Proc. 14th Int. Symp. on Nuclei in the Cosmos (NIC2016)
JPS Conf. Proc. **14**, 010605 (2017)
https://doi.org/10.7566/JPSCP.14.010605

Nucleosynthesis in Supernovae, Hypernovae/Gamma-Ray Bursts and Compact Binary Mergers

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(Received September 9, 2016)

We present the status and open problems of the astrophysical sites responsible for the nucleosynthesis of Fe-group and heavier elements (with the exception of the s-process). This involves type Ia supernovae with the requirement to have a low Y_e-component (for the explanation of ^{55}Mn), the role of the core collapse supenova explosion mechanism in the composition of the Fe-group (and heavier?) ejecta, the transition between neutron star and black hole remnants as the result of the collapse of massive stars, and the relation of the latter with supernova and/or gamma-ray bursts / hypernovae. In addition, the role of compact binary mergers is discussed, especially with respect to forming the heaviest r-process elements in galactic eveolution.

KEYWORDS: massive stars, type Ia supernovae, core collapse supernovae, compact binary mergers, nucleosynthesis, r-process, galactic chemical evolution

1. Introduction

The observation of low metallicity stars tells us that all elements, except for H, He, and Li (produced in the big bang), have a stellar origin. The production of C, N, and s-process element is related to low and intermediate mass stars, their winds and their wind ejecta in planetary nebulae. The ratio of alpha-elements to Fe [α/Fe] can be explained by the early dominance of massive stars, reaching their evolutionary endpoints fast, and producing (in core-collapse supernovae CCSNe) α/Fe ratios which are on average a factor of 2-3 higher than the solar composition. This turns over when delayed binary evolution - involving white dwarfs - leads to type Ia supernova (SNIa) events, which produce larger amounts of Ni/Fe and smaller amounts of alpha-elements (and among them only elements from Si onwards). While this general picture was introduced a while ago, major open questions are related to the detailed composition of the Fe-group (and the respective role of SNeIa vs. the core collapse of massive stars), and especially the origin of r-process nuclei. The large scatter of up to two orders of magnitude, observed at e.g. in [Eu/Fe] at low metallicities, points to rare events being responsible for their production. This is also supported by the fact that we see recent additions of ^{60}Fe (of massive star origin) to deep sea sediments, while this is not the case for ^{244}Pu, a heavy r-process element. The present article focuses on the understanding of Fe-group elements and beyond, including the origin of the r-process, passing through all possibly responsible sites. This also addresses findings from low metallicity stars about correlations/non-correlations of Zn, Ge, Sr, Y, Zr and heavy r-process elements with the Fe-group.

2. End Stages of Massive Stars

Stars beyond 8M$_\odot$ undergo core collapse, either up to about 10M$_\odot$ due to electron capture on C-burning products in the O-Ne-Mg core, resulting in the formation of an Fe-core during collapse (electron capture or EC supernovae) or via core collapse after central Si-burning. EC supernovae produce small amounts of alpha- and Fe-peak elements (see e.g. [77]). 10 - 90 $M_{\odot}$ stars undergo Fe-core collapse. A major question is how the transition occurs from "regular" core-collapse supernovae (CCSNe) to the formation of a central black hole and possibly hypernovae / long duration gamma-ray bursts (lGRBs). The occurence of hypernovae/lGRbs is dependent on rotation and magnetic fields. For the nucleosynthesis, aspherical explosions are or might be important. 90 - 140 $M_{\odot}$ stars undergo pulsational nuclear instabilities at various nuclear burning stages. 140 - 300 $M_{\odot}$ stars become pair-instability supernovae, if the mass loss is small enough to permit this final endstage. Very massive stars (> 300$M_{\odot}$) undergo core-collapse to form intermediate mass black holes. Detailed reviews on the present understanding of the end stages of massive stars are given e.g. in [10, 20, 28, 53]. CCSNe contribute to galactic evolution via their wind ejecta, and after explosion via (a) ejecta of essentially unburned matter from the outer stellar zones and (b) explosively processed matter from the inner ejecta. ^{60}Fe (half-life 2.6×10^6 y) is an example for (a) and goes back to hydrostatic burning stages [34, 37, 81]. Recent findings show that it can witness the last CCSNe near the solar system about 2 to 3 million years ago [30, 76].

