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Stars from birth to death: Laboratories for exotic nuclei?

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Abstract. Recent developments in theoretical model calculations for the synthesis of the chemical elements in stars are reviewed. Special emphasis is put on a discussion of various astrophysical sites, including the Sun and core collapse and thermonuclear supernovae. Results of numerical simulations are presented and discussed, together with new results concerning solar-system abundances as well as abundances observed in very metal-poor stars, in the context of searches for constraints on the still rather uncertain nuclear-physics data and astrophysical models.

PACS. 26.30.+k Nucleosynthesis in novae, supernovae, and other explosive environments – 26.20.+f Hydrostatic stellar nucleosynthesis

1 Introduction

Stars synthesize exotic nuclei, mainly because of the high densities and temperatures they reach in the course of their evolution. The most prominent examples are massive stars, $M > 8M_{\odot}$, which undergo all hydrostatic burning phases, from H burning through He, C, O, Ne, and Si burning, and finally collapse to nuclear-matter density. Moreover, because of the high densities involved, electron captures on nuclei make their matter neutron-rich, and even nuclei with mass numbers $A \simeq 500$ and neutron-to-proton ratios of about 2 are possible in nuclear statistical equilibrium. Alternatively, very massive, $M > 100M_{\odot}$, primordial stars may have synthesized some proton-rich nuclei in hot H burning.

It is therefore tempting to try to use stars as laboratories for exotic nuclei. However, in doing so, one faces an *inverse problem.* The information we can get from astrophysics are element and, occasionally, also isotopic abundances, but mostly not from individual stars. In addition, even in those cases where we can get direct observations, they do not show us the nuclei *in situ* but after they have been mixed and transported to the stellar chromosphere. So in all cases we have to compute backwards to their formation site by means of astrophysical *models* which are never unique and, moreover, often contain poorly determined parameters. Finally, most often, many different nuclear species and reactions are involved and are coupled in a very complicated manner. This makes it difficult to single out particular ones which, in turn, could then be studied by laboratory experiments, thus removing some of the uncertainties of the astrophysical models.

In this paper I will first discuss the Sun as such a laboratory because only in this case do observations constrain the models sufficiently to allow conclusions on nuclear reactions and fundamental physics questions. I then will briefly outline some of the major problems which are encountered if one attempts to use massive stars and supernovae for this purpose. A summary and conclusions follow in sect. 4.

2 Solar physics

Hydrogen burning in main-sequence stars via the proton-proton chains is considered as well understood since long, and models explaining the present age, luminosity, and chemical composition of the Sun have been very successful [1–4]. However the lower-than-expected flux of electron-neutrinos (*e.g.*, [5]) casted doubts on some of the key nuclear-reactions rates, which are still extrapolations of experimental data to solar energies.

Recently, a new tool has become available which allows to determine the internal structure of the Sun independent of any model, namely helioseismology (*e.g.*, [6]). In practice, one measures the power spectrum of pressure (p-) modes. Low-frequency p-modes penetrate deep into the Sun, but there are only a few of them. Low-frequency modes, in contrast, only map the outer parts of the Sun, but thousands of them have been measured. Finally, convection in the outer zones of the Sun introduces some errors. However, in total, helioseismology allows to measure the sound velocity as a function of position, and thus the temperature and density, to better than a few % and, actually, to better than 1% through most of the Sun's interior (see fig. 1).

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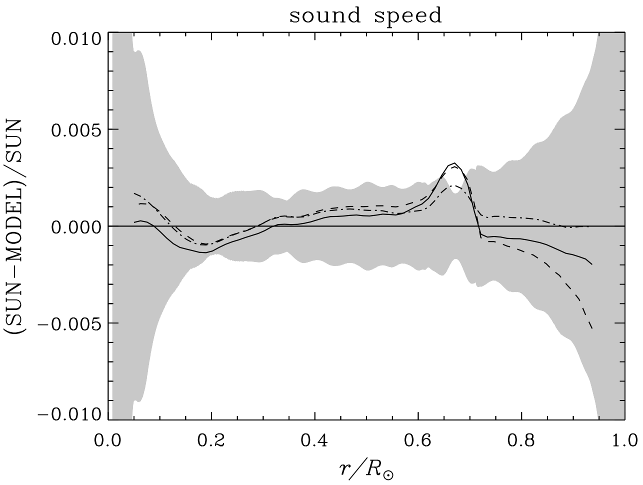

Fig. 1. Sound speed obtained from solar oscillations in comparison with the predictions from various "standard solar models". The shaded area shows conservative error estimates for the seismic data (from [7]). The models are: [5] (dashed line), [1] (dash-dotted line), and [3] (solid line).

