Core-collapse supernovae

Martin Obergaulinger

Departament de Astronomia i Astrofísica, Universitat de València

Compact Objects, Gravitational Waves & Deep Learning, Valencia, 2022/06/22

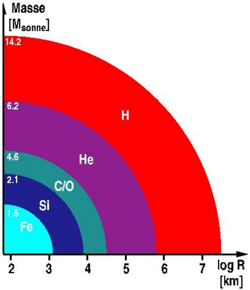
Pre-collapse state

Stability of stars

- balance between pressure gradient and gravity:
  $\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm\rho}{r^2}$
- responsible for pressure: hot or degenerate electrons, internal energy and density
- density increases slowly (contraction)
- internal energy: heating by nuclear reactions vs. radiative energy loss (photons, neutrinos)

→ if reactions cease, the core contracts until the ρ, T are sufficient for a new burning phase (unless Fe is already reached)

- onion-shell structure of a star of $M_{\mathrm{ZAMS}} \gtrsim 8\,M_\odot$

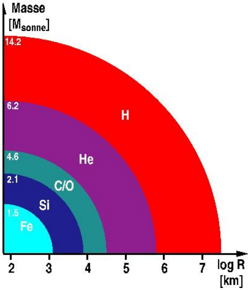


onion-shell structure of a massive star (Janka, Kifonidis & Müller, 2001)

Pre-collapse state

The details of the core at collapse are fairly uncertain, in particular for high M_{ZAMS}. The evolution depends on, e.g.,

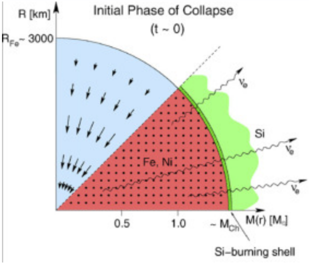
- convection (difficult to model numerically)
- mass loss, stellar winds
- initial metallicity
- rotation
- binary evolution



onion-shell structure of a massive star (Janka, Kifonidis & Müller, 2001)

Collapse

- $\rho \uparrow \Rightarrow$ the Fermi energy of the electrons increases, allowing for electron capture, $e^- + (A, Z) \rightarrow (A, Z-1) + \nu_e$
- some electrons react with free protons (created, e.g., by photodissociation), $e^- + p^+ \rightarrow n + \nu_e$ cross section: $\sigma \sim 4.5 \times 10^{-44}\text{cm}^2 \left(\frac{\epsilon_\nu}{1\,\text{MeV}}\right)^2$
- (almost) only electron neutrinos are produced
- the neutrinos leave the core freely
- these reactions decrease the electron fraction from $Y_e \approx 0.44$ at the onset of collapse to $Y_e \sim 0.3$ at its end
- deleptonisation accelerates the collapse

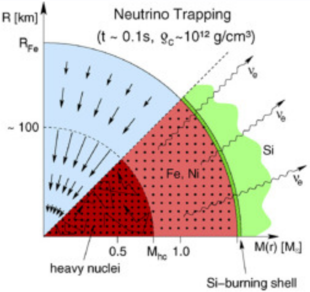


Physics of the collapse of an iron core (Janka et al., 2007)

Collapse

- reactions of neutrinos with matter increase with density, e.g., for scattering off nucleons, and nuclei,
  $\{n, p, (A, Z)\} + \nu \rightarrow \{n, p, (A, Z)\} + \nu$
- mean free path due to scattering off heavy nuclei with mass A and neutron number N and neutrons (X_i are the mass fractions of the two species):
  $$\lambda_\nu \sim 10^8 \mathrm{cm}\, \rho_{12}^{-1} \left[\frac{N^2 X_h}{6A} + X_n\right] \left(\frac{1\,\mathrm{MeV}}{\epsilon_\nu}\right)^2$$
- neutrino degeneracy increases, leading to higher energies of emitted ν, while leakage of low-energy ν is favoured

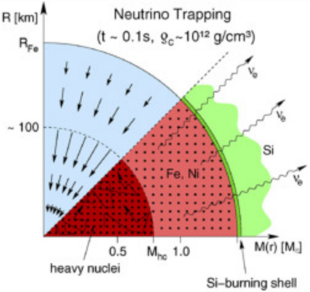
→ inelastic scattering $e + \nu \rightleftharpoons e + \nu$, reducing ν energy, is important



