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Nucleosynthesis in AGB stars

S. Palmerini and M. Busso

Dipartimento di Fisica, Università di Perugia, via A. Pascoli, 06123 Perugia
e-mail: `palmerini@fisica.unipg.it; busso@fisica.unipg.it`

Abstract. A review on Nucleosynthesis phenomena occurring in asymptotic Giant Branch (AGB) Stars is presented. We discuss the modifications of the abundances of intermediate-mass elements due to proton captures in slow mass circulation phenomena above the H-burning shell (the so-called cool bottom processes). They are smaller in magnitude but of the same nature of the abundance changes do to the occurrence of H burning at the hot base of the convective envelope of massive AGB stars (hot bottom burning). The elements affected cover the range from ^{3}He and ^{7}Li up to Mg-Al. We also consider nuclear processes from the He-rich intershell zone, producing ^{12}C, ^{19}F, ^{22}Ne, ^{25,26}Mg and neutron-rich elements from the *s*-process. In these issues the main problems are connected to uncertainties in nuclear cross sections, to the complexity of partial mixing mechanisms and to the poorly known physics of mass loss.

1. AGB abundances and model uncertainties

Asymptotic Giant Branch stars are today universally known as the place where carbon is produced, together with heavy elements originated by slow neutron captures. The nucleosynthesis path for producing these neutron-rich species runs along the valley of β-stability and generates about 50% of nuclei heavier than Fe (Busso et al. 2004). The elements more heavily affected are those of the *main component* of the *s*-process (from Sr to Pb).

Apart from ^{12}C, ^{22}Ne and a few other nuclei typical of He burning zones, most light element isotopic changes come from proton captures in regions across and above the H-burning shell. Actually nucleosynthesis in AGB stars must be limited to the processed typical of H and He burning, as these red giants do not proceed further in their evolution and die leaving a compact C-O remnant (a white dwarf). Direct observation in AGB photospheres in the Planetary Nebulae that are formed out of their envelope offer a potential laboratory for measuring abundances of several nuclei directly in the producing stars, something that is in general precluded for higher masses.

The appearance of the He-burning products at the stellar surface is mainly due to the repeated downward extension of the convective envelope, in mixing events called the ”third dredge up”. They drag matter from the He-rich intershell region upward. Instead, isotopic peculiarities of light elements related to proton captures are not satisfactorily explained by purely convective mixing phenomena and require the action of some slower, continuous extra-mixing (Wasserburg et al. 1995). Hence, in order to understand AGB abundances we

Send offprint requests to: M. Busso
Correspondence to: Dipartimento di Fisica, Università di Perugia, via A. Pascoli, 06123 Perugia

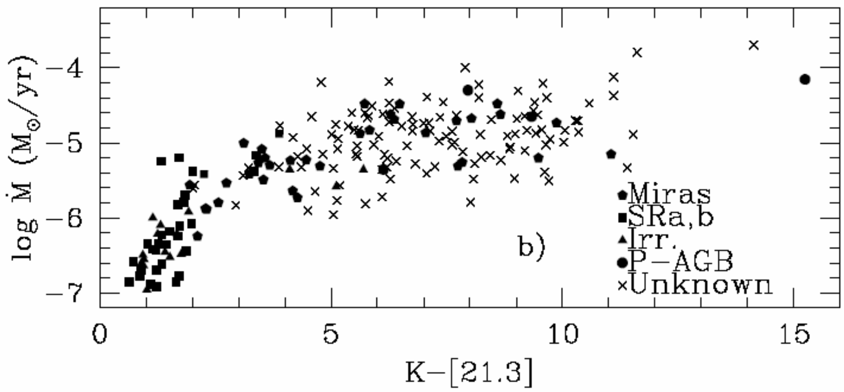

Fig. 1. Mass loss rates of various classes of C-rich AGB stars (taken from the sample of Guandalini et al. 2006). They are plotted as a function of the infrared color K-[21.3], computed from observations listed in the 2MASS, ISO and MSX catalogues. The relations are not linear and still include considerable dispersion.

need to understand the complex mechanisms of mass transport, still affected by many sources of uncertainty.

