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Understanding Cosmic Nucleosynthesis: the puzzling case of ^{44}Ti

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We briefly review the production site of the intermediate mass nuclei ($8 < Z < 30$) and highlight the role of the γ ray astronomy in shedding light on the evolutionary properties of massive stars: in particular we discuss the role of the γ ray emitter ^{44}Ti in the scenario of the stellar explosions. The synthesis of this isotope still constitutes a challenge for the theoreticians. In fact, its high electric charge (Z=22) would require temperatures in excess of a few billions of K for its production, but at these temperatures matter is in a statistical equilibrium configuration, condition that disfavors its production. Only an extremely fast expansion of the inner region of the ejecta, usually referred to as "α-rich" freeze out, would favor its synthesis though its final abundance would remain, also in the extreme (unrealistic) cases, short by at least an order of magnitude with respect to what would be required to explain the γ ray flux (at 1.157 MeV) detected in the direction of Cas A

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1. Introduction

The very fast cooling of the matter that occurred just after the Big Bang, firstly forced matter to freeze on a Nuclear Statistical Equilibrium configuration populated only by protons and neutrons and then, when the temperature dropped to 3×10^9 K or so, allowed the nuclear reactions to glue protons together and hence build up heavier nuclei. Unfortunately the quite inefficient ^{3}He+p nuclear reaction prevented the build up of nuclei heavier than ^{3}He by simple gluing of protons. Matter had to await the production of a sufficient amount of ^{3}He in order to activate the ^{3}He+^{3}He nuclear reaction and therefore produce α particles. Also the proton capture on ^{4}He is very inefficient, so that once again the synthesis of heavier nuclei needed to await the synthesis of enough ^{4}He to activate the ^{3}He+^{4}He nuclear reaction. Unfortunately the ^{7}Be synthesized by this last nuclear reaction efficiently captures a proton or an electron and, in both cases, a ^{8}B is eventually formed, nucleus highly unstable that quickly (i.e. with respect to the cooling timescale) decays back in two α particles. The net result is that the lack of stable nuclei of atomic masses A=5 and A=8 prevented the Big Bang Nucleosynthesis from significantly synthesize nuclear species heavier than ^{4}He. Current Big Bang Nucleosynthesis calculations predict that the metallicity [1] that emerged from the Big Bang did not exceed $Z = 10^{-10}$ at most [1, 2].

In spite of the failure of the Big Bang to significantly synthesize nuclei heavier than He, we are surrounded by a substantial amount of matter having atomic mass (A) greater than 4 all over the Universe. The analysis of the surface chemical composition of large samples of stars shows the existence of a clear (inverse) correlation between the metallicity and the age of a star: the older the star the lower its global initial metallicity (see, e.g., [3, 4]). In addition to that, it has become evident that also the relative abundances among the various nuclear species varies with the metallicity of a star. As an example, "α" nuclei as O, Si, S, Ar and Ca are in many cases overabundant with respect to Fe in Fe poor stars (see, e.g., [7, 5, 6]). On the contrary, nuclei as Cr and Ni preserve roughly scaled solar proportions with respect to Fe over the full range of Fe abundances. Of course the observed temporal evolution of the "metallicity" as well as the change of the relative proportions among the various nuclear species demands a proper understanding and hides important informations concerning the history of our Universe.

The main obstacle to the activation of the nuclear reactions, and hence to the synthesis of the elements, is given by the electric forces. Only an environment in which particles have a high relative velocity (in other words are at high temperature) allows them to get close enough that the tunnel effect may provide a not negligible probability that two particles form a compound nucleus. Even in the most favorable case, i.e. the fusion of two protons (which means the lowest possible Coulomb barrier between charged particles), temperatures in excess of (at the very minimum) a few millions of K for a timescale of the order of millions of years are necessary to significantly activate this nuclear reaction.

