PROCEEDINGS OF SCIENCE

New simulations of neutron captures in-between the s-/ and r-process

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Neutron-capture processes with neutron densities in-between the slow (s) and the rapid (r) neutron-capture process are becoming relevant to describe a number of stellar conditions that may occur in AGB and post-AGB stars, from proton ingestion episodes (the i process) to degenerate thermal pulses. These are needed to address a number of observational constraints, from carbon-enhanced metal-poor (CEMP)-s/r stars to the composition of unusual stardust grains. We are testing the modelling of such processes using an extended r-process network code.

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1. Introduction

The cosmic abundances of the elements heavier than iron are predominately produced via the capture of free neutrons, as the increasing number of protons (Z > 26) results in a strong Coulomb barrier preventing charged particle reactions. Neutron captures can occur on a relatively long time scale of the order of years and result in an production path along the stable heavy nuclei in the valley of stability. When an unstable nucleus is produced it decays before it captures another neutron. This is known as slow neutron capture process, or the s-process. It is characterised by typical neutron densities in the order of $N_n \approx 10^8$ cm^{-3}, and occurs during the hydrostatic burning phases of massive stars and during the asymptotic giant branch (AGB) phase of stars of low mass.
Traditionally, the s-process is opposed to rapid neutron captures (the r process), during which, opposite to what happens during the s-process, unstable nuclei capture a neutron before they β-decay. The r-process is characterised by neutron densities $N_n > 10^{20}$ cm^{-3} and occurs on time scales of the order of seconds during core-collapse supernovae and/or neutron star mergers.
We note, however, that recent observations of the oldest stars known in the Universe have demonstrated to us the limits of this simplified scenario: some of these stars are rich in both the s-process element Ba and the r-process element Eu and appear to require a process intermediate between the two, a so-called s/r (Lugaro et al. 2012) or i process, more specifically related to episodes of proton ingestion into a He-rich region (Cowen et al. 1977, Herwig et al. 2011).
Low mass stars ($M \leq 8\ M_\odot$) enter their Asymptotic Giant Branch (AGB) phase when the central helium burning ceases. Having insufficiently high central temperatures to ignite carbon burning, the energy source of the star proceeds alternately in a helium burning shell and a hydrogen burning shell, separated by a helium rich intershell. The hydrogen burning continuously adds helium to the shell, increasing its mass. If this helium shell reaches a certain critical mass, it re-ignites. As this shell is partly degenerate, the re-ignition leads to a thermal runaway which induces a local expansion of the different shells and a convective energy transport in the He-rich intershell - a 'thermal pulse' occurs. The expansion causes the H burning to stop for a short period and the He burning instead takes over. The star however then quickly returns to the previous conditions with a quiescent H burning.

2. Possible sites for an s/r or i-process

In addition to the previous suggested sites for the s/r or i process, such as in post-AGB stars during a very late thermal pulse (e.g. Herwig et al. 2011), or proton ingestion episodes in low-metallicity, low-mass AGB stars (e.g. Campbell et al. 2010, Cruz et al. 2013) we suggest three other potential sites: 'Dredge-out' event in super-AGB stars, 'normal' thermal pulses of super-AGB stars and 'degenerate' thermal pulses in intermediate-mass AGB stars.

2.1 Dredge-out event in super-AGB stars

Super-AGB stars are intermediate mass stars ($M \approx 6.5$ - $10\ M_\odot$) which undergo off-centre carbon ignition prior to the thermally pulsing AGB phase. The most massive super-AGB stars can

