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The nuclear processes responsible for the CNO synthesis

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Abstract. The abundances of the isotopes of the elements C, N and O are mainly affected by the cold CNO cycles in non-explosive stellar situations, or by the hot CNO chains that can develop in certain explosive sites, like classical novae. Helium burning phases can modify the composition of the ashes of the CNO transmutations through several α-capture reactions, the most famed one being $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$. This contribution presents a short review of the purely nuclear physics limitations imposed on the accuracy of the predicted C, N and O yields from H-burning in non-explosive stars or novae. This analysis makes largely use of the NACRE compilation for the rates of the reactions on stable targets making up the cold CNO cycle. Some more recent rate determinations are also considered. The analysis of the impact of the rate uncertainties on the abundance predictions is conducted in the framework of a simple parametric astrophysical model. These calculations have the virtue of being a guide in the selection of the nuclear uncertainties that have to be duly analyzed in detailed model stars, particularly in order to perform meaningful confrontations between abundance observations and predictions. They are also hoped to help nuclear astrophysicists pinpointing the rate uncertainties that have to be reduced most urgently. A limited use of detailed stellar models is also made for the purpose of some specific illustrations.

1. Introduction

As it is well known, the isotopes of the C, N and O elements derive their abundances at the stellar surfaces and in the interstellar medium from the hydrogen and helium burning episodes taking place in the central regions or in peripheral layers of all stars. These photospheric signatures may be inherited from the stars at their birth, or result from so-called 'dredge-up' phases, which are expected to transport the H- or He-burning ashes from the deep production zones to the more external layers. This type of surface contamination is encountered especially in low- and intermediate mass stars on their first or asymptotic branches, where two to three dredge-up episodes have been identified by stellar evolution calculations. Nuclear burning ashes may also find their way to the surface of non-exploding stars by rotationally-induced mixing, which has been started to be investigated in some detail, in particular by André Maeder and his collaborators (Maeder & Meynet 2000), or by steady stellar winds, which have their most spectacular effects in massive stars of the Wolf-Rayet type (these stars are very much beloved by André; e.g. Maeder & Conti 1994). Non-explosive mass losses by Asymptotic Giant Branch or massive stars and catastrophic supernova ejecta are especially efficient agents for the C, N and O budget of galaxies.

The confrontation between calculated abundances and the wealth of observed elemental or isotopic C, N and O abundances in stellar photospheres and in the interstellar medium can provide essential clues to the stellar structure and evolution models, as well as to models for the chemical evolution of the galaxies. Of course, the information one can extract from such a confrontation is most astrophysically useful if the discussion is freed from nuclear physics uncertainties to the largest possible extent.

Thanks to the impressive skill and dedication of some nuclear physicists, remarkable progress has been made over the years in our knowledge of reaction rates at energies which are as close as possible to those of astrophysical relevance (e.g. Rolfs & Rodney 1988). Despite these efforts, important uncertainties remain. This relates directly to the enormous problems the experiments have to face in this field, especially because the energies of astrophysical interest for charged-particle-induced reactions are lower than the Coulomb barrier energies, especially in non-explosive conditions. As a consequence, the corresponding cross sections can dive into the nanobarn to picobarn abyss, which imposes to explore the 'world of almost no event'. In general, it has not been possible yet to measure directly such small cross sections. Theoreticians are thus requested to supply reliable extrapolations from the lowest energies attained experimentally to those of most direct astrophysical relevance. The problem is of a different nature in explosive situations. The typical temperatures being higher in these cases, the energies of astrophysical relevance come closer to the Coulomb barrier, which implies larger cross sections. However, there is a high price to pay to enter this regime. The nuclear flows associated with stellar explosions are indeed mostly located away from the valley of nuclear stability, which imposes the study of reactions involving more or less highly unstable nuclei. The laboratory study of this 'world of exoticism' is another major challenge in nuclear astrophysics.

Recently, a consortium of European laboratories has undertaken the difficult, but necessary, task of setting up well documented and evaluated sets of experimental data or theoretical predictions for a large number of astrophysically interesting nuclear reactions (Angulo et al. 1999). This compilation of reaction rates, referred to as NACRE (Nuclear Astrophysics Compilation of REaction rates), comprises in particular the rates for all the charged-particle-induced nuclear reactions involved in the non-explosive ('cold') pp-, CNO, NeNa and MgAl chains, the first two burning modes being essential energy producers, all four being relevant nucleosynthesis agents. It also includes the most important reactions involved in non-explosive helium burning as well as many other nuclear data of astrophysics interest, but of no direct relevance here.

