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The synthesis of ^{44}Ti and ^{56}Ni as a function of the initial rotational velocity, metallicity and mass

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In this talk we showed how the yields of the unstable nuclei ^{44}Ti and ^{56}Ni depend on the initial mass, metallicity and rotational velocity. The main result is that non rotating models are still not able to produce a sufficient amount of ^{44}Ti as required by the observations of the supernova remnant Cas A and 1987A, falling short by a factor four or five. Vice versa a few rotating models develop an extended O convective shell in which a significant amount of ^{44}Ti is produced hydrostatically and preserved during the explosion. Though also in this case not enough ^{44}Ti is synthesized, falling short by a factor of two or so, the possible contribution of an extended O burning shell on the global synthesis of this nucleus should be taken into account

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1. Abstract

According to the latest INTEGRAL data, the signal coming from Cas A is compatible with an amount of $^{44}\mathrm{Ti} \simeq (1.37 \pm 0.19) \times 10^{-4} \mathrm{M}_\odot$[1]. Also NuSTAR detected a signal compatible with a similar amount of ^{44}Ti, i.e. $\simeq (1.25 \pm 0.3) \times 10^{-4} \mathrm{M}_\odot$[2]. As far as the SN1987A is concerned, INTEGRAL detected an amount of $^{44}\mathrm{Ti} \simeq (3.1 \pm 0.8) \times 10^{-4} \mathrm{M}_\odot$[3] while NuSTAR quotes a value of $^{44}\mathrm{Ti} \simeq (1.5 \pm 0.3) \times 10^{-4} \mathrm{M}_\odot$[4]. Putting together these data it comes out that in both explosions the amount of ^{44}Ti ejected was of the order of $1 \div 3 \times 10^{-4} \mathrm{M}_\odot$. It is worth noting that no other signal attributable to ^{44}Ti has been observed so far from other possible sources (discrete or extended). From a theoretical point of view, since the 60's [5][6] it has been recognized that ^{44}Ti may be produced in the deepest regions of a star where the Nuclear Statistical Equilibrium (NSE) is attained, when it is followed by an α-rich freeze out. Without any additional constraint, there would not be any difficulty in ejecting an amount of ^{44}Ti of the order of $10^{-4} \mathrm{M}_\odot$ or so, because in most cases some layers in the deepest interior of a massive star experience the NSE + α-rich freeze out. Unfortunately (or fortunately) the layers that produce ^{44}Ti also produce ^{56}Ni, whose decay powers the light curve for an extended amount of time, so that it may be determined with accuracy. SN1987A ejected $\simeq 0.075 \mathrm{M}_\odot$ of ^{56}Ni [7] [8] while the supernova remnant Cas A did not show up in 1680 (the alleged year of the explosion, but see [9]), so that we can just put an upper limit to the amount of ^{56}Ni produced in that supernova explosion.

We have recently computed a new grid of stellar models that extend in mass between 13 and 120 $\mathrm{M}_\odot$, span four metallicities ([Fe/H]=0,-1,-2,-3) and three initial equatorial rotational velocities (v=0, 150 and 300 km/s). The paper describing in detail the physical properties of these models together to the yields obtained for different choices of the mass cut will be available shortly [10]. Here we will use the yields of ^{44}Ti corresponding to the contemporaneous ejection of $0.1 \mathrm{M}_\odot$ of ^{56}Ni (value close to the one ejected by the SN1987A).

Figure 1 shows the yield of ^{44}Ti (red solid line) as a function of the initial mass in the interval 13 to 60 $\mathrm{M}_\odot$. The horizontal light black dotted line shows what can be considered a fair lower limit of the amount of ^{44}Ti ejected by Cas A and SN1987A. It is quite evident that the theoretical yields run short of the detected abundances over the full mass interval (and in particular around $20 \mathrm{M}_\odot$, the progenitor of the SN1987A). Reducing the metallicity to [Fe/H]=-1 does not help (solid blue line): actually the yields are even smaller than the ones obtained at solar metallicity (for the same amount of ^{56}Ni ejected). In order to raise the yield of ^{44}Ti it would be necessary to eject also a larger amount of ^{56}Ni: the magenta ([Fe/H]=0) and cyan ([Fe/H]=-1) solid lines in Figure 1 show, as an example, the amount of ^{44}Ti that would be ejected if all the explosions were tuned to eject $0.30 \mathrm{M}_\odot$ of ^{56}Ni. It is clear that, without the constraint coming from the observed amount of ^{56}Ni ejected, it would be quite easy to raise significantly the yield of ^{44}Ti.