The possibility of observing abundance changes at the photosphere, induced by the internal nuclear phenomena and by mixing events, is strictly related to the physical properties of AGB stars. In particular, observations are hampered by the development of opaque envelopes rich in dust, which hide the photosphere especially for very evolved giants. For less reddened sources, optical spectroscopy is made difficult by the dynamic behavior of the atmospheres, which pulsate originating their long-period variability.

The occurrence of mass loss is an effect of both the above phenomena. The mass loss history is in itself relevant for understanding the origin of surface abundances; actually, too strong mass loss rates, preventing a star from passing through at least a few thermal pulses before ejecting the planetary nebula, would strongly limit the expected chemical peculiarities in the photosphere.

Our knowledge of mass loss rates and of the AGB luminosities is unfortunately very poor and only recently, thanks to the availability of large sets of mid-far infrared (IR) data from space missions like ISO, MSX and Spitzer, it is starting to become quantitative. As an example, in Figure 1 we show how known mass loss rates (measured at radio wavelengths) can now be related to IR colors, in the aim of calibrating these last as a measure of stellar wind intensities (for details see Guandalini et al. 2006). Despite the use of space-based observations and of astrometric distance estimates, the relation of Figure 1 still gives rather poor constraints.

2. Nucleosynthesis in AGB Stars by Proton Captures

Observations of red giant stars above the so-called *luminosity bump* reveal that the isotopic mix of CNO elements is complex and not due to purely convective dredge-up, at least for masses up to $\sim 2.5\ M_{\odot}$. The change of these isotopic abundances is accompanied by extensive destruction of Li. Now many sets of observations, accumulated since the early nineties for various elements up to Ne, confirm this fact (Gilroy & Brown 1991; Pilachowski et al. 1991; Gratton et al. 2000). Sometimes also elements up to the Mg-Al group show ”anomalies”, namely regularities (correlations and anti-correlations). These have been shown to occur already on the Main Sequence in

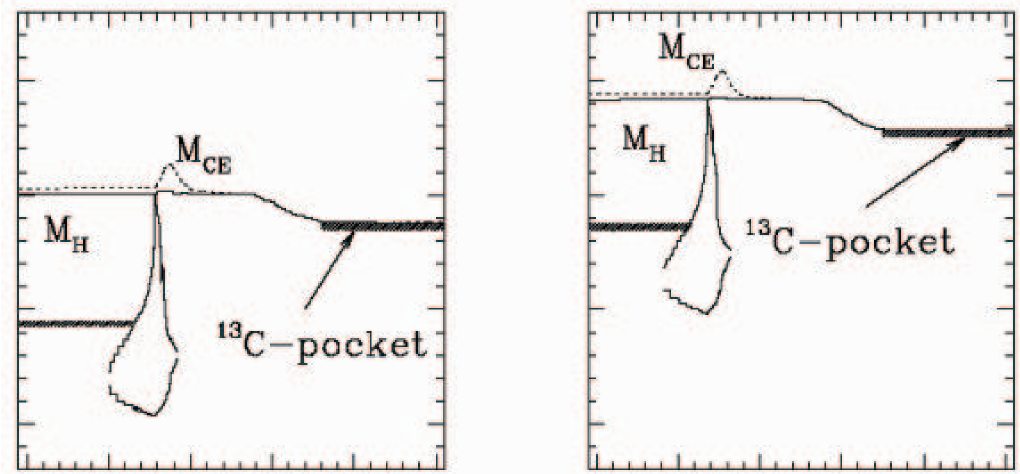

Fig. 2. The sequence of two thermal pulses, followed by envelope penetration in the third dredge-up phenomenon and by the formation of the ^{13}C pocket. M_H indicates the position of the H-he interface (where the H shell has been active previously), while M_{CE} marks the innermost limit of the convective envelope. The AGB mass, in unit of solar mass, is on the vertical axis while the time, in year, on the abscissa.

stars of Globular Clusters (Gratton et al. 2001). They, too, can be interpreted as being due to mixing phenomena occurring in red giants if they were inherited from previous generations of AGB stars. Excellent reviews of these phenomena can be found in the literature (see e.g. Kraft 1994; Charbonnel 2004).

