Nucleosynthesis on the Asymptotic Giant Branch: A Comparison Between Codes

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Introduction

The thermally pulsing asymptotic giant branch (TP-AGB) is a phase of stellar evolution that must be treated extremely carefully in evolution codes. The occurrence of third dredge-up (TDU) is known to be sensitive to the spatial and temporal resolution used in the models, as well as the treatment of convection and mixing in the code. Different codes are known to give distinctly different results and it is important to understand the reasons for this.

The Cambridge stellar evolution code (STARS) was originally written by Eggleton (1971) and has been updated by many contributors (e.g. Pols et al. 1995). It solves the equations of stellar structure, nuclear burning and mixing *simultaneously*, unlike most codes which treat mixing in a separate step. The first detailed calculations made by Stancliffe, Tout and Pols (2004) yielded significantly different results to other codes, with more efficient TDU that occurs at lower core masses. We investigate the impact that this has on the nucleosynthesis in these stars.

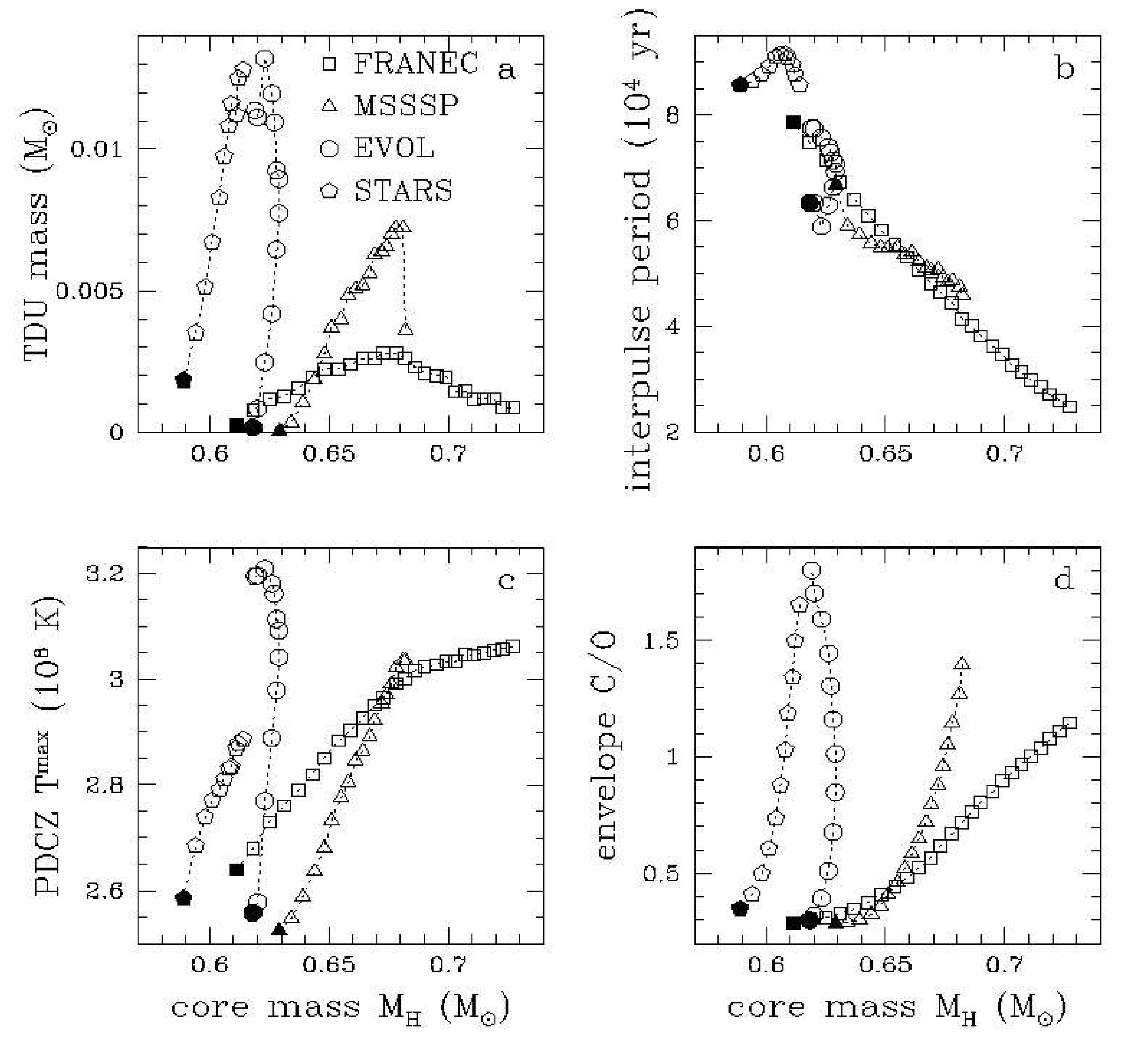

Figure 1. The evolution of the physical characteristics of a 3 solar mass model with Z=0.02 according to four different evolutionary codes. Adapted from Lugaro et al. (2003).

Figure 1 shows a comparison of some of the physical details of a 3 solar mass model at Z=0.02 computed using four different evolution codes. The STARS code shows evolution occuring at much a lower core mass than the other codes. This leads to the formation of carbon stars at lower luminosity. The evolution of the envelope C/O ratio (panel d) and the amount of material dredged-up (panel a) are similar for the EVOL (Herwig 2000) and STARS codes. However, the models of the former are evolved using convective overshooting, increasing the extent of the convective zones beyond that prescribed by the Schwarzchild criterion. The STARS models do not use this but produce similar results.

In terms of the maximum temperature in the pulse driven convective zone (PDCZ) the STARS code produces similar results to the FRANEC and MSSSP (Frost & Lattanzio 1996) models. This is important for the *s*-process as the maximum temperature in the PDCZ determines the isotopic ratios of the *s*-process elements. The efficient TDU of the STARS code together with its PDCZ temperature will produce a much different *s*-process element distribution than the other codes.

