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Chemical signature of GRB progenitors at low metallicities

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Abstract. Long and soft GRBs have now been firmly connected with the death of massive stars. Stellar evolution models predict that GRBs are favoured at low metallicities because of the metallicity dependence of mass loss. In this paper, we study the chemical signature of low-Z GRB progenitors. For this purpose, we calculated stellar evolution models of low-Z fast rotating stars with a very large nuclear reaction network. Our models show that rotating models boost the production of s process at low Z, whereas non-rotating models predict a negligible production. In particular, our models predict a scatter of ratios like [Y/Ba] due to the distribution of initial rotation velocities leading to more or less production of elements in the barium peak. Observations of a large scatter for these ratios in both EMP stars and the oldest globular cluster in the galactic bulge provide support for our models and rotation induced mixing in general. This thus gives support to the idea that low-Z GRB progenitors could lose their hydrogen-rich envelope by mixing rather than mass loss and it is exciting for the prospect of using GRBs as cosmological probes up to high redshifts ($z \lesssim 20$).

Key words. Nucleosynthesis Stars: abundances chemically peculiar Population II massive rotation - Gamma rays: theory, bursts, supernova:general

1. Introduction

Long and soft GRBs have now been firmly connected with the death of massive stars as type Ic SNe (Woosley & Bloom 2006). Several stellar evolution groups have calculated grids of massive star models (Hirschi et al. 2005; Yoon et al. 2006; Woosley & Heger 2006) in order to predict which stars would lead to a GRB event in the framework of the collapsar model (Woosley 1993). The grid of models of (Hirschi et al. 2005) only includes the effects of rotation while the other two studies also include the effects of magnetic field according to the Taylor-Spruit dynamo (Spruit 2002). The last two studies (Yoon et al. 2006; Woosley & Heger 2006) predict an upper metallicity threshold around or below the LMC metallicity for the occurrence of Ic supernova with enough angular momentum to power a GRB event. This upper limit is explained by the metallic-

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ity dependence of mass loss, which leads to too much angular momentum removal at high metallicity. This is in line with most GRB-SNIc events observed so far. There are, however, two dark GRBs and one radio-relativistic SN, that have been observed at high, supersolar metallicity (see Modjaz 2011, for a full discussion and references). These new events pose a real challenge to the theoretical predictions, especially the models with the Taylor-Spruit dynamo, which predict an upper metallicity limit around $Z = 0.003$. In the study of Hirschi et al. (2005), models (not including the Taylor-Spruit dynamo, which slows down the core during the pre-supernova evolution) retain enough angular momentum and could produce GRB-SNIb events at all metallicities but the majority of stars would, in this case, require a braking mechanism during the formation of the compact remnant in order to explain the observed rotation rate of pulsars and white dwarfs (Suijs et al. 2008). This is an interesting challenge that will need to be studied in more details in the future. In this paper, however, we will focus on the low metallicity range. The low Z range is very important since GRBs are amongst the events that can probe the Universe up to the highest redshifts ($z \lesssim 20$), the current record holder, GRB090423, having z=8.26 (Tanvir et al. 2009). Furthermore, GRBs could be much more common in the early universe than in the nearby universe, in particular according to the quasi-chemically homogeneous models of Yoon et al. (2006). In these models, the hydrogen is not removed by mass loss but by the internal mixing induced by rotation, thus allowing the star to retain more of its angular momentum. Rotation induced mixing is questioned by recent observational campaigns (see e. g. Hunter et al. 2007) but the evidence is not conclusive yet and more work needs to be done on this topic as well (Frischknecht et al. 2010). At low Z, rotation induced mixing offers an elegant explanation for the primary nitrogen observed in extremely metal-poor (EMP) low-mass stars in the halo of our galaxy that bear the chemical signature of the first stellar generations (Chiappini et al. 2006). The primary nitrogen production is due to mixing between the helium burning core and hydrogen burning shell. Primary carbon and oxygen are produced in the core and are mixed into the hydrogen burning shell where both are converted into nitrogen via the CNO cycle. In this paper, we want to look at other chemical signatures of internal mixing due to fast rotation in massive low Z stars. These signatures will help us determine the importance of mixing and potentially give us clues concerning the frequency of GRB events in the early Universe, which will be the key to use GRBs as cosmological probes of star formation at high redshifts.

2. Stellar evolution models

Fast rotating stellar models at low Z have been calculated by Meynet et al. (2006) and Hirschi (2007). In these rotating models, primary nitrogen yields are much larger than in non-rotating models. When yields from these rotating models are used as input ingredients in chemical evolution models, a nice fit of the N/O in very metal poor halo stars can be obtained as mentioned above (Chiappini et al. 2006). This provides a strong support for the occurrence of rotation induced mixing at low Z and for our models. The primary nitrogen production in rotating low-Z stellar models is accompanied by the primary production of other isotopes like ^{13}C, and especially ^{22}Ne, which is the neutron source for s process in massive stars (e.g. Käppeler et al. 2011, and references therein).