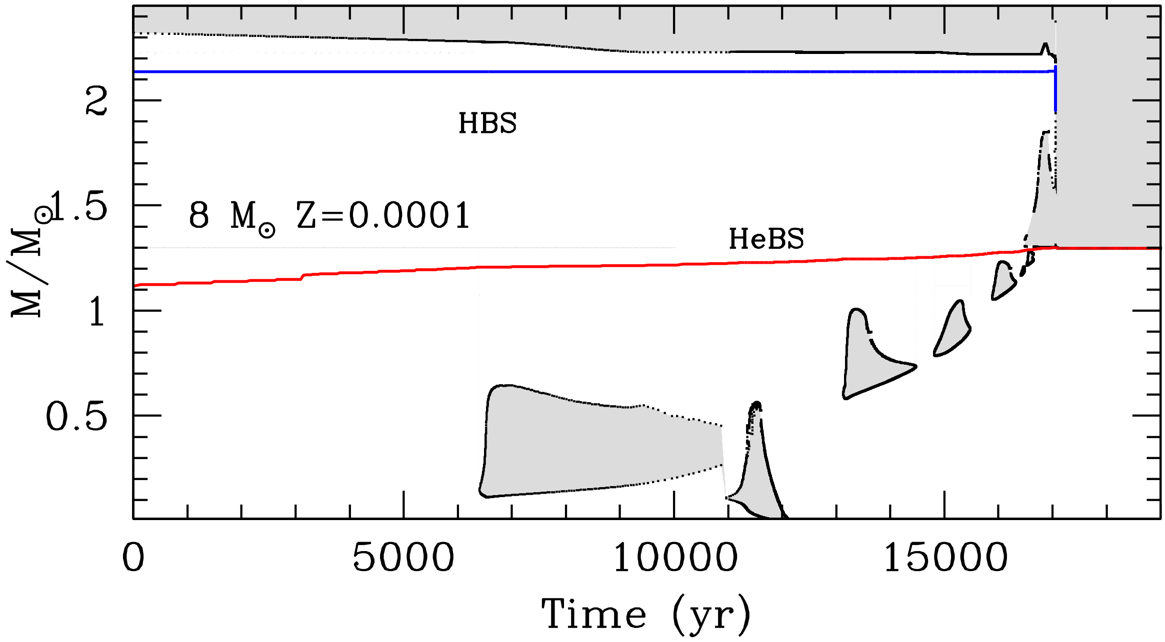

Figure 1: Dredge-out event in a 8 M$_\odot$ Z=0.0001 super-AGB star (at t $\approx$ 17000 yrs). The time axis has been offset to zero at the time when carbon burning luminosity exceeds unity. The blue and red lines represent the hydrogen and helium burning shells respectively. The grey shaded regions show convection.

undergo a 'dredge-out' event, where near the cessation of carbon burning a convective helium burning region forms and then merges with the incoming convective envelope (Ritossa et al. 1997). In Fig. 1 we show an example of a dredge-out model calculated using the MONSTAR stellar evolution program (Doherty et al. 2015). During this merging phase a substantial amount of ^{13}C will be created, via proton captures on ^{12}C. Because of the high temperatures in this helium-rich region the ^{13}C(α,n)^{16}O reaction will produce large neutron densities, potentially of the order 10^{15} cm^{-3}.

2.2 Normal thermal pulses of super-AGB stars

In the most massive super-AGB stars very high temperatures (in excess of T = 400 MK) are attained at the base of the thermal pulse which result in very efficient activation of the ^{22}Ne(α,n)^{25}Mg neutron source. It is still under examination if the neutron density in these normal thermal pulses is high enough to produce an s/r process pattern.

2.3 Degenerate thermal pulses in intermediate-mass AGB stars

We suggest that the rare class of degenerate thermal pulses (Frost et al. 1998) may also produce a high enough neutron density for an s/r process. These thermal pulses (TPs) can occur in intermediate mass AGB stars (M $\sim$ 5 M$_\odot$) and are more massive, longer lived and can reach far higher temperatures than a standard TP for the same mass. This would also result in them producing higher neutron densities.