It has to be emphasized that the NACRE collaboration recommends the use in stellar evolution codes of numerical reaction rates in tabular form. This philosophy differs markedly from the one promoted by the previous widely used compilations (Caughlan & Fowler 1988; hereafter CF88), and is expected to lead to more accurate rate evaluation. However, as some stellar model builders still stick to the use of analytical approximations, NACRE provides such formulae

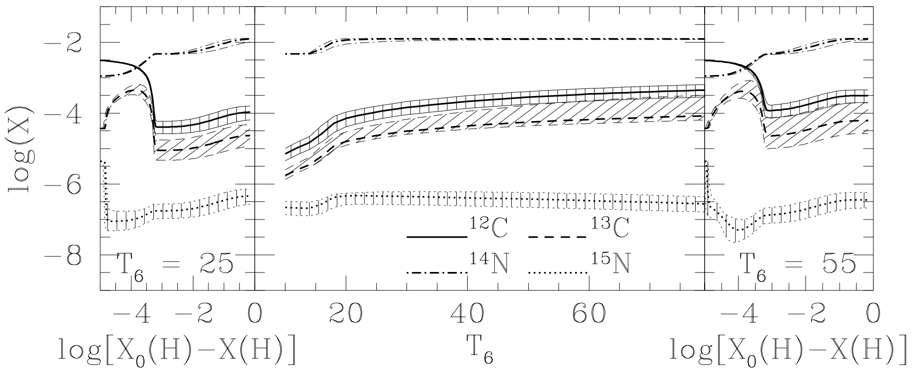

Figure 1. *Left and right panels:* Time variations of the mass fractions of the stable C and N isotopes versus the amount of hydrogen burned at constant density $\rho = 100$ g/cm^3 and constant temperatures $T_6 = 25$ and 55. The H mass fraction is noted X(H), the subscript 0 corresponding to its initial value; *Middle panel:* Mass fractions of the same nuclides at H exhaustion [X(H)=10^{-5}] as a function of T_6 [$T_6 \equiv T/10^6$]. The shaded areas delineate the uncertainties resulting from the reaction rates

for the recommended rates. They differ in several respects from the classically used expressions (e.g. CF88), the reasons for these changes being discussed in Angulo et al. (1999).

The NACRE data are used in Sect. 2 to derive the abundances of the isotopes of C, N and O involved in the cold CNO cycles. The abundance calculations are performed in the framework of a simple parametric model that enlightens the impact of the rate uncertainties on the derived abundances. These calculations have the virtue of being free from blurring effects generated by the many intricacies of the stellar evolution models. They thus help identifying in a clearer way purely nuclear uncertainties which may have a significant impact on abundances predicted by detailed stellar models, or on the build-up of models for the chemical evolution of galaxies. They are also hoped to help nuclear astrophysicists pinpointing the rate uncertainties that have to be reduced most urgently. Some post-NACRE data concerning ^{14}N(p, γ)^{15}N and the famed ^{12}C(α, γ)^{16}O are briefly discussed in Sects. 3 and 4. Section 5 is devoted to an identification of the reactions of the explosive ('hot') CNO cycles that may have an impact on C, N and O novae yields. Brief conclusions are drawn in Sect. 6.

2. The Cold CNO Cycles

The reactions involved in the cold CNO cycles can be found in many places (e.g. Arnould, Goriely, & Jorissen 1999; hereafter AGJ), and need not be repeated here. It is well known that this H-burning mode results in the production of ^{4}He from H, and in the transformation of the C, N and O isotopes mostly into ^{14}N as a result of the relative slowness of ^{14}N(p, γ)^{15}O with respect to the other involved reactions. This ^{14}N build-up is clearly seen in Fig. 1.

