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Nuclear Astrophysics has a long tradition, going back to the early days of nuclear physics, when it started to be considered as the source of energy generation in stars. Bethe and Weizsäcker proposed first the CNO-cycle(s) and later also the pp-cycle(s), responsible for transforming four hydrogen nuclei (protons) - via capture reactions and two beta-decays - into ^{4}He (1937-1939, leading also to Bethe's Nobel Prize in 1967). This stimulated further questions about the origin of the elements in the Universe and our Solar System. Alpher, Bethe, Gamow (1948) in fact suggested that essentially all (also heavy) elements were made in the Big Bang from an initial hot soup of neutrons and protons. This suggestion – although a possible scenario – was finally rejected by Wagoner, Fowler, Hoyle (1969), realizing that apparently the entropy in the Big Bang was too high – or the density at the relevant temperatures too small – in order to bridge the extremely short-lived nuclei with nuclear masses 5 and 8. Thus, the Big Bang explains only the ^{1}H, ^{2}H, ^{3}He, ^{4}He and ^{7}Li abundances. Another question remained, whether there exist further burning stages in stars beyond hydrogen burning, which utilize the "ash" of hydrogen burning (^{4}He) as "fuel".

It requires high densities in stellar interiors to provide a constant and considerable production of ^{8}Be (which decays in 2.6x10^{-16} s), in order to permit a further alpha-capture ^{8}Be(a,g)^{12}C to produce stable ^{12}C. Hoyle realized that this was only possible with a resonance (excited state) in ^{12}C with the right energy, spin, and parity, a hypothesis worked out further by Salpeter (1952). The state was experimentally determined in 1957 and its structure is still a matter of most modern theoretical analysis (Epelbaum et al. 2012).

The 1950s were the time when a first picture emerged how to put all pieces together. Suess and Urey (1956) published a comprehensive abundance table of the element abundances in the solar system, based on the composition of primitive meteorites (carbonaceous chondrites, agreeing essentially with the analysis of the solar spectrum, with the exception of volatile elements - like noble gases – which evaporated from meteorites). In 1957, independent of each other, two teams (1) the astronomers J. and M. Burbidge, the nuclear experimentalist W. Fowler, and the theoretical astrophysicist F. Hoyle, as well as (2) the (in those days) nuclear theorist A. Cameron, worked on a comprehensive theory to understand the origin of the full abundance pattern as we find it today (B^{2}FH 1957, Cameron 1957). They postulated further fusion processes up to the elements around Fe, possessing the highest binding energies, as well as sequences of neutron captures and beta-decays which can form the elements up to Pb and Bi or even Th, U, Pu and beyond (leading to the Noble Prize for Fowler in 1983).

It followed a long period of experimental activities, measuring the major reactions of nuclear burning stages in stellar evolution (also causing neutrino emission from beta-decays - first detected with underground detectors in the Homestake Goldmine, Nobel Prize for R. Davis in 2002) and neutron captures for the s-process (slow neutron capture) which is responsible for the formation of about half of the heavy elements up to Pb and Bi (see Käppeler et al. 2011 for a recent review). In parallel first theoretical efforts were undertaken to predict cross sections for reactions involving intermediate and heavy nuclei, based on the compound nucleus or Hauser-Feshbach model (see Rauscher, Thielemann 2000, Rauscher 2012 for the present status). Step by step a transition occurred from pure nucleosynthesis studies with assumed/approximated conditions to real astrophysical models, i.e. detailed stellar evolution models including all relevant nuclear physics as well as dynamics, radiation transport, mixing via convective instabilities or induced by rotation, and mass loss via stellar winds (for present models