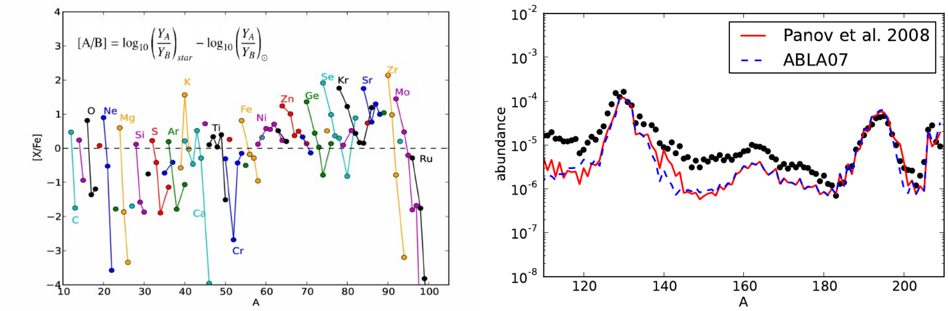

Fig. 1. a. Nucleosynthesis features of a 17$M_{\odot}$ SN explosion in 2D [49], featuring a strong νp-process with the production of nuclei up to A=100 (see contribution by Eichler). b. Ejecta composition of an MHD-jet supernova from a 15 $M_{\odot}$ progenitor with a $5x10^{12}$ Gauss magnetic field of the collapsing Fe-core [80]. With a Y_e=0.1-0.15 in the ejecta and modern fission fragment distributions (here ABLA [29]), peaks as well as intermediate nuclei are reproduced well for such a weak fission-cycling environment.

2.1 Core Collapse Supernovae

2.1.1 Neutrino-driven Explosions

The nucleosynthesis yields of CCSNe are characterized by an average ejected ^{56}Ni mass of about 0.1 $M_{\odot}$ and strong contributions to the so-called alpha elements O, Ne, Mg, Si, S, Ar, Ca, and Ti. They result either from hydrostatic burning in stellar evolution (O, Ne, Mg, and some Si) or from explosive burning (Si, S, Ar, Ca, and Ti) [10]. There exists observational indication that also Ge and Zn are co-produced with the Fe-group [11]. In the νp-process CCSNe can contribute some nuclei beyond the Fe-group like Sr, Y, Zr, e.g. [15]. In a weak s-process they can produce nuclei up to A=100 (and even beyond [14]). One of the major open questions is whether they can also be a dominant site for r-process nucleosynthesis. As shown from other contributions at this conference, the full solution to the CCSN problem in a self-consistent way is still not converged. There exists a growing set of 2D and 3D CCSN explosions, see e.g. [7, 26], and the progress of active groups in Garching/Belfast/Monash, Princeton/Caltech/North Carolina, Oak Ridge, Tokyo/Kyushu, Paris, and Basel (see contributions by Pan, Lohs, Heinimann, Hempel, and Kuroda), but it is still too early to provide complete nucleosynthesis predictions from self-consistent multi-D simulations. A few preliminary nucleosynthesis results exist (see Fig.1a by Eichler, based on axis-symmetric simulations [49]). This example features a nice/strong νp-process caused by $Y_e > 0.5$ conditions, but large-scale nucleosynthesis predictions are presently still based on induced spherical explosions ("induced pistons" or "thermal bombs").

When comparing such results (e.g. [20]), integrated over a standard inital mass function (IMF) from 10 to 100 $M_\odot$, utilizing a piston model with an explosion energy of $E = 1.2 \times 10^{51}$ erg), with a representative sample from low metallicity stars [8] representing CCSN yields, this leads to an underproduction of Sc, Ti, Co and Zn for zero metallicity stars. For higher metallicities nuclei beyond Ni are produced (s-process), but the dominant fraction of solar Zn (^{64}Zn) cannot be made this way. Those results made use of the initial stellar structure (and Y_e!), when inducing artificial explosions. This neglects the effect of the explosion mechanism on the innermost zones. Three aspects are important and can in principle only be solved by self-consistent explosion models in 3D: (a) predicting a consistent explosion energy, (b) even in spherical symmetry the neutrino interactions with nuclei are neglected, which affect Y_e strongly. (c) On top of this, multi-D effects will play a role.

