameters and AGB star initial masses. The observed dispersions can still be explained by matching different total amounts of 13C nuclei in the pocket.

Liu et al. pointed out that for AGB models with fixed metallicity and initial mass, the final s-process elemental yields depend not only on the total 13C mass but also on the 13C pocket mass, the 13C mass fraction, and to a lesser extent, the 13C distribution. For instance, AGB models based on larger 13C pockets over-predict the observed astronomical [hs/ls] values, but the predicted [hs/ls] can easily be reduced by decreasing the 13C mass fraction within the larger pocket. Therefore, all parameters of the 13C pocket should be considered when explaining observed dispersions in s-process elemental abundances at a given metallicity. However, observational data on s-process elemental abundances are not sufficiently sensitive to different 13C pocket parameters adopted in AGB stellar models because the s-process essentially modifies the abundances of individual nuclides rather than individual elements, while spectroscopic observations primarily provide elemental abundances, with isotopic ratios measurable for only a very few elements. Consequently, fine constraints on the 13C pocket structure are difficult to obtain from stellar spectroscopic observations.

2.3 Observational Constraints from Young Stars in the Milky Way

Over the past decade, improved observational techniques have revealed new constraints on 13C pocket parameters. Measurements comparing s-process elemental abundances between the Sun and stars in young open clusters show that neutron-rich s-process elements Y, Zr, Ba, La, and Ce are enhanced relative to the Sun, with heavier s-elements (Ba, La, and Ce) and lighter s-elements (Y and Zr) showing comparable enhancement levels, thus maintaining roughly solar proportions between the two groups. Recently, papers from the ESO-GAIA spectroscopic survey using the UVES spectrograph on the Very Large Telescope have systematically confirmed enhancements of s-process elements in young stars.

Maiorca et al. (hereafter M12) conducted an in-depth analysis of these observational results. They noted that according to traditional s-process nucleosynthesis scenarios, Galactic chemical and dynamical evolution models predict that [X/Fe] for neutron-rich elements after solar formation should be flat or even decreasing, but not increasing. M12 argued that these observational results can only be understood if the contribution from the 13C(α, n)16O neutron source in low-mass stars is larger than currently adopted in AGB models. M12 demonstrated that only a threefold increase in the 13C reservoir in very low-mass (M < 1.5 M) AGB stars—a 13C pocket mass of 4×10^{-3} M with an average effective 13C mass fraction of $X_{13} = (3\text{–}5) \times 10^{-3}$ in this depth range (compared to $X_{13} = 5 \times 10^{-3}$ in the G98 ST case)—is needed to explain the observed enhancements through Galactic evolution and nucleosynthesis models. M12' s large-pocket scenario combines limited pulse-to-pulse interpulse cycles with high s-process efficiency, requiring no special neutron capture processes (such as the "LEPP—Light Element Primary Process" suggested by Travaglio et al.) to compensate for deficiencies in s-nuclei at A < 120 in the solar system, and it does not alter previous explanations for s-process enhancements in more massive (1.5 M -2.5 M) AGB stars near the Sun.

M12' s large-pocket model satisfies recent observational constraints from stellar luminosities, which demonstrate that effective mass loss prevents AGB luminosities from exceeding 10^4 L , implying fewer thermal pulses than in previous models. Herwig et al. and Cristallo et al. found that convective overshoot alone cannot form 13C pockets more massive than 10^{-3} M , while rotating convective mixing models indicate that low-metallicity or rapidly rotating metal-rich AGB stars can form massive 13C pockets, with different rotation velocities potentially altering the mass and distribution of 13C within the pocket.

Particularly noteworthy is that in recent years, the magnetohydrodynamic (MHD) induced mixing mechanism for 13C reservoir formation has been systematically elaborated and provides favorable support for M12' s large-pocket scenario. First, Trippella et al. suggested that magnetic buoyancy (or other forcing mechanisms) is a good candidate for forming a 13C reservoir similar to that proposed by M12. Subsequently, Nucci and Busso found that a rather general, exact analytical solution is possible for the full MHD equations in the radiative regions of AGB stars. Trippella et al. then made the first attempt to describe a physical mechanism for MHD-induced mixing in 13C reservoir formation, implementing exact solutions of the MHD equations to compute the composition distribution of the 13C pocket produced during the 6th dredge-up in a 1.5 M , solar-metallicity AGB star. Palmerini et al. recalculated this distribution, with results shown in Figure 2 [Figure 2: see original paper]. They also computed the penetration of protons into the He-rich intershell and subsequent formation of the 13C neutron source for models with metallicities 1.0 Z and masses in the range (1.5-3) M . These studies show that MHD-induced 13C reservoirs are characterized by low concentrations, extending in most cases to about 10^{-3} M , with an almost flat distribution of 13C nuclei. The depth of this region is about 5×10^{-4} M for the first pulse of the lowest-mass model, then decreases with increasing initial mass and thermal pulse number. This confirms M12' s suggestion that in at least the lowest-mass AGB stars ($M \leq$ 1.5 M), the 13C reservoir formed during TDU is much larger than previously assumed. Recently, Busso et al. computed MHD-induced 13C pocket formation for AGB star evolution models with masses of 1.5 M , 2 M , and 3 M and metallicities $-1.3 \leq$ [Fe/H] ≤ 0.1, providing analytical fits for 13C pocket masses. Their results further validate previous conclusions.