Recent solar models, constructed on the basis of standard input physics (equation of state, nuclear reactions and initial composition, opacities, mixing-length theory of convection, etc.) reproduce the results of helioseismology extremely well (see fig. 1), leaving no room for major changes. In fact, modifications of the input physics, including nuclear reactions, must leave this agreement untouched in order to be acceptable. In this sense, the Sun has become a "laboratory for fundamental physics". For example, suggestions to change the screening corrections to nuclear reactions in the solar plasma considerably can be ruled out on the basis of the seismic data alone if the changes modify the commonly used Salpeter formula by more than 10% [8]!

The standard solar models have also been used successfully to calibrate the expected flux of neutrinos from the Sun, and helioseismology rules out most of the nonstandard astrophysical explanations for the missing flux [9]. Moreover, most of the key reactions of the pp chains are experimentally known to better than about 10 to 20% [10] and, therefore, cannot account for the neutrino deficit. The remaining explanation, namely neutrino (flavor) oscillations, has recently been confirmed by the heavy-water "Sudbury Neutrino Observatory" (SNO [11]).

3 Massive stars, supermassive stars, and supernovae

Only in exceptional cases stars do offer enough information to draw firm conclusions on the processes that go on or went on in their deep interiors. This includes certain well-observed stars, including the Sun, and a few nearby supernovae, SN 1987A being the best studied example. Difficulties arising from this fact are discussed in this section.

3.1 "Hydrostatic" burning

During most of their lives stars change their internal structure on time-scales much longer than the hydrodynamic time-scale, governed by quiet nuclear burning and heat transport. This phase, therefore, is called hydrostatic burning. Because of the moderate densities and temperatures involved, after H burning, total neutron and proton numbers are approximately equal and mainly α-nuclei form. Those become "exotic" for large mass numbers only which, however, are not synthesized because at high enough temperatures, in nuclear statistical equilibrium, iron group nuclei such as ^{56}Ni dominate the composition of matter. Towards the end of pre-supernova stellar evolution weak-interaction rates play a certain role but the effects due to uncertainties in those rates are of minor importance for stellar evolution [12].

There are two exceptions from this general rule. Firstly, free neutrons emerge from α-capture reactions on ^{18}O, ^{22}Ne and, possibly, ^{13}C in hydrostatic He burning, and will transform some of the pre-existing iron group nuclei into heavy elements up to Bi and Pb by the slow neutron capture (s-) process (see, *e.g.*, [13] for a recent review). But, again, mostly only nuclei very close to stability play a role. Secondly, under certain circumstances, H burning temperatures might be sufficiently high such that certain proton-rich isotopes form even in hydrostatic burning.

This latter situation may have emerged in primordial intermediate-mass [14], massive [15–17], very massive [18, 19] or supermassive stars [20]. Because the gas from which those (hypothetical) first generations of stars were born contained no CNO nuclei, H burning had to proceed via the pp chains (rather than the CNO cycles) which do not produce enough energy. It is more likely that they began their nuclear fusion at He burning temperatures ($T \simeq 2 \times 10^8$ K) and first produced a small amount of C via the 3α reaction, and then continued to burn hydrogen by the (hot) CNO cycles.

The statements made above do not mean that nuclear reaction rates in general are unimportant for hydrostatic stellar evolution. In contrast, there are certain reactions, including the famous ^{12}C$(\alpha,\gamma)^{16}$O reaction, which have to be known precisely in order to be confident about nucleosynthesis predictions from stellar models. However, for example, changes in the core masses of massive stars by modifications of this rate can easily be compensated by changing the model of (non-local) convection appropriately. So stellar evolution does not provide a clue as to what the value of this reaction rate should be.