The cold CNO cycles comprise branching points at ^{15}N, ^{17}O, and ^{18}O. In terms of the NACRE rates, their main characteristics may be very briefly summarized as follows: (i) At $T_6 = 25$ ($T_6 \equiv T/10^6$), $^{15}\mathrm{N}(\mathrm{p},\alpha)^{12}\mathrm{C}$ is 1000 times faster than $^{15}\mathrm{N}(\mathrm{p},\gamma)^{16}\mathrm{O}$, and the CN cycle reaches equilibrium already before 10^{-3} of the initial protons have been burned; (ii) $^{17}\mathrm{O}(\mathrm{p},\alpha)^{14}\mathrm{N}$ and $^{17}\mathrm{O}(\mathrm{p},\gamma)^{18}\mathrm{F}$ are the competing ^{17}O destruction reactions. The uncertainties in their rates have been strongly reduced in the last years, but remain quite substantial. The rate of $^{17}\mathrm{O}(\mathrm{p},\alpha)^{14}\mathrm{N}$ recommended by NACRE is larger than the CF88 one by factors of 13 and 90 at $T_6 = 20$ and 80, respectively. Smaller deviations, though reaching a factor of 9 at $T_6 = 50$, are found for the $^{17}\mathrm{O}(\mathrm{p},\gamma)^{18}\mathrm{F}$ rate; (iii) the reactions $^{18}\mathrm{O}(\mathrm{p},\gamma)^{19}\mathrm{F}$ and $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}$ compete at destroying ^{18}O. At the temperatures of relevance, NACRE predicts that $^{18}\mathrm{O}(\mathrm{p},\gamma)^{19}\mathrm{F}$ is roughly 1000 times slower than $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}$. However, at low temperatures, large uncertainties still affect the $^{18}\mathrm{O}(\mathrm{p},\gamma)^{19}\mathrm{F}$ rate.

The C, N and O isotopic compositions displayed in Figs. 1 and 2 are calculated by assuming that H burning takes place at a constant density $\rho = 100$ g cm^{-3} and at two different constant temperatures, $T_6 = 25$ and 55. The curves are constructed by combining in all possible ways the lower and upper limits of all the relevant reaction rates. One 'reference' abundance calculation is also performed with all the recommended NACRE rates. All the initial abundances are assumed to be solar (Anders & Grevesse 1989). In spite of its highly simplistic aspect, this analysis provides results that are of reasonable qualitative value, as testified by their confrontation with detailed stellar model predictions.

Let us restrict ourselves here to some comments on the derived O isotopic composition and on the production of ^{19}F, which has long remained a puzzle in the theory of nucleosynthesis. As it is well known, the O isotopic composition depends drastically on the burning temperature. In particular, ^{17}O is produced at $T_6 \lesssim 25$, but is destroyed at higher temperatures. This has the important consequence that the amount of ^{17}O emerging from the CNO cycles and eventually transported to the stellar surface is a steep function of the stellar mass. This conclusion could get some support from the observation of a large spread in the oxygen isotopic ratios at the surface of red giant stars of somewhat different masses (Dearborn 1992, and references therein). Figure 2 also demonstrates that the oxygen isotopic composition cannot be fully reliably predicted yet at a given temperature as a result of the cumulative uncertainties associated with the different production and destruction rates. This situation prevents any meaningful comparison to be made with spectroscopic data, and, even more so, any firm conclusion to be drawn from models for the chemical evolution of galaxies.

As far as ^{19}F is concerned, only its solar system abundance has been known for a long time. The observational situation has changed substantially with the measurements by Jorissen, Smith, & Lambert (1992) of fluorine at the surface of red giant stars considered to be in their post-first dredge-up phase, as well as of AGB stars, some of the analyzed stars exhibiting a F enhancement with respect to solar. Theoretically, the slowness of the recommended NACRE rate for $^{18}\mathrm{O}(\mathrm{p},\gamma)^{19}\mathrm{F}$ relative to the one of the competing $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}$ reaction undermines the path leading to the production of ^{19}F from oxygen. However, the NACRE upper bound for the proton radiative capture by ^{18}O could be comparable to the $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}$ rate, and at the same time larger than the