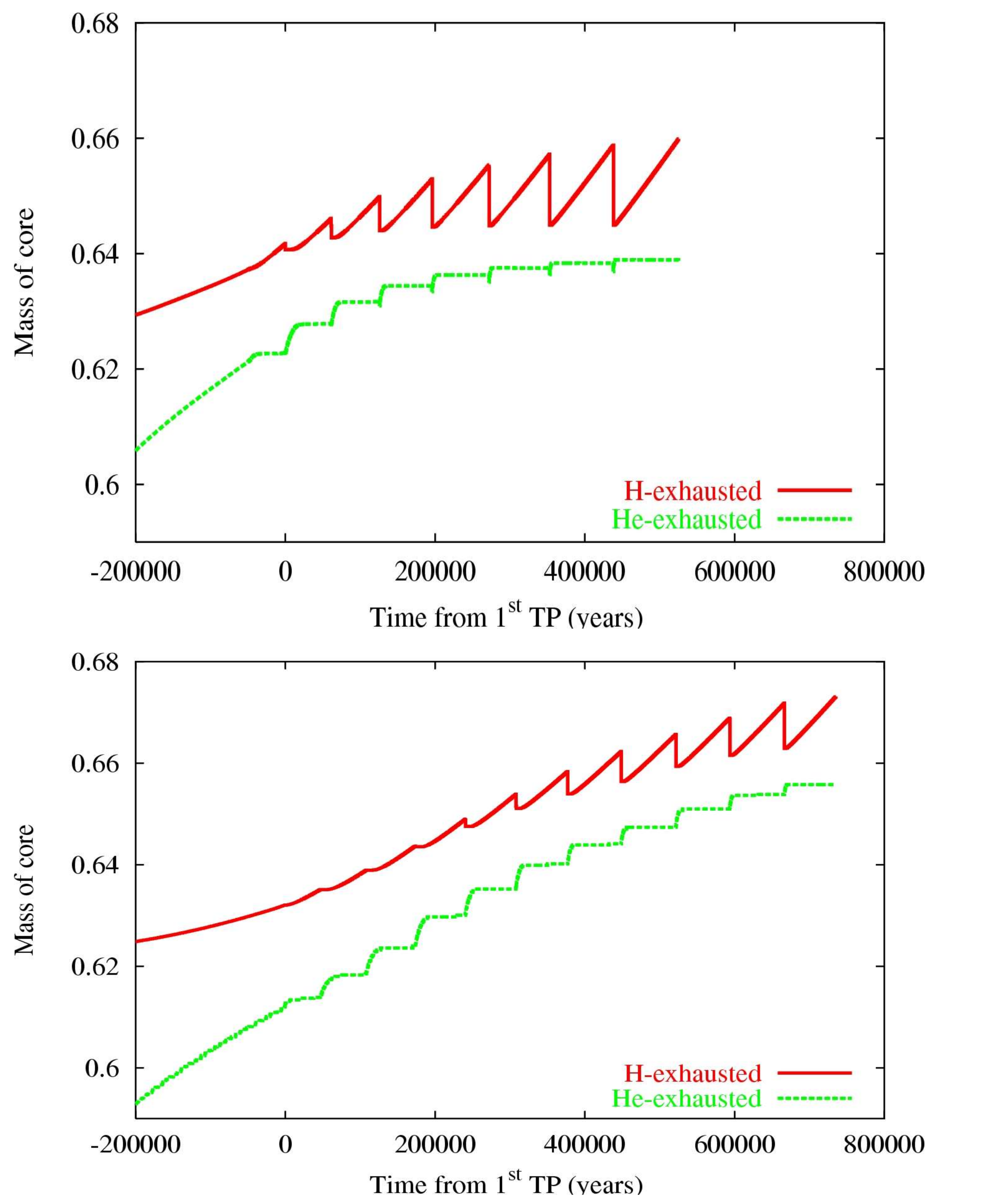

Figure 2. Plot of the evolution of the H- and He-exhausted core (red and green lines respectively) as calculated with STARS (top panel) and MSSSP (lower panel). Note the penetration of the He-core at each TP event in the STARS model.

Detailed Comparison: STARS versus MSSSP

A 3 solar mass model with Z = 0.008 was evolved from the pre-main sequence using the STARS and MSSSP codes. No convective overshooting was used. Mass loss was taken into account with the Reimers prescription using eta=1. The STARS code uses NACRE reaction rates (Angulo et al. 1999).

A plot of the evolution of the H- and He-exhausted core for both the models is shown in Figure 2. While STARS has larger core masses on the early AGB, it begins to deeply dredge-up much sooner with a H-exhausted core mass of 0.64 solar masses compared to MSSSP's 0.65 solar masses. As the evolution continues the STARS model gives much deeper dredge-up with the core barely growing over the last few pulses. The dredge-up in the MSSSP model is much more modest as can be seen from Figure 4. This may be related to the helium luminosity generated by each pulse. The pulses in the MSSSP model are weaker and it is well known that stronger pulses lead to more dredge-up. However, more dredge-up leads to a longer interpulse period. A longer interpulse period allows the He-shell more time to cool, making the region more degenerate and allowing for a more intense pulse (note the lower shell He temperature of the STARS model in Figure 3).

It should also be noted that the STARS model shows evidence for the penetration of the intershell convection zone below the He-burning shell (note the small depressions in the position of the He-shell in Figure 2). Such behaviour has been seen in codes using convective overshooting (e.g. Herwig 2000) but no such additional mixing is applied in this model. The effect of this penetration is to boost the oxygen abundance in the intershell.

