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Nucleosynthesis in Supernovae

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Abstract. The evolution of gas abundances in galaxies and the enrichment of heavy elements as a function of space and time reflects the history of star formation and the lifetimes of the diverse contributing stellar objects. Supernovae of type Ia and type II/Ib/Ic are the main contributors to nucleosynthesis in galaxies. Despite many efforts, a full and self-consistent understanding of supernova explosion mechanisms is not existing, yet. However, they leave fingerprints, seen either in spectra, lightcurves, radioactivities/decay gamma-rays or in galactic evolution. Here we want to address the relation of model uncertainties to the composition of ejecta and test them with constraints from abundance observations.

1. Introduction

The chemical composition of the intracluster and intergalactic medium, the focus of the present conference, acts as a witness for its stellar sources similar to the interstellar medium in galaxies. In a first step, however, we want to understand these sources. Therefore, we make use of the tighter observational constraints for supernova ejecta coming from the direct observations of supernova spectra, from the observation of remnants, and from stellar surface abundances of old stars as witnesses of the evolution of the interstellar medium in galaxies. We review the present status of supernova calculations, the related nucleosynthesis and ejecta composition as well the agreement with the chemical evolution of our Galaxy.

Galactic evolution for the elements in the range O through Ni is dominated by two alternative explosive stellar sources, i.e by the combined action of SNe II and Ia, originating either from massive stars with $M > 8M_\odot$ or intermediate or low mass stars with $M < 8M_\odot$ which end as mass accreting white dwarfs in binary systems. The site for the production of the heaviest elements up to U and Th (the r-process based on neutron captures in environments with very high neutron densities) is still debated and most probably related to supernovae and/or neutron star ejecta (from binary mergers or jets).

The surface abundances of stars, indicating the interstellar medium abundances at the time of their birth, are a clear indicator of galactic evolution as a function of metallicity $[\mathrm{Fe/H}]=\log[(Fe/H)/(Fe/H)_\odot]$. Observational data for [x/Fe] at low metallicities ($-2 <[\mathrm{Fe/H}]< -1$), x standing for elements from O through Ca, show an enhancement of the alpha elements (O through Ca) by a factor of 2-3 (0.3 to 0.5 dex in [x/Fe]) in comparison to Fe (Gratton & Sneden 1991; Nissen et al. 1994; Argast et al. 2001). This is the clear fingerprint of the exclusive early contribution of fast evolving massive stars, i.e. SNe II. The higher ratio of Fe-group elements to Si-Ca in SNe Ia has to compensate for these overabundances in SNe II in order to obtain solar abundance ratios for the combined nucleosynthesis products at solar metallicity [Fe/H]=0. Such global tests can constrain the average features of SNe II and SNe Ia mixed in frequency ratios of $N_{\mathrm{Ia}}/N_{\mathrm{II}} = 0.15 - 0.27$ (van den Bergh & Tammann 1991; Cappellaro et al. 1997) and require an Fe contribution from SNe Ia of 50-60%, if average ejected Fe masses of 0.1 $M_\odot$ and 0.6 $M_\odot$ are taken for SNe II and SNe Ia.

An interesting feature is that also the Fe-group ejecta of both types of supernovae have to differ. For Ti, Sc, Cr, Mn, Co, Ni one finds at low metallicities average SN II values [x/Fe] of 0.25, 0, -0.1, -0.3, -0.1, -0.1 (Iwamoto et al. 1999). Taken the typical uncertainty of 0.1 dex, this leaves Ti and Mn as elements with clear signatures for a SN II behavior different from solar, which asks for the opposite effect in SN Ia. The features discussed so far apply to average SNe II and Ia compositions. A more complete understanding, however, would require observational clues for the range of individual SNe II and Ia which can directly constrain theoretical models.

2. Type II Supernovae

Stars with masses $M > 8M_\odot$ develop an onion-like composition structure, after passing through all hydrostatic burning stages, and produce a collapsing core at the end of their evolution, which proceeds to nuclear densities (Chieffi et al. 1998; Umeda et al. 2000; Heger et al. 2001). The high densities in late phases of O- and Si-burning result in partially or fully degenerate electrons with increasing Fermi energies (Nomoto & Hashimoto 1988). When these supercede the Q-value thresholds of electron capture reactions, this allows for electron capture on an increasing number of initially Si-group and later Fe-group (pf-shell) nuclei. Because sd-shell reactions were well understood in the past (Fuller et al. 1985), O-burning predictions are quite reliable. The recent progress

