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Modeling The Nucleosynthesis Of Massive Stars

T. Rauscher

Department of Physics and Astronomy, University of Basel, Basel, Switzerland

Abstract

This overview discusses issues relevant to modeling nucleosynthesis in type II supernovae and implications of detailed studies of the ejecta. After a brief presentation of the most common approaches to stellar evolution and parameterized explosions, the relevance of a number of nuclei to obtain information on the evolution and explosion mechanisms is discussed. The paper is concluded by an outlook on multi-dimensional simulations.

Key words: stellar evolution, massive stars, nucleosynthesis, Supernovae

1 Introduction

Nowadays it is commonly accepted that stars with masses $M > 8M_\odot$ complete all possible phases of hydrostatic burning up to Si burning and end their life in a collapse of the Fe core, followed by an explosive ejection of matter. The most common type of core collapse supernovae are type II supernovae, showing H lines in their spectrum and resulting from the explosion of a progenitor with $M > 10M_\odot$. The details of hydrostatic stellar evolution depend on hydrodynamical effects like convection as well as on nuclear physics. Regarding the latter, the most famous example is the one of the ^{12}C(α,γ)^{16}O reaction which sensitively determines energy generation during and the ^{12}C/^{16}O ratio after He burning. Therefore, also the subsequent burning phases depend sensitively on this reaction and thus the evolution of the star (see, e.g., Heger et al., 2002). Due to the still large uncertainty in the cross section, this reaction contributes the largest uncertainty in hydrostatic stellar evolution and its nucleosynthesis. More recently, it has been shown that two other reactions are also of major importance, namely the ones of the branching between ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg. The neutrons released by the former reaction alter abundances by neutron capture reactions and are responsible for the weak s-process component produced in massive stars. At sufficiently high temperatures the neutron release can be so effective that nuclei several units away from stability can be created in a so-called n-process (Rauscher et al., 2002). On the other hand, prevailing uncertainties in the treatment of convection and semi-convection will influence the reaction of the star to altered nuclear physics. While nuclear reactions dominate the error in calculating hydrostatic abundances, the proper hydrodynamic treatment of the core collapse currently seems to be the source of most problems connected with the explosion mechanism. Nevertheless, nuclear properties like neutrino cross sections and the nuclear equation of state have to be known accurately, too.

Observing the abundances of radioactive species in supernova remnants help us gain a deeper understanding concerning the production of those nuclei and also on the underlying physical processes. Looking at nuclei produced in different phases of evolution and explosion will probe different aspects. Therefore it is important to distinguish the relevant nucleosynthetic processes.

2 How to model nucleosynthesis

In principle, multi-dimensional (multi-D) hydrodynamical calculations are necessary to follow convection, mixing and especially the explosion. However, due to limitations in both computer power and numerical approaches, it is not yet possible to couple full reaction networks, including all nuclei ever produced in such stars, to multi-D hydrodynamical solvers. Moreover, even multi-D models have problems describing the explosion mechanism because they currently do not show explosions at all (see, e.g., Buras et al., 2003). Focussing on nucleosynthesis, one traditionally resorts to a number of approximations: Instead of multi-D, the simulation is reduced to one spatial dimension; two reaction networks are used, a smaller one which provides the nuclear energy generation and is directly coupled to the hydro solver, and a larger one without feed-back to hydro but carrying all the nucleosynthesis; multi-D effects such as convection and mixing are treated in approximations, like mixing length theory, and by invoking convection criteria (Schwarzschild, Ledoux); the explosion itself is parameterized. Even which such approximations it became only recently possible to consistently follow synthesis of all nuclei up to Bi in a single, large network (Rauscher et al., 2002). Despite the limitation, one expects mostly reliable results for nucleosynthesis of nuclei independent of the explosion mechanism, with the exceptions mentioned in the Introduction. This has been nicely proven by comparison with observational data, both regarding yields and velocity distributions of the ejecta.

There are mainly two ways to parameterize the explosion. The first is to artificially increase the entropy in the core of an evolved progenitor. This is done by a sudden temperature enhancement in the Fe core, resulting in an increase in pressure, a shock wave, and finally ejection of the outer layers. The mass cut, i.e. the mass coordinate separating material which will fall back from the one really ejected, is another free parameter in this type of simulation. The induced thermal energy is adjusted as to reproduce observed explosion energies whereas the mass cut can be chosen to be in accordance with abundances of nuclei produced in the explosion in the inner-most layers, such as ^{56}Ni. This approach is applied by, e.g., Thielemann, Nomoto and Hashimoto (1996) and co-workers.

Another way to create an artificial explosion is to input kinetic energy by a one-dimensional moving piston. The piston first moves inward with a fraction of the local gravitational acceleration as the core collapses and then outward in another ballistic trajectory to induce a shock. The outward acceleration is usually considered the only open parameter in this model. The mass cut is implicitly obtained by the mass settled on the piston after a sufficiently large time. The free parameter thus can either be determined by reproducing the observed kinetic energy in the ejecta or by the ejected amount of inner material, such as ^{56}Ni. The latter is usually used for stars with $M > 20M_\odot$ because those usually have higher Ni yields. It should be noted, however, that there are two further implicit parameters, the inward piston acceleration and the initial position of the piston, which are usually treated as fixed. The fall back, and thus the ^{44}Ti and ^{56}Ni yield, is not only dependent on the piston energy but also on the latter. This approach was introduced by Woosley and Weaver (1995) and subsequently used by that group (for recent examples, see Hoffman, Woosley, and Weaver, 2001; Rauscher et al., 2002). Very recently, also Limongi and Chieffi (2003) adopted it.