A first attempt to assess the impact of rotation on the s-process nucleosynthesis in low-Z massive rotating stars was made by Pignatari et al. (2008), who investigated the impact of primary ^{22}Ne in a parametrised way. The recent observation of large s-process enhancements in one of the oldest globular clusters in the bulge of our galaxy supports the view that massive stars could indeed be also important sources for these elements (Chiappini et al. 2011), highlighting the need for comprehensive calculations of s process in low-Z massive rotating stars. In this paper, we present a few of the most recent models calculated for low-Z massive rotating stars including a full s-process network (Frischknecht et al. 2011).

We calculated our models with the Geneva stellar evolution code (GENEC), which is described in detail in (Eggenberger et al. 2007). The main improvement brought to GENEC for this work is the integration of a 613-isotope nuclear reaction network, almost identical to the s-process network used by The et al. (2000, see their table 1). GENEC with the enhanced nucleosynthesis network was first used to study the evolution of the abundance of light elements at the surface of main sequence massive stars (Frischknecht et al. 2010).

We used the reaction library (REACLIB) from Rauscher & Thielemann (2000), but with major updates. The charged particle reaction rates from Angulo et al. (1999) were used except for the following reactions: ^{22}Ne(α,n) and the 3α-rate were taken from Jaeger et al. (2001) and from Fynbo et al. (2005), respectively. If available, the neutron captures were taken from the KADoNiS compilation (Dillmann et al. 2006) and the temperature dependent beta-decays from Takahashi & Yokoi (1987). Note that several reaction fits were downloaded from the JINA-REACLIB website (groups.nscl.msu.edu/jina/reaclib/db). For ^{17}O(α,γ) and ^{17}O(α,n) reaction rates we used the rates of Caughlan & Fowler (1988) (hereafter CF88) and Angulo et al. (1999), respectively. Their ratio determines the strength of ^{16}O as a neutron poison and is very uncertain at the moment. Indeed, Descouvemont (1993) predicts that the ^{17}O(α,γ) should be a factor of 1000 smaller than the CF88 rate. This huge uncertainty strongly affects the s process in massive stars at low Z (Hirschi et al. 2008), where ^{16}O is known to be a strong neutron absorber/poison (Rayet & Hashimoto 2000). Recently, two independent groups measured the ^{17}O(α,γ) rate (Best et al. 2011, and Taggart et al NICXI-045) but it is not yet clear if the new rate will be lower than the CF88-rate at the relevant energies (priv. comm. A. Laird). In order to assess the impact of a decreased rate, we also calculated 25 M$_\odot$ models with the CF88 rate divided by a factor 10, which will probably still be inside the uncertainties of the new measurements in the relevant energy range.

We have calculated models of 25 M$_\odot$ stars at initial metallicities, $Z = 10^{-3}$, 10^{-5} and 10^{-7} (Frischknecht et al. 2011) and present below our results for the 25 M$_\odot$ models at $Z = 10^{-5}$ ([Fe/H] = -3.8).

3. Rotation boosted s process

The standard s process in massive stars is a secondary process (see e.g. Raiteri et al. 1992). It is a secondary process because the main neutron source (^{22}Ne) and the seeds (mainly iron) have a secondary origin. Indeed, in non-rotating models, the main neutron source, ^{22}Ne, comes only from the initial C, N, and O. During helium burning, the neutron poisons are a mixture of secondary (mainly ^{25}Mg) and primary (mainly ^{16}O) elements, whereas during carbon burning the neutron poisons are primary elements (^{20}Ne, ^{24}Mg). Thus, at very low Z, the standard s process is even less efficient than a secondary process and the contribution from the carbon shell becomes very small.

Rotation significantly changes the structure and pre-SN evolution of massive stars (Hirschi et al. 2004) and thus also the s-process production. Rotating stars have central properties similar to more massive non-rotating stars. In particular they have more massive helium burning cores and higher central temperature. The latter means that the He-core contribution increases at the expense of the C-shell contribution. This and the primary origin of neutron poisons during carbon burning lead to a very small C-shell contribution to the pre-SN yields at low Z: i.e. lower than 10% in our rotating models.

Apart from the seeds, the s process is strongly dependent on the neutron source and neutron poisons. Both are still quite uncertain at present. The neutron source, ^{22}Ne, depends on rotation induced mixing and thus on the initial velocity of stars at very low Z. In order to assess the uncertainty linked to the primary production of ^{22}Ne, we calculated additional models with a higher initial velocity ($\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0.5). Compare to the standard case ($\upsilon_{\rm ini}/\upsilon_{\rm crit}$= 0.4), the increase in the production of ^{22}Ne is about a factor of 3. This leads to a higher neutron capture per seed (n_c) and thus to a production of elements like Ba at the expense of elements like Ge but the total production (sum of all isotopes heavier than iron) is