Interim approaches beyond piston or thermal bomb models [20, 34, 53, 81] try to mimic multi-D neutrino heating in a spherical approach in order to obtain more appropriate predictions of the explosion energy, mass cut between neutron star and ejecta, as well as nucleosynthesis (including the effects of neutrinos on Y_e, the proton/nucleon ratio): Fröhlich et al. [15] multiplied neutrino-capture rates by a factor, causing additional ν-heating, to obtain observed explosion energies. Ugliano, Ertl, and Sukhbold et al. [68] introduced a tuned, time-dependent central neutrino source that approximately captures the essential effects of (3D) neutrino transport (PHOTB). Perego et al. [57] utilize the energy in muon and tau neutrinos as an additional energy source that approximately captures the essential effects of (3D) neutrino transport (PUSH, see also contributions by Ebinger and Sinha). The latter approaches make it possible, to predict the variation of explosion energies as a function of stellar mass and in this way can provide improved nucleosynthesis yields for chemical evolution modeling. There exist detailed results by now from PHOTB, but only PUSH includes the Y_e effects due to neutrino interactions with nuclei. A major open question is whether core collapse leads finally to a supernova explosion and neutron star remnant or whether the final outcome is a central black hole. Expectations from observations and their interpretation [53] would argue for a gradual transition between these two regimes as a function of initial stellar mass. PHOTB [68] shows that both results can be obtained within the same mass interval, dependent on the stellar model and its compactness parameter. This might pose questions about the stellar models. Could such scatter be avoided in general by the inclusion of rotation, leading possibly to a smearing out of radial gradients?

When going back to initiated explosions with explosion energies of 10^{51} erg, a major uncertainty is related to the treatment of the innermost ejecta. Spurious abundance effects by Y_e-values which stem from the pre-collapse stellar models would not be realistic with a consistent explosion treatment. Realistic explosion scenarios, including a full treatment of weak interactions, are affected by (electron) neutrino and anti-neutrino captures on neutrons and protons. If the neutrino flux is sufficient to have an effect (scaling with $1/r^2$), and the total luminosities are comparable for neutrinos and anti-neutrinos, only conditions with $E_{av,\bar{\nu}} - E_{av,\nu} > 4(m_n - m_p)c^2$ lead to $Y_e < 0.5$. Present calculations [1, 40, 59] therefore exclude strong r-process conditions in CCSNe and the interaction with neutrinos leads even to proton-rich conditions. The latter favors improvements in the Fe-group composition of elements like Sc, Ti, Co, as well as for ^{64}Ge (decaying to ^{64}Zn!), and the νp-process, which can produce nuclei up to Sr, Y, Zr and Mo. (see e.g. [15], also seen in Fig.1a). In general, explosive Si-burning in CCSNe occurs with a strong alpha-rich freeze-out (dependent on the explosion energy/entropy), which favors for identical Y_e conditions those Fe-group nuclei which would result from additional alpha-captures on the nuclei produced in a normal freeze-out. Thus, ^{56}Ni can be moved up to ^{64}Ge (decaying to ^{64}Zn) or ^{54}Fe up to ^{58}Ni. The first effect takes place for very high explosion energies, only attained in hypernovae, the second one in all regular CCSNe. Thus, ^{64}Ge(Zn) can result from Y_e values >0.5 in regular CCSNe as well as in hypernovae.

The innermost regions are prone to convective Rayleigh-Taylor instabilities and also to some fallback caused by a reverse shock. As a pragmatic solution, utilizing a combination of mixing and fallback, can minimize the Y_e-effects of the innermost regions for approximated spherical models. This mixes some Fe-group nuclei to larger radii, while the fallback reduces the ejected amount of Fe-group elements and can this way create C-rich ejecta, as observed in some extremely low metallicity stars. Such behavior is suggested to stem from very massive stars, possible being more frequent in the early Galaxy [53].

