THE s–PROCESS IN AGB STARS

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1. THE PHENOMENOLOGICAL ANALYSIS OF THE s–PROCESS: THE MAIN COMPONENT

The evidence of an exponential distribution of neutron exposures for reproducing the solar–system s–isotopes between Zr and Pb, the *main* component, comes from a phenomenological analysis of the s–path in the σN versus A plot (see Käppeler, Beer and Wisshak, 1989). The resulting mean neutron exposure is $\tau_0 = 0.30 \pm 0.01$ mb^{-1}. The study of branchings with no or weak temperature dependence (^{95}Zr; ^{147}Nd, ^{147,148}Pm; ^{185}W, ^{186}Re) allows one to derive an effective neutron density $n_n = (3.4\pm1.0)\times10^8$ cm^{-3}. On the other hand, an effective temperature is obtained from the branchings ^{134,135}Cs, ^{151}Sm, ^{154}Eu and ^{176}Lu: $T_8 = 3.4 \pm 0.5$ (Käppeler et al., 1990). Although the phenomenological approach is very useful because it is independent of stellar models, nonetheless it can only lead to effective physical conditions, symplifying the complexity of the astrophysical sites.

2. s–PROCESSING IN A LOW MASS STAR DURING TP–AGB PHASE.

An exponential distribution of neutron exposures is naturally obtained during recurrent thermal pulses of the He shell in AGB stars (the TP–AGB phase; Iben and Renzini, 1983). The intermediate mass stars (M=3–8 M$_\odot$) were first considered as the best candidates through the activation of the ^{22}Ne(α,n)^{25}Mg reaction (Iben, 1975), but this scenario was successively severily questioned both on observational and theoretical grounds. Presently, the most promising site for the synthesis of the bulk of the s–nuclei appears to be related to the ^{13}C(α, n)^{16}O reaction operating in low mass stars (M=1–3 M$_\odot$) during the TP-AGB phase (Iben and Renzini, 1982; Hollowell and Iben, 1988; Gallino, 1989). In the interpulse phase, a thin semiconvective region forms at the H–discontinuity, mixing a few protons from the envelope with the ^{12}C–rich zone. By the reactivation of the H-shell a small ^{13}C–rich pocket of few 10^{-4} M$_\odot$ is then built. When this zone is engulfed by the next thermal instability, neutrons are released at a typical temperature of 12 keV, giving rise to a major s–processing episode. The mean neutron density rapidly increases, reaching a plateau of about 4×10^8 cm^{-3}, and then sharply decreases when the residual ^{13}C is consumed. A second minor neutron spike occurs later, at the higher temperature of 23 keV when the convective He region spreads over its maximum extension and the ^{22}Ne source is marginally activated. Although this second neutron exposure is negligible, nevertheless the fact tha it occurs at high temperature determines the production of the few branching–dependent s–only isotopes that are considered as thermometers for the s–process: ^{80}Kr, ^{152}Gd, ^{164}Er, ^{176}Lu, ^{180}Ta, with minor effects on other isotopes such as ^{86}Sr, ^{148}Sm, ^{154}Gd, ^{170}Yb.

Assuming a metallicity of 1/3 the solar one, a good reproduction of the main component is obtained as shown in Figure 1, where the overabundances with respect to the initial composition are displayed as a function of the atomic mass A. In the figure the s–only isotopes are indicated by stars or diamonds; the + and × symbols refer to isotopes with s–contribution greater than 80 or 60 % respectively. The diamonds represent the 7 unbranched s–only isotopes with the best determined cross sections. After correcting for small p–contributions (see Käppeler et al.,

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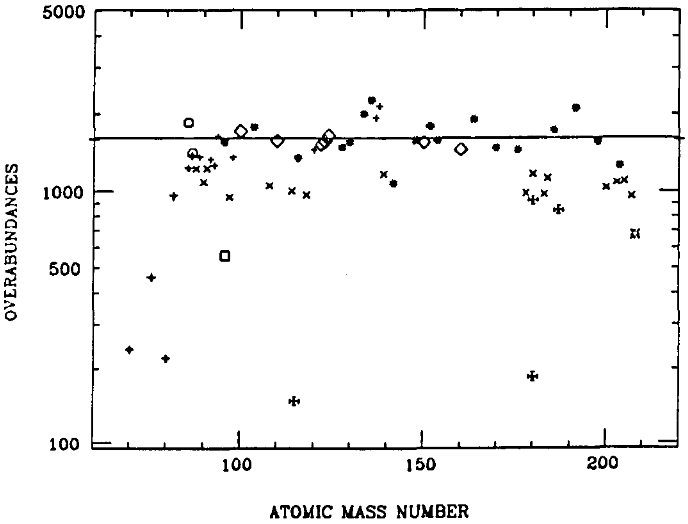

Figure 1: The main component from a TP–AGB star of low mass with metallicity 1/3 of the solar one.