Physics of the collapse of an iron core (Janka et al., 2007)

Collapse

- once the density reaches $10^{12}\,\mathrm{g\,cm^{-3}}$, λ_ν gets smaller than the core radius: ν are trapped inside the neutrinosphere due to frequent absorption and scattering
- deleptonisation stops, ν and gas get into local thermodynamic equilibrium due to frequent absorption (i.e., inside the ν-sphere)



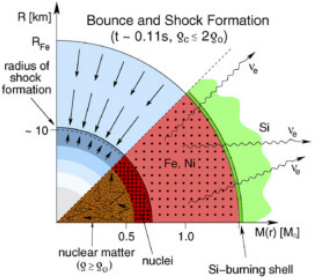
Physics of the collapse of an iron core (Janka et al., 2007)

Core bounce, shock formation

- nuclear matter ($\rho_{\rm nuc} \sim 2 \times 10^{14}\,{\rm g\,cm^{-3}}$) is highly incompressible, i.e., $\gamma \gtrsim 2$;

$\Rightarrow$ star composed of nuclear matter is stable

- $\rho_{\rm c} \sim \rho_{\rm nuc}$: phase transition to nuclear matter, formation of a proto-neutron star (PNS)
- collapse stops and a shock wave begins to propagate outwards into the layers that continue to fall towards the PNS
- shock energy: several 10^{51} erg, i.e., $\gtrsim$ typical SN energy
- Is a prompt explosion viable?



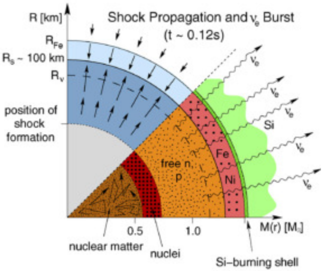
Core bounce and shock formation (Janka et al., 2007)

Core bounce, shock formation

- post-shock matter is very hot

→ photodissociation of nuclei into nucleons consumes most of the shock energy (and undoes ages of nuclear burning), and the shock stalls inside the core

- once the shock crosses the ν-sphere, the ν_e trapped inside can leave in a short intense burst carrying away energy, which would otherwise be available for pushing the shock further out
- How can we revive the shock?



Core bounce and shock formation (Janka et al., 2007)

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

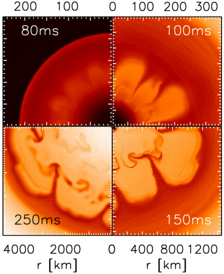
- energy losses due to photodissociation are too strong

$\rightarrow$ does not work

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

- works for O-Ne-Mg cores ($M_{ZAMS} \lesssim 10\,M_{\odot}$)
- hydro instabilities are present, but not essential
- may explain the Crab SN (Kitaura, Janka, & Hillebrandt, 2006)



movie by Kitaura, Janka, & Hillebrandt (2006)

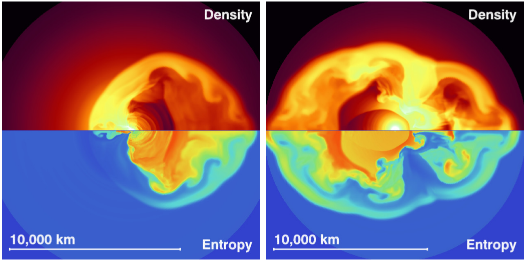
Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

- instabilities enhance ν heating efficiency

$\rightarrow$ explosions for more massive progenitors

- uncertainties: robust explosions across a wider mass range? 3d effects? Role of convection vs. SASI? Magnetic fields? Energy transfer by acoustic waves?



Simulations of SASI-dominated SN explosions (Scheck et al., 2004)

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

The Astrophysical Journal, 770:66 (16pp), 2013 June 10 — Hanke et al.