Before looking at the effects of rotation on the predicted relation between ^{44}Ti and ^{56}Ni, it is important to briefly summarize where ^{44}Ti is synthesized within a star. It is produced by either the O burning shell, the incomplete explosive Si burning and the complete explosive Si burning. In most cases the amount of ^{44}Ti synthesized by the O burning shell is fully destroyed by the passage of the shock wave since it is confined to a small region whose chemical composition is fully modified by the passage of the bast wave. Though most of the ^{44}Ti is synthesized by the complete explosive Si burning, the fraction of it produced by the incomplete explosive Si burning

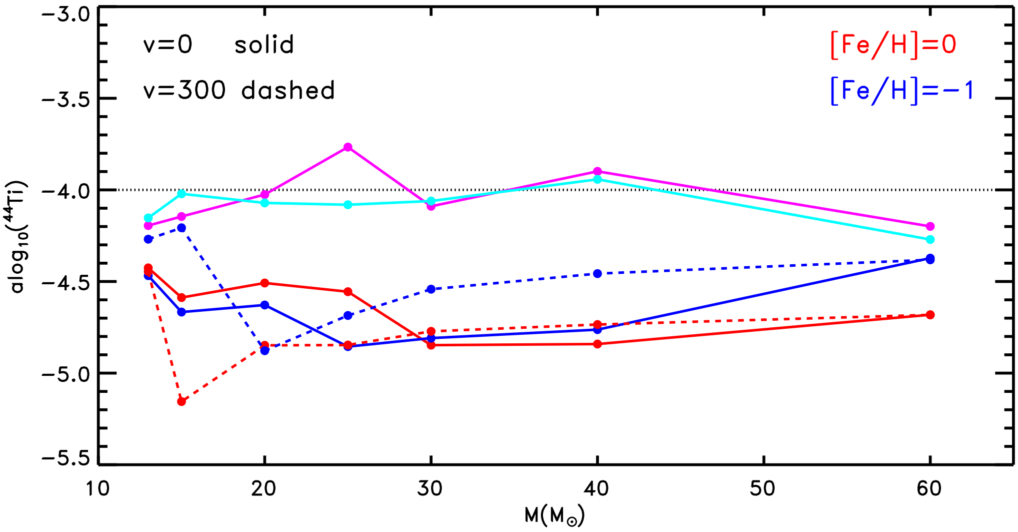

Figure 1: The red and blue lines show the amount of ^{44}Ti corresponding to 0.1M$_\odot$ of ^{56}Ni while the magenta ([Fe/H]=0) and cyan ([Fe/H]=-1) solid lines show the amount of ^{44}Ti that would correspond to 0.3M$_\odot$ of ^{56}Ni.

is not negligible (roughly 20% in the mass range 15-20M$_\odot$ at [Fe/H]=0), raising significant at lower metallicities (roughly 40% in the mass range 15-20M$_\odot$ at [Fe/H]=-1).

Keeping this in mind, the amount of ^{44}Ti ejected by rotating stars ($v_{ini} = 300$ km/s) is shown in Figure 1 as dashed lines: the red one refers to [Fe/H]=0 while the blue one refers to [Fe/H]=-1. At solar metallicity rotation does not help at all, actually it goes in the opposite direction since it reduces significantly the amount of ^{44}Ti corrsponding to 0.1M$_\odot$ of ^{56}Ni. Vice versa at [Fe/H]=-1 rotating models produce more ^{44}Ti then their non rotating counterparts (with the exception of the 20M$_\odot$). Though also rotating models are not able to get very close to the threshold value of 10^{-4} M$_\odot$ of ^{44}Ti, something very interesting occurs in the mass interval 13-15M$_\odot$ at [Fe/H]=-1. These are the two models which get closer to the threshold value, and this does not occur because of a more favorable conditions of matter exposed the complete explosive Si burning, but because rotation in these two models favors the formation of a very extended O convective shell where a consistent amount of ^{44}Ti produced by the O burning shell is stored and brought at a sufficient distance from the centre that it is not destroyed by the passage of the shock wave. This result is not interesting per se but because it opens new scenarios and additional channels for the synthesis of ^{44}Ti worth of being explored. The key point is the formation of a buffer (convective shell in this case) where the ashes of the O burning may be stored. The formation of such a buffer is not necessarily related to rotating models. Even a better treatment of the growth of the convective instabilities in the advanced burning phases [11] could lead to more extended mixing and therefore to the preservation of nuclei like ^{44}Ti during the passage of the shock wave.

A much more detailed analysis of the topic discussed in this talk has been recently published by us [12].

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