The above anomalies are usually explained with non-convective transport of matter that underwent partial H burning (Herwig 2005). Mechanisms invoked to account for the required partial mixing, often called *cool bottom processes* (hereafter cbp), include shear instabilities and the meridional circulation induced by rotation (Zahn 1992; Denissenkov et al. 1998). In the models the mixing is usually described as a form of diffusion, where the amount mass involved and the diffusion coefficient are left as free parameters, to be constrained by observations (see e.g. Denissenkov & Tout 2000). Diffusive mixing of heterogeneous nature are expected in boundary layers, so that what the models do is actually to assume that the last radiative zones below the envelope do behave as a boundary layer in which the rigid rotation of the stellar core gradually transforms into the differential rotation of the convective envelope, as observed in the solar tachocline. This leads to the idea of rotationally-induced mixing, exploited by many authors. However, this idea has recently met strong difficulties (Goriely & Siess 2004; Palacios et al. 2006). In fact, as the star readjusts rather quickly to rotational disturbances, reorganizing its structure, any mixing is rapidly quenched. The situation, however, is not clearly settled. It has also been suggested that magnetic buoyancy below the convective envelope might help in maintaining cbp (Busso et al. 2006).

In any case, it was shown (Nollett et al. 2003) that a circulation occurring an a suitable rate $\dot{M}$, reaching down to a maximum temperature T_P, close to, but lower than, the H-burning shell temperature, can approximate a diffusive cbp, yielding essentially the same results. A number of abundance anomalies observed in pre-solar oxide grains of AGB origin, like the destruction, in the stellar envelope, of ^{18}O, the production of ^{17}O (sometimes close to CNO equilibrium), and production of ^{26}Al, could be described by this simple scheme. Any such circulation should also decrease the $^{12}C/^{13}C$ ratio, in a percentage that is mainly a function of the circulation rate, and perhaps increase the abundance of ^{14}N as well (any Al production is then essentially a function only of the temperature T_P reached by the circulating material).

Admixtures of envelope material and partially CNO-cycled matter originally laying above the H shell, and carried to the surface by rotational or magnetic mixing mechanisms can explain all the above abundance changes expected in low mass AGB stars. Actually stronger abundance variations are introduced in more massive stars (those between 5 and 8 $M_{\odot}$, referred to as *Intermediate Mass Stars*, or IMS) by hot CNO cycling, called *hot bottom burning* (hbb), occurring directly in the envelope. This phenomenon occurs because the temperature of the underlying H-burning shell becomes extremely hot (10^8 K), so that conditions for efficient p-captures can be found even above the formal layer where the maximum energy generation occurs, in the bottom zones of the convective envelope (Frost et al. 1998).

Generally hbb induces abundance changes of the same nature as cbp, just quantitatively more effective. It was shown that cbp can yield $^{26}Al/^{27}Al$ envelope ratios of the order of 0.01 (Wasserburg et al. 2006); hbb at its extreme level can bring this ratio to unity (Karakas & Lattanzio 2004). It was also shown that cbp can delay the formation of a C-star by burning some ^{12}C (Nollett et al. 2003); it is expected that hbb hampers the formation of a C star completely, apart from some special and rare cases (Frost et al. 1998). Hence, from observations of intermediate elements alone, it might be not so simple to understand which kind of stellar mass was involved. Mg isotopes might provide a more stringent constraint, in fact in massive ($M \geq 5\ M_{\odot}$) AGB stars efficient burning of ^{22}Ne in the He-layers produces ^{25}Mg and ^{26}Mg. The first one might be partly affected, in hbb conditions, by p-captures producing ^{26}Al; but the second should remain. Only for rather massive AGB progenitors remarkable enhancements of ^{26}Mg should occur and might be an efficient observational monitor of the stellar mass.

3. AGB Nucleosynthesis from the He-burning and the *s*-process

In the last twenty years the reaction $^{13}C(\alpha, n)^{16}O$ has been recognized as the main neutron source for activating neutron captures in the thin layers ($\sim 0.01\ M_{\odot}$) between the H-burning shell and the degenerate C-O core. Also in this case however the resulting nucleosynthesis critically depends on poorly known slow mixing mechanisms, as for the already-quoted proton capture phenomena occurring above in the star.