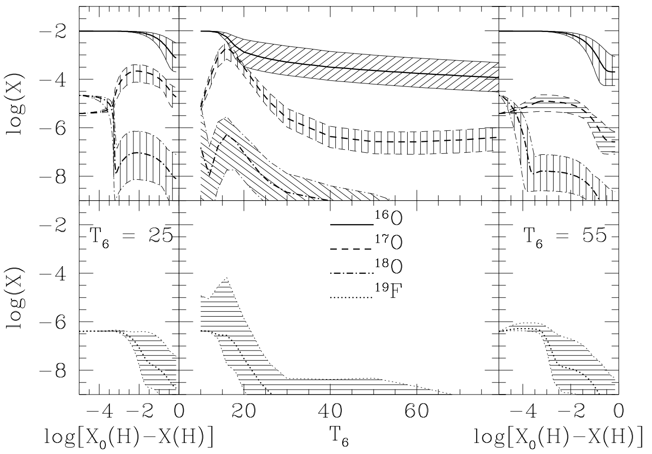

Figure 2. Same as Fig. 1, but for the O and F nuclides

^{19}F (p , α) ^{16}O rate at $T_6 \lesssim 20$. As a result, some ^{19}F might be produced in the wake of the CNO cycles, in contradiction with the conclusion drawn from the adoption of the CF88 rates. Figure 2 indeed confirms that fluorine could be overproduced (with respect to solar) by up to a factor of 100 at H exhaustion when $T_6 \approx 15$. However, Fig. 2 also reveals that the maximum ^{19}F yields that can be attained remain very poorly predictable as a result of the rate uncertainties. In fact, some hint of a non-negligible production of fluorine by the CNO cycles might come from the observation of fluorine abundances slightly larger than solar at the surface of red giant stars considered to be in their post-first dredge-up phase (Jorissen et al. 1992; Mowlavi, Jorissen, & Arnould 1996). Other possibilities of significant production of ^{19}F have also been identified, the most promising ones being shell He burning in AGB stars [and more specifically the partial mixing of protons in the C-rich layers at the time of the third dredge-up (Goriely & Mowlavi 2000) which could account for the F overabundance in AGB stars observed by Jorissen et al. 1992] or central He burning in Wolf-Rayet stars (Meynet & Arnould 1996, 1999; Mowlavi, Jorissen, & Arnould 1998). Finally, let us note that any important leakage out of the CNO cycles to ^{20}Ne is prevented by the fact that ^{19}F (p , α) ^{16}O is always much faster than ^{19}F (p , γ) ^{20}Ne , this conclusion being independent of the remaining rate uncertainties.

3. Post-NACRE Data for ^{14}N (p , γ) ^{15}O : No Revolution in Stellar Evolution

The ^{14}N (p , γ) ^{15}O reaction is the slowest of the CN cycle. It is thus expected to play a special role in the structure, evolution and concomitant nucleosynthesis of stars in which the burning mode is not dominated by the p-p chains (i.e. $M \gtrsim 1.3 M_\odot$ in case of solar metallicity).

The estimate of the ^{14}N (p , γ) ^{15}O reaction cross section at low energies has recently been revisited by Angulo et al. (2001). As in the NACRE compilation, the experimental data of Schröder et al. (1987) are adopted for the calculation of

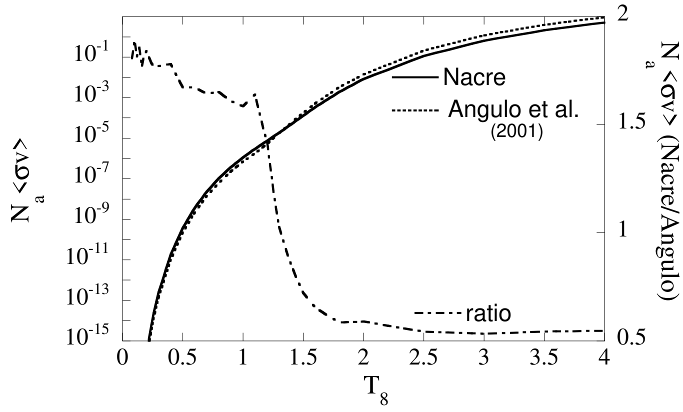

Figure 3. Comparison of the reaction rate for ^{14}N(p,γ)^{15}O between the adopted NACRE rate and the new determination of Angulo et al. (2001) as a function of the temperature [$T_8 \equiv T/(10^8)$ K]. The dot-dash line gives the ratio of the two rates, to be read on the right axis.

the non-resonant contribution to the reaction rate. The rate is estimated to be about 70% smaller than the NACRE one at temperatures $T_6 \lesssim 150$, and about twice larger above (Fig. 3). This significant difference originates from the new R-matrix calculation of the direct transition to the ground-state which is responsible for the major contribution to the low-energy S-factor. The ^{14}N (p , γ) ^{15}O reaction has also been re-analyzed experimentally using the inverse kinematics approach (Galloy & Terwagne, private communication).

