Brainstorming and Fun:

Nuclear Input, Stellar Simulations, Explosions, Remnants, Chemical Evolution, Observational Constraints

27./28. September 2012, Basel

Schedule and Locations

27.09.2012

Room 2.04

10-12:45 setting up list of topics and topic leaders, results:

- *evolution and s-process in rotating massive stars (M. Pignatari),*
- *p-process abundances and its origin(s) (T. Rauscher),*
- *core collapse supernovae, explosion mechanism and ejecta (M. Liebendörfer)*
- *r-process, input physics, sites, and observational constraints (G. Martinez-Pinedo)*

12:45-13:45 lunch in Mensa 3rd floor

13:45-16:30 Discussions, passing through list of topics

16:30-17:00 Coffee break

Lecture Hall 2

17:15-18:30 seminar by Gabriel Martinez-Pinedo:

Challenges in Heavy Element Nucleosynthesis of Supernovae

19:30 Dinner, Restaurant Schnabel

28.09.2012

Seminar Room (Komiteezimmer) in Bildungszentrum 21

9:00-10:30 passing through list of topics

10:30-10:50 Coffee break

10:50-12:20 continuation …

12:30-13:30 Lunch

13:30-14:30 Summary, Conclusions, Future Directions

Short Summary of Results

Stellar Evolution in rotating massive stars and the s-process (Pignatari):

- s-process in fast rotators, triggered from primary production of ^{22}Ne.

s-process up to 2 orders of magnitude more efficient at low metallicity compared to standard s-process in non-rotating massive stars. This is NOT the weak s-process, this is a possible different component. The elemental distribution is peaked at the Sr-Y-Zr neutron magic peak.

- Primary production of ^{22}Ne connected with production of nitrogen in fast rotators, that is observed at low metallicity.

- secondary nature of the s-process in fast rotators. Primary neutron source, primary poisons but secondary seeds (iron). On the other hand, stars rotate faster with decreasing metallicity. The consequence is that the s-process maximum efficiency is around [Fe/H] ~ -2.5 to -3. Decrease do to secondary nature below this metallicity.

- Can be this a source of LEPP? For now there exists no identified LEPP star at [Fe/H] < -3 . In case this star is found, would question the s-process in fast rotators as source of LEPP? Possibly yes.

- s-process in fast rotators is an s-process. Therefore, only s-process elements can be produced. For instance, Ag or Rh cannot be produced. Is there a zoo of processes contributing to the inventory of the elements between Sr-Y-Zr up to Te (solar LEPP range) ?

- Identification of an old bulge Globular Cluster, Chiappini et al. 2011, at metallicity [Fe/H] ~ -1. For a sample of stars Sr, Y, Ba, La and Eu is measured. One group clearly shows the LEPP signature. At this metallicity it is possible to study the same process(es) observed at work in the halo, at much lower metallicities. More observations are needed to confirm and take advantage of this opportunity.

- s-process yields from fast rotators are strongly affected by nuclear uncertainties. First by Ne22+alpha, then by the O17+alpha reaction (branching ^{17}O(α,n) vs. ^{17}O(α,n)). This is affecting in particular the production above the Sr neutron magic peak, whereas Sr-Y-Zr yields are more robust and less affected by such uncertainties.

- measurement of more elements are needed. The work for Pd and Ag is an example. More elements are needed also below the Sr peak, e.g. the effort to measure Se (Roederer, Cowan), or Cu, Ga and Ge, to constrain nucleosynthesis processes.

Origin of p-Nuclei: summary keywords (Rauscher):

Status: the long-time favored process is the gamma-process (photodisintegration) in ccSN; problems reproducing solar distribution (perhaps also absolute level, see GCE); two regions: light p-isotopes (A<100, not produced in current ccSN), heavy p-isotopes (region around 150<A<165 underproduced but contributions of neutrino-process and s-process are re-evaluated); nuclear physics uncertainties in photodisintegration may account for deficiencies in heavy region, not sufficient to explain lack of light p; separate treatment of these regions necessary? separate processes?