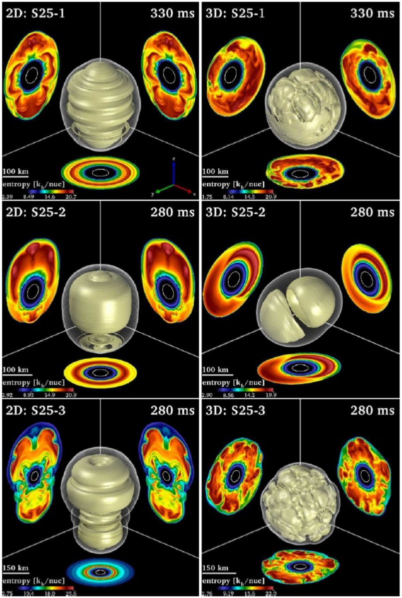


Figure 10. Structure of the 2D (left) and 3D (right) models of our set of parameterized 25 $M_\odot$ simulations (top: S25-1; middle: S25-2; bottom: S25-3) at representative postbounce times (as given in the upper right corner of each panel). The central object in all panels provides a three-dimensional visualization of the supernova shock

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

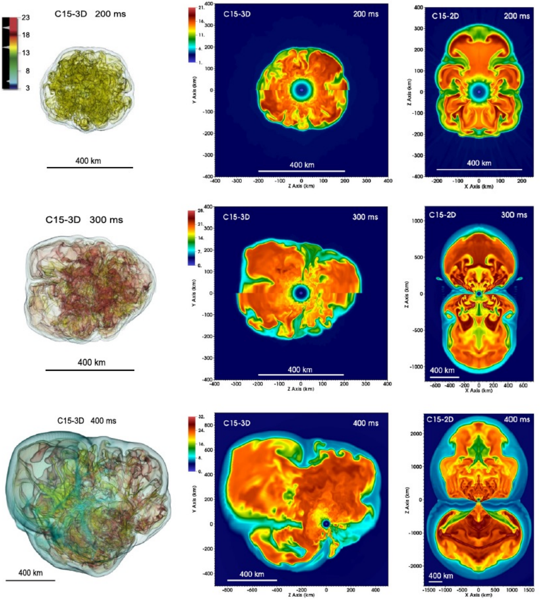


Figure 4. Specific entropy (k_B baryon^{-1}) at 200, 300, and 400 ms with 400 km scale bars in each panel. (left) Column (a): volume rendering for C15-3D using a fixed transfer function, highlighting rising plumes. (middle) Column (b): polar slice through C15-3D, aligned with column (a). In the upper two panels (200 and 300 ms), the 180° ϕ shift between upper and lower halves is exaggerated by the 8.5° zone at the pole. The 400 ms panel shows the effect of the transition to ϕ

Explosion mechanisms

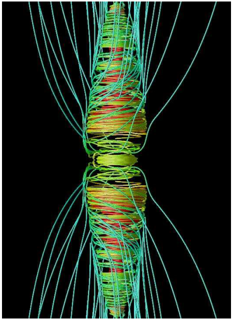
- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

- PNS density is $\gtrsim \rho_{\text{nuc}}$, but increases while matter is accreted onto the PNS
- if a phase transition to quark matter occurs, the PNS might collapse a second time, leading to a new shock that might suffice for an explosion
- alternatively, unknown ν physics in the core could enhance the heating and trigger an explosion
- explosions found in simulations, but only for extreme parameters

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

- some NSs rotate rapidly: $E_{\rm rot} \sim 10^{51} \left(\frac{\Omega}{10^3 s^{-1}}\right)$ erg, i.e., could be of the order of the kinetic energy of a CCSN
- magnetic fields can tap into $E_{\rm rot}$ and launch a (jet-like) explosion
- requires extreme values of rotation and field



Field lines in a bipolar explosion launched by rotation and magnetic fields (Burrows et al., 2007)

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields

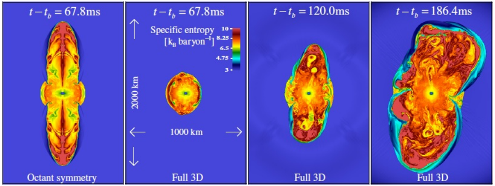


Figure 1. Meridional slices (x–z-plane; z being the vertical) of the specific entropy at various postbounce times. The "2D" (octant 3D) simulation (leftmost panel) shows a clear bipolar jet, while in the full 3D simulation (three panels to the right) the initial jet fails and the subsequent evolution results in large-scale asymmetric lobes.