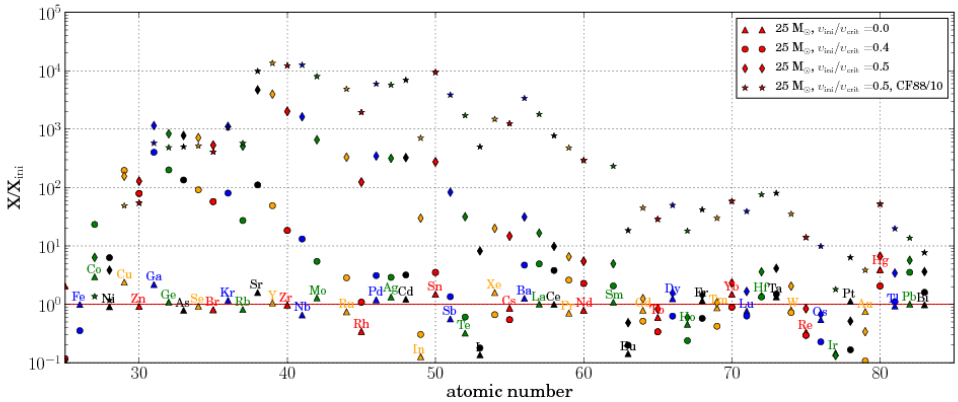

Fig. 1. Overproduction factors (abundances divided by their initial values) for the 25 M$_\odot$ models with Z = 10^{-5} ([Fe/H]= -3.8) after the end of core He-burning. The model without rotation (triangles) does not produce s-process efficiently whereas the rotating models (circles, $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0.4 and diamonds, $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0.5) do. The additional rotating models with reduced ^{17}O(α,γ) rates (stars, CF88/10 and $\upsilon_{\rm ini}/\upsilon_{\rm crit}$ = 0.5) highlights the uncertainty linked to the neutron poison ^{16}O (Figure taken from (Frischknecht et al. 2011)).

still limited by the iron seeds. A major uncertainty concerning neutron poisons is the importance of ^{16}O as a neutron poison. As explained in the previous section, at low Z, ^{16}O is a strong neutron absorber during core He-burning. The neutrons captured by ^{16}O$(n,\gamma)^{17}$O may either be recycled via ^{17}O$(\alpha,n)^{20}$Ne or lost via ^{17}O$(\alpha,\gamma)^{21}$Ne. To investigate the impact of the ^{17}O$(\alpha,\gamma)^{21}$Ne rate uncertainty, we calculated models with the CF88 rate divided by a factor of 10. The impact of a change of even a factor of 10 in this rate is strong (see Fig. 1). Given the differences between models with the CF88 and CF88/10 rate, the experimental determination of the ^{17}O(α,γ)-rate and the ^{17}O(α,n) is crucial to give a more accurate prediction for the s process in massive rotating stars at low metallicity.

We can see from Fig. 1 that rotation induced mixing enables a strong production of elements heavier than iron up to the strontium peak (typical for the weak s process in massive stars) and for fast rotation to the barium peak. The exact quantitative production is still uncertain given nuclear rate uncertainties but one of the predictions of our models is a scatter of ratios like [Y/Ba] and [Sr/Ba] due to the distribution of initial rotation velocities of low Z massive stars leading to more or less production of the barium peak elements. The scatter in these ratios have been observed both in EMP stars (Frebel 2010) and the oldest globular cluster in the galactic bulge (Chiappini et al. 2011) and our models are able to reproduce the full observed scatter.

4. Conclusions

In this paper, we have looked at the chemical signature of GRB progenitors at low Z, which are fast rotating massive stars. The rotation induced mixing in these stars boosts the s process production and enables the production of elements up to the barium peak. The fact that our models can reproduce the observed scatter of ratios like [Y/Ba] in both EMP stars and the oldest globular cluster in the galactic bulge gives support for a strong rotation induced mixing at low Z. This gives support to the idea that GRB progenitors can lose their hydrogen rich envelope by internal mixing (quasi-chemically homogeneous evolution) rather than mass loss (Yoon et al. 2006). A stronger mixing is required for a quasi-chemically homogeneous evolution than for a boosted s-process production. Thus the frequency of GRB will depend on the distribution of initial velocities at low Z, with only the fastest stars producing GRBs. The frequency will also depend on the source of mixing (rotation or rotation + magnetic fields). Recent star formation simulations by Stacy et al. (2011) show that the initial rotation could be higher than average in the first stellar generations. These results are thus encouraging for the prospect of using GRBs as cosmological probes.

Within the current uncertainties of the $^{17}O(\alpha,\gamma)$-rate, ^{16}O can be either a strong or a moderate neutron poison at low metallicities and new experiments are necessary to reduce this uncertainty. Another interesting aspect of our models not discussed above is the large primary production of ^{22}Ne in the He-shell occurring in all the rotating models calculated, i.e. 1-2% in mass fraction at all Z. This can have a strong impact on the supernova nucleosynthesis in He-burning shell, since it could provide a primary neutron source for neutron capture nucleosynthesis at low Z. Further stellar and galactic chemical evolution models (Chiappini et al in prep.) will assess the full impact of this boosted s process on the composition of metal poor stars.

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