Therefore, need to either change p-production in massive stars (ccSN) or to find a different site.

Key questions:
- seeds: crucial for photodisintegration mechanism; may affect light p only or all p-nuclei, depending on seed distribution;

SNIa models assume strongly enhanced (by factors of several 100s to 1000s) s-process seeds;

models still under construction but in principle not ruled out by observation;

seeds in ccSN may be changed, e.g., by different weak s-process due to changed neutron producing reactions or stellar physics; impact of rotation (fast rotating massive stars at low metallicity make more s); $^{12}C+^{12}C$ also strongly affects s-processing.

what seeds (amount, distribution) are reasonable?? (within any site; also from GCE point of view)

- influence of neutrino-winds (νp-process?) in ccSN: have to be added to explosive nucleosynthesis in outer layers; would allow a "primary" production of p-nuclei.

- T-evolution (freeze-out): important to determine certain isotopic ratios, e.g., $^{144}Sm/^{142}Nd$ measured in meteorites.

- nuclear physics: affects production of s-process seeds in massive stars as well as photodisintegration; gamma-process is not an equilibrium process, many 100s of reactions and reaction sequences have to be considered;

heavy p: possible problems found in sub-Coulomb (alpha,gamma) rates on heavy nuclei in comparisons to experiment, implications on (gamma,alpha) not yet clear, may be a laboratory effect; for isotope ratios also ratios (gamma,alpha)/(gamma,n) important;

light p (+ all?): all reactions affecting s-processing, e.g., neutron sources and neutron poisons, $^{12}C+^{12}C$, etc.

- GCE: Not well constrained because of lack of observations; no stellar isotopic abundances for most elements (except Eu, Ba in a few(?) stars); meteoritic data (both early SS or presolar grains) available but interpretation difficult;

could there be any further (current, future) observations which are feasible and may help? Mo at low metallicity (if primary and not stemming from photodisintegrations)? stellar isotopic abundances from young stars (metal-rich) to compare to solar?

Core Collapse Supernova models (M. Liebendörfer):

- There is agreement between all groups about the results of spherically symmetric supernova models. Explosions are only found for the 8.9 Msol mass ONeMg progenitor of Nomoto et al. and in simulations that feature an early phase transition to quark matter (Sagert et al. 2009). An alternative low mass progenitor of Hirschi et al. exists, but core-collapse simulations have not yet been completed. The input physics of spherically symmetric models can still be improved. The models are useful for comparisons with approximations that enable simulations of higher dimensionality.

- Core-collapse supernovae are believed to explode by one (or a combination) of the two following mechanisms: 1) neutrinos of all flavors are emitted from the hot protoneutron star (PNS) and stream out through the cooler (in temperature, not entropy) layers between the surface of the PNS and the stalled bounce-shock. If a small percentage of these neutrinos is absorbed behind the standing accrection shock (SAS), the shock is driven outward and may lead to the explosion. 2) If strong magentic fields are present, they increase by compression during collapse and winding of field lines during the postbounce phase. A magneto-hydrodynamic (MHD) jet might form that leads to matter ejection.

- It is well known and undisputed hat fluid instabilities between the PNS and the standing accretion shock increase the efficiency of the neutrino heating. They lead to asymmetric accretion patterns and enable convection and the standing accretion shock instability (SASI). Simulations of these effects are mostly done in axial symmetry (2D) where fluid instabilities can be combined with sophisticated neutrino transport. Most groups obtain explosions for progenitor stars smaller ca. 15 solar masses. However, the results between groups have not yet converged with respect to the time of the onset of the explosion, the shock radius, the mass of the remnant etc. Problematic is that the explosion energies are still on the low side ($\sim 10^{50}$ erg), especially in the more sophisticated models. Another problem is that axial symmetry prefers one direction (along the axis) onto which all oscillation modes are projected so that the corresponding modes are overestimated.