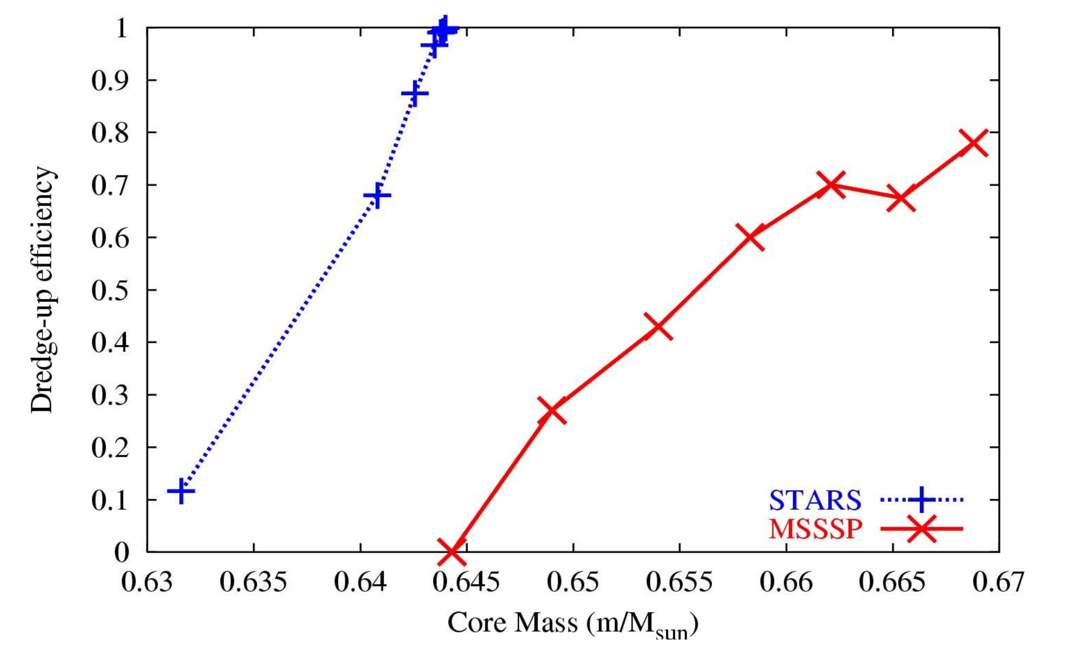

Figure 4. A comparison of the dredge-up efficiency as a function of core mass.

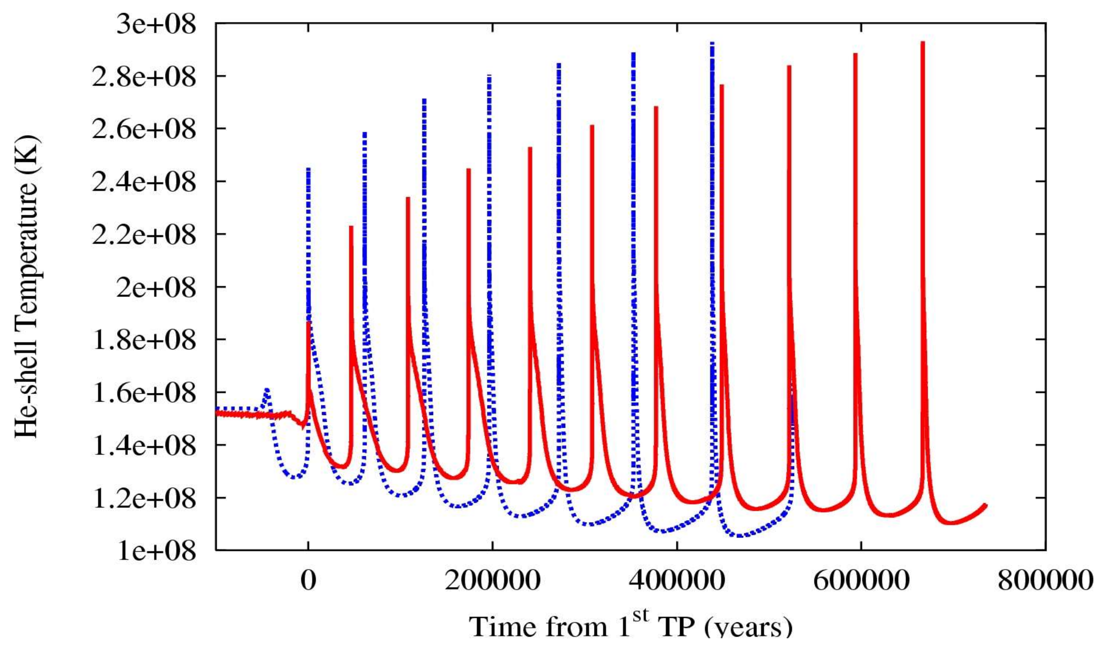

Figure 3. Evolution of the temperature of the He burning shell from MSSSP (red line) and STARS (blue line).