All these considerations naturally, and unavoidably, point towards a stellar origin for the elements heavier than He since only stars can maintain high temperatures for an extended period of time and also return the newly synthesized nuclei to the interstellar medium. It is therefore clear that a proper understanding of the evolutionary properties of stars on a wide mass interval is fun-

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[1] by "metallicity" Z astronomers usually mean the cumulative abundance of all nuclear species heavier than He

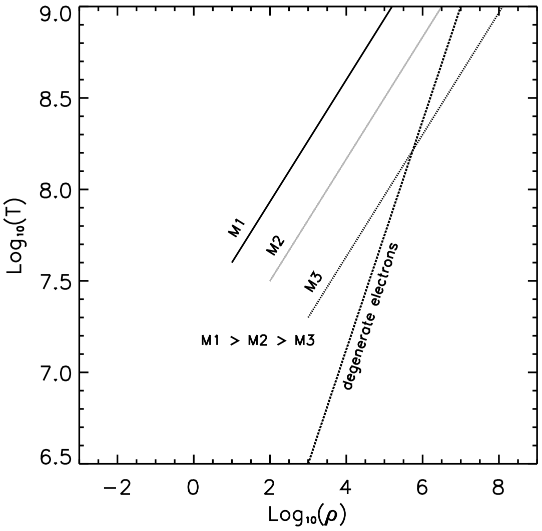

Figure 1: Basic evolutionary sequences of three stars of decreasing masses together to the line marking the region beyond which electron degeneracy becomes important

damental if we want to understand the history of the elements that surround us and hence of our Universe.

In the following we will describe the basic differences in the evolution of stars of different masses and we will briefly discuss the production sites of the intermediate mass nuclei ($8 < Z < 30$), pointing also to the importance of the γ ray astronomy to shed light on the still large uncertainties in the yields provided by different mass intervals. In particular we will briefly discuss the synthesis of the γ ray emitter ^{44}Ti.

2. Basic properties of a stars

A star may be basically described as a gas cloud in hydrostatic equilibrium, i.e. in a configuration in which pressure gradient and gravitational force counterbalance each other. In this case one may write that $\mathrm{dP/dr = -GM\rho/r^2}$ where P is the pressure, G the gravitational constant, M the mass coordinate, r the radial distance and ρ the density. A continuity equation for the mass controls the mass conservation: $\mathrm{dM/dr} = 4\pi \mathrm{r}^2\rho$. Since the pressure tends towards zero at the surface while the radius tends to zero at the center, the hydrostatic equilibrium basically implies that $\mathrm{P_c} \propto \mathrm{M}\rho/\mathrm{R_s}$, where $\mathrm{P_c}$ is the central pressure and $\mathrm{R_s}$ the stellar radius. But $\rho = \mathrm{M/R^3}$, so that it is possible to write $\mathrm{P_c} \propto \mathrm{M}^{2/3}\,\rho^{4/3}$. If the equation of state is mainly provided by a perfect gas, i.e. $\mathrm{P} \propto \rho\,\mathrm{T}$, one eventually obtains an important relation among central temperature ($\mathrm{T_c}$), central density (ρ_c) and mass M of a star: $\mathrm{T_c^3}/\rho_\mathrm{c} \propto \mathrm{M}^2$. This relation implies that the evolution of the central region of a star in the $\mathrm{Log(T_c)}$, $\mathrm{Log}(\rho_\mathrm{c})$ plane basically follows a straight line and that this line moves towards larger densities as the initial mass of the star decreases. Figure 1 schematically shows the evolutionary sequences of three stars of decreasing masses in the $\mathrm{Log(T_c)}$, $\mathrm{Log}(\rho_\mathrm{c})$ plane together to the line marking the region beyond which electron degeneracy becomes important.

Though this figure is basically a cartoon, it well explains why stars may be divided in two main groups according to their initial mass. Stars more massive than a threshold value (hereinafter massive stars) will evolve out of the region where the degenerate electrons play a relevant role in determining the properties of the equation of state (at least until they reach a central temperature of several billion of K), so that they will be able to contract and to heat until the core collapses to neutron densities, while stars less massive than this threshold value (hereinafter low and intermediate mass stars) inevitably enter the region where the pressure due to the Pauli exclusion principle counterbalances the gravity force, halting the contraction and heating of the core. This basic difference between the evolution of a low/intermediate mass star and a massive star inevitably implies that their contribution to the cosmic nucleosynthesis will be very different. In the following we will basically address the contribution of the massive stars.

