The Physics of Core-Collapse Supernovae

ANITA Summer School 2020 – "Cosmic Explosions"
Monash University

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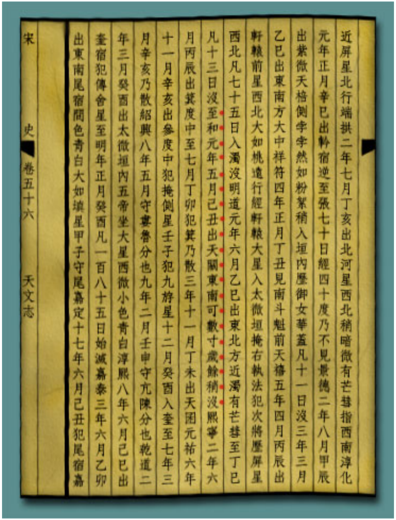
February 3, 2020

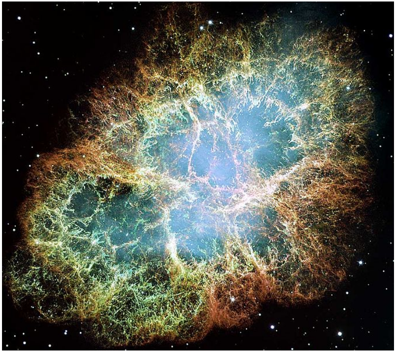
Historical Background



宋史 卷五十六 天文志

近屏星北行端拱二年七月丁亥出北河星西北稍暗微有芒彗指西南淳化
元年正月辛巳出軫宿逆至張七十日經四十度乃不見景德二年八月甲辰
出紫微天棓側孛孛然如粉絮稍入垣內歷御女華蓋凡十一日沒三年三月
乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出
軒轅前星西北大如桃速行經軒轅大星入太微垣掩右執法犯次將歷屏星
西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳
凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六
月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年
十一月辛亥出參度中犯掩側星壬子犯九斿星十二月癸酉入奎至七年三
月辛亥乃散紹興八年五月守婁魯分也九年二月壬申守亢陳分也乾道二
年三月癸酉出太微垣內五帝坐大星西微小色青白淳熙八年六月己巳出
奎宿犯傳舍星至明年正月癸酉凡一百八十五日始滅嘉泰三年六月乙卯
出東南尾宿間色青白大如填星甲子守尾嘉定十七年六月己丑犯尾宿嘉

Chinese record of the Crab Supernova from 1054.



The Crab nebula as seen today.

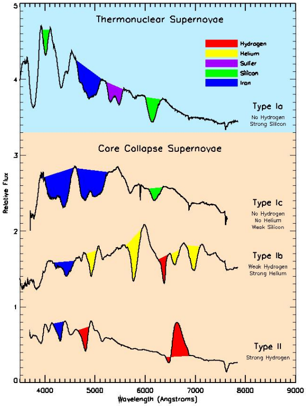
Connecting Supernovae and Massive Stars

1054:	Observation of SN 1054 by Chinese astronomers as "guest star"
1572:	Tycho Brahe's *stella nova* or ""new star" (thermonuclear) identification as a far-away object (e.g. not a comet)
1604:	Kepler's *stella nova* (thermonuclear)
1885:	""Nova" in Andromeda, 6th magnitude
1928:	Hubble suggests Crab Nebula as remnant of SN 1054
1932:	Discovery of the neutron
1934:	Collapse of massive stars to neutron stars proposed as explanation for "supernovae" by Baade & Zwicky
1967:	Bell & Hewish discover the first pulsar
1968:	Crab pulsar discovered
1987:	SN 1987 in the Large Magellanic Cloud first identification of a supernova progenitor first detection of supernova neutrinos

Supernova Types

Based on their composition (no H/He spectral features) and environment, one identifies type Ia supernovae as thermonuclear explosions of C/O white dwarfs. The other types (II, Ib, Ic) are associated with explosions of massive stars (core-collapse SNe):

- Type II supernovae (including IIP, IIL, IIb) with H lines are most common, and for a number of them we also have a direct identification of a massive star as progenitor.
- Supernovae of type Ib and Ic have lost (part of) their envelope either by mass transfer in a binary (likely the most frequent case) or by extremely strong winds (Wolf-Rayet stars).