2.4 Heavy Element Isotopic Ratios in Presolar SiC Grains

Independent observational evidence indicating that the 13C pocket differs substantially from traditional assumptions comes from recent analyses by Liu et al. of s-element isotopic ratios in presolar SiC grains.

Given that the s-process occurs in a relatively low neutron density environment in AGB stars, the neutron flux reaches a steady state between magic neutron numbers, where the product of the Maxwellian-averaged stellar (n, γ) cross-section (MACS) σ and the corresponding s-process abundance N , σ N , remains nearly constant (see Figure 2 of reference [3]). Therefore, except for nuclei affected by branching points, nuclide abundances N between magic neutron numbers are inversely proportional to their σ and are almost insensitive to the 13C pocket parameters adopted in AGB star models. On the other hand, the neutron magic nuclei ^{88}Sr (N = 50), ^{138}Ba (N = 82), and ^{208}Pb (N = 126) have very small neutron capture cross-sections, making them bottlenecks for neutron capture flux along the s-process path and regulating the neutron flux. The MACS values of ^{88}Sr and ^{138}Ba are 1/10 those of their respective normalized s-only isotopes ^{86}Sr and ^{136}Ba, making AGB model predictions for the isotopic ratios $\delta(^{88}\mathrm{Sr}/^{86}\mathrm{Sr})$ and $\delta(^{138}\mathrm{Ba}/^{136}\mathrm{Ba})$ extremely sensitive to the details of the 13C pocket adopted in model calculations. These ratios can therefore serve as tracers of the 13C pocket. The δ value for an isotopic ratio is defined as the per mil deviation of the sample ratio relative to the standard ratio: $\delta($ X/ X$) =$ [(X/ X)grain/(X/ X)standard $- 1] \times 1000$.

SiC is a refractory mineral phase that condenses in C-rich environments (C/O > 1). SiC grains were first discovered in carbonaceous chondrites. Most presolar SiC grains (>90%) originate from low-mass AGB stars with metallicities near (1.5-3) M and contain heavy trace elements with s-process isotopic signatures. Analysis precision for heavy element isotopic compositions in SiC grains reaches about 1%-10%, providing a unique opportunity to study s-process nucleosynthesis in AGB stars with precision currently unattainable through astronomical observations.

Liu et al. demonstrated that in most cases, using only one tracer of the 13C pocket, such as $\delta(^{138}\mathrm{Ba}/^{136}\mathrm{Ba})$, cannot separate the effects of 13C mass fraction from pocket mass. Coupled measurements of ^{138}Ba/^{136}Ba and ^{88}Sr/^{86}Sr ratios in SiC grains are needed to monitor neutron flux at two peaks along the s-process path. Liu et al. used resonance ionization mass spectrometry (RIMS) to simultaneously measure Sr and Ba isotopic ratios in 61 presolar SiC grains from the Murchison meteorite. The results showed that varying only the initial stellar mass in Torino post-processing AGB models cannot explain the range of isotopic ratios observed in the grains. By comparing correlated ^{88}Sr/^{86}Sr-^{138}Ba/^{136}Ba values with Torino post-processing AGB models of near-solar metallicity (represented by 2 M and 0.5 Z AGB models), constraints on the 13C pocket in low-mass AGB stars were obtained.

The results indicate that for explaining isotopic composition variations in SiC grains, the importance of the three fundamental 13C pocket parameters ranks as: 13C nuclei concentration, 13C pocket mass, and 13C nuclei distribution. Changing the size of the 13C pocket to less than 1×10^{-3} M is insufficient to cover the entire observational data range; larger pockets are required. Since AGB model predictions for $\delta(^{88}\mathrm{Sr}/^{86}\mathrm{Sr})$ are sensitive to the 13C mass fraction, the $\delta(^{88}\mathrm{Sr}/^{86}\mathrm{Sr})$ values in SiC grains constrain it well below ST = 1.3, explicitly ruling out small 13C pockets with concentrated nuclei as the dominant pocket type and favoring the existence of large pockets with diluted nuclei in parent AGB stars. To reproduce the observed ^{138}Ba/^{136}Ba and ^{88}Sr/^{86}Sr signatures in SiC grains, the parent AGB stars typically require 13C pockets with masses of (1-2) $\times 10^{-3}$ M . Furthermore, the distribution shape of 13C nuclei within the reservoir must be quite flat with low concentrations throughout most of the pocket, differing from traditional assumptions. These characteristics have become general constraints that any mixing model aiming to generate an appropriate 13C reservoir must consider.