Here we need that limited amounts of proton be injected into the He-rich regions, reaching layers below the formal convective border and can thus be mixed in the C-rich intershell. This happens during a phase where the H-burning shell is extinguished and envelope convection penetrates downward (third dredge-up). The star is in fact expanding its envelope both outward and inward, in order to radiate the extra energy produced by a previous thermal instability of the He-shell (a "thermal pulse"). Subsequently the star contracts and heats again, so that protons react on the abundant ^{12}C producing ^{13}C in a layer (or *pocket*) where the $^{13}C(\alpha, n)^{16}O$ reaction will then release neutrons and give rise to *s*-processing (see Figure 2). Nitrogen is a strong neutron absorber and would hamper the *s*-process, so the amount of protons must be small enough to limit consumption of ^{13}C itself by further p-captures, producing ^{14}N.

Any ^{13}C produced in the radiative He-rich layers at dredge-up burns locally before a convective pulse develops, as shown by stellar model calculations (see e.g. Straniero et al. 1997). The average neutron density never exceeds 10^7 n cm^{-3} and the temperature is rather low for He-burning conditions [$(0.8-0.9)\times10^8$ K]. A pocket of *s*-enhanced material is formed, as a consequence of neutron captures, and subsequently engulfed into the next pulse. Here *s*-elements are modified by the marginal activation of the $^{22}Ne(\alpha, n)^{25}Mg$ neutron source and are mixed over the whole He intershell by convection. The changes induced by the $^{22}Ne(\alpha, n)^{25}Mg$ reaction concern mainly nuclei affected by reaction branchings depending on the neutron density, as a very limited neutron exposure is produced, but at a relatively high neutron density (up to 10^{10-11} n cm^{-3}).

During the rise of a convective He-shell instability (see the pulse shape in Figure 2) the isotopes of nitrogen can capture α particles and give rise to the reactions ^{14}N(α,γ)^{18}F($\beta^{+}\nu$)^{18}O and ^{15}N(α,γ)^{19}F. The first reaction continues to a further α capture to produce the neutron source ^{22}Ne, while the second one is a source for stable F, which is therefore among the typical products of AGB He-burning. Its abundance is indeed observed and correlates with ^{12}C and *s*-elements (Renda et al. 2005).

The newly synthesized nuclei are brought from the envelope to the surface during the following episode of dredge-up, which is actually a repetition of a few to many individual episodes (one after each He-shell instability). Such a scheme has been confirmed by all recent works in the literature (see e.g. Goriely & Siess 2001; Lugaro et al. 2003).

For the formation of the ^{13}C pocket through proton diffusion various physical mechanisms have been proposed (see e.g. Herwig et al. 2003; Herwig 2005), like for the extra-mixing occurring above the H-burning shell. *S*-processing affects a large number of observable elements, and depends only on few basic quantities (the neutron density, the total neutron flux, the very small cross sections of key nuclei, having *magic* neutron numbers, i.e. closing nuclear shells). However, none of the above proposed models for the formation of the neutron source is exempt from free parameterizations, so that the amount of ^{13}C burnt has usually been assumed as a free parameter, to be calibrated by observations. Due to these features, observational constraints are very important. Luckily, the recent advent of precise isotopic measurements on pre-solar grains formed in AGB circumstellar environments helps us in specifying very well the local conditions (Gallino et al. 1997; Amari et al. 2001). We can therefore say that neutron captures in AGB stars are among the best known nuclear processes in Astrophysics despite the big problems involved in the formation of the neutron source. Probably reflecting differences in the triggering mechanisms as a function of the stellar mass (Busso et al. 2001), a large spread exists at any metallicity in the amount of ^{13}C produced, but a sort of universal average is also required, at any [Fe/H] value, to reproduce the chemical evolution of *s*-process nuclei, yielding a few $\times 10^{-6}$ $M_{\odot}$ of ^{13}C burnt per each pulse-interpulse cycle. This value has been often indicated as the *standard* (ST) one.

The ^{13}C neutron source operating in AGB stars is of "primary" origin, i.e. derives from processes starting directly from the original H of the star. One of the main consequences is that the *s*-process distribution is extremely affected by the initial abundance of Fe-group seeds, i.e. by the stellar metallicity. In other words, the neutron exposure τ is roughly proportional to the number of available ^{13}C nuclei per Fe seed, hence inversely proportional to the metallicity. Then the neutron exposure tends to be smaller in AGB stars of higher [Fe/H]. This behavior is observationally proven by the gradual enhancement of the Ba-peak elements, as compared to the Sr-peak ones, when looking at AGB stars of lower-than-solar metallicity.