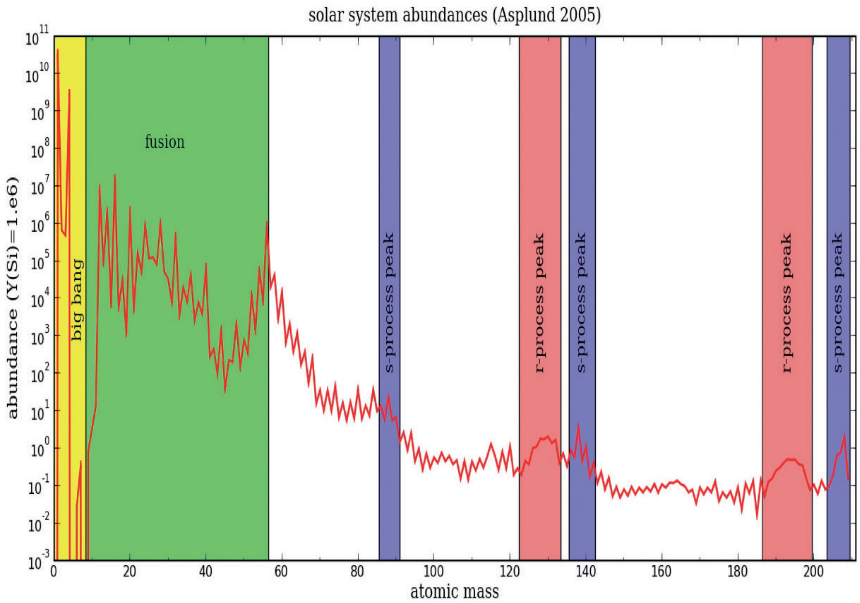


Fig.1: Abundances from H to Bi isotopes as a function of mass number A, spanning over 12 orders of magnitude. For historical reasons Si is normalized to 10^{12}. Only H, He, an Li were formed in the Big Bang, all heavier elements are due to stellar evolution and stellar explosions. Up to the Fe-peak these are fusion reactions. The heavier elements are formed by neutron captures with peaks (red/blue shades) related to the closed neutron shells 50, 82, and 126. The separation is caused by experiencing these shell closures among stable nuclei or short-lived neutron-rich unstable nuclei.