3. Nucleosynthesis in the s/r- or i-process

We have used 1-zone trajectory models to explore the neutron densities obtained in a variety of stellar environments, including those related to the ^{13}C and ^{22}Ne neutron sources. Our network code is based on the XNet code of Hix and Thielemann (1999) and was extended for r-process network calculations (Petermann et al. 2012), thus being able to take large networks, including even very neutron rich isotopes far beyond β-stability, into account. Reaction rates were updated from the JINA Reaclib database, see for example Cyburt et al. (2010) for recent updates.
We present a model to compare to the study by Bertolli et al. (2013) which also used a 1-zone trajectory approach to explore s/r, i process nucleosynthesis. The initial conditions were chosen to mimic conditions where neutrons for heavy element production are produced via the ^{13}C neutron source. The trajectory was calculated assuming a constant temperature (T = 200 MK) and density (ρ = 10^4 g cm^{-3}) with an initial composition of (in mass fractions): X(^{1}H)=0.2, X(^{4}He)=0.2496, X(^{12}C)=0.5, X(^{16}O)=0.03485 and X(Z)=0.0155.
The maximum neutron density achieved in our simulation was $N_n \approx 2\times10^{15}$ cm^{-3} similar to as in the previous study. In Fig. 2 we show the N-Z plane at a time close to peak neutron density. Clearly seen in this figure is the extent that the composition has been pushed to the neutron-rich side, far from the valley of β-stability.

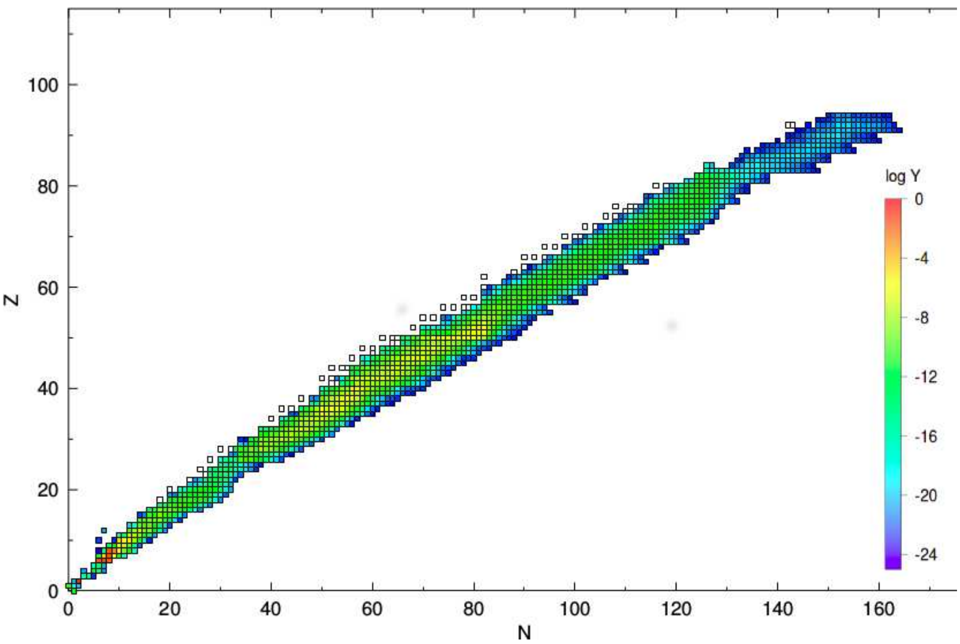

Figure 2: Abundances shown on the N-Z plane for time at peak neutron density. The black bold boxes denote stable isotopes, the abundances are color coded as shown in the key on the right side.

In summary, we have calculated a series of 1-zone trajectories which explore conditions related to the s/r or i process, with the case presented here relating to the ^{13}C neutron source, however we have also examined the ^{22}Ne neutron source.

Traditionally, most nuclear reaction networks used for studying AGB stars include only species close to the valley of β-stability because this is all that is required for the lower neutron densities found in the standard s-process. This is clearly not the case for the s/r or i process, where the neutron-rich isotopes far past the valley of stability can be produced.

We are currently using the results from our calculations as a basis to extend our detailed post-processing nuclear network to be applicable for full s/r or i calculations. We intend to explore heavy element nucleosynthesis in a range of stellar sites in particular the dredge-out, massive super-AGB stars and degenerate thermal pulses.

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