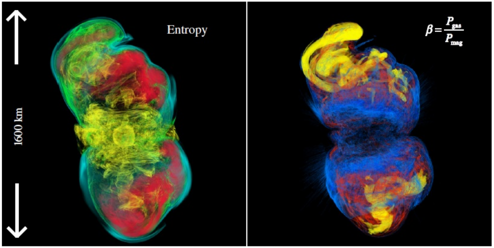
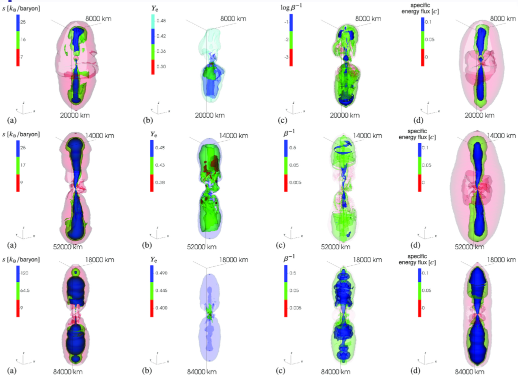


Figure 4. Volume renderings of entropy and β at $t - t_b = 161$ ms. The z-axis is the spin axis of the protoneutron star and we show 1600 km on a side. The colormap for entropy is chosen such that blue corresponds to $s = 3.7k_b$ baryon^{-1}, cyan to $s = 4.8k_b$ baryon^{-1} indicating the shock surface, green to $s = 5.8k_b$ baryon^{-1}, yellow to $s = 7.4k_b$ baryon^{-1}, and red to higher entropy material at $s = 10k_b$ baryon^{-1}. For β we choose yellow to correspond to $\beta = 0.1$, red to $\beta = 0.6$, and blue to $\beta = 3.5$. Magnetically dominated material at $\beta < 1$ (yellow) is expelled from the protoneutron star and twisted in highly asymmetric tubes that drive the secular expansion of the polar lobes.

Mösta et al. (2014), see also https://stellarcollapse.org/cc3dgrmhd

Explosion mechanisms

- prompt shock
- neutrino heating
- ν heating plus hydrodynamics
- nuclear physics
- rotation plus magnetic fields



Obergaulinger & Aloy (2021)

Direct observables

Neutrinos

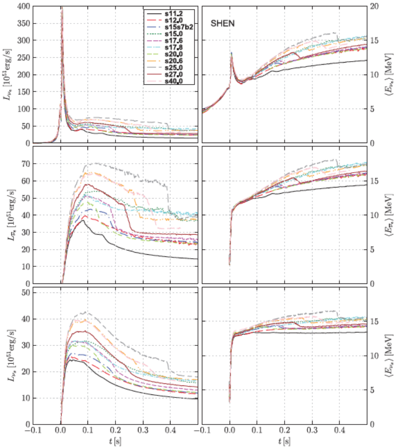
- ν_e burst at bounce, later persistent high luminosity in all flavours
- extremely challenging detection
- detectors for SN neutrinos: Super-Kamiokande (later Hyper-Kamiokande), IceCube (for high-energy ν)
- tell us about SN physics, but also ν properties such as (collective) flavour oscillations
- current status: 24 ν from SN 1987A detected, a galactic SN would produce a clear signal, upper limits for background

Gravitational waves

- "ripples of space-time", produced if large masses (energies) are accelerated nonspherically, i.e., for rotating collapse and by convection, SASI and aspherical ν emission
- interact only weakly with matter, i.e., direct messengers from the central core
- Michelson interferometers: LIGO, VIRGO
- status: no detection so far (SN 1987A: all detectors offline), feasible only for galactic SN

Neutrinos

- ν_e burst at bounce, later persistent high luminosity in all flavours
- mean energies of a few MeV
- detectors for SN neutrinos: Super-Kamiokande (later Hyper-Kamiokande), IceCube (for high-energy ν)
- tell us about SN physics, but also ν properties such as (collective) flavour oscillations
- current status: 24 ν from SN 1987A detected, a galactic SN would produce a clear signal, upper limits for background