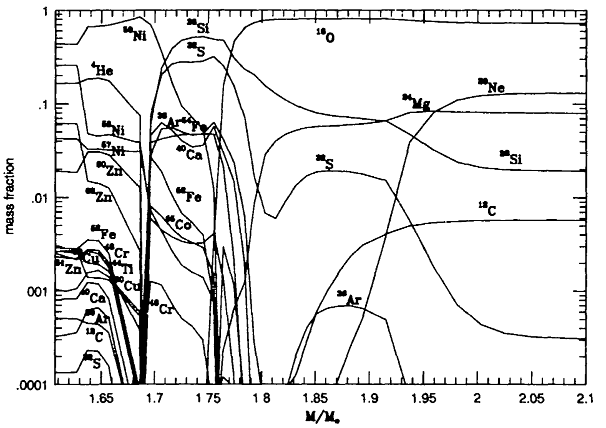

Figure 1. Isotopic composition for the explosive C-, Ne-, O- and Si-burning layers of a core collapse supernova from a $20M_\odot$ progenitor star with a $6M_\odot$ He-core and an induced net explosion energy of 10^{51} erg, remaining in kinetic energy of the ejecta. $M(r)$ indicates the radially enclosed mass, integrated from the stellar center. The exact mass cut in $M(r)$ between neutron star and ejecta and the entropy and Y_e in the innermost ejected layers depends on the details of the (still unknown) explosion mechanism. The abundances of O, Ne, Mg, Si, S, Ar, and Ca dominate strongly over Fe (decay product of ^{56}Ni), if the mass cut is adjusted to $0.07M_\odot$ of Ni ejecta as observed in SN 1987A.

in calculating pf-shell rates (Langanke & Martinez-Pinedo 2000) led to drastic changes.

In the late phases of Si-burning (Heger et al. 2001) this recent change in electron capture rates sets new conditions for the subsequent Fe-core collapse after Si-burning, the size of the Fe-core and its electron fraction Y_e=$<Z/A>$ (Martinez-Pinedo et al. 2000). It has been pointed out that stellar rotation adds important features to the evolution in general and composition in particular via diverse mixing processes (Heger et al. 2000; Meynet & Maeder 2000).

The present situation in supernova modeling is that self-consistent spherically symmetric calculations (with the presently known microphysics) do not yield successful explosions (Mezzacappa et al. 2000; Liebendörfer et al. 2001ab; Rampp & Janka 2000) based on neutrino energy deposition from the hot collapsed central core (neutron star) into the adjacent layers. This seems to be the same for multi-D calculations, which however lack good neutrino transport schemes and do not yet consider the combined action of rotation and magnetic fields. The hope that the neutrino driven explosion mechanism could still succeed is based on uncertainties which affect neutrino luminosities (neutrino opacities with nucleons and nuclei and convection in the hot proto-neutron star, Hauser 2001) as well as the efficiency of neutrino energy deposition (convection in the adjacent layers).

Observations show typical kinetic energies of 10^{51} erg in supernova remnants. This permits one to perform light curve as well as explosive nucleosynthesis calculations by introducing a shock of appropriate energy in the pre-collapse stellar model (Woosley & Weaver 1995; Thielemann et al. 1996; Nomoto et al. 1997; Hoffman et al. 1999; Nakamura et al. 1999; Umeda et al. 2000; Rauscher et al. 2001). Such induced calculations lack self-consistency and cannot predict the ejected ^{56}Ni-masses from the innermost explosive Si-burning layers (powering supernova light curves by the decay chain ^{56}Ni-^{56}Co-^{56}Fe) due to missing knowledge about the detailed explosion mechanism and therefore the mass cut between the neutron star and supernova ejecta. However, the intermediate mass elements Si-Ca are only dependent on the explosion energy and the stellar structure of the progenitor star, while abundances for elements like O and Mg are essentially determined by the stellar progenitor evolution. Thus, when moving in from the outermost to the innermost ejecta of a SN II explosion, we see an increase in the complexity of our understanding, depending (a) only on stellar evolution, (b) on stellar evolution and explosion energy, and (c) on stellar evolution and the complete explosion mechanism (see Fig. 1).