3.2 "Explosive" burning

Explosive nuclear burning in stars means that the nuclear burning time-scale is shorter than the hydrodynamic time-scale which, in turn, implies that the nuclear composition changes dynamically. This is only possible if either the matter is degenerate such that the nuclear energy is mainly used to remove the degeneracy before it leads to the star's expansion, or if a shock wave is launched by some other process which then heats the matter, thereby triggering fast nuclear reactions (for recent reviews see [21,22]).

Examples for the first mechanism are novae (explosive H burning on top of an accreting white-dwarf star) [23–25], X-ray bursters (explosive H burning on the surface of an accreting neutron star) [26,27], and thermonuclear (type-Ia) supernovae (fusing C and O to ^{56}Ni and other intermediate-mass nuclei) [28,29]. An example for the second mechanism are core collapse (type-II and type-Ib,c) supernovae, where a shock wave from a newly born neutron star (or black hole) passes through the outer stellar layers and transforms pre-existing nuclei into more exotic ones [30–32].

From the nuclear-physics viewpoint, certain weak-interaction (electron capture) rates play an important role in all those cases, and many of them are not well known [33]. In addition, in core collapse supernovae the high-density equation of state and neutrino interactions in dense matter seem to be the most important ingredient and, again, they are only poorly known [34,35]. Therefore, one is tempted to use astrophysics to constrain them. However, as in hydrostayic burning, in the astrophysical models uncertainties in nuclear reactions are often accompanied by uncertainties in other physical processes, such as a poorly known theory of convection and mixing, other hydrodynamic instabilities, the role of magnetic fields, rotation, etc., and it is difficult, if not impossible, to disentangle all these effects on the basis of observations alone.

The observational data one can obtain from novae, supernovae, and other explosive nucleosynthesis events, in the best cases, are bolometric and filter lightcurves and reasonably well-resolved spectra in various wave bands. From those data one can, in principle, reconstruct the physical conditions at the photosphere at the time the observations were made, such as the temperature and velocity of the stellar matter, as well as its chemical composition. On the basis of a model, the data are then extrapolated back to time zero of the explosion (and beyond).

There is a principle problem related to this approach which would persist even if one could get complete spectral coverage. The observations tell us about the distribution of the elemental composition (and very rarely about the isotopes) in *velocity space* and not in real space. Mapping the velocity space onto real space, however, is impossible given the turbulent nature of all explosive nucleosynthesis events (see fig. 2 for an example). In practice, therefore, one either ignores hydrodynamic instabilities in the models (making the mapping a trivial exercise, but introducing new "free" parameters) or does the comparison between model predictions and observations on the basis of certain averages accompanied, of course, by a loss of information. In conclusion, claimed agreement between models and observations should be taken with care because there are potential sources of large systematic errors.

A more practical problem is that in nearly all cases observational data are sparse and do not allow to get a complete picture, even under the simplifying assumptions discussed earlier. Only for a few supernovae observed spectra and lightcurves extend well into the optically thin (nebular) phase when, in principle, there are straightforward ways to interpret the data. In contrast, in the early phases when supernovae are still bright and easy to observe, interpretation of the data is difficult since it relies on radiative transfer calculations. Moreover, abundance determinations are restricted to a few elements with strong lines where complications arise from the fact that often those lines are saturated.