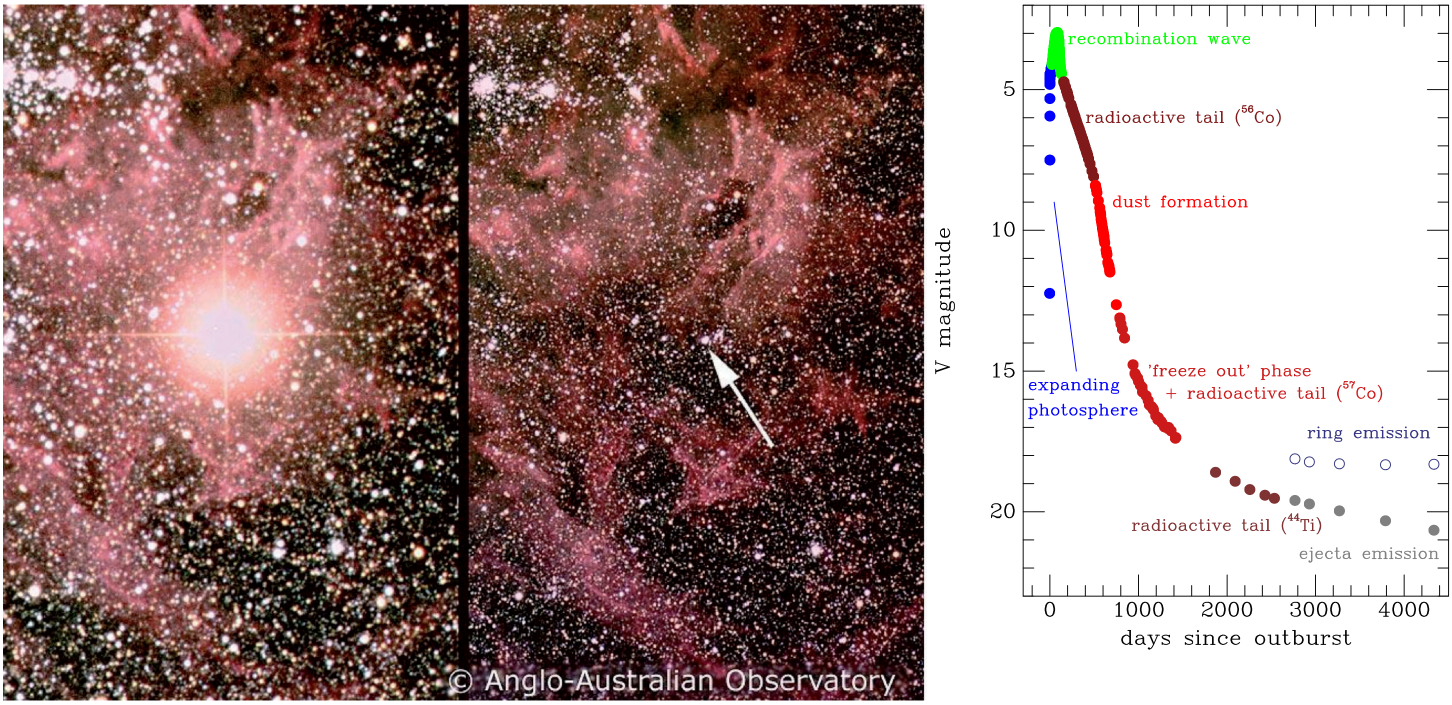


Fig.2: Left, Supernova 1987A; middle, the identified progenitor star (Sanduleak –69°202) in the Large Magellanic Cloud, a 20$M_\odot$ star (for more details see Arnett et al. 1989); right, the observed light curve, exhibiting the decay-heat of unstable ^{56}Co, ^{57}Co, and ^{44}Ti (Fransson et al. 2007).

see e.g. Heger et al. 2003). Similarly, the collapse to nuclear densities at the end of the evolution of massive stars was investigated, leading to central neutron stars and the explosive ejection of the outer layers (for recent reviews see Burrows 2013, Janka 2012). The latter is powered by neutrinos which release the gravitational binding energy of 10^{46} J (measured for the first time for Supernova 1987A with the Kamiokande, IMB and Baksan detectors, Nobel Prize for M. Koshiba 2002, jointly with Davis).

Supernovae belong to the most powerful explosions in galaxies (only gamma-ray bursts GRB seem to be more energetic). They are also the dominant sources of intermediate and heavy elements in the Universe (Thielemann et al. 1986, 1996, 2004, 2012). Supernovae come in two different kinds, both similar in their output of kinetic energy close to 10^{44} J. One type (classified as type Ia) is related to the explosion and complete disruption of a white dwarf star in a binary system which due to mass transfer from the binary companion exceeds its maximum stable mass (the Chandrasekhar mass, 1.4$M_\odot$), contracts and ignites nuclear burning of C and O in an explosive manner (combustion). The nuclear burning front which disrupts the whole star ejects about 0.6$M_\odot$ of Ni/Fe, smaller amounts of intermediate mass elements from Si through Ca, and some unburned C and O into the interstellar medium (Nomoto et al. 1984, for recent studies see Röpke et al. 2012). As these objects start from very similar initial conditions (a 1.4$M_\odot$ white dwarf), they lead to close to identical light outbursts and can be utilized as standard(izable) light candles, thus also serving as distance indicators in the Universe (leading e.g. to the 2011 Nobel prizes for S. Perlmutter, B. Schmidt, and A. Riess).

Stars with an original mass of less than 8$M_\odot$ end their stellar evolution as white dwarfs (after having finished hydrogen and helium burning and losing significant amounts of mass in stellar winds, observable as planetary nebulae). The remaining central C/O-core, although lacking any energy source, is stabilized by the pressure of the low-temperature degenerate Fermi gas of electrons (Nobel Prize 1983 for S. Chandrasekhar, jointly with Fowler). More massive stars pass through all nuclear burning stages, also encountering C, Ne, O, and Si-burning and end with a central Fe-core. Consisting of matter with the highest binding energy per nucleon, no further nuclear burning stage can prevent collapse up to nuclear densities, which causes the formation of a neutron star, stabilized by the degenerate Fermi gas of nucleons. Of the released gravitational binding energy (about 10^{46} J) in form of neutrinos of all types, about 10^{44} J is converted into local thermal energy via neutrino and antineutrino captures on free neutrons and protons (elastic scattering would not deposit energy). The possibly combined effect with the winding of magnetic fields due to rotation, can cause the ejection of the outer layers with a total kinetic energy of about 10^{44} J, similar to type Ia supernovae (Burrows 2013, Janka 2012). These core collapse supernovae occur typically with a frequency larger by a factor of 2 to 3 than type Ia supernovae in spiral galaxies similar to our own.