A correct prediction of the amount of Fe-group nuclei ejected (which includes also one of the so-called alpha elements, i.e. Ti) and their relative composition depends directly on the explosion mechanism and the size of the collapsing Fe-core. Three types of uncertainties are inherent in the Fe-group ejecta, related to (i) the total amount of Fe(group) nuclei ejected and the mass cut between neutron star and ejecta, mostly measured by ^{56}Ni decaying to ^{56}Fe, (ii) the total explosion energy which influences the entropy of the ejecta and with it the amount of radioactive ^{44}Ti as well as ^{48}Cr, the latter decaying later to ^{48}Ti and being responsible for elemental Ti, and (iii) finally the neutron richness or $Y_e = < Z/A >$ of the ejecta, dependent on stellar structure, electron captures and neutrino interactions. Y_e influences strongly the ratios of isotopes 57/56 in Ni(Co,Fe) and the overall elemental Ni/Fe ratio. The latter being dominated by ^{58}Ni and ^{56}Fe. The pending understanding of the explosion mechanism also affects possible r-process yields for SNe II (Takahashi et al. 1994; Woosley et al. 1994; Qian & Woosley 1996; Freiburghaus et al. 1999a; Mclaughlin et al. 1999).

If SNe II are also responsible for the solar r-process abundances, given the galactic occurance frequency, they would need to eject about 10^{-5} $M_\odot$ of r-process elements per event (if all SNe II contribute equally). The scenario is based on the so-called "neutrino wind", i.e. a wind of matter from the neutron star surface (within seconds after a successful supernova explosion) is driven via neutrinos streaming out from the still hot neutron star (Woosley et al. 1994; Takahashi et al. 1994; Hoffman et al. 1996; Hoffman et al. 1997; Qian & Woosley 1996; Meyer et al. 1998; Otsuki et al. 2000).

This high entropy neutrino wind is expected to lead to a superposition of ejecta with varying entropies. The r-process by neutrino wind ejecta of SNe II faces two difficulties: (i) whether the required high entropies for reproducing heavy r-process nuclei can really be attained in supernova explosions has still to be verified (Rampp & Janka 2000; Mezzacappa et al. 2001; Liebendörfer et al. 2001ab; Nagataki & Kohri 2001; Thompson et al. 2001), (ii) the mass region 80–110 experiences difficulties to be reproduced adequately (Freiburghaus et al. 1999a, Wanajo et al. 2001). It has to be seen, for example, whether the inclusion of non-standard neutrino properties (McLaughlin et al. 1999) can cure both difficulties or lower Y_e zones can be ejected from SNe II.