1990), they provide a mean *s*–enhancement of about 1600. To get Figure 1 the most updated nuclear parameters were used, including the recent evaluations of not 1/v trends of neutron capture cross sections (Beer, Voß and Winters, 1991); the beta–decay rates were taken from Takahashi and Yokoi (1987), improved by more recent results. Special cases are ^{187}Os, whose solar abundance receives about 50 % contribution by the decay of ^{187}Re, ^{208}Pb, for which a further *strong* component is needed, and the very rare isotopes ^{115}Sn, ^{180}Ta, ^{180}W. The three not *s*–only isotopes ^{86}Kr, ^{87}Rb and ^{96}Zr are indicated with special symbols. All of them depend on the peak neutron density. The mean exposure being the same, a factor of 2 higher peak neutron density would increase their overabundances only (by 15%, 30%, and 85%, respectively). We notice that a consistent fraction of ^{96}Zr has recently been found in the atmospheres of S stars showing *s*–enrichments (Lambert, 1988). Moreover, the ^{86}Kr and ^{87}Rb production depends on the difficult branching at ^{85}Kr. The results shown here were obtained by introducing a consistent direct capture contribution at 12 keV to the cross section of ^{86}Kr, which is plausible for such a magic nucleus. The *s*–only nuclides that deviate from the mean are to be interpreted in the light of present uncertainties affecting nuclear parameters and stellar models. In particular, the excess of Ba isotopes may be ascribed to a poor determination of their maxwellian averaged neutron capture cross sections.

Below A<90 the *s*–only isotopes alone are shown; the fall of the overabundances is evident. This is the region where the weak component from massive stars is contributing (Raiteri et al., 1991a,b). The resulting match to the solar system distribution of all the *s*–isotopes is very satisfactory, including ^{80}Kr.

3. THE PROBLEM OF THE ^{13}C POCKET FORMATION

In Figure 1 asymptotic values are presented, as resulting after roughly 15 pulses. Actually, a typical pulse is assumed to repeat under the same conditions, but the situation is clearly more complex. However, we think that the present uncertainties affecting the way convective mixing is treated do not allow to improve the model much more. The major problem regarding *s*–processing in low mass stars is connected with the formation of the ^{13}C pocket. Our results were obtained following the prescriptions by Hollowell and Iben (1988, 1989), that refer to a low metallicity star in which overshooting is introduced when mixing protons into the carbon–rich region. According to Iben (1983) stars of higher metallicity would not experience the above semiconvective episode. In addition, one has to recall that other evolutionary calculations of low mass stars did not confirm the occurrence of such mixing (Boothroyd and Sackmann, 1988; Lattanzio, 1989) even in metal poor stars. However, observations of MS, S and C stars demonstrate that *s*–processing must operate in disc stars of low mass (Smith and Lambert,1990). The point is to study in deep details the physics of a very thin region close to a strong discontinuity in the chemical composition, between the convective envelope and the carbon–rich zone.

4. EFFECTS OF METALLICITY IN DISC STARS

The distribution of the *s*–isotopes depends on the assumed initial composition. As a first approximation the ^{13}C source can be thought as a primary one, since the ^{13}C formation results from proton captures on newly synthesized ^{12}C, while the iron seeds vary with the metal content. Actually, stellar models also depend on metallicity, affecting in particular the formation of the ^{13}C pocket, and the shape and overlapping between subsequent pulses. For halo stars, the lower initial metal content favours a higher neutron exposure, and the *s*-distribution peaks on ^{208}Pb, indicating the astrophysical origin of the *strong* component (Gallino et al., 1991). For disc stars, an increase of the overlapping factor (by $\sim$ 20 %) as it is found when passing from population II to population I stars counterbalances the fall of the *s*–process efficiency at higher metallicities. A demanding analysis is required to reach a consistent picture for the observations of *s*–enhancements in MS, S, C, and Ba stars (Smith and Lambert, 1990), for the primary-like trend of [Ba/Fe] versus [Fe/H] observed in giants and red dwarf stars, and finally for these "pieces" of carbon stars that are the SiC microscopic grains recently found in pristine meteorites (Lewis et al., 1990; Gallino et al., 1990).

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