Nucleosynthesis Comparison

The ratio of $^{16}O/^{18}O$ increases much more rapidly in the STARS model. There are two reasons for this. As mentioned above this model shows an enhanced ^{16}O abundance in the intershell owing to the intershell convection zone penetrating into the C/O core. This, couplted with the models deeper dredge-up, leads to a more rapid increase in the $^{16}O/^{18}O$ ratio than seen in the MSSSP model.

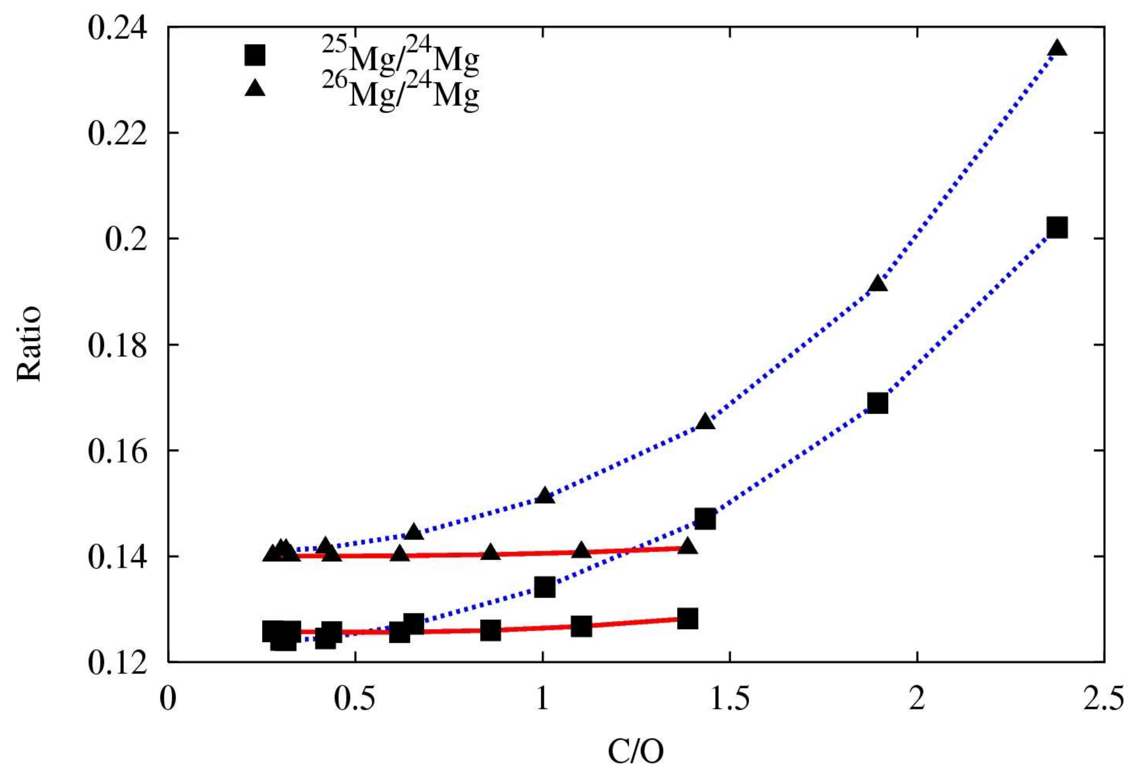

Figure 5. Comparison of the magnesium isotope ratios. Output from STARS is in blue; the MSSSP model is in red.