2.1.2 The effect of strong magnetic fields

Recent observations [19] underline that there exist core-collapse supernova explosions whose light curves are not determined by (large) amounts of ^{56}Ni ejecta, but rather by the energy release of a fast rotating neutron star (pulsar) with extremely strong magnetic fields of the order 10^{15} Gauss (magnetars). The question is how can neutron stars of such extremely high magnetic fields (in comparison to the typical 10^{12} Gauss) emerge from supernova explosions. A logical indication is that they originate from massive stars which are fast rotators with initially strong magnetic fields. Such objects, with assumed initial rotation rate and magnetic fields, have been modeled [45, 50, 80], called here magneto-rotational or MHD-jet supernovae. The result is typically (when starting with initial fields of the order 10^{12} Gauss) that the winding up of magnetic fields results in strong magnetic pressure along the polar rotation axis and jet-like ejection of matter. This matter has experienced high densities (and degenerate electrons with high Fermi energies), leading to strongly neutron-rich matter with Y_e=0.1-0.15. The fast ejection along the poles avoids that the interaction with neutrinos and anti-neutrinos causes a major rise of Y_e. Such conditions permit a strong r-process [50]. A fully self-consistent treatment would require high resolution simulations which can resolve magneto-rotational instabilities (MRI) and would predict reliably the possible amplification of magnetic fields during the explosion. Present calculations depend on the assumed initial conditions, which either cause strong jet ejection or can develop kink instabilities of the jets [45]. Fig.1b shows the nucleosynthesis results of the 3D collapse of a fast rotator with a strong initial magnetic field of $5x10^{12}$ Gauss. A 15 $M_\odot$ progenitor with an initial shellular rotation period of 2s at 1000 km results in a rare class of supernovae with a central magnetar and negligible amounts of Fe-group ejecta. Fig.1b shows the effect of modern fission fragment distributions which avoid abundance troughs below and above the A=130 peak originally obtained in [80]. This result should be taken into account with respect to other investigations [65], which rely on quite different abundance features for MHD-jet supernovae and neutron star mergers, based on fission barriers which cause fission in the r-process only for A>300. In terms of applications to galactic chemical evolution it should be noticed that the MHD-jet supernovae discussed here are expected to occur as a fracton of 0.1-1 percent of all CCSNe, probably being somewhat metallicity-dependent. Another feature is that these events are expected to show small amounts of Fe-group ejecta [50].

2.2 Long Duration Gamma-Ray Bursts and Hypernovae

Massive stars, which fail to explode as CCSNe via neutrino-powered explosions, will eventually experience the formation of central black hole (BH) remnants. Rotating BHs and the formation of accretion disks with accretion rates of about $\approx$ 0.1 $M_\odot$/s can lead - for certain conditions (strong magnetic fields) - to long duration gamma-ray bursts (lGRBs) or hypernovae. Many authors have contributed to the discovery and laying out first ideas for theoretical explanations (see the reviews by Piran [58] and Nagataki [48]). The collapsar model was proposed by Woosley, MacFadyen and others (see also [35, 36, 46, 47, 62]), based on neutrino heating from the accretion disk and/or the winding of strong magnetic fields and MHD jets [41, 54]. Hydrodynamic simulations (injecting explosion energies artificially) were performed, either by introducing high explosion energies (up to 10^{52} erg) in a spherically symmetric way or aspherically in order to understand jet-like explosions [53]. For the role of weak interactions and resulting nucleosynthesis see e.g. [25, 69, 70]). The basic (consensus) picture is the following: explosion energies can be found up to 5×10^{52} erg, ^{56}Ni ejecta up to 0.5

$M_\odot$, and the ejecta are beamed with relativistic jets. Many attempts have been undertaken to model such events. There exists uncertainty in predicting Y_e, following weak interactions and especially neutrino transport in disks and jets, but there exists also the constraint of high ^{56}Ni ejecta. Therefore the dominant Y_e in matter has to be of the order of 0.5. High explosion energies lead to high entropies and a strong alpha-rich freeze-out, including interesting amounts of ^{45}Sc, ^{64}Zn and other Fe-group elements. Magnetars have also been suggested to explain lGRBs (see previous subsection). However, present simulations lead rather to a strong r-process and negligibe amounts of Ni-ejecta (supported by light curve observations being powered by pulsar emission rather than ^{56}Ni decay [19]).