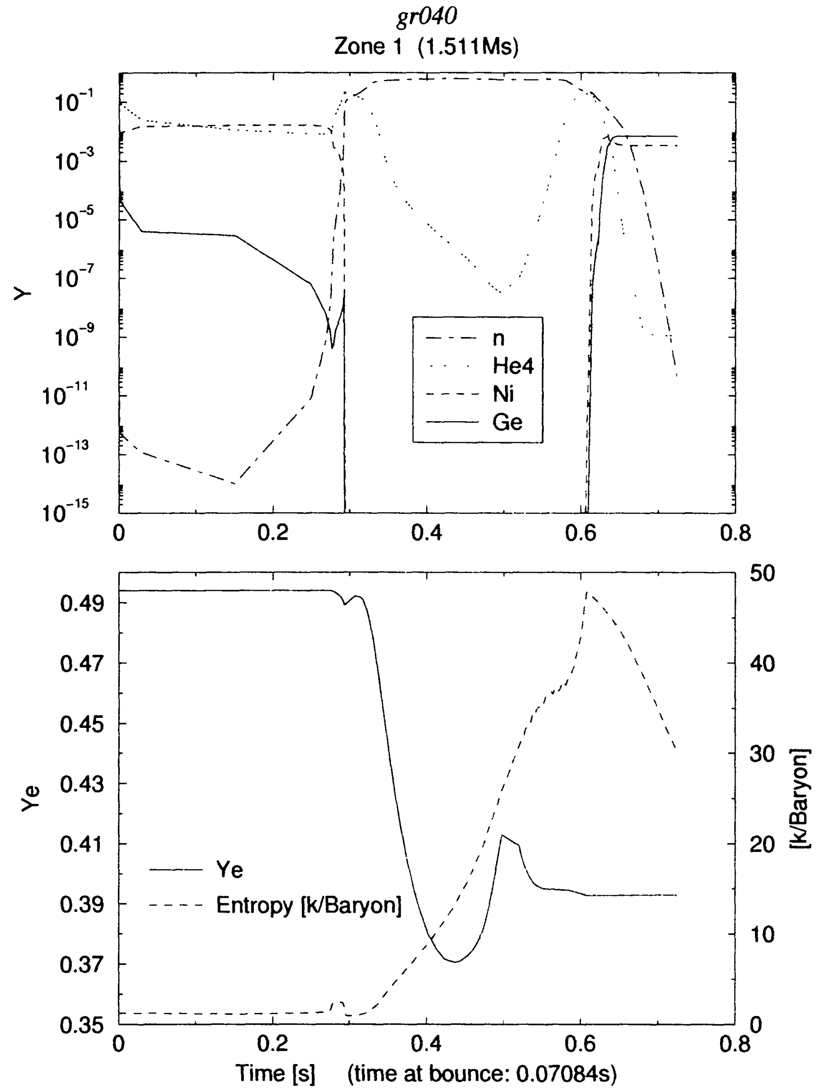

Figure 2. Composition evolution in the innermost ejected zone of a SNe II simulation. We see the freeze-out with remaining neutrons, leading to the onset of a (weak?) r-process, indicated by the rise of Ge beyond Ni (Ge is the upper limit of the nuclear network employed). This result seems to be possible as a combination of high entropies and a low Y_e=0.39 (Hauser 2001)

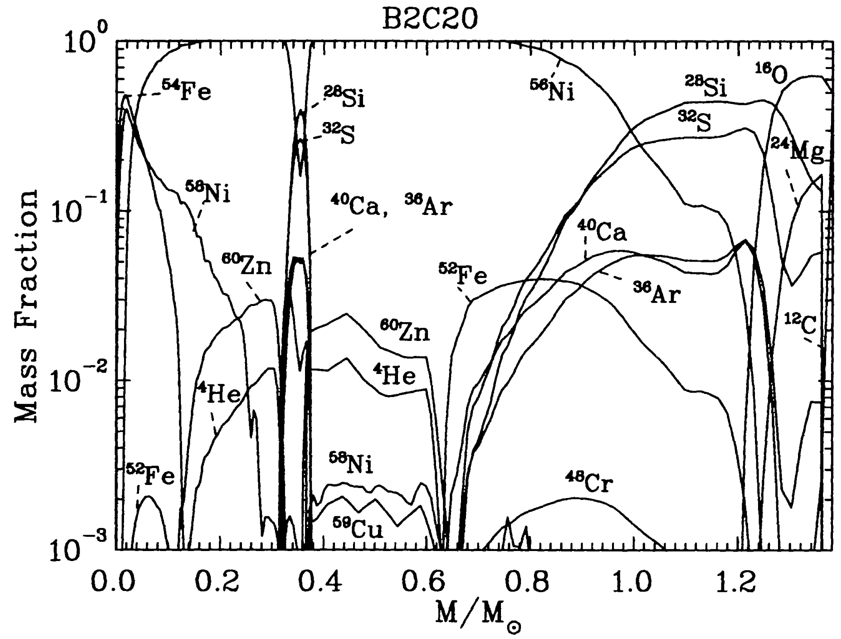

Figure 3. Isotopic composition for the layers of a type Ia supernova, starting thermonuclear burning with a deflagration front which turns into a detonation at 0.32 $M_\odot$, seen by the ^{56}Ni feature which sandwiches explosive O-burning products like ^{28}Si through ^{40}Ca. $M(r)$ indicates the radially enclosed mass, integrated from the stellar center. We see the products of explosive Si-burning (^{56}Ni), O-burning (^{28}Si), Ne-burning (^{16}O and ^{24}Mg), minor amounts of C-burning (^{20}Ne) and unburned matter at the surface. The central Fe-group composition depends on Y_e which is directly related to the amount of electron capture on free protons and nuclei.

Fig. 2 shows the abundance evolution in the innermost zone of a SNe II simulation (Hauser 2001, based on Liebendörfer et al. 2001a but with varied neutrino opacities permitting a successful explosion). It seems to indicate the onset of an r-process, however probably a weak one? Another supernova related site responsible for the "weak" r-process component (i.e. nuclei with $A<130$) could also be related to explosive C or He-burning in the outer ejected shells (Thielemann et al. 1979; Wheeler et al. 1998; Truran et al. 2001; Meyer et al. 2000).

3. Type Ia Supernovae

There are strong observational and theoretical indications that SNe Ia are thermonuclear explosions of accreting white dwarfs in binary stellar systems (Höflich & Khokhlov 1996; Nugent et al. 1997; Nomoto 2000; Livio 2000) with carbon ignition and a thermonuclear runway causing a complete explosive disruption of the white dwarf (Nomoto et al. 1984, Woosley & Weaver 1994). The mass accretion rates determine the ignition densities. A flame front then propagates at a subsonic speed as a deflagration wave due to heat transport across the front (Hillebrandt & Niemeyer 2000).