Figure 5 shows a comparison of the evolution of the ratios of the magnesium isotopes from the two models. Both codes show an increase in $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg$ which is to be expected as the two heavier isotopes are synthesized in the intershell convection zone via alpha captures onto ^{22}Ne. The STARS models displays a much more rapid increase in these ratios because of the deep dredge-up it undergoes; deeper dredge-up brings more of the products of nucleosynthesis during a thermal pulse to the surface.

The behaviour of the $^{26}Al/^{27}Al$ ratio can also be explained in terms of the enhanced dredge-up in the STARS model. ^{27}Al is formed from proton captures onto ^{26}Mg in the H-burning shell. While the two models both have a H-shell temperature of about $6x10^7$ K during the interpulse, the STARS model has a higher abundance of ^{26}Mg which leads to more ^{27}Al and hence the $^{26}Al/^{27}Al$ ratio grows at a slower rate. The outputs of both models are consistent with the values measured in SiC grains where the $^{26}Al/^{27}Al$ ratio is measured to be between 10^{-5} and 10^{-2} (Hoppe & Ott 1996).

At Z=0.02, the STARS model dredges up material that has seen lower pulse temperatures. The ^{22}Ne(alpha,n) reaction is less activated and a smaller neutron flux is produced than in other calculations. The neutron flux is responsible for the activation of branching points on the s-process path. A lower neutron density in the pulse will help in matching the Zr isotopic composition of single presolar SiC grains from AGB stars showing $^{96}Zr/^{94}Zr$ tending to zero, where ^{96}Zr is produced by a branching on the s-process path at ^{95}Zr. Detailed calculations will be performed to check the effects on s-process element abundances.

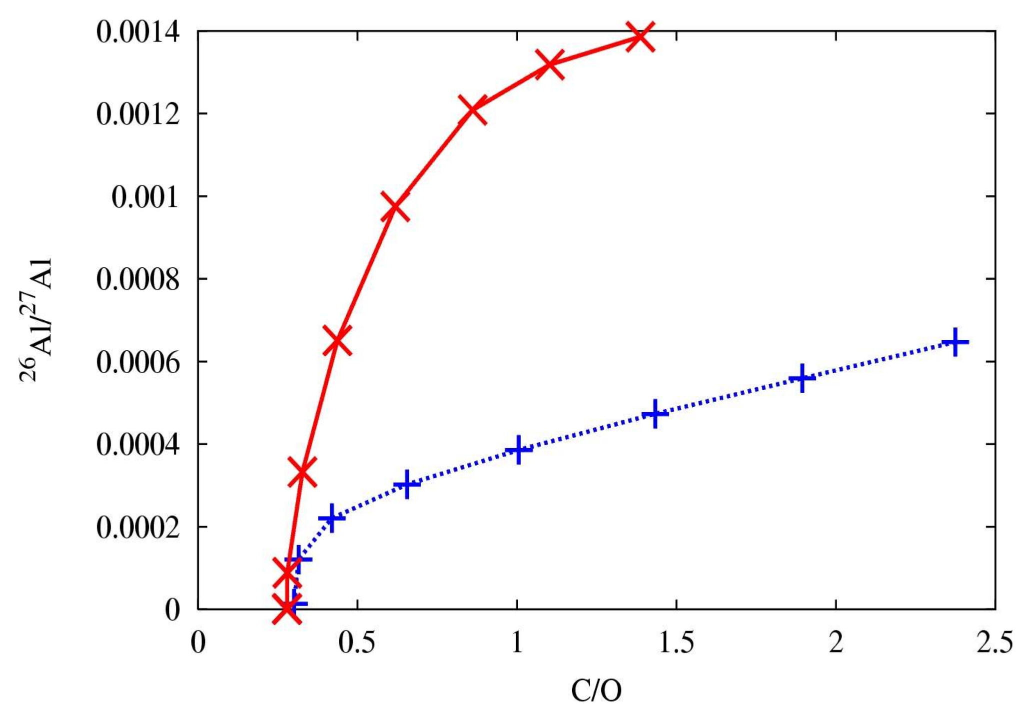

Figure 6. The evolution of the $^{26}Al/^{27}Al$ ratio. The MSSSP model is the red line; the STARS model is the blue line.

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