Galactic chemical evolution of Ba-peak elements

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Abstract. The chemical evolution of the Galaxy is followed for the elements affected by neutron capture, in particular for those in the atomic number range 56 to 63 (Ba, La, Ce, Pr, Nd, Sm and Eu). Neutrons by the major 13C source, released in radiative conditions in the interpulse periods of TP-AGB stars, give rise to an efficient s-processing, making low mass AGB the major contributors to the chemical evolution of heavy elements. The s-process scenario, characterized by the combined operation of the two neutron sources 13C(α,n)16O and 22Ne(α,n)25Mg, is analyzed using AGB stellar evolutionary calculations with the FRANEC Code (FRASCATI Raphson-Newton Evolutionary Code), and are applied over a wide range of stellar masses and metallicities. The presence of r-process elements in low metallicity stars is indicative of a prompt enrichment of the Galaxy by early generation of stars, and low mass SNII appear to be good candidates for primary production of r-nuclei. The chemical evolution model used here is organized over three-zone, halo, thick and thin disk. A comparison between model abundance predictions of the r- and s-process elements observed in unevolved halo and disk stars confirms the overall consistency of the theoretical framework and reveals a number of striking features deserving a careful analysis.

1 s-process from Asymptotic Giant Branch Stars

Since the pioneering work on stellar nucleosynthesis by Burbidge et al. (1957), the synthesis of nuclei heavier than iron has been recognized to be dominated by neutron capture processes, both slow (the s-process), and rapid (the r-process). For the s-process, the abundance distribution in the solar system is currently considered as the superposition of two components, the weak and the main component. The weak component, responsible for the s-process nuclides up to A ≈ 90, is due to neutron captures occurring in massive stars by the activation of the 22Ne(α,n)25Mg reaction. The main component, feeding the heavier s-process nuclides, originates in low mass AGB stars during the recurrent thermal instabilities in the He shell. Many theoretical and observational works converge on the idea that neutrons are released in radiative conditions in the interpulse period via the 13C(α,n)16O reaction. A tiny 13C-pocket is assumed to develop as a consequence of the penetration of a small amount of protons from the envelope in the 12C-rich intershell. The s-process yields adopted here have been obtained performing post-process calculations starting from stellar evolutionary models obtained with the FRANEC code (Straniero et al. 1997; Gallino et al. 1998). In these models, the third dredge-up mechanism, mixing with the envelope newly synthesized 12C and s-process elements, is self-consistently found after a limited number of thermal pulses. Concerning the dependence of the results on the Galactic chemical evolution of the s-elements on the choice of the amount and profile of the 13C-pocket and on the dredged-up mass in the envelope we refer to the discussion in Travaglio et al. (1998). Since the 13C-pocket is of primary origin, the s-process distribution is strongly dependent on metallicity (Clayton 1988). Typical production factors (with
Figure 1: Production factors as a function of metallicity of selected elements in the He shell material cumulatively mixed with the surface of a $M = 2 \, M_\odot$ AGB star.

respect to solar) of elements belonging to the three major $s$-process peaks are shown in Fig. 1 as a function of metallicity. The production factor of Eu, an element mostly fed by the $r$-process, is also shown for comparison. For more details see Gallino et al. (1999).

2 Chemical evolution model

The chemical evolution model adopted for this work is described in Ferrini et al. (1992). It is based on the interconnected evolution of three zones: halo, thick disk and thin disk, whose relative composition in stars, gas phases, and stellar remnants, is followed during the Galactic age. The thin disk is divided into concentric annuli. Here we consider the evolution of the solar annulus, located 8.5 kpc from the Galactic center. The Star Formation Rate (SFR) is obtained as outcome of self-regulating processes occurring in the molecular gas phase, either spontaneous or stimulated by the presence of massive stars. In Fig. 2 the SFR is plotted as a function of [Fe/H] during the evolution of the Galaxy.

3 Galactic evolution of Ba from AGB stars

The chemical evolution of Ba, taken as representative of the heavy $s$-process elements, is plotted in Fig. 3 and is compared with spectroscopic observations of unevolved stars of different metallicities. The lower and upper limit of AGB stellar masses were taken to be 2 and $4 \, M_\odot$, respectively, similar to the observed range of chemically peculiar AGB stars. At $t = t_\odot$ we obtain a Ba $s$-process contribution to solar of 80%. From Fig. 3 one can see that the $s$-process contribution begins to dominate the galactic evolution
at [Fe/H] $\simeq -1.5$, whereas at lower [Fe/H] the contribution of low-mass AGB stars is by far too low. This is essentially due to the strong dependence of the $s$-process yields on metallicity. To check the sensitivity of this result, Travaglio et al. (1998) also considered the effect of adding the $s$-process contribution by intermediate mass AGB stars in the range $4 - 8 M_\odot$, starting from FRANEC evolutionary models of a 5 $M_\odot$ and a 7 $M_\odot$ (Vaglio et al. 1999). However, the efficiency of these more massive stars in producing Ba is too low to contribute significantly to the chemical enrichment of the Galaxy.

4 $r$-process treatment in our model

As first stressed by Truran (1981), the heavy element abundance patterns in very metal-poor stars are compatible with an $r$-process origin. This point was been recently sustained by new HST observations of low metallicity unevolved stars, reported by Sneden et al. (1998). From the theoretical point of view, despite a large number of recent works, the astrophysical site of the $r$-process is still uncertain (Baron et al. 1998; Wheeler at al. 1998). In order to quantify the $r$-contribution, we treated the $r$-process as a typical primary process originating from low-mass Type II SNe ($M = 8 - 10 M_\odot$), in agreement with recent theoretical predictions from Wheeler et al. (1998). Then, at $t = t_\odot$ we derived the $r$-residuals, after subtracting from the solar abundances the predicted $s$-fractions.

5 Galactic evolution of Ba and Eu

In Fig. 4 the predicted Galactic evolutionary trends for the $s + r$ contributions to Ba and Eu are shown, as compared with the available spectroscopic data for unevolved halo and disk stars. These plots make clear that a delay in the $r$-process production...
Figure 4: Evolution of [Ba/Fe] and [Eu/Fe] vs. [Fe/H] according to our model predictions for halo (short-dashed), thick disk (long-dashed) and thin disk (solid), compared with the available spectroscopic observations.

with respect to other heavy elements from SNII (i.e. Fe) is needed in order to match the spectroscopic data at [Fe/H]<-2. Since Eu is mostly made by r-process nucleosynthesis (94% at $t=t_\odot$), the predicted [Eu/Fe] trend vs. [Fe/H], compared with observations, is a good test of our assumption to quantify the r-process fraction in the Galaxy. The declining in [Ba/Fe] and in [Eu/Fe] at [Fe/H] ≃ -2.5 can be explained by the finite lifetime of the low-mass SNII, hence discriminating the production of the r-process from the Fe production in more massive SNe. The large observational scatter for the stars at the lowest metallicities can be essentially attributed to chemical heterogeneity in the Galactic halo. In conclusion, the Galactic barium enrichment can be explained through the interplay of a complex s-process mechanism taking place in low mass AGB stars at various metallicities, and of a primary-like r-process occurring in the lower mass range of SNIIe.

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