The distribution also gradually changes in shape and the production factors change in level, for a given amount of ^{13}C burnt, until, for very low metallicity, AGB stars produce mainly the heaviest nuclei above Ba and up to Pb and Bi (Figure 3). This fact reflects the increase of the number of neutrons available per Fe nucleus when Fe itself decreases. This is also the physical explanation of the existence, in the galactic halo, of the famous "Pb-stars" (Aoki et al. 2002).

More quantitatively, if we assume an average ^{13}C abundance per pulse-interpulse cycle of 5×10^{-6} $M_{\odot}$/yr (the ST value of Gallino et al. 1997), the neutron exposure available at solar metallicity would produce mainly *s*-elements at the Sr-Y-Zr peak (neutron magic number N = 50). Decreasing [Fe/H], the neutrons available per Fe seed increase and the higher-mass nuclei up to Ba-La-Ce-Pr-Nd are produced, with a maximum at $Z \approx Z_{\odot}/4$, because the N = 50 bottleneck is bypassed (Travaglio et al. 1999). For even lower metallicity, there are enough neutrons per Fe seed to feed Pb, in particular the abundant isotope ^{208}Pb at the

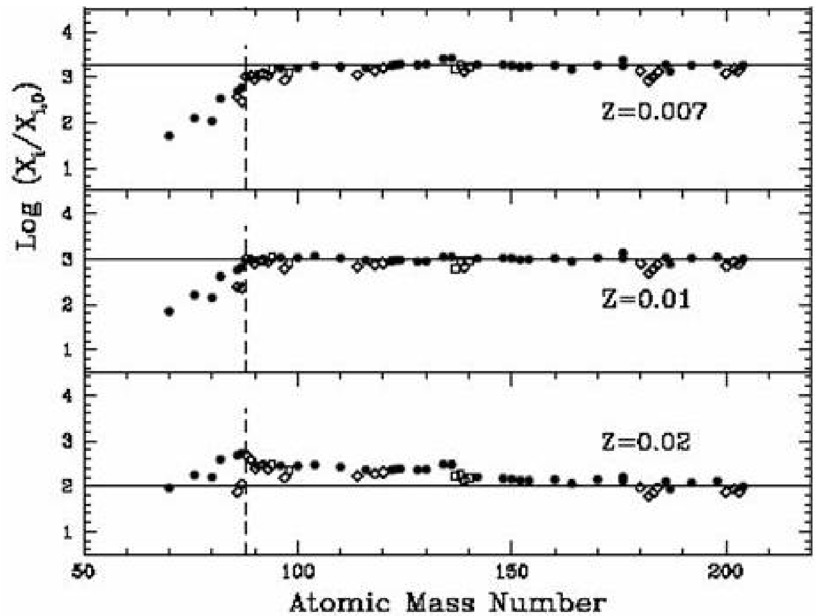

Fig. 3. Model predictions of *s*-element enhancement factors in the AGB intershell regions as a function of the stellar metallicity. The choice of the amount of ^{13}C burnt is the same (see text).

magic neutron number N = 126 (Travaglio et al. 2001).

Finally, below [Fe/H] = −1, though all the initial Fe is efficiently converted to Pb and to heavy *s*-elements, so that the abundances relative to iron of neutron-rich elements continue to increase, the shortage of iron itself becomes dominant. In this way the *absolute* production of all *s*-elements, including Pb, starts to decrease with metallicity. Therefore *s*-process abundances in the Galaxy are expected to vanish at very low values of [Fe/H], where the neutron-rich elements must be dominated by the *r*-process (see, e.g. Simmerer et al. 2003). This fact is also due to the long lifetimes of stars ending their evolution on the AGB, which allow them to contribute only late to the chemical evolution of the interstellar medium. The above trend, combined with the spread of ^{13}C abundances at each [Fe/H] value implies a wide spectrum of different abundance distributions in AGB stars of spectral types MS-S-SC and C, i.e. those normally seen to be enriched in *s*-elements. In general, however, each distribution can be rather precisely modelled with a suitable choice of the ^{13}C abundance.