3. Binary Systems With Compact Objects

This very general topic would include systems with white dwarfs, and thus novae as well as type Ia supernovae, and also systems involving neutron stars, where accretion of matter in binary systems can lead to X-ray bursts and possibly also superbursts (see Basel contribution by J. Reichert). Mergers of neutron stars can lead to short duration gamma-ray bursts sGRBs. With the exception of type Ia supernovae and neutron star mergers, these topics have been covered in a number of contributions by other authors. Here we want to focus on these two events and their nucleosynthesis.

3.1 Type Ia Supernovae

From the beginning (laid out by Iben & Tutokov and Webbing) two explanations existed for type Ia supernovae, both involving white dwarfs in binary stellar systems: the single-degenerate scenario (involving only one accreting WD), and the double-degenerate scenario (involving spiraling in WD mergers). For a while the Chandrasekhar mass models (single degenerates), causing growth towards the Chandrasekhar mass and then central ignition, leading initially to deflagration, possibly changing into a detonation in the outer layers, was the favorite case (see e.g. the W7 model by Nomoto and collaborators [52]). But in the meantime the spectrum of scenarios has widened a lot, involving single-degenerates with off-center ignition and double detonations via He-accretion (see the contribution by Ken Shen to this conference), as well as double degenerate mergers and even WD collisions, which might be all responsible for the observational diversity with multiple subclasses from recent extended surveys. Light curves and spectra show faint SNeIa with weak intermediate-mass elements (IME), bright cases with early Fe-group lines (IGE), faint and fast evolving cases, as well the normal ones utilized for cosmology. Although there has been further progress since then, the review by Hillebrandt et al. [21] gives an enlightening overview over all these options. The Mn/Fe ratio as a function of metallicity seems to be a sensitive measure whether near Chandrasekhar mass single-degenerate models (deflagrations like W7 [52] or delayed detonations [24, 63]) occur at all, because only they show low Y_e-regions close to the center of the WD. Mn comes in form of its only stable isotope ^{55}Mn, and is the decay product of ^{55}Co, produced in incomplete and complete Si-burning under optimal conditions with $Y_e = Z/A = 0.491$. In alpha-rich freeze-out of explosive Si-burning, determined by the entropy $S \propto T^3/\rho$ of explosive burning layers with values of T_9 and ρ_8 exceeding $T_9^3/\rho_8 > 180$, ^{55}Co is moved to ^{59}Cu ($\rightarrow$ ^{59}Co). The inner zones of M_{Ch}-models experience only moderate entropies and such lower Y_e's are attained via electron capture, due to degenerate electrons with high Fermi energy. In the outer zones it can be approached via metallicity as CNO nuclei are burned in He-burning to (slghtly neutron-rich) ^{22}Ne. For initial metallicities of the WD progenitor with values of [Fe/H]=$-\infty$,0,025,and 0.5 this leads to Y_e= 0.5, 0.499, 0.498, and 0.496 is attained in the SNIa ejecta. This leads also to an increase of in [Mn/Fe] and the appearance of ^{54}Fe (moved to ^{58}Ni in alpha-rich freeze-out).

The evolution of [Mn/Fe] as function of [Fe/H] from recent studies is displayed in Fig.2 (from Mishenina et al. [44]). [Mn/Fe] from CCSNe results in about ≈-0.4. The old W7-model predicts for SNe Ia ejecta [Mn/Fe]=0.067, 0.227, 0.30, 0.38 at [Fe/H]=$-\infty$,0,0.25,0.5. Seitenzahl et al. [63] find