3. Massive stars

Massive stars contribute to the chemical enrichment of the matter mainly in the region of the intermediate mass nuclei, namely the nuclear species between Oxygen and Zinc. The reason is that the nucleosynthesis is basically driven in these stars by the progressive increase of the temperature, occurrence that via via activates the burning of the main outcome of the previous burning (see, e.g. [8, 9, 10]). In sequence, H mainly produces He (at roughly 40-70 $\times 10^6$ K) that produces C and O (at $\simeq 200 \div 400 \times 10^6$ K). C then converts in Ne when the temperature raises to roughly $800 \div 1000 \times 10^6$ K, while Ne photo-disintegrates in O at a temperature of the order of 1.3×10^9 K. When the temperature exceeds $1.6 \div 1.8 \times 10^9$ K, O burning mainly produces Si and S while at larger temperatures the bulk energies of the photons become comparable to the binding energies of most of the nuclei so that matter tends towards an equilibrium condition in which synthesis and disruption of the various nuclear species tend to balance each other. In this equilibrium condition (called Nuclear Statistical Equilibrium) the most abundant nuclei are those having the largest binding energy. For a neutron to proton ratio equal to 1 (i.e. an electron mole number $Y_e = 0.5$), at 5×10^9 K or so the most abundant nucleus is ^{56}Ni while at 7×10^9 K matter is mainly locked in α particles whereas at higher temperatures only protons and neutrons may survive. Note that the weak processes, i.e. those that allow the conversion of protons in neutrons and vice versa, do not reach an equilibrium condition at T lower than, say, 10×10^9 K. This means that the neutron to proton ratio (or, alternatively, Y_e) changes according to specific weak processes that become efficient in these conditions, i.e. electron captures on ^{33}S, ^{53,54}Mn, ^{54,55}Fe and ^{55,56,57}Co. The abundances of the various nuclear species within a star at the moment of the core collapse reflect its past history, i.e. the extension of the various convective zone associated to different nuclear burning (that spread the newly synthesized nuclei over a region wider than the one in which they are produced), the speed at which each shell burning advances in mass (that affects the size of the various core masses), the specific temperature at which each core/shell burning occurs as well as the amount of mass lost from the surface (that affects the binding energy of a star if it is strong enough to reduce the size of the He core): as an example Figure 2 shows the typical chemical structure of a 20 $M_\odot$ of solar metallicity just prior the Fe core becomes unstable and collapses.

When the center of a massive star reaches a temperature of the order of several billion of K and a density of several 10^9 g cm^{-3}, the inner core starts collapsing up to nuclear densities,