The averaged spherical flame speed depends on the development of instabilities of various scales at the flame front. Multi-dimensional hydro simulations suggest a speed $v_{\rm def}$ as slow as a few percent of the sound speed $v_{\rm s}$ in the central region of the white dwarf. Electron capture affects the central electron fraction Y_e and depends on (i) the electron capture rates of nuclei, (ii) $v_{\rm def}$, influencing the time duration of matter at high temperatures (and with it the availability of free protons for electron captures), and (iii) the central density of the white dwarf ρ_{ign} (increasing the electron chemical potential i.e. their Fermi energy) (Iwamoto et al. 1999; Brachwitz et al. 2000; Langanke & Martinez-Pinedo 2000). After an initial deflagration in the central layers, the deflagration might turn into a detonation (supersonic burning front) at lower densities (Niemeyer 1999). The nucleosynthesis consequences can be viewed in Fig.3 (Brachwitz et al. 2001).

Nucleosynthesis constraints can help to find the "average" SN Ia conditions responsible for their contribution to galactic evolution, i.e. especially the Fe-group composition. While ignition densities ρ_{ign} determine the very central amount of electron capture and thus Y_e, the deflagration speed $v_{\rm def}$ determines the resulting Y_e -gradient as a function of radius (Iwamoto et al. 1999). Y_e values of 0.47-0.485 lead to dominant abundances of ^{54}Fe and ^{58}Ni, values between 0.46 and 0.47 produce dominantly ^{56}Fe, values in the range of 0.45 and below are responsible for ^{58}Fe, ^{54}Cr, ^{50}Ti, ^{64}Ni, and values below 0.43-0.42 are responsible for ^{48}Ca. The intermediate Y_e-values 0.47-0.485 exist in all cases, but the masses encountered which experience these conditions depend on the Y_e-gradient and thus v_{def}. Whether the lower vales with Y_e<0.45 are attained, depends on the central ignition density ρ_{ign}. Therefore, ^{54}Fe and ^{58}Ni are indicators of v_{def} while ^{58}Fe, ^{54}Cr, ^{50}Ti, ^{64}Ni, and ^{48}Ca are a measure of ρ_{ign}. A test for these (hydrodynamic) model parameters is shown in Fig.4 where B1 and B2 indicate increasing propagation speeds of the burning front and C20 through C80 increasing ignition densities (results from Brachwitz et al. 2001).

Nuclear uncertainties based on electron capture rates enter as well (Brachwitz et al. 2000; 2001). Conclusions from these results are: (i) a v_{def} in the range 1.5–3% of the sound speed is preferred (Iwamoto et al. 1999), and (ii) the change in electron capture rates (Langanke & Martinez-Pinedo 2000) made it possible to have ρ_{ign}=2 × 10^9 g cm^{-3} without destroying the agreement with solar abundances of very neutron-rich species (Brachwitz et al. 2000). It seems, however, hard to produce amounts of ^{48}Ca sufficient to explain solar abundances from SNe Ia when applying more realistic electron capture rates, even for very high ignition densities (Woosley 1997; Brachwitz et al. 2001).

While uncertainties in the detailed 3D burning front propagation have been parametrized in terms of propagation speed and detonation transition density, it is expected that in a self-consistant simulation both "parameters" will be adjusted to the same values for the same initial models. The ignition density is a system indicator, reflecting the accretion history in a binary system. A similar hidden system parameter is the mass of the initial white dwarf, which determines the C/O ratio within the original white dwarf before accretion sets