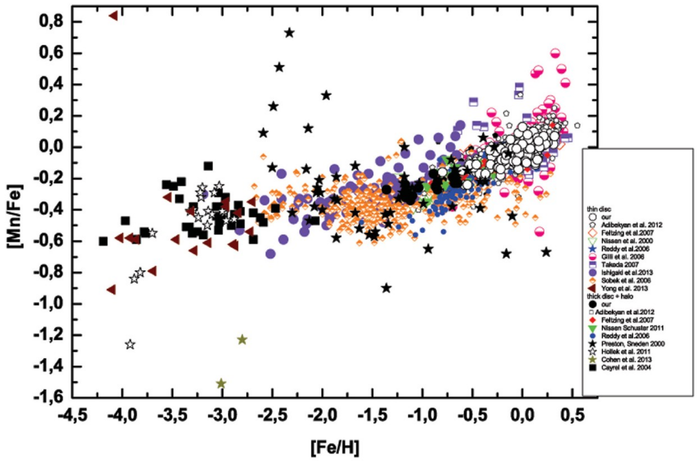

Fig. 2. The evolution of [Mn/Fe] as function of [Fe/H] from recent studies/observations [44]. Notice the rise of [Mn/Fe] from subsolar values at metallicities close to -1 to ratios exceeding solar beyond solar metallicities, which acts in a similar way as the decline of [α/Fe] from supersolar values at the same metallicity. The rise of [Mn/Fe] seems to require some contribution from single degenerate central deflagration models of SNeIa.

[Mn/Fe]=0.4 already for solar [Fe/H] values and conclude that M_{Ch} models have to contribute in order to explain the observed trend. (see also [31] who conclude that 50% of type Ia supernovae require deflagration models with low central Y_e-values and 50% can be explained by He-detonations, discussed in the contribution by Ken Shen.

3.2 Neutron star mergers

Short-duration GRBs (sGRBs, with a light curve decline of less than about two seconds) are due to relativistic jets created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). Mergers of this kind are also expected to produce significant quantities of neutron-rich radioactive species, whose decay should result in a faint transient, known as kilonova, in the days following the burst. Recent calculations suggest that much of the kilonova energy should appear in the near-infrared, because of the high optical opacity created by these heavy r-process elements. Optical and near- infrared observations of such an event, accompanying the short-duration GRB130603B have been reported [71] (see also [4]). After the first detailed nucleosynthesis predictions (following ideas of [33]) of such an event [13], many more and more sophisticated investigations have been undertaken, involving quite a number of authors [5, 12, 16, 17, 27, 32, 39, 42, 51, 56, 61, 78] as well as the black hole accretion disk system after the formation of a central black hole [27, 70, 78, 82].

Here we want to focus on the early dynamical ejecta and their dependence on nuclear properties. Non-relativistic simulations (e.g. [32, 61]) lead to large amounts of ejecta of the order 10^{-2} $M_\odot$ with very small Y_e-values of 0.04 and less. This causes a very strong r-process with fission cycling. The utilized mass model, beta-decay half-lives, fission barriers, and fission yield prescriptions [12, 18, 29, 38, 42, 55, 65, 78] have a strong effect on the final abundance distribution. While during the r-process (when reactions are still in $n, \gamma - \gamma, n$ equilibrium) the 2nd and 3rd r-process peak are exactly at the right position. the neutron capture of large amounts of fission neutrons (after freeze-out from this equilibrium) has some effect on abundances below A=165, and the third peak seems always shifted to heavier nuclei. Deviations (troughs) in the mass range A=130-165 can be improved with modern fission fragment distribution (ABLA0 [29]), but not the shift of the 3rd peak. One option to remedy this effect are variations in beta-decay rates. Shorter half-lives [38] of heavies release neutrons from fission earlier, when $n, \gamma - \gamma, n$ equilibrium is still in place and can avoid or strongly reduce the late shift of the 3rd peak [12] (see Fig.3a). This effect is also seen with the HFB mass model (see also

[18]), while Mendoza-Temis [42] analyzed additional nuclear uncertainties and showed especially an improvement with the Duflo-Zuker mass model. Investigations [65], based on quite different fission barrier predictions, which introduce fission in the r-process only above A=300, do not reproduce the 2nd r-process peak in neutron star mergers. Alternative ways to cure the problems of the 3rd r-process peak discussed above, come from full general relativistic modeling of the merger event. This leads to deeper gravitational potentials, higher temperatures (including neutrino energies), electron-positron pairs, which - via positron captures and neutrino interaction with nuclei/nucleons - increase Y_e to values of the order 0.15, comparable to those mentioned above in MHD-supernova (magnetar) jets [18, 78], where the 3rd peak shift did not occur.

After ballistic/hydrodynamic ejection of matter (i.e. the dynamic ejecta), a hot and massive combined neutron star, forming (dependent on the equation of state) before collapsing to a black hole, evaporates a neutrino wind [39, 56, 61] with neutrino wind contributions from matter in more polar directions with Y_e's up to 0.4. These can contribute also the lighter r-process nuclei. In a similar way ejecta of the black hole accretion disk, also powered by neutrinos (and viscous disk heating), provide the additional abundance component of light r-process nuclei [18, 27, 78, 82].