- In Basel we perform models based on the isotropic diffusion source approximation (IDSA), which is more efficient than full transport and permits explorations of parameters like different equations of state (EOS), rotation rates or magnetic field setups in three dimensional models (3D). It would be interesting to also obtain 3D progenitor models and evolve them through collapse, where the models are especially sensitive to details. But these asymmetries might be wiped out by the bounce-shock before the postounce phase is reached.

- Our 3D models lead a clear explosion of the 11 solar mass progenitor, a still undecided (but optimistic) outcome for the 15 solar mass progenitor, and did not lead to an explosion for the 40 solar mass progenitor. Small differences are found for the 180, 220 and 375 MeV incompressibility parameter K of the Lattimer-Swesty (LS) EOS and larger differences are found for the Shen et al. EOS, which leads to more pessimistic results. The LS EOS with K=220 MeV is currently the only one that is consistent with experiments and observation of neutron stars. Supernova models are becoming more optimistic as modellers change from Shen to LS220.

- Our 3D models of the MHD mechanism can eject matter (Winteler et al.), but require the assumption of fast rotation in combination with a strong poloidal magnetic field. If these conditions are not obtained by stellar evolution (unlikely?), they might build up during the postbounce evolution (by magneto-rotational instabilities?). However, the expected field would initially rather be toroidal or turbulent. Also the explosion would launch later and for different conditions than in the present simulations.

- The uncertainties in the simulations are too large to determine the IMF-integrated supernova yields based on supernova models. It appears plausible that there might be islands of progenitor masses that explode, dependent on the compactness of the core. But to be sound this information currently has to come from observation rather than simulation. (Of course, this would also affect the ^{60}Fe ejecta which depend strongly on the progenitor mass).

- The electron fraction of the inner ejecta is crucial for the nucleosynthesis. It depends on the explosion mechanism and ejection time scale. Slow ejection supported by neutrino absorption (neutrino driven mechanism 1) leads to an alpha-rich freezeout from initially proton-rich conditions. Fast ballistic ejection of neutron-rich matter leads to neutron-rich ejection under conditions more favorable for the r-process (MHD jet 2).
All models suffer from rather low explosion energies that may not lead to abundances in the outer layers that fit observation as well as the older piston or thermal energy-driven induced models that were based on observational explosion energies.

- Some of these results may change due to a more careful consideration of nuclear potentials in the charged current interactions, these are discussed in detail in the r-process session. Here a few words on nucleosynthesis effects.
The explosion mechanism, leading to a Ye, entropy and expansion timescale of the ejecta has a

strong effect on the upper so-called alpha elements like Ca (=40Ca + ^{44}Ti), Ti (=^{48}Cr), with ^{44}Ti also visible from remnant observations. This line can in principle be extended up to ^{52}Fe(Cr), ^{56}Ni(Fe), ^{60}Zn(Ni) and ^{64}Ge(Zn), experiencing an entropy effect (argueing for hypernovae to obtain low metallicity Zn) or a p-rich Ye effect (vp-process which can reproduce Zn as well as elements up to Sr?).
The transition from the early innermost ejecta to the neutrino-wind of the nascent proto-neutron star is again affected by Ye and entropy. While until recently there seemed to be no way out of having a p-rich ejecta environment for extended timescales of seconds, the treatment of neutron and proton potentials in medium seem to change it again and might open an option for a weak r-process in all supernovae (see r-process section)?

Summary of r-process discussion (G. Martinez-Pinedo):

Traditionally the r-process is identified with the rapid neutron capture process that accounts for the production of at least half of the elements heavier than iron. In the following, we will denote as r-process any primary process that can account for the observations of metal-poor stars. These stars show abundance patterns that clearly do not correspond to the solar system s-process abundance. Many of this stars show an abundance pattern for elements heavier than Z>50 that matches almost perfectly the solar system r-process abundances. In the following we will denote these type of stars as Sneden type stars. Another subset of metal-poor stars show abundances depleted in elements heavier than Z>50 (however also show abundances for elements as heavy as Eu), but nevertheless they are enriched in light r-process elements like Sr, Y and Zr. We will denote this stars as Honda type stars.