In spite of the bottleneck role of ^{14}N (p , γ) ^{15}O , its rate changes displayed in Fig. 3 have only a very small impact on the 5 and 20 $M_\odot$ star models we have tested. The use of the faster rate instead of the slower 2001 rate increases the duration of the main sequence by only $\sim 2\%$ as a result of a smaller central temperature. This difference cannot be identified observationally. The effects on the central CNO abundances of these two different rates are illustrated in Fig. 4. Obviously, using the highest (NACRE) rate favors the production of all the species entering the CN cycle at the expense of ^{14}N. However, these changes barely affect the surface composition after the first dredge up. The most prominent difference is a 5% increase in the ^{15}N/^{14}N ratio when using the fastest rate. As a conclusion, no decisive observational effects result from the use the two rates of Fig. 3 and the effects on the evolution are extremely weak.

4. The ^{12}C (α , γ) ^{16}O : Where do we stand?

This reaction has long been recognized as essential in many stellar physics questions. The precise knowledge of its rate is indeed a *necessary* condition for a reliable evaluation of the ^{12}C to ^{16}O abundance ratio at the time He is exhausted by non-explosive burning, and consequently of the progeny of the subsequent non-explosive or explosive (supernova) C or O burnings. Even the precise fate of massive stars at the end of their evolution is influenced by the rate of the transformation of ^{12}C into ^{16}O, which, needless to say, is also not beside the

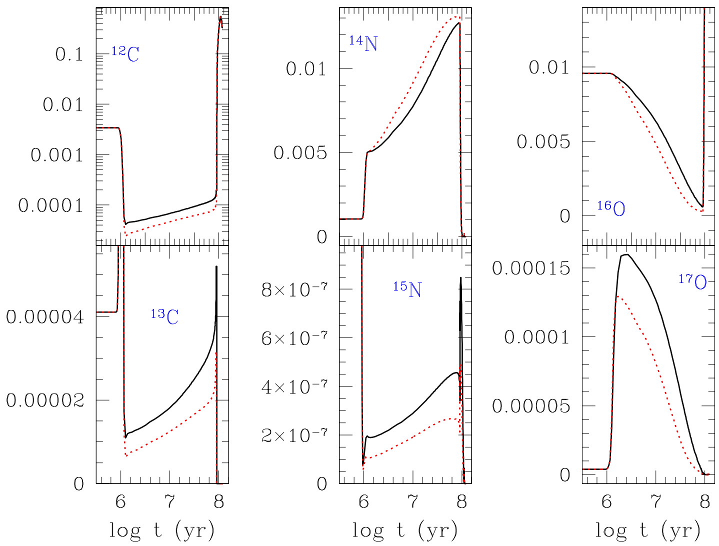

Figure 4. Evolution of the central mass fraction of the main CNO nuclei in a 5 $M_\odot$ stellar models of solar metallicity. The solid and dotted lines refer to calculations performed using the Nacre and Angulo et al. reaction rates for ^{14}N(p,γ)^{15}O reaction, respectively

point of describing the chemical evolution of galaxies. Of course, the knowledge of this rate is in no way *sufficient* to provide high quality predictions for all the above matters, stellar or galactic models having many difficulties of their own. The reader is referred to e.g. Imbriani et al. (2001) for a discussion of the impact of the ^{12}C$(\alpha,\gamma)^{16}$O rate on the modeling of stars in a wide mass range.

The nuclear physics data concerning ^{12}C$(\alpha,\gamma)^{16}$O are summarized by e.g. Angulo et al. (1999). Since the NACRE compilation, many laboratory efforts have been devoted to reducing its rate uncertainties, but the challenge is impressive. No measurement can be foreseen at the energies of astrophysical relevance, and the extrapolation to them from the lowest energy measurements is especially risky. The reaction mechanism presents a remarkable accumulation of intricacies, the existence of two sub-threshold states and their interferences with states above threshold being clearly not the least. Kunz et al. (2002) have recently published new direct measurements, from which Fig. 5 is extracted. At the non-explosive He-burning temperatures (T around 10^8 K), their recommended rate is not substantially different from the NACRE adopted values. However, uncertainties remain.