4. Chemical Evolution With a Special Focus on r-Process Sites

4.1 Observational Constraints

The general tendency of the dominance of CCSN ejecta during low metallicities (showing increased [α/Fe] ratios) until the emergence of SNeIa, contributing large amounts of Ni(Fe), has been discussed already in the introduction. In section 3.1 we have already shown that the behavior of [Mn/Fe] can be explained in a similar way, due to the production of ^{55}Mn in SNeIa. In the remaining part we want to focus here on the origin of the r-process. Abundances in low metallicity stars [23, 60, 66] seem to show two types of (extreme) patterns: (a) so-called Sneden stars come with a solar r-process pattern (i.e. the responsible site dominates the solar r-process and apparently produces it in each single event). Thus, solar r-abundances, which are in principle an average over many possible different signatures, are dominated by one identical signature. (b) so-called Honda stars, with abundance distributions which look like a weak r-process and include some Eu but no 3rd r-process peak, can be seen at low metallicities. (c) Apparently some combinations of (a) and (b) can be found before the solar r-process pattern of (a) is also the general pattern beyond metallicities of [Fe/H]≈-2. Eu, as the best observed (almost pure) r-process element, shows a big scatter in [Eu/Fe] at low metallicities, indicating that the r-process is a rare event and it takes longer to arrive at average values than for elements produced in frequent events like supernovae. A second indication that the r-process is produced in sites of rare occurence is the recent addition of ^{60}Fe found in deep-sea sediments probably due to the last nearby CCSN about 2 million years ago, while ^{244}Pu has not been added at this point in time and its low value must come from rarer and earlier events which permitted for some subsequent decay [30, 76] A final indication that supernovae (and at low metallicities these are regular CCSNe) are not responsible for the heavy r-process elements is the non-correlation of r-process elements with the Fe-group, which is produced by CCSNe [11].

Historically a number of possible astrophysical sites for the r-process have been discussed: 1. Neutrino-driven winds in regular CCSNe, but this site is contradicted by observational constraints and present simulations result at most in a weak r-process [40, 59]. 2. Electron capture supernovae, do not produce much Fe/Ni, thus, the non-correlation with r-elements would hold, but this mass range in the IMF leads to frequent events, and simulations (e.g. [77]) also indicate that at most a weak r-process can be obtained. 3. Neutron star mergers produce large amounts of r-elements (as shown above), negligible amounts of Fe/Ni and they are rare events, of the order of 1% of CCSNe. 4. Black hole accretion disks are the final stage of neutron star mergers and can also provide the lower mass r-process elements [27, 82]. They will also occur for the collapse of massive stars resulting in lGRBs/Hypernovae, but are not expected to produce heavy r-elements (unless special neutrino properties permit so, [69]). But these clearly produce large amounts of Ni/Fe which would be in contradiction with the non-correlation of r-process elements with Fe/Ni. 5. Explosive He-burning in outer shells of massive stars has been suggested in the past, but realistic simulations did not attain the required conditions, unless this occurs at very low metallicities [3]. In that case charge-current neutrino interactions would permit sufficient amounts of neutrons, but with low number densities, producing an abundance patter with peaks shifted to lower mass numbers, thus tending more towards an s-process pattern. In addition, these would not be rare events (at these low metallicites). 6. Finally, polar jets from fast rotators with strong magnetic fields, leading to a rare class of CCSNe producing magnetars. These objects have been discussed in detail in section 2.3 [45, 50, 80], they are rare (0.1% to 1% of regular CCSNe), do not produce much Ni/Fe, but large/comparable amounts of heavy r-elements as neutron star mergers. As a result of this discussion only 3/4 and 6 remain as possible sites to produce heavy r-elements and we will discuss them in the following with respect to their appearance in the chemical evolution of galaxies.