The above observations suggest that elements with Z>=50 and Z<50 are produced in two different astrophysical environments. This can be either two different astrophysical sites/events occurring with different frequencies along galactic history or two different environments within the same astrophysical event(s). As an example in the case of neutron-star mergers there can be contributions from material dynamically ejected from the merger, from winds from the accretion disc and from the two previous supernova explosions. All these environments (dependent on the delay timescale between supernovae and mergers might in GCE models) constitute a single event.

The data presented by John Cowan show that all metal-poor stars observed so far have some abundance of Eu. This suggest, and this suggestion is rather weak at the moment due to the low statistics, that we may have two different astrophysical events: one that produces nucleosynthesis patterns a la Honda and another one that produces nucleosynthesis patterns a la Sneden.

From the point of view of current astrophysical modeling and nuclear physics it will be more "natural" to have events that produce elements below Z=50 and elements above Z=50. The consequence of this type of nucleosynthesis patterns is that there should be stars with only elements below Z<50 and no Eu. As this has not "yet" been observed we have to assume that events producing elements Z>50 are more frequent or evolve faster at low metalicities. However, this will mean that we should expect stars with no abundance of elements Z<50. As these has not been seen either we are left with the existence of the two type of events discussed above.

The above hypothesis can be tested by additional observations and chemical evolution models. The evolution of the Eu abundance with metalicity indicates that the production of Eu is not correlated with iron. This points to the fact that Eu is produced in rare events with very little or no iron production. This may be the case for Sneden type events but an interesting question is what happens with Honda type events. Currently, we think that they can be related to core-collapse supernova that produce iron and consequently a correlation between iron and heavy elements including Eu, Sr, Zr should be present in these stars. Unfortunately, at this moment the number of Honda type stars observed is rather low to get any conclusion.

From the astrophysical modeling point of view core-collapse supernova and in particular neutrino-driven winds were suggested long time ago as the "site" for r-process nucleosynthesis. They were considered to be the ideal site for the high entropy version of r-process. However, from the very beginning it was a problem to achieve the large entropies (~200 k/nucleon) required to produce r-process elements around A~195. In the recent years, we have seen how the predictions for the neutron-richness of the ejecta have changed completely. With the development of accurate three flavor Boltzmann neutrino transport codes, it was shown that the ejecta, contrary to initial expectations, is in fact proton-rich. However, in the last months several groups have shown that an improved treatment of neutrino-matter interaction at high densities that is consistent with the underlying EoS results in ejecta that are neutron-rich. At this moment the neutron-richness of the ejecta is not completely determined. Nevertheless, the fact that Boltzmann neutrino transport simulations are almost free of modeling approximations allows us to relate the neutron-richness of the ejecta to basic properties of the EoS, i.e. the nuclear symmetry energy. The results of the Darmstadt and Santa Cruz/Seattle groups show ejecta with Ye ~ 0.4. The preliminary results presented by Matthias Hempel and Albino Perego, based on an approximate treatment of neutrino transport and an equation of state with a large value of the symmetry energy show Ye values as low as 0.25 with entropies around 100. If such a neutron rich ejecta are in fact produced in neutrino-winds, we expect that they can account for a Honda type nucleosynthesis pattern but they will never be able to account for Sneden type nucleosynthesis. Furthermore, we will expect a correlation between Fe and Sr, Zr and Eu observed in Honda type stars.

Honda type nucleosynthesis can also take place in electron capture supernova from the collapse of starts around 9 solar masses that develop and ONeMg core. These stars produce very little iron. However, in this case the heavy elements should be produced in material ejected dynamically during the explosion as shown in both 1D and 2D simulations and not in the later neutrino wind.