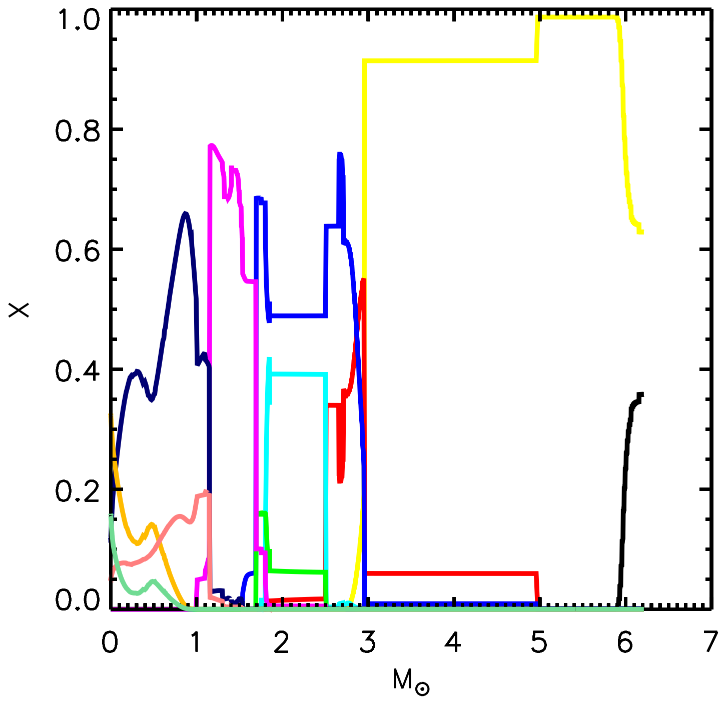

Figure 2: Abundances by mass fraction of the main nuclear species just before the core collapse in a 20 $M_\odot$of solar metallicity. The various lines refer to: H (black), He (yellow), C (red), O (blue), Ne (cyan), Mg (green), Si (violet), ^{52}Cr (pink), ^{54}Cr (light green), ^{56}Fe (dark blue) and ^{58}Fe (orange).

releasing roughly 10^{53} erg of energy (gravitational), a fraction of this forming a shock wave that crosses outward the whole star reverting the motion of the collapsing mantle and ejecting it in the interstellar medium. On its way out, the shock wave induces additional important nucleosynthesis, the so called explosive nucleosynthesis. A few distinct zones may be identified, depending on the peak temperature reached by each mass layer. More specifically there is an innermost region where the full NSE is obtained ($T>5\times 10^9$ K, complete explosive Si burning), an intermediate region ($5>T>4 \times 10^9$ K) where a partial NSE is reached (called Quasi Statistical Equilibrium - QSE - or incomplete explosive Si burning) and an outer region where a still lower degree of statistical equilibrium is reached ($4>T>3.2 \times 10^9$ K), usually called double QSE or explosive oxygen burning. In the mass interval where the peak temperature of the shock wave ranges between 3.2 and 1.8×10^9 K additional nucleosynthesis occurs but in this case it not determined by any kind of statistical equilibrium (because the temperature is too low) but it is driven by the actual efficiency of the nuclear reactions.

The total abundances of the nuclear species returned to the interstellar medium at the end of their lifetime (by either mass loss and the explosion itself) are called the "yields" provided by that star, while the ratio between the ejected and the preexisting abundance of each nuclear species (called production factor - PF) gives a quantitative determination of freshly synthesized matter; in fact a PF=1 means no production nor destruction, a PF<1 means that an isotope has been basically

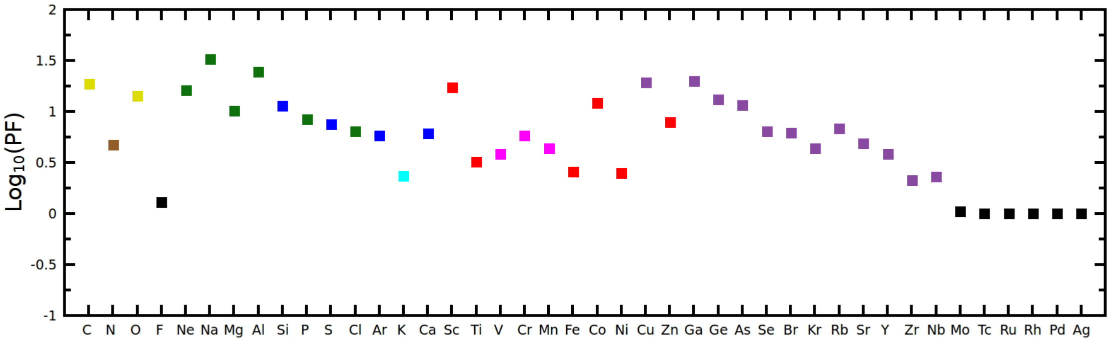

Figure 3: Elemental production factors coming from the explosion of a 20 $M_\odot$model. The various colors refer to elements produced by: H burning (brown), He burning (yellow), C-shell burning (green), explosive O burning (cyan), explosive O burning and incomplete explosive Si burning (blue), incomplete explosive Si burning (magenta), complete explosive Si burning (red), n-capture nucleosynthesis in He and C burnings (violet). The elemental species marked black are not produced by massive stars.

destroyed while a value larger than one implies a net production of that nuclear species. Figure 3 shows the PF of the elemental yields provided by a 20 $M_\odot$ star of solar metallicity.