This very brief and simplified description of the two responsible supernova explosion mechanisms is depending highly on the nuclear physics entering the understanding of such hot, high density plasmas. While nuclear burning through fusion is one important ingredient, weak interactions (beta-decays, electron captures, neutrino interactions) are essential (Langanke et al. 2003, 2004, 2008, 2011) and only the inclusion of neutrino oscillations solved the solar neutrino puzzle (via observations of different neutrino flavors in the Sudbury Neutrino Observatory -SNO- in Canada, Jelley et al. 2009). The nuclear equation of state at and beyond nuclear densities enters the simulation of core collapse supernovae, the maximum neutron star mass (Lattimer 2012), the possible transition to black holes combined with a transition from supernovae to hypernovae (Nomoto 2011)

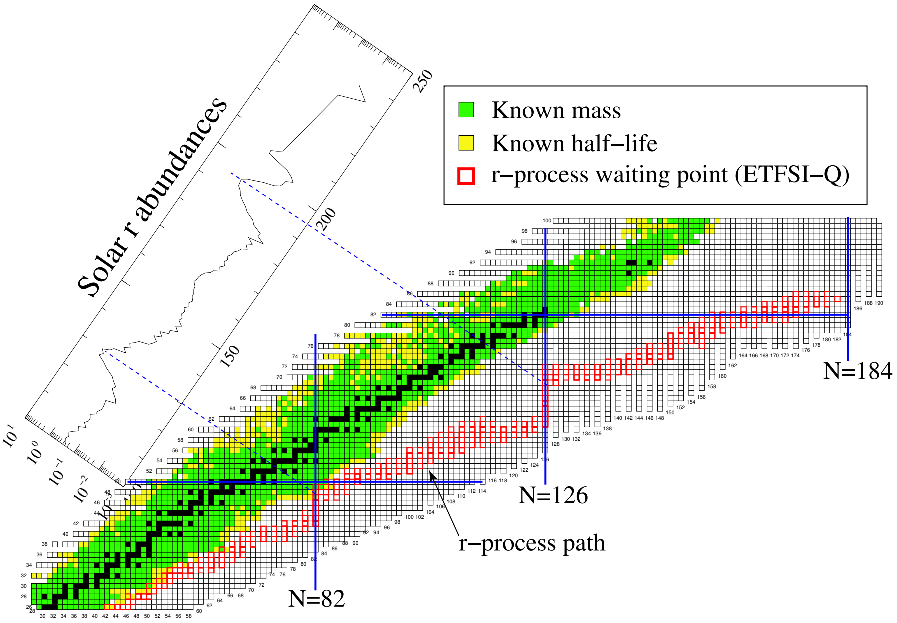
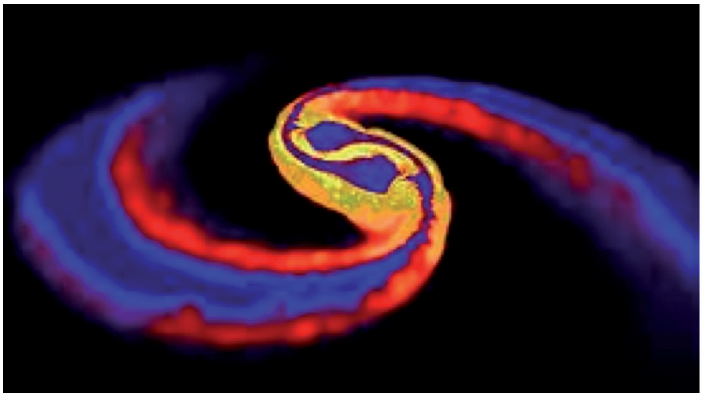


Fig.3: The nuclear chart (N,Z) with stable isotopes (black), unstable isotopes with known masses (green), or known half-lives (yellow). In order to produce the solar r-process component (rapid neutron capture) a very neutron-rich reaction path has to be encountered, which passes the relevant neutron shell closures at specific charge numbers Z (closest to stability with the longest beta-decay half-lives), in order to reproduce the peaks at A=130 and 195 (Grawe et al. 2010).

and gamma-ray bursts (Piran 2004). For the conditions in all these events, electrons behave close to degenerate fermions with sufficiently high Fermi energies to initiate electron capture on protons and nuclei. This is essential for the overall neutron/proton ratio in matter (affecting also the nuclear equation of state for core collapse supernovae) and thus for the composition of the ejecta. In core collapse supernovae the neutrinos play a major role. First, they are essential for the explosion mechanism, if a sufficient fraction of their energy is absorbed in the outer ejected layers. Second, neutrino and antineutrino absorption on neutrons and protons dominates the overall neutron/proton ratio in the innermost ejected layers (Martinez-Pinedo et al. 2012). This is important for the composition of the Fe-group (from Ti to Ge), but also whether proton or neutron-rich isotopes of elements heavier than Fe are produced in these events. Recent investigations showed that the early phases of this so-called neutrino wind can produce elements up to Sr on the proton-rich side of nuclear stability (Fröhlich et al. 2006). We are still searching for the exact conditions which permit to produce highly neutron-rich environments, leading to the so-called rapid neutron capture process (r-process), responsible for the production of the heaviest elements up to Th, U and Pu, where the understanding of nuclear structure far from stability is essential (Lunney et al. 2003, Petermann 2012).