In several cases, the enrichment of s-elements has been shown to be the result not of a direct nucleosynthesis phenomenon on the same star we see now, but rather of a mass transfer episode from an AGB companion evolved previously. In such cases, chemical peculiar compositions might be the signature of a binary system. These cases can be discriminated observationally by the absence of Tc in the spectra. Actually, the unstable ^{99}Tc, with $t_{1/2} = 2 \times 10^5$ yr, (first seen on AGB stars by Merrill 1952), lays on the main *s*-process path, and is therefore expected to be produced copiously. Its lifetime is longer than any inter-pulse phase, so that in a normal AGB star it should be present in the photosphere. However, looking at a binary system in which *s*-enriched material was transferred a long time ago, Tc must be absent in the spectrum. On the other hand, the decay of ^{93}Zr ($t_{1/2} = 1.56 \times 10^6$ yr) should at that point have produced ^{93}Nb. We have therefore a double check: in single, bona-fide TP-AGB stars Tc must be present and Nb absent (its original abundance is destroyed by n-captures, and it is not significantly produced by the *s*-process directly), while in binary stars polluted by an AGB companion the reverse must be true. PNe descending from the two classes of progenitors (single or binary) should show the same evidence in terms of Tc and Nb as the progenitor itself did, as the formation of a PN is too short in time to significantly affect the absence/presence of the two isotopes. Note that sometimes the presence of live Tc is the only observable trace of *s*-processing in weak, far away stars that appear for the rest as "normal" M giants (Uttenthaler et al. 2007).

In a range of masses from around 1.7 to about 4 $M_\odot$ ^{12}C from He burning is formed and dredged-up so efficiently that the whole envelope becomes carbon rich, forming a C(N) star. The mass range is about the same that most efficiently produce *s*-elements (Abia et al. 2001, 2002). For lower masses, dredge-up is not efficient enough to increase the C/O ratio above unity, at least for solar metallicity stars (Busso et al. 2001). On the other hand, above 4−5 $M_\odot$ hbb can quickly burn any carbon carried to the envelope (Karakas & Lattanzio 2004).

The enrichment in ^{22}Ne is another important feature of AGB stars. This isotope derives from two α-captures on the abundant ^{14}N, so that in the He-layers it grows to very high abundances. Since we now recognize that ^{22}Ne is only marginally burnt in most AGB stars (at least below 5 $M_\odot$), a considerable portion of it should be dredged up. Here ^{22}Ne can dominate over ^{20}Ne, thus AGB stars are at the origin of the known solid materials (recovered in meteorites) transporting the so-called Ne-E chemical anomaly, where ^{22}Ne is enhanced over ^{20}Ne. (Gallino et al. 1990). In post-AGB stars and in PNe any Ne-enhancement has to be ascribed to ^{22}Ne.

4. Conclusions

The state of the art on AGB nucleosynthesis studies gives us a number of characteristic features in the distribution of elements and isotopes produced in the thermally pulsing stage. In the same time it also makes clear that the predictions still depend on uncertain parameters, especially mixing mechanisms and mass loss rates. In general, abundance expectations from the modelling of AGB nucleosynthesis and from the dredge-up of its products to the surface can be summarized as follows.

Firstly, the distribution in atomic mass of the *s*-abundances produced informs about the amount of ^{13}C burnt and/or the metallicity of the star. Independent measurements of this last (e.g. through elements not affected by AGB nucleosynthesis) can disentangle the effects of the two parameters.

A special role is played by the unstable Tc, or alternatively by Nb, among the *s*-nuclei. The first nucleus is enhanced in single AGB stars undergoing thermal pulses, the second is produced by ^{93}Zr decay in a binary system in which *s*-elements were added by a mass transfer (e.g. if the companion that receives the transfer has a mass too small to produce and/or dredge-up an *s*-element enrichment of its own).

A measurable enrichment in fluorine is expected. An enhanced Ne abundance should also be present, dominated by ^{22}Ne from the He-shell. The isotopic and elemental mix of intermediate elements suggests the slow circulation of partially H-burned materials (this is seen from the enhancement of ^{13}C, ^{14}N, ^{17}O, from the destruction of ^{18}O, from the presence of ^{26}Al). This evidence is mild for low mass progenitors with cbp, strong for higher mass progenitors with hbb.

An anomalous Mg isotopic mix should arise, with enrichment in ^{25,26}Mg, if the AGB star is massive enough to trigger ^{22}Ne burning efficiently.

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