If "standard" core-collapse supernova are in fact the site for Honda type nucleosynthesis, the obvious question is what is the site for the production of Sneden type nucleosynthesis events. We know that any astrophysical even that ejects very neutron rich material with Ye <~0.15 will naturally produce r-process elements reaching U and Th. This requires that the material is ejected dynamically and not subject to neutrino interactions during the ejection as they tend to increase the Ye to values that may not be suitable for a strong r-process.

The latest neutron star mergers simulations of Stephan Rosswog show a robust ejection of 0.01 solar masses of material with Ye ~ 0.05 that is originally located in the crust of the neutron stars. The properties of the ejected material seem rather insensitive to the initial conditions for the merger, i.e. independent of the masses of the neutron stars and neutron star black hole systems.

Another possible scenario is "non-standard" supernova explosions. In this case the explosion is not driven by neutrinos but a combination of rotation and magnetic fields that produces jets of very neutron-rich material where r-process nucleosynthesis can take place. These magnetorotational (MHD) supernova may explain the existence of pulsars with magnetic fields reaching 10^{15} Gauss, known as magnetars (and may be related to hypernova and long gamma-ray bursts?). An open issue in the amount of Fe produced in this events. If they are in fact responsible of the production of heavy r-process elements including Eu, we should expect little Fe production in this events to account for the lack of correlations between Fe and Eu at low metalicities. An open issue for this type of events is their frequency as a function of metalicity. If they are in fact related to long gamma ray bursts, we expect that they will be rare events that occur predominantly at low metalicities.

Both neutron star mergers and magnetorotational supernova are expected to produce a rather robust abundance patter of elements above Z>50 (A>120) due to fission cycling. Elements below Z<50 are not expected to be produced in this very neutron rich ejecta if binary fission is assumed. If ternary fission becomes a dominant fission channel for very neutron-rich superheavy nuclei one will be able to produce elements below Z<50 but this is pure speculation at this moment.

In order to produce and Sneden type abundance pattern in neutron-star mergers and/or magnetorotational supernova we will need that a second environment in the same event contributes to the production of elements with Z<50 like Sr and Zr. For MHD supernova this may occur in high entropy wind type ejecta from the neutron star. For neutron-star mergers wind type of ejecta are expected from the accretion disc around the neutron star/black hole produced in the merger. However, one should keep in mind that the amount of material expected in the wind is around 10^{-3} solar masses that is much smaller than the canonical value of 0.01 solar masses of dynamical ejecta. Furthermore, depending on Ye the wind ejecta may consist of mainly alpha-rich freeze-out products, i.e. alpha particles, with heavy elements representing around 1% in mass. A recent study by Wanajo and Janka shows that with Ye ~ 0.3 one obtains an Honda type nucleosynthesis pattern while with Ye ~ 0.2 the nucleosynthesis pattern becomes Sneden type. Additionally, in the case of mergers one will also expect wind type ejecta from the two previous supernova explosions that created the neutron stars. If the merger occurs in the same galactic region where the two supernova took place it becomes difficult to explain the lack of correlation between Eu and Fe at low metalicities. An alternative is that the neutron stars travel before the merger to galactic regions far away from the place where they were born. This will require a long time between the merger and supernova events making difficult for mergers to account for the abundances of elements with Z>50 at low metalicities. In fact, the delay between the time were the neutron stars are born and the merger remains one of the most uncertain aspects in order to explain the contribution of mergers at low metalicities. Another important issue is the location of the merger. Current galactic models assume that they occur mainly in the galactic disc but as suggested by Stephan Rosswog the merger may occur far above/below the galactic disc and in this case the ejecta will be missed with a much larger region of the Galaxy.

Giving the large amount of r-process material, ~ 0.01 solar masses, ejected in neutron star mergers, they constitute the best candidate for a direct observation of r-process nucleosynthesis. The signature will be a faint SN-like transient produced from the radioactive decay of r-process ejecta with maximal luminosities around 10^{42} ergs/s peaking at time scales of days after the event. However, the maximum luminosity, time scale and band depend on the poorly known photon opacities for r-process ejecta.