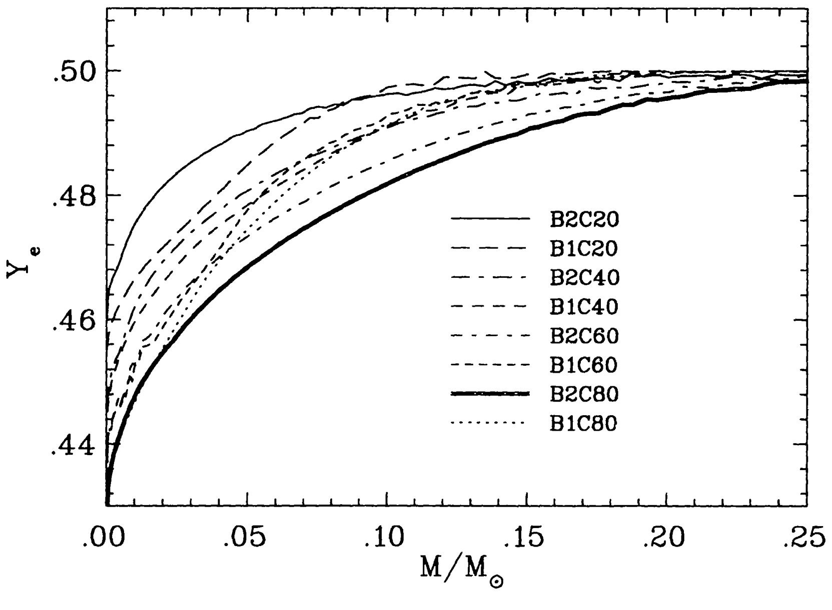

Figure 4. Y_e after freeze-out of nuclear reactions measures the electron captures on free protons and nuclei. Small burning front velocities lead to steep Y_e-gradients which flatten with increasing velocities (see the series of B1 vs. the B2 models). Lower central ignition densities shift the curves up (see changes from 20 through 80, i.e. central ignition at 2-8$\times 10^9$ g cm^{-3}), but the gradient is the same for the same propagation speed (from Brachwitz et al. 2001).

in (Höflich 2001; Dominguez et al. 2001 and Fig.5 left). The accretion burning at higher temperatures leads always to comparable C and O mass fractions.

Fig.5 (right) shows the resulting abundances for explosions with different C/O ratios also in the central part of the initial white dwarf (C and O like in Fig.5 left or C/O=1). The reason is related to the different energy release for burning ^{16}O or ^{12}C to ^{56}Ni. A further change is seen if the metallicity of the object (or the accreted matter) is changed. Existing CNO burns in H-burning to ^{14}N and He-burning to ^{22}Ne, a nucleus with two more neutrons than protons. This affects the energy generation in the outer Si-burning layers where the neutron-richness of matter is not due to electron captures as in the inner high-density layers but originating from the initial pre-ignition composition (measured here in the fraction of ^{22}Ne, 1 vs. 2.5% in case W). We see how the production of ^{56}Ni is changed which directly determines the light curve properties. The central C/O ratio, reflecting the white dwarf mass in the pre-explosion binary system (Domiguez et al. 2001), can thus serve as a parameter which reflects the supernova and lightcurve properties and must be related to the empiricial brightness decline relation (Leibundgut 2000; Riess et al. 2000). In Fig.5 we see, however, that the initial metallicity (measured by the original ^{22}Ne content) can have similar effects. It remains to be seen whether this introduces an empirical two rather than one parameter dependence (see also Höflich et al. 1998).

The general nucleosynthesis outcome of SNe Ia is dominated by Fe-group products, but involves sizable fractions of Si-Ca and minor amounts of unburned

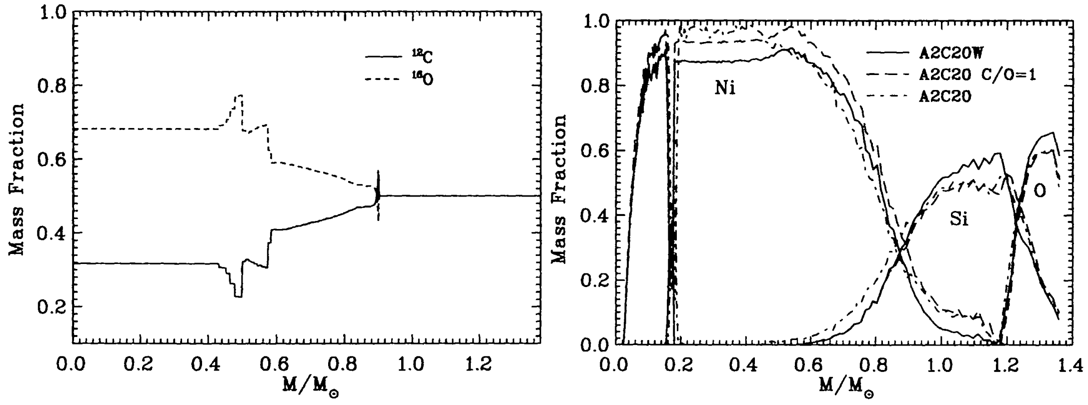

Figure 5. Left: Mass fractions of C and O throughout the white dwarf before undergoing thermonuclear ignition. The inner part (where O dominates) shows the initial white dwarf before accretion, the outer part the matter which underwent H- and He-burning during the accretion phase (at higher temperatures) where the mass fractions of C and O are comparable. Right: Mass fractions of Ni (^{56}Ni), Si (^{28}Si) and O (^{16}O) throughout the white dwarf after a thermonuclear explosion. The model A2C20 stands for a burning front propagation of 2% of the sound speed and a central ignition density of 2×10^9 g cm^{-3} and is based on a white dwarf composition as indicated on the left, C/O=1 stands for a modified white dwarf composition with equal amounts of C and O also in the inner region of the original white dwarf. The third model A2C20W reflects a higher metallicity of the material. This is measured by the amount of ^{22}Ne (2.5% in comparison to 1% for the other models, Brachwitz et al. 2001).