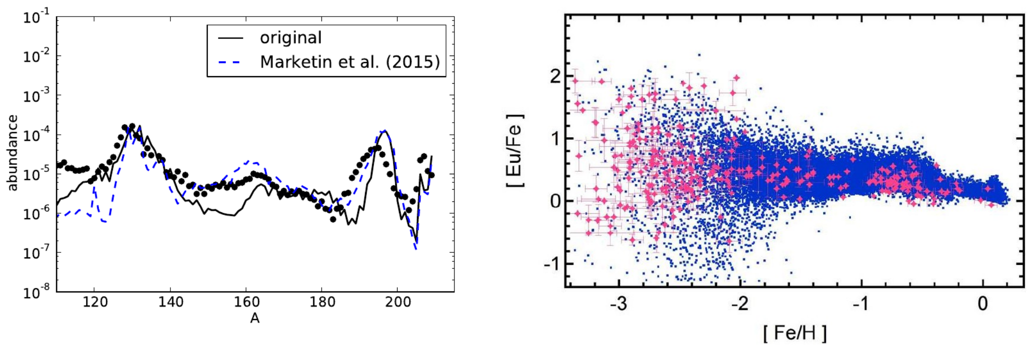

Fig. 3. a. r-process abundance distribution in dynamical ejecta of neutron star mergers, utilizing different mass models, fission fragment distributions, and half-lives [12]. The effect of improved half-lifes [38], in comparison to the original FRDM based ones, is shown. b. The evolution of [Eu/Fe] as function of [Fe/H] from observations (SAGA data base [67]) and inhomogeneous chemical evolution predictions [79] (see contribution by Wehmeyer). The combination of MHD-jet supernovae (leading to magnetars) at low metallicities and neutron star mergers, occurring later, reproduces nicely the large observational scatter and the overall trend.

4.2 Chemical evolution simulations

Chemical evolution modelling of rare events requires inhomogeneous models, which do not automatically assume instantaneous mixing of explosive ejecta with the (whole) interstellar medium. Such approaches have recently been undertaken by a number of authors [2, 9, 22, 64, 75, 79]. While [2, 9, 79] came to the conclusion that the contribution of neutron star mergers with respect to heavy r-process elements shows up too late, i.e only at metallicities around [Fe/H]=-2, different from observations which see them already for [Fe/H]<-3, [22, 64, 75] argue otherwise. The question is how the delayed binary evolution and explosion enters into the interstellar medium, after the related supernovae producing the two neutron stars already ejected ample amounts of Fe. The explanation is essentially due to the assumptions of ejecta mixing with the interstellar medium. If e.g. one assumes that only the typical mass swept up by a Taylor-Sedov blast wave is polluted (of the order a few $10^{-5}M_\odot$), then the results of [2, 9, 79] are reproduced (but see also in the high resolution run of [75]). There are two ways to avoid such conclusions (and there is of course an uncertainty related to them): (1) permitting large scale mixing (like turbulent mixing as argued in [64, 75]), or (2) proposing that our Galaxy results from a mixture of initially different galactic substructures with different star formation rates which can shift [Eu/Fe] as a function of [Fe/H] to smaller and larger values [22]. (1) is either an artifact of too large star particles in SPH codes, which automatically assume a well mixed abundance distribution in each one of such star particles, while smaller masses of star particles in high resolution runs of [75] actually reproduce the results of [2, 9, 79] or Nature actually provided such large-scale turbulent mixing, a feature which we still need to understand. There is no doubt that compact binary mergers are a highly important or the dominant r-process site. However, other rare events like magnetars [19] could help avoiding problems to explain r-process observations at low metallicities. In fact, the combination of neutron star mergers and MHD-jet supernovae can reproduce the observations nicely in (stochastic) inhomogeneous galactic chemical evolution models [79] (see Fig.3b). Both events produce the strong r-process, including the actinides, are rare with a frequency of about 1% to 1 permille of regular CCSNe, consistent with constraints from recent additions to the solar neighborhood as well as the early Galaxy, and the non-correlation with Ni/Fe production.

Acknowledgements

This research was supported by the Swiss SNF and an ERC advanced grant (FISH). Thanks go to all members of the Basel nuclear and computational astrophysics group (with results displayed in a number of figures) and our collaborators in Darmstadt (A. Arcones, G. Martinez-Pinedo), Moscow (I.Panov), North Carolina (C. Fröhlich), Odessa (T. Mishenina), as well as in Tokyo (K, Nakamura, T. Takiwaki) and Kyushu (K. Kotake) and their respective groups.

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