Obviously, both approaches do not account for the detailed collapse process and therefore cannot provide a consistent description of the expected neutrino pulse. In order to study neutrino-induced nucleosynthesis, usually parameterized neutrino burst profiles are applied, mostly influencing light element nucleosynthesis of Li, B, F, and partially also of ^{138}La and ^{180}Ta in the ν-process (Heger et al., 2003). Both approaches also cannot follow the innermost high-entropy convective zones thought to be a possible site of the r-process. R-process abundances cannot be obtained although the thermal approach yields a slightly better description of the entropy in the lowest shells. It should be noted, however, that also more self-consistent multi-D simulations are not able to obtain the entropies required for the r-process. Whether this is an indication that supernovae are not the site of the r-process or whether this reflects deficiencies in the modeling, perhaps related to the failing explosions, remains an open question. For further considerations concerning problems with the r-process in type II supernovae, see Freiburghaus et al. (1999).

For completeness, a third approach has to be mentioned which is, to my knowledge, only rarely used: the radiation dominated shock approximation

(Weaver and Woosley, 1980; Arnett , 1996). It is a simpler description of the outgoing shockwave than the above approaches. Until recently, it was used by Chieffi, Limongi and Straniero (1998); Limongi, Straniero and Chieffi (2000) and co-workers. See Limongi and Chieffi (2003) for a comparison to the piston approach.

3 Nuclide classes

Different nuclides probe different aspects of stellar evolution and explosion. One can define three coarse classes. In the following, examples for nuclei in each class are provided but that is by no means meant to be a complete list. The yields of species in the first class are determined by stellar evolution only, they are mainly produced in hydrostatic burning but their abundances can also be altered by explosive burning in the supernova shock front. They are sensitive to uncertainties in the reaction rates and to mixing effects as given by the stellar structure. Their yields vary with the mass of the progenitor star. Such elements are He, C, O, Ne, Mg. Among the radioactive species are ^{26}Al, ^{59}Co, ^{60}Fe. It is interesting to note that there is no experimental determination of the rate of the reaction ^{59}Fe(n,γ)^{60}Fe, producing ^{60}Fe. Therefore, its yield also has a considerable nuclear uncertainty.

The second class comprises nuclei whose yields depend on stellar evolution as well as the explosion energy. They are only weakly dependent on the progenitor mass. Examples are isotopes of Si, S, Ar, Ca.

The yields of the nuclear species in the final class probe the explosion mechanism. They depend on the size of the pre-supernova Fe core, the assumed mass cut, the explosion energy, and on the electron abundance Y_e which provides a measure of the neutronization of the matter. The nuclei in this class are those from ^{44}Ti to mostly Fe-group nuclei (including ^{56,57}Ni). Also r-process nuclei would fall in this category but they cannot be treated in the parameterized models introduced above. This nuclide class can be used to fix the model explosion parameters. However, Y_e in the inner zones can be altered by neutrino-induced weak interactions. As mentioned before, this effect is not included and therefore the obtained parameters are rather effective parameters than actual measures of physical quantities. In this context it is arguable whether a higher number of free parameters is a lack of consistency or a merit, providing more flexibility.

4 Prospects

Future improvements in parameterized models will concern the size of the reaction networks (specifically also the one used for energy generation, Woosley et al., 2003) and the treatment of convection. Better constrained nuclear reaction rates would also provide a major improvement. Improved parameterizations of the explosion and the neutrino pulse within the discussed limitations can be obtained from comparisons with observation and multi-D models. First steps have been taken (e.g. Kifonidis et al., 2000, and Travaglio et al., this volume) to couple nucleosynthesis networks to 2-D simulations. As in early 1-D simulations one has to resort to very limited networks yet, and it is not clear whether one has to go to higher dimensions to properly model the convective flows. Similar to the 1-D approaches, an artificial explosion has to be invoked since self-consistent calculations still offer little guidance as to the exact placement of the mass cut, the entropy and Y_e of the innermost ejecta, or even if a given model will explode (Herant et al., 1994; Janka and Müller, 1996; Fryer and Heger, 2000). Nevertheless, multi-D effects such as mixing and asphericity can be studied in such models. These can have two consequences. If the explosive nuclear burning zones (i.e. the shock wave) become non-spherical, explosive nucleosynthesis would be altered, leading to different explosive yields. However, recent calculations still show a mainly spherical shock propagation (Kifonidis et al., 2000). The second consequence concerns the mixing behind the burning front. It will not directly affect nucleosynthesis but the burning products will be mixed into different layers behind the shock front, affecting the observational signature (see Travaglio et al., this volume).

It should be kept in mind that any exhaustive investigation of the origin of the elements has to consider, among others, a variety of progenitor stars with different initial masses and metallicities. Despite of the progresses in multi-D simulations, nucleosynthesis studies with full reaction networks on an extensive grid of masses and metallicities are only feasible with parameterized 1-D models, yet. Therefore, such models will stay with us for a while.

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