Massive stars cannot produce a significant amount of elements heavier than the Fe group because the low proton abundance in the regions where proton captures on these Z rich nuclei could in principle be efficient keeps their production rate practically negligible. By the way, the existence of these "heavy" nuclei demands another production channel and site: it has been recognized a long time ago that low and intermediate mass stars are the responsible for the production of roughly half of the matter beyond the Fe group by means of successive (slow) n captures. Neutrons' flux is efficiently produced by either the ^{13}C(α,n)^{16}O and the ^{22}Ne(α,n)^{25}Mg nuclear processes. The other half of the nuclei beyond the Fe group is produced by the r-process (rapid neutron capture) very probably during the explosion of a Supernova.

Coming back to the massive stars, how we have already said above, the uncertainties on the yields of the various nuclear species produced by massive stars reflect the uncertainties in the computation of both the hydrostatic part of the life of a star as well as the explosion that follows the collapse and core bounce. The weakest points in the computation of the evolution of a massive star (actually of the stars in general) are the treatment and extension of the convective regions, the efficiency of mass loss and the role of rotation. As far as the explosion is concerned we are still facing a situation in which a real self consistent explosion has not been obtained yet, so that it is usually still mimicked in a parametric way, assuming "a priori" the final kinetic energy of the ejecta. This failure heavily penalizes our ability in predicting the yields of all the nuclear species that are produced in the deep interior of a star by the explosive nucleosynthesis, see Figure 3, as well as a reliable determination of the mass spectrum of the remnants.

Gamma ray line astronomy plays a pivotal role in our endless effort to better understand the evolution and the explosion of a massive star since it allows the detection of the decay of unstable nuclei produced in the deep interior of a star either during the hydrostatic part of its evolution as well as during the explosion. The detection of unstable nuclei is in general of particular interest

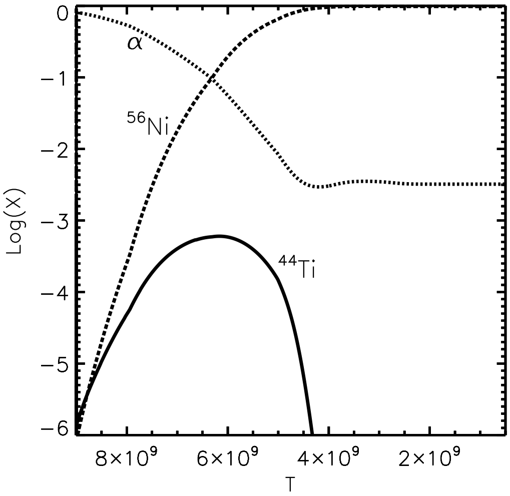

Figure 4: Temporal evolution of a gram of matter exposed to a peak temperature of 9×10^9 K and a density of 3 10^8 g cm^{-3} in which the density has been assumed to drop exponentially with a characteristic timescale of the order of the free fall timescale while the temperature has been assumed to follow the constant entropy law for the photons (i.e. T^3/ρ=constant.). The temperature has been used as abscissa to better illustrate the trends

because of their nature: they are normally not present in nature and their production in not negligible amount occurs only under well specific physical conditions. Hence their detection, either in the interstellar medium and/or in the light curve - ejecta of a supernova, poses very useful constraints on the modeling of these stars as well as hints on the kind of star we are observing.

Few years ago we made an extensive study of two important γ ray emitters, i.e. ^{26}Al and ^{60}Fe, [11] and we refer the reader to that paper for an exhaustive discussion of these two nuclei. Here we want to briefly discuss another very important γ ray emitter: ^{44}Ti. In order to understand the importance of this unstable nucleus it must be remembered that it is a multiple α nucleus that lies at the proton rich side of the stability valley, detached from it. Given the high electric charge (Z=22), in principle temperatures in excess of a few billions of K would be necessary to glue enough α particles to form it but, on the other side, at these temperatures matter is typically at the NSE. Unfortunately the NSE disfavors the formation of this nucleus that has therefore a very low equilibrium abundance. As far as we know, all available computations of the explosive nucleosynthesis (obtained by assuming a final kinetic energy of the ejecta of the order of 10^{51} erg or so) still fail to produce a significant amount of ^{44}Ti. On the contrary an appreciable abundance of ^{44}Ti alive ($\sim$ 1.6 10^{-4} $M_\odot$) has been observed in the direction of Cas A [12, 13, 14, 15, 16].