or pure C-burning products (e.g. C, O, Ne, Mg). The ratio of Fe to Si-Ca is about a factor of 2-3 higher than in solar composition (Grevesse & Sauval 1998). This typical feature is shown in Fig.6 for models discussed above. In pricipal one expects major differences for the Fe-group composition as a function of paramters like burning front propagation and ignition density (Iwamoto et al. 1999; Brachwitz et al. 2000). Here we present models which agree with the general constraints but also show a change in metallicity. One difference which becomes apparent immediately is the change in Mn. ^{55}Mn (the only stable isotope of Mn) is a decay product of ^{55}Co which is mainly produced in incomplete Si-burning. In this respect it was discussed by Iwamoto et al. (1999) as an indicator of the deflagration-detonation transition in delayed detonation models. Here we see that it is affected by metallicity as well (strongly changing from A2C20 to A2C20W, more details in Brachwitz et al. 2001).

4. Observational Constraints and Galactic Evolution

Galactic evolution can serve as a test for all contributing stellar yields, especially the ejecta of SNe II and SNe Ia (for details see e.g. Thomas et al. 1998; Chiappini et al. 1999). Here we want to focus on specific observational clues to SNe Ia

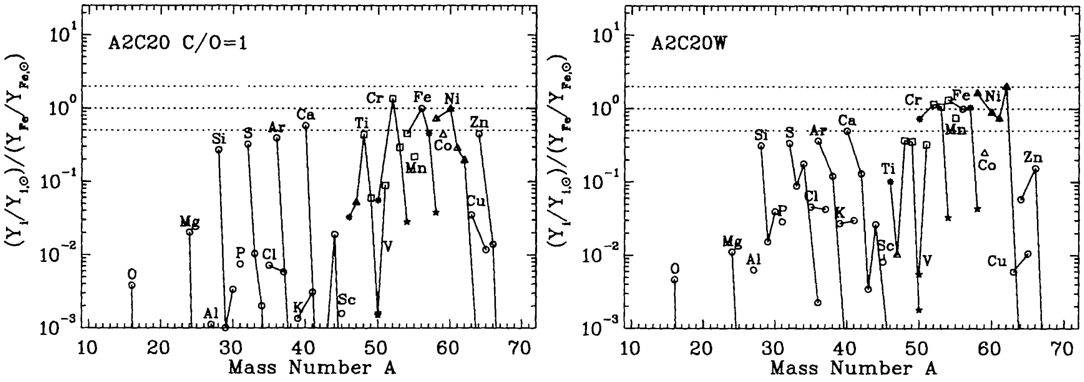

Figure 6. Abundance ratios of nuclei compared to their solar values and normalized for ^{56}Fe, the decay product of ^{56}Ni. Isotopes of the same element are connected by lines. The general feature is that the ratio of Fe to Si-Ca is about a factor of 2-3 higher than solar. For the changes in the Fe-group composition see text (from Brachwitz et al. 2001).

and SNe II nucleosynthesis and indicate how very low metallicity stars might witness individual rather than only integrated SNe II yields.

There have been detailed discussions (Thielemann 2000; Thielemann et al. 2001; Iwamoto et al. 1999; Thielemann et al. 1996) on observational constraints from supernova spectra, lightcurves, and X-ray and gamma-ray observations of remnants. They refer mainly to ^{56,57}Ni, and ^{44}Ti abundances and possibly stable Ni/Fe ratios in SNe II, giving insight into the details of the explosion mechanism with respect to the mass cut between the neutron star and the SN ejecta, the total energy of the explosion, the entropy and the Y_e in the innermost ejecta (see section 2). The intermediate mass elements Si-Ca provide information about the explosion energy and the stellar structure of the progenitor star, while elements like O and Mg are essentially determined by the stellar progenitor evolution.