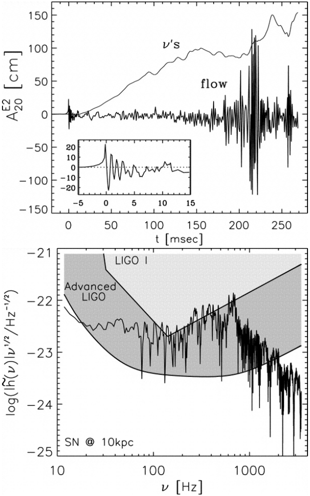


Janka et al (2012)

Gravitational waves

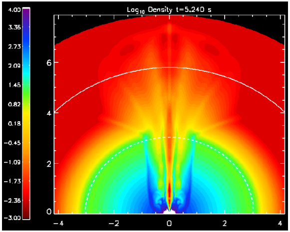
SNe produce GWs by...

- instabilities such as convection or SASI
- oscillations of the PNS (modes visible in the GW signal)
- rotation (strong bounce signal)
- bipolar explosions
- non-spherical neutrino emission
- state: no detection so far; an SN in the galaxy would be audible

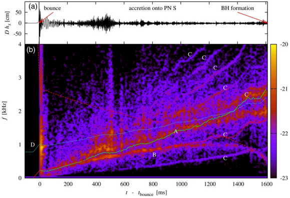


Müller et al. (2004)

Gravitational waves



Aloy et al. (2002)

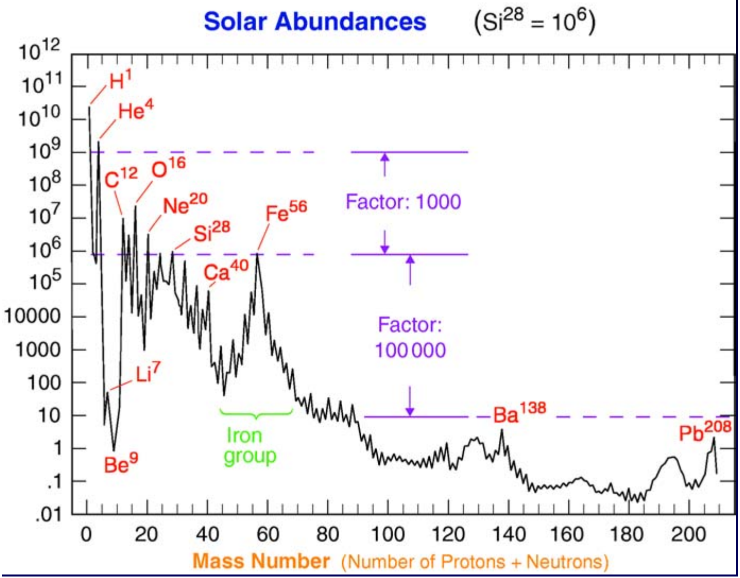


Cerdá-Durán et al. (2013)

How to form stellar-mass BHs

- If the SN fails (or goes off asymmetrically), accretion increases the mass of the PNS.
- If it reaches the maximum mass for PNS ($\gtrsim 2\,M_\odot$), collapse to a BH will ensue.
- Surrounding layers of the star will be (partially) swallowed and the BH may end up with $> 5\,M_\odot$.
- Formation of the BH may be accompanied by a GRB, an explosion characterised by relativistic jets.

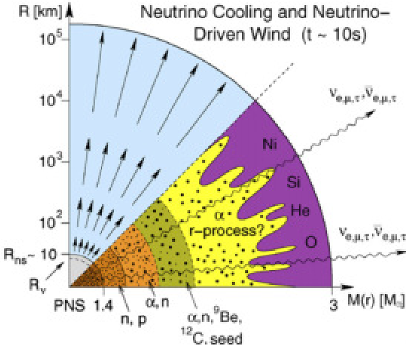
Nucleosynthesis



Solar abundances (Asplund et al., 2009)