An environment in which ^{44}Ti could be produced requires certainly a high temperature (to overcome the electric forces), an habitat far from the NSE (because this isotope is not produced when matter is at the NSE) and a consistent α-flux (because this is an α nucleus preferentially produced by α-captures). These requirements obviously imply that its synthesis will be determined by the relative efficiency of the nuclear processes that produce and destroy it. Anyway, this is a very demanding scenario that may be realized if the expansion triggered by the shock wave is

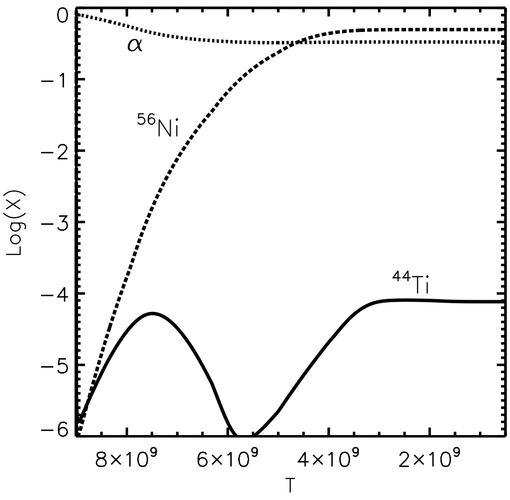

Figure 5: As Figure 4 but with a timescale of the expansion 10^5 times faster.

so fast that the associated density drop forces matter to depart from the NSE condition when the temperature is still very high, leaving a consistent amount of free α particles (relic of the NSE abundances typical of T=7-8 $\times$ 10^9 K). This condition is usually called "α-rich" freeze-out and it is probably the most favorable case for a substantial ^{44}Ti production [17, 18]. Figure 4 shows, as an example, the temporal evolution of a gram of matter exposed to a peak temperature of 9 $\times$ 10^9 and a density of 3 10^8 g cm^{-3} in which the density has been assumed to drop exponentially with a characteristic timescale of the order of the free fall timescale and the temperature follows the density assuming a constant entropy for the photons (i.e. T^3/ρ=constant.). It is clear that under these circumstances no ^{44}Ti is produced. But if we speed up the expansion by a factor 10^5 (i.e. we impose an α-rich freeze out, see Figure 5), the final abundance may increase up to roughly 10^{-4} by mass fraction. Such a fast expansion is probably unrealistic and in any case the concentration obtained even in this extreme case would require roughly 1 $M_\odot$ of matter processed in this way in order to reproduce the amount observed in the direction of Cas A. On the contrary only a fraction of the order of 10^{-2} $M_\odot$ or so could be exposed to these extreme conditions. Since the synthesis of this nucleus depends on the efficiency of the processes that produce and destroy it, also a proper analysis of the reliability of the cross sections involved in the production/destruction of this nucleus must be addressed. In this respect various groups, e.g. [19, 20], are heavily involved in the measure, as precisely as possible, of the key process leading to the synthesis of ^{44}Ti, i.e. the ^{40}Ca(α,γ)^{44}Ti. There is also a strong activity in the field of both the study of the effect of the presupernova evolution on the synthesis of ^{44}Ti, e.g. [21], as well as extended parametric studies, [22], of the (explosive) physical conditions which could lead to a significant production of this unstable nucleus.

This brief, largely incomplete, review of the nucleosynthesis of the ^{44}Ti shows how the detection of a consistent amount of this nuclear specie alive in the direction of Cas A, still constitutes an unsolved problem but also demonstrates the importance of the γ ray line astronomy in providing vital informations (or, better, challenges) about the life/explosion of a star.

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