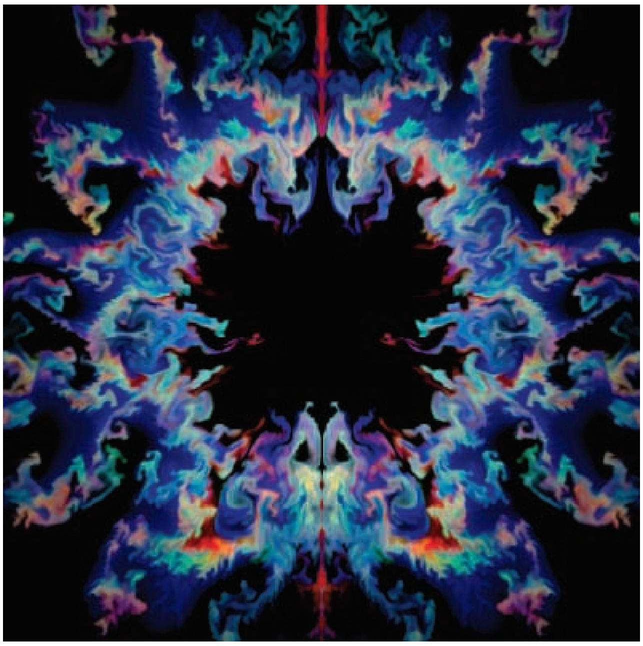

Fig. 2. Composition of the ejecta of a core collapse supernova about 1000 s after the shock was launched near the proto-neutron star. Shown is the spatial distribution of the products of explosive O burning (mainly ^{28}Si and ^{56}Ni). The radial zones out to about 10^5 km are displayed (from [36]).

However, all these difficulties do not exclude supernovae as laboratories for fundamental physics questions, provided one asks the right questions. The neutrinos emitted from SN 1987A and detected on Earth are an obvious example. Just the fact that its distance was fairly well known allowed to place constraints on neutrino masses which were truly model independent (see, *e.g.*, [37]). A second example are type-Ia supernovae which have become a powerful tool to measure cosmological distances and, thus, the dynamics of cosmic expansion. The fact that they appear to be dimmer at high redshifts then in our cosmic neighborhood is interpreted as being due to an accelerating expansion of the Universe, caused by a non-zero (positive) cosmological constant (interpreted as the energy density of the vacuum) (see, *e.g.*, [38–42]). Therefore, type-Ia supernovae seem to provide an answer to a very fundamental question.

Again, the question has to be addressed whether or not these conclusions are solid. As is shown in fig. 3 thermonuclear burning in type-Ia supernovae is complicated, involving even turbulence on small length-scales. On the

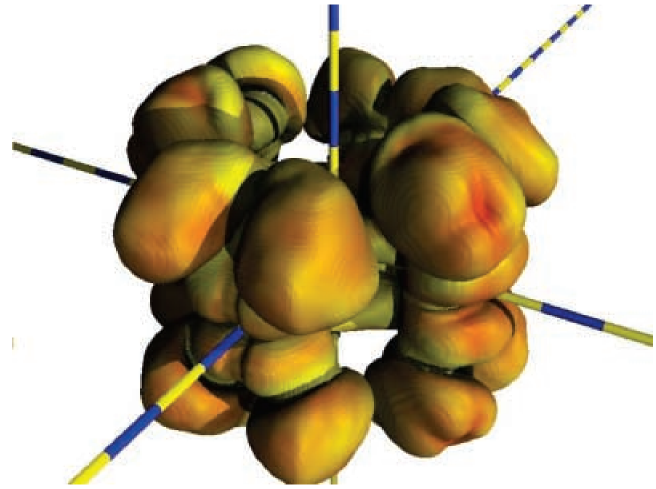

Fig. 3. Thermonuclear fusion front in a type-Ia supernova 0.36 s after ignition. The lengths scale shown on the orthogonal bars is 10^7cm. Again, large asymmetries are apparent which are the result of rising hot bubbles ("ashes") in "cold" nuclear (C + O) fuel (from [43]).

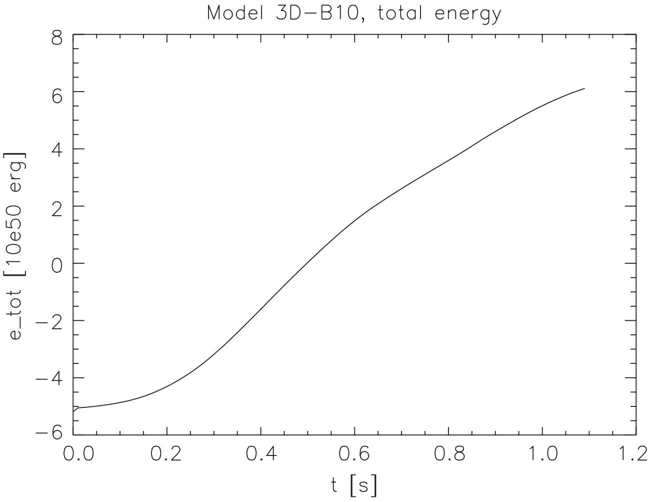

Fig. 4. Energy liberated by nuclear fusion in an exploding C + O white dwarf. The observed explosion energy of a type-Ia supernova is typically around 10^{51} erg, in good agreement with the model (from [43]).