Nucleosynthesis

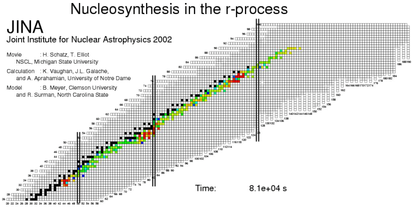
- shock leaves behind a tenuous, hot medium around the PNS
- the PNS cools emitting ν, which drive a fast wind of n and p
- during expansion (i.e., cooling), the nucleons recombine to nuclei up to Fe
- depending on the ratio of n to p, different nuclear reactions leading past the Fe peak are possible: r-process (rapid capture of abundant n), νp-process ($\bar{\nu}_e + p^+ \rightarrow e^+ + n$ followed by n-capture)



Explosion, ν wind, and nucleosynthesis (Janka et al., 2007)

Nucleosynthesis

- shock leaves behind a tenuous, hot medium around the PNS
- the PNS cools emitting ν, which drive a fast wind of n and p
- during expansion (i.e., cooling), the nucleons recombine to nuclei up to Fe
- depending on the ratio of n to p, different nuclear reactions leading past the Fe peak are possible: r-process (rapid capture of abundant n), νp-process ($\bar{\nu}_e + p^+ \rightarrow e^+ + n$ followed by n-capture)

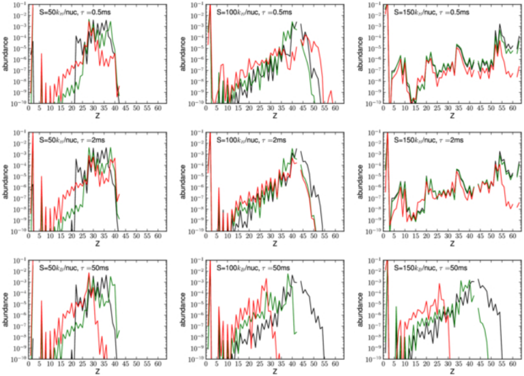


r-process nucleosynthesis path (Joint Insititute for Nuclear Astrophysics (JINA))

r-processs sites: supernovae

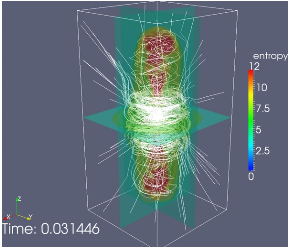
Standard explosion mechanism

- late time: ν-driven wind
- once the prime suspect for the r-process, but too low Y_e

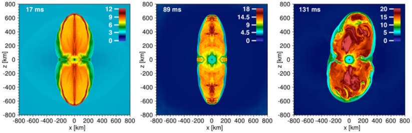


Arcones & Thielemann (2013)

r-processss sites: supernovae



Winteler et al. (2012)

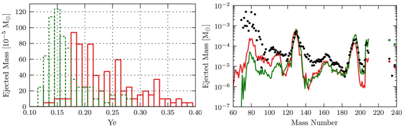


Mösta et al. (2018)

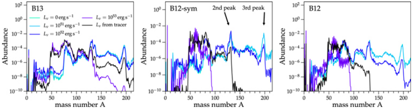
Magnetically driven explosions

- ejecta with fewer neutrino reactions
- more neutron-rich
- alternative to NS mergers in the early universe?

r-processs sites: supernovae



Winteler et al. (2012)

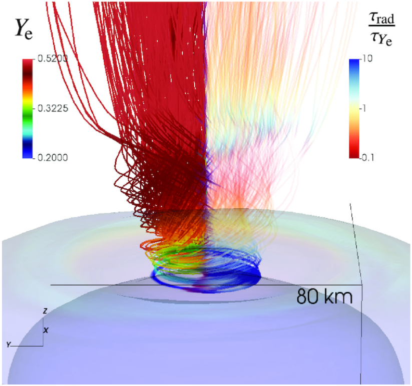


Mösta et al. (2018)

Magnetically driven explosions

- ejecta with fewer neutrino reactions
- more neutron-rich
- alternative to NS mergers in the early universe?

r-processs sites: supernovae

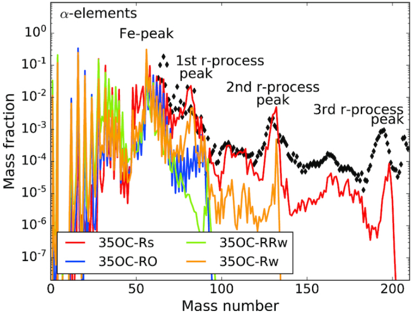


⇑ Obergaulinger & Aloy (2021)