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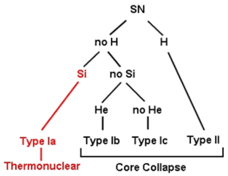


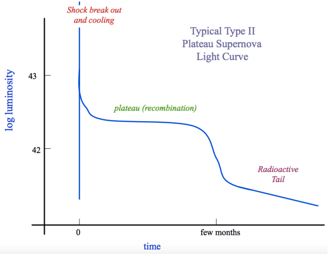
Light Curves – Type IIP

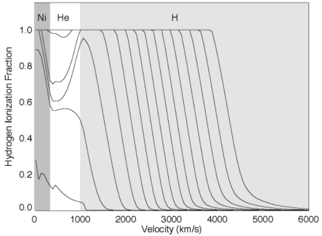
The light curves of CCSNe depend both on explosion and progenitor properties. Unfortunately, we can't treat them extensively here, and consider only a few salient points:

- Most frequent type, progenitors with an extended H envelope
- After a brief burst at shock breakout, there is a plateau of a few months. During the plateau, the photosphere recedes through the envelope as hydrogen recombines at 5000–6000 K. Afterwards, there is a tail powered by the decay of $^{56}\mathrm{Ni}$
- Plateau luminosity and duration scale as (Popov 1993)

$$L \propto M^{-1/2} R_{\mathrm{prog}}^{2/3} E_{\mathrm{expl}}^{2/3},$$

$$\tau \propto M^{1/2} R_{\mathrm{prog}}^{1/6} E_{\mathrm{expl}}^{-1/6}$$

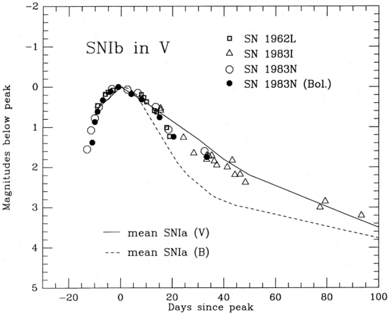




Credit: S. Woosley

Light Curves – Type Ib/c

- Mostly powered by radioactive decay, and the peak luminosity can be related to the mass of $^{56}\mathrm{Ni}$, and the width of the light curve
- Explosion energy and ejecta mass influence peak width also for Ib/c SNe.
- Both for Type IIP and Ib/c, light curves usually do not constrain E_{expl} and M_{ejecta} very well; supplementary information from the spectra is needed.

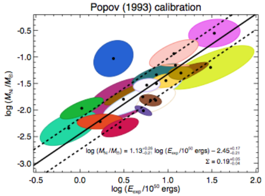


Ensman & Woosley (1988)

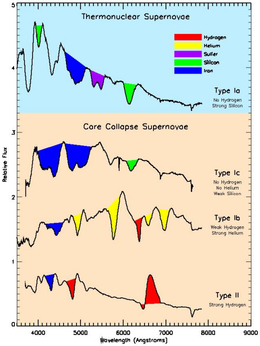
Explosion and Progenitor Properties inferred from Light Curves and Spectra

- Explosion energy: $10^{50} \ldots 10^{52}\,\mathrm{erg}$
- Ejecta mass: up to $\sim 20 M_\odot$
- Range of $^{56}\,\mathrm{Ni}$ mass: a few $10^{-3} M_\odot$ up to $0.3 M_\odot$, Ib/c tend to make more than IIp.
- Various degrees of mass loss in progenitor (type II with hydrogen envelope, type Ib/c without).
- Some CCSNe show sign of interaction with circumstellar medium (winds, outbursts?)

What does this imply about the mechanism?



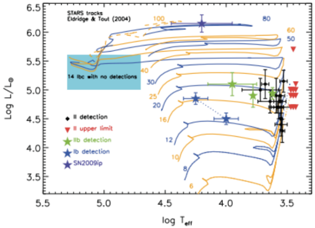
Pejcha & Prieto (2015)



Possible energy sources for $\sim 10^{51}$ erg:

- Gravitational binding energy of neutron stars $\sim 1.3 \times 10^{53}\,\mathrm{erg}(M/M_\odot)^2 = (2\ldots3)\times 10^{53}\,\mathrm{erg}$ (*core-collapse SNe*)
- Nuclear burning?
  - $1\ldots 2 M_\odot$: $\sim 10^{51}\,\mathrm{erg}$ require burning $\sim 1 M_\odot$ from C/O to Fe
  - Not seen in type II and type Ib/c $\rightarrow$no major role of burning in the mechanism
  - But nuclear burning powers *thermonuclear SNe* (type Ia) and could power *pair-instability SNe*

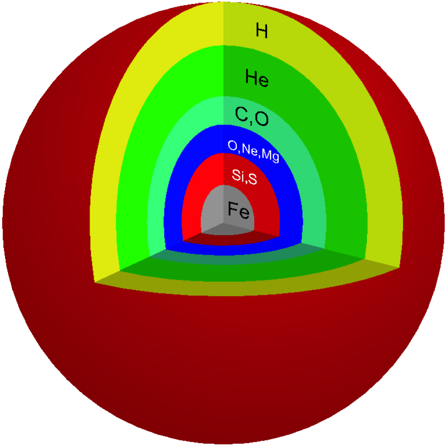
Supernova Progenitors



Smartt (2015)