Currently the ejecta from neutron star mergers in binary stellar systems or the ejection of polar jets of supernova from progenitor stars with fast rotation and strong magnetic fields are the primary candidates.

The discussion of the astrophysical conditions, the essential nuclear physics aspects entering for these conditions, plus the description how this leads to the abundances of ejected elements has been at the heart of quite a number of researchers over the past 30 years. The major frontiers are



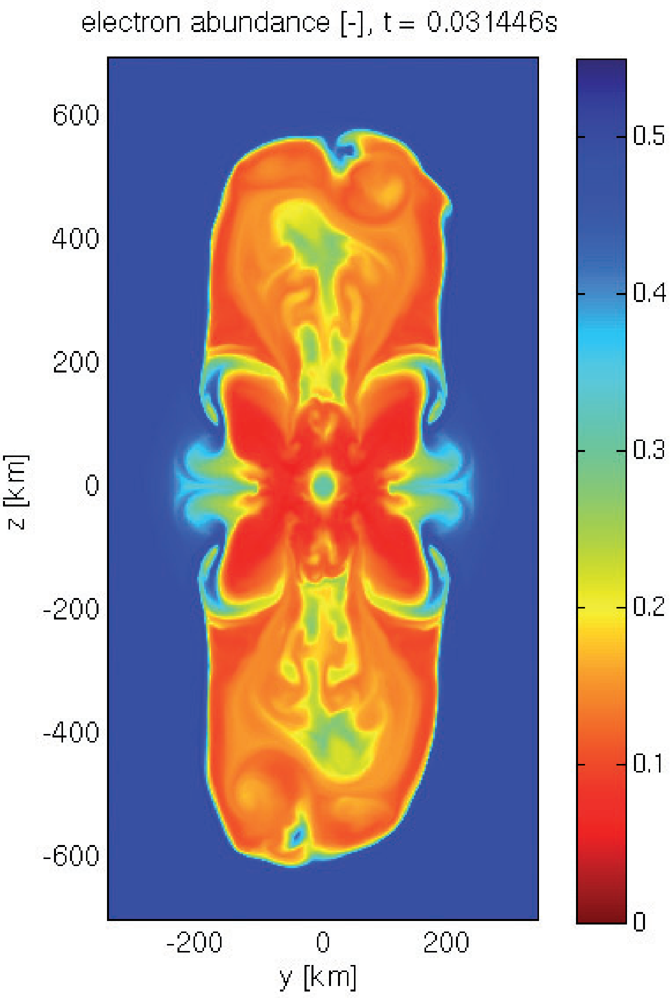


Fig.4: Left: a color contour plot of the magnetic field strength after the merger of two neutron stars in a binary stellar system (Price and Rosswog 2006), which merge due to energy loss via gravitaional wave radiation (as discovered for the binary pulsar in 1974, Nobel Prize for Hulse and Taylor 1993). The ejecta of the spiral arms are higly neutron-rich and cause a strong r-process during the expansion (Freiburghaus et al. 1999, Korobkin et al. 2012). Right: color contour plot of the proton/nucleon ratio (indicating the neutron-richness of matter) from a fast rotating core collapse supernova with strong magnetic fields (magnetar) which leads to similar r-process conditions (Winteler et al. 2012).

- cross section measurements at the lowest possible energies which correspond to the energies in stellar evolution. Such measurements of minute cross sections are only possible in cosmic ray shielded underground laboratories (e.g. LUNA)
- the understanding of nuclear structure far from stability, including masses, ground state properties, fission barriers, giant resonances, and especially the behavior of neutron and proton shell closures
- the understanding of weak interactions (beta-decay, electron capture, neutrino interactions with nuclei – in the vacuum and in high density media – as well as neutrino flavor oscillations at high densities when neutrinos form a thermalized Fermi gas)
- the nuclear equation of state beyond nuclear densities. Which particles contribute and when does a transition from hadrons to quarks take place? What is the maximum neutron star mass, when do black holes form?

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