Magnetically driven explosions

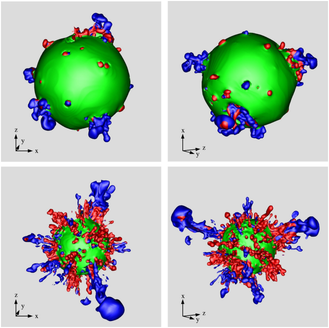
- ejecta with fewer neutrino reactions
- more neutron-rich
- alternative to NS mergers in the early universe?

Reichert et al. (2021) ⇒



Toward the remnant

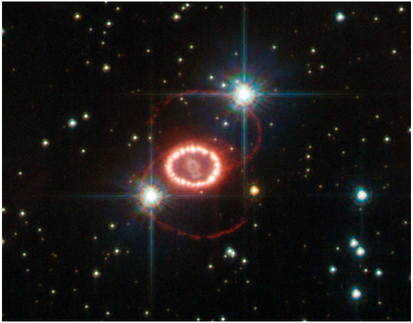
- the shock reaches the stellar surface after hours...days
- initial asymmetries and further hydrodynamic instabilities lead to mixing of different elements and clumpy ejecta
- the ejecta include not only the elements synthesised during the SN but all nucleosynthesis products from hydrostatic burning phases



Time series from a 3d simulations of shock propagation through the envelope (Hammer et al, 2010). Colours indicate different elements: C, O, Fe are green, red, blue, respectively.

Toward the remnant

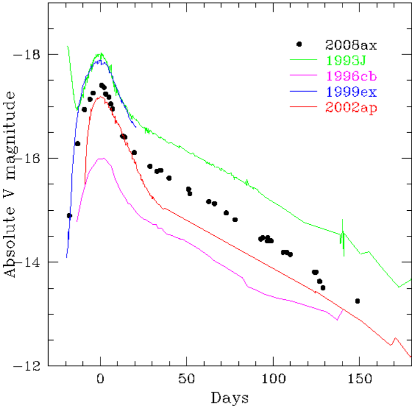
- the shock reaches the stellar surface after hours...days
- initial asymmetries and further hydrodynamic instabilities lead to mixing of different elements and clumpy ejecta
- the ejecta include not only the elements synthesised during the SN but all nucleosynthesis products from hydrostatic burning phases



Asymmetric ejecta in SN 1987A (ESA/Hubble, NASA). Note the elongated shape in the centre; the rings are a result of the pre-SN winds.

Photon emission

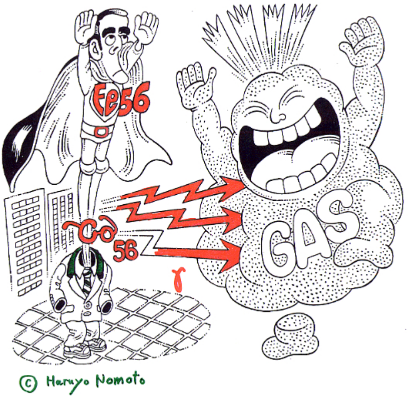
- shock breakout signature (UV, X-rays), but: short duration
- early EM emission is powered by kinetic energy
- brightness depends also on the amount and composition of matter (opacity)
- recombination in the expanding, cooling H envelope: thermal plateau
- long-term emission: exponential tail due to radioactive decay of $^{56}_{28}\mathrm{Ni} \to ^{56}_{27}\mathrm{Co} \to ^{56}_{26}\mathrm{Fe}$



Light curves of type-Ic/II SNe (Tsvetkov et al, 2009)

Photon emission

- shock breakout signature (UV, X-rays), but: short duration
- early EM emission is powered by kinetic energy
- brightness depends also on the amount and composition of matter (opacity)
- recombination in the expanding, cooling H envelope: thermal plateau
- long-term emission: exponential tail due to radioactive decay of ${}^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe}$



The physics of the late-time emission from SNe (Nomoto, 2012)