Some had the dream of constraining the ^{12}C$(\alpha,\gamma)^{16}$O rate by confronting the solar system composition with the predictions from models for the chemical evolution of the Galaxy. A new fashion has also developed recently, based on the precision study of white dwarf pulsations. From these, the hope has been expressed to derive the interior C/O abundance ratios accurately, and so to get accurate ^{12}C transmutation rates. We consider that these astrophysics methods to obtain a reliable information on the microphysics of the α-capture rate represents an impossible inverse problem. We advise to better go to the nuclear physics laboratory, even if the task is far from being trivial!

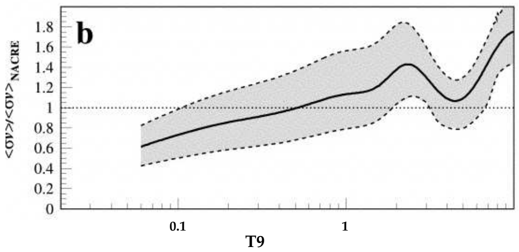

Figure 5. Comparison between the $^{12}C(\alpha,\gamma)^{16}O$ stellar rates derived by Kunz et al. (2002) and the adopted NACRE rates versus temperature [$T_9 \equiv T/(10^9)$K]. The shaded area corresponds to the rate uncertainties assigned by Kunz et al. (2002)

5. Novae and the Hot CNO Burning

Hydrogen can burn explosively in various astrophysical events, like novae or x-ray bursts. The corresponding hot burning modes (hot p-p and CNO or NeNa-Mg-Al chains, rp- or αp processes) involve a variety of unstable nuclei, and have specific nucleosynthesis signatures. They raise many difficult experimental and theoretical nuclear physics questions, and highly intricate astrophysical problems as well. They develop when some produced β-unstable nuclei decay more slowly than they capture protons, which is in contrast to the situation characterizing the corresponding cold burnings.

Of concern here is the hot CNO chain, first introduced by Audouze, Truran, & Zimmerman (1973) and Arnould & Beelen (1974). The cold CNO cycles switch to the hot mode when $^{13}N(p,\gamma)^{14}O$ becomes faster than the ^{13}N β-decay. This occurs typically at temperatures in excess of 10^8 K, which can be attained in thermonuclear runaways of the classical nova type. Such explosions of such a type are predicted to occur as a result of the accretion at a suitable rate onto a C-O or O-Ne white dwarf of material from a companion in a binary system. A sensitivity analysis of the nova yields to reaction rate uncertainties has been conducted recently by Iliadis et al. (2002). The uncertainties in the rates of $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$ and $^{18}F(p,\alpha)^{15}O$ are found to be responsible for variations by at least a factor of 2 in the C-O nova yields of ^{17}O and ^{18}F. Let us just note that the proton capture rates on ^{17}O have been re-examined recently by Blackmon (private communication) for typical nova conditions. They are also uncertain in cold CNO burning regimes (Sect. 2). On the other hand, the radionuclide ^{18}F ($t_{1/2} = 110$ min) predicted to be produced in novae is considered by some as important for γ-ray astrophysics. The annihilation with electrons of the positrons emitted in its β^+-decay and Compton scattering produce a γ-ray radiation that might be observable when the expanding nova envelope becomes transparent to γ-rays in the relevant energy range (e.g. Hernanz et al. 1999).

6. Conclusions

As an aid to the confrontation between spectroscopic observations and theoretical expectations, the nucleosynthesis associated with the cold CNO cycles is studied with the help of the recent NACRE compilation of nuclear reaction rates. Special attention is paid to the impact on the derived abundances of the carefully evaluated uncertainties that still affect the rates of many reactions. In order to isolate this nuclear effect in an unambiguous way, a very simple constant temperature and density model is adopted. Some post-NACRE data are also discussed briefly, sometimes in the framework of detailed model stars. Finally, a recent analysis of the impact of the uncertainties in the rates of the hot CNO chain on the C, N and O yields from classical novae is summarized.

It is shown that large spreads in the abundance predictions for several nuclides may result not only from a change in temperature, but also from nuclear physics uncertainties. This additional intricacy has to be kept in mind when trying to interpret the observations and when attempting to derive constraints on stellar models from these data.

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