other hand, side observations seem to indicate that this class of supernovae, defined by the absence of hydrogen lines and the presence of Si, is very homogeneous, as far as peak luminosity and lightcurve shapes are concerned. There even exists an empirical correlation between peak luminosity and the form of the lightcurve which allows to calibrate them as "standard candles" (see, *e.g.*, [44] for a recent review).

Recent numerical simulations have shown that most of these findings can be understood in the framework of a particular model, an exploding white-dwarf star, composed of C and O, near the critical (Chandrasekhar) mass of about 1.4 $M_\odot$. For example, these models release about the right amount of energy (see fig. 4) and produce the "observed" abundance of ^{56}Ni without any parameters *not* motivated by physics. They do not yet explain the observed inhomogeneities among type-Ia supernovae, but there is hope that this will be achieved soon [29].

3.3 Remarks on the r-process

Ever since its invention by Burbidge *et al.* in 1957 [45] the r-process which very likely synthesized the neutron-rich isotopes of the heavy elements and the actinides has been a puzzle. The generally accepted scenario assumes that under certain circumstances, presumably in a core collapse supernova, matter becomes so neutron rich that heavy nuclei form from iron-seed by (fast) neutron captures and successive (slow) β^--decays very near to the neutron drip line. It has even been speculated that the r-process might occasionally reach superheavy nuclei [46].

The problems with this general picture are manifold, and up to now there is no working model that provides the conditions necessary for the operation of the r-process and, in addition, reproduces the solar-system r-process abundances. The mass zones near to the newly born neutron star in a core collapse supernova have been suggested, but it is unclear whether or not those zones are ever ejected (see [47] for a recent discussion of this process). In addition, these models require a lot of fine tuning since the amount of r-process material ejected typically per supernova has to be small, of the order of $10^{-4} M_\odot$ only, in order to avoid that the Galaxy is over-polluted with r-process nuclei. The material heated by the high flux of neutrinos from the proto-neutron star has been suggested [48–50]. In this case, overproduction is not an issue, but the number of neutrons per seed nucleus seems to be far too low to generate solar-system abundances [50, 51]. More exotic scenarios, such as merging pairs of neutron stars or neutron stars with black holes [52–54], or evaporating neutron stars near their minimum stable mass [55] have also been suggested, but it is still largely unclear whether or not they can work in principle and, if so, whether they would reproduce observed (solar-system) abundances. On the other hand, one would like to know more because the r-process seems to be the top candidate for applying the physics of exotic nuclei to astrophysics.

Since the Sun formed from the debris of many supernovae, explaining solar abundances involves models of galactic chemical evolution which are complicated in themselves (*e.g.*, [56]). Therefore, it makes little sense to relate nuclear structure to a particular r-process model unless the r-process is identical in every site, which at first glance seems to be very unlikely, given the fact that neutron densities and temperatures will vary from star to star. Therefore it appears to be more promising to study very old stars instead which may have been polluted by only one or a few supernovae. Moreover, because of their low heavy-element content, in particular iron, it should be easier to detect unblended spectral lines of elements with mass numbers exceeding 50 in those stars.