In SNe Ia the ^{56}Ni production and the Si-Ca/Fe ratio are related to the total explosion energy and burning front speed in layers of the exploding white dwarf extending as far as $M(r)$=1M$_\odot$ and beyond. Constraints on the ignition density and burning front speed in the central regions (as discussed in section 3) are reflected e.g. in minor isotopic abundances like ^{50}Ti and ^{54}Cr, where direct supernova or remnant observations cannot be used. Here one can only make use of global abundance constraints from galactic evolution, which therefore permit only statements about an "average" SN Ia. The application of present day electron capture rates makes it hard to account for our solar system ^{48}Ca (Brachwitz et al. 2001). On the other hand, observations of varying stable Ni/Fe ratios during the evolution of a supernova (by spectral means) related to ^{54}Fe and ^{58}Ni, might give clues to the metallicity of the exploding white dwarf (Höflich et al. 1998).

Stars (with understood exceptions) do not change the surface composition during their evolution. Thus, surface abundances reflect the interstellar medium (out of which the stars formed) at the time of their formation. Therefore, observations of the surface composition (via spectra) of very low metallicity stars (i.e.

very old stars) give a clue to gas abundances throughout the evolution of our Galaxy. Recent promising trends in galactic evolution modeling might provide constraints on individual supernova models rather than only global properties of SNe II and SNe Ia. The reason for this possibility is the fact that there is no instantaneous mixing of ejecta with the interstellar medium, and therefore early phases of galactic evolution can present a connection between low metallicity star observations and a single supernova event. On average, each supernova pollutes a volume of the interstellar medium containing $\approx (3-5) \times 10^4 M_\odot$. (Each volume of the interstellar medium containing $\approx 3 \times 10^4 M_\odot$ needs to be enriched by $\approx 10^3$ SNe in order to obtain solar metallicities).

After a supernova polluted the previously pristine environment mass it results in values for [x/Fe] and [Fe/H] in the remnant and a scatter in [x/Fe] is expected for the same [Fe/H]. The amount of the polluted volume depends on the explosion energy, and if there is a strong variation of explosion energies with progenitor mass this could affect the relation between [x/Fe] and the metallicity [Fe/H] (Nakamura et al. 1999). The scatter in [x/Fe] expected for the same [Fe/H] is observed up to metallicities of [Fe/H]=-2 where it vanishes because overlapping contributions from many SNe II behave like a well mixed medium (Argast et al. 2000; 2001).

Successive enrichment of many (and finally overlapping) remnants leads to a metallicity evolution which approaches at [Fe/H]=-2 the IMF-averaged SNe II yields. These features (at [Fe/H]>-2) agree nicely with previous galactic evolution calculations which applied our yields (Tsujimoto et al. 1995; Thomas et al. 1998; Matteucci et al. 1999; Chiappini et al. 1999), assuming instantaneous mixing of yields with the ISM. However, the observed and predicted scatter at very low metallicities bears information which was previously unavailable (Argast et al. 2000; 2001). It indicates a problem in the stellar models which might improve with more recent calculations (Chieffi et al. 1998; Umeda et al. 2000; Heger et al. 2000; 2001) and has to be tested.

The main conclusion we can draw is that such investigations can also test individual stellar yields rather than only IMF integrated samples. This is a large advantage over the very few data points we have from individual supernova observations. Such tests seem also very useful for other applications, where one is not certain about the stellar site of a nucleosynthesis product or possible contributions from objects with different evolution timescales. Hypernova contributions should be considered in a similar way (Nakamura et al. 2001).

The r-process is an example where the alternative site to supernovae, neutron star mergers, occur with a much smaller frequency. In that case, the mixed phase (orrurring for SNe II at about [Fe/H]=-2) should be delayed to larger metallicities. In addition, one expects with the large amounts of r-process ejecta from each occasionally occurring neutron star merger (Freiburghaus et al. 1999b) a much larger scatter than for the smoothly changing supernova yields as a function of stellar mass. Both effects are seen in the r/Fe observations (a scatter of almost a factor of 1000 (Sneden et al. 2000; Cayrel et al. 2001) at low metallicities, which still amounts to about a factor of 10 at [Fe/H]=-1 (see Fig. 2 in Truran et al. 2000). It argues for a very rare event, even if some specific type of supernova is responsible for it. Further galactic evolution calculations without instantaneous mixing are needed in order to test the expected amount of scatter as a function of metallicity to give clues on the r-process site. A discussion of the advantages and disadvantages of both possible r-process sources (SNe II vs. neutron star mergers) is given in (Qian 2000; Rosswog et al. 2001).

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