Additionally, among the 61 measured grains, six showed strong depletions in ^{138}Ba with $\delta(^{138}\mathrm{Ba}/^{136}\mathrm{Ba}) < -400‰$. Liu et al. reproduced the Sr-Ba isotopic ratios in these grains using a 13C pocket with ST = 7.5 and mass of 8×10^{-3} M . They suggested that these extremely negative $\delta(^{138}\mathrm{Ba}/^{136}\mathrm{Ba})$ values observed in rare SiC grains indicate that some AGB stars may have extremely large 13C pockets.

Subsequently, Liu et al. found that using the magnetic buoyancy-induced 13C pocket from Trippella et al. (hereafter Trippella pocket), observational values of Ni, Sr, and Ba isotopic ratios from SiC grains in the literature could be explained by Torino post-processing nucleosynthesis calculations updated with FRUITY stellar models. Adopting the 13C mass fraction from the Trippella pocket shown in Figure 2 of Trippella et al. as the initial value, Liu et al. compared model predictions with grain data by varying the 13C mass fraction (from 1/3 to 1.5 times the initial value) and 13C pocket mass (from 1.7×10^{-3} to 5.0×10^{-3} M) for a 3 M , 1.5 Z AGB model. They found that only with the initial 13C mass fraction could similar explanations be provided for both Sr-Ba and Ni isotopic data. Further investigation revealed that the 13C mass fraction most similar to the grain data is a linear function of the chosen stellar metallicity. Overall, the combined Sr-Ba and Ni isotopic data indicate that large Trippella pockets exist in the parent AGB stars of most SiC grains, corresponding to deep mixing of H into the He intershell at low concentrations. For reference, a Trippella pocket with initial mass of 3.3×10^{-3} M contains about 6.74×10^{-6} M of 13C, giving an average 13C mass fraction of about 2×10^{-3} (approximately half that of the G98 ST pocket). Palmerini et al. and Busso et al. further confirmed these conclusions. As Palmerini et al. explicitly stated, this result arises because MHD-induced 13C reservoirs possess the general characteristics that Liu et al. identified as necessary. Therefore, the observational results of Liu et al. strongly support the MHD-driven mixing formation mechanism for the 13C neutron source.

3 Summary and Outlook

This paper has reviewed how four categories of s-process elemental abundance observations constrain the 13C pocket in AGB stars: (1) constraints from the solar system s-process abundance pattern, which define the ST case 13C pocket; (2) constraints from s-process abundance patterns in stars of different metallicities, which limit the range of total 13C amount in the pocket; (3) recent observations of s-element enhancements in open clusters younger than the Sun, which require larger 13C reservoirs in low-mass AGB stars than traditionally assumed; and (4) high-precision measurements of isotopic ratios of Sr, Ba, and Ni in presolar SiC grains, which demand that most AGB stars have 13C pockets with greater mass, lower concentration, and flatter distribution than conventionally assumed. These observational evidences strongly support the MHD scenario for 13C pocket formation, though mechanisms such as rotation and convective overshoot cannot be excluded.

Clearly, continued exploration of new observational constraints on the 13C pocket, testing of existing conclusions, and provision of new insights into the physical conditions of nucleosynthesis in AGB stars remain important for current research. For example, the validity of conclusions based on Torino post-processing nucleosynthesis calculations could be further tested by running stellar evolution models coupled with complete nucleosynthesis networks (such as FRUITY models) and implementing a detailed treatment of magnetic buoyancy-induced mixing within a stellar model. Additionally, Zr is the most typical ls element. AGB model predictions for $\delta(^{92}\mathrm{Zr}/^{94}\mathrm{Zr})$ increase with 13C pocket mass but are independent of stellar mass and metallicity changes. In contrast, predictions for $\delta(^{96}\mathrm{Zr}/^{94}\mathrm{Zr})$ for the last TP increase with initial stellar mass, with an unchanged minimum value, because the final ^{96}Zr yield in AGB stars strongly depends on the 22Ne(α, n)^{25}Mg rate. An upcoming research topic is obtaining new high-precision Zr isotopic data for SiC grains to better distinguish between the effects of stellar mass and pocket mass, which would allow placing an upper limit on the mass of AGB stars that formed mainstream SiC grains.

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