A program of this kind has recently been carried out by Sneden and collaborators with great success (*e.g.*, [57]

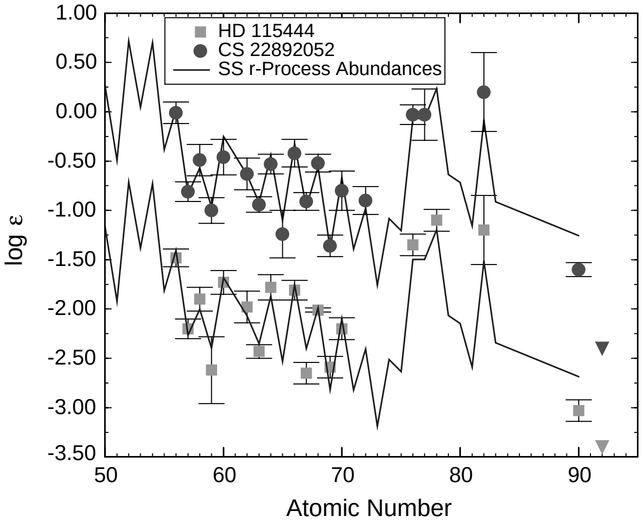

Fig. 5. Heavy-element abundances in two very metal-poor stars in comparison with the solar-system r-process abundances (solid lines), scaled. The agreement is nearly perfect, indicating pure r-process composition (from [58]).

and references therein). Figure 5 shows some of their surprising results. They find that very metal-poor stars with iron abundances of about 10^{-3} of the Sun only, contain no s-process material, but r-process nuclei are sometimes over-abundant by up to a factor of 50 (relative to iron). Even more surprising, in all those cases the r-process nuclei follow almost exactly the solar-system pattern (see fig. 5), but only for the heavy r-process component ($A > 130$, the second r-process abundance peak).

Their findings leave us with yet another puzzle: How can it be that stars which formed in completely different parts of our Galaxy and received heavy r-process nuclei from at most a few different (nearby) supernovae have exactly the same r-process abundances which, moreover, resemble those of the much younger sun very closely? The only explanation seems to be that the heavy r-process is very robust and produces always the same abundances, *independent* of the astrophysical conditions! This can only happen if the time dependence drops out of the r-process equations which in turn means that the r-process operates under steady-state conditions, since in this case the abundances are determined by nuclear physics only and, therefore, they would be "universal".

It is easy to estimate a lower limit for the time that is needed to achieve a steady state, namely a few times the sum of all β-decay times along the r-process path from the second abundance peak up to the line of neutron-induced fission, and finds a time-scale of the order of tens of seconds to minutes, much longer than the hydrodynamic time-scale of any astrophysical scenario investigated until now. In principle, a steady state could be established by fission recycling which would also explain why the universality of the r-process abundances only holds for the heavy component.

One can only speculate where such long time-scales and high neutron excess (which, in stars, usually goes with high densities and thus *short* time-scales) can be found. A possibility could be magnetically driven core collapse supernovae, where the clock for the explosion is set by the amplification of the magnetic field by differential rotation which, for realistic initial conditions, could be well in excess of one minute [59]. If this supernova mechanism should work at all, it would only operate in a few extreme cases and, therefore, this kind of r-process should be rare, too. A prediction then is that in addition to the very metal-poor stars which are rich in r-process elements, there should be another more frequent class with very little (or even no) r-process nuclei at all.

4 Conclusions

It is obvious that nuclear physics and, in particular, the physics of exotic nuclei, has significant impact on astrophysical models which attempt to explain the formation of the chemical elements, and beyond, and that it helps astrophysics to get reliable nuclear data. Here I have asked a different question: Is it possible to use the information we can obtain from astrophysics to constrain fundamental physics and, in particular, the physics of exotic nuclei?

The answer to this latter question is less obvious, mainly due to lack of sufficient information. For example, it is a difficult and non-trivial task to extract abundance information from exploding stars, and it is even more difficult to relate the sparse information to the processes that led to their formation. Consequently, the physical conditions under which the elements formed cannot be extracted from observed data alone but require models to bridge the gaps. This, in turn, makes most predictions model dependent, which could otherwise be used as constraints.

I also discussed a few exceptions to this general rule which exist because either the star under consideration, our Sun, is so close that we know a lot more about it, or specific questions can be asked which by chance find an answer in astrophysics, even though the objects under consideration are not fully understood. Type-Ia supernovae and their use as calibrated standard candles are an example here, and very metal-poor stars are another one. But, unfortunately, such examples are rare, mainly because of the complexity involved.

In conclusion, stars may be used as laboratories for exotic nuclei occasionally, but this requires a lot of care!

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