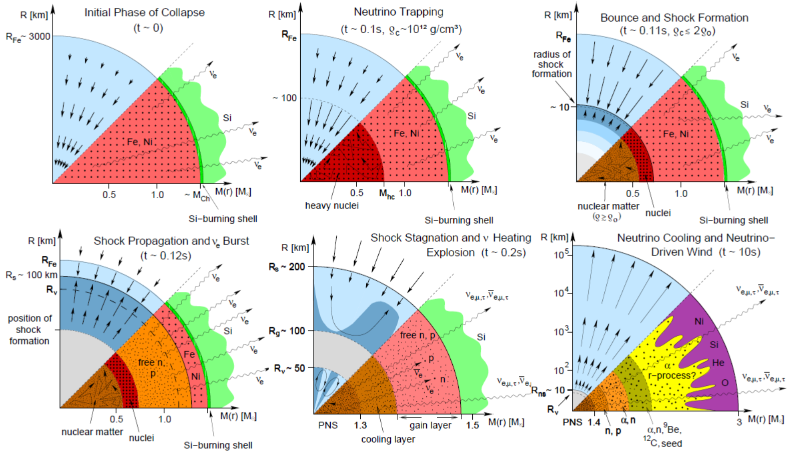
- Identification of progenitors unambiguously shows that some massive stars explode as supernovae.
- Progenitor identification based on HR trackes suggest stars with ZAMS mass in the range of $8 \ldots 18 M_\odot$) explode, more massive ones may form black holes.
- Based on their rate, Ib/c supernovae should mostly come originate from stripped stars in binaries rather than from massive progenitors that evolve into Wolf-Rayet stars.

From Massive Stars to Supernovae



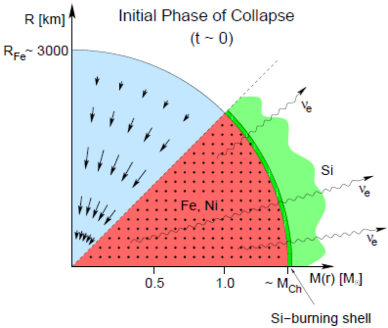
Onion shell structure of massive stars. Alex Heger will cover how we get up to this point.

Overview – From Collapse to Explosion



from Janka et al. (2007)

The Collapse Phase



Iron core supported mainly by electron degeneracy pressure:

$$P \propto (\rho Y_e)^{4/3} + \text{temperature corrections}$$

(Y_e: net number of electrons per baryon *electron fraction*)

Chandrasekhar limit for core mass:

$$M_{\mathrm{ch}} \approx 5.8 Y_e^2 M_\odot$$

Y_e and pressure reduced by electron captures:

$$\begin{aligned} (Z, N) + e^- &\rightarrow (Z-1, N+1) + \nu_e, \\ p + e^- &\rightarrow n + \nu_e, \end{aligned}$$

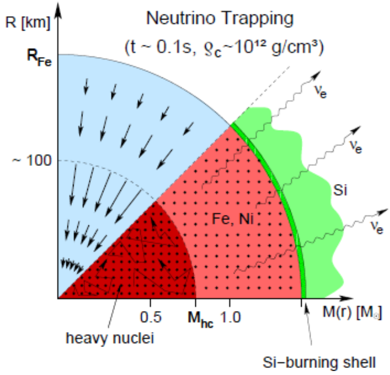
which become possible as $\mu_e > -Q$ (Q: Q-value for reaction).

For higher masses: pressure reduction due to photo-dissociation of nuclei:

$$^{56}Fe \rightarrow 13\alpha + 4n$$

Both effect result in collapse on free-fall time-scale.

The Collapse Phase – Neutrino Trapping



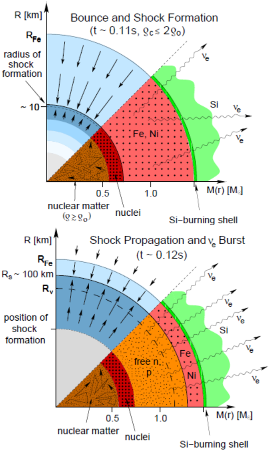
Y_e-reduction (*deleptonization*) accelerates during collapse, for electron capture on protons:

$$\frac{\mathrm{d}Y_e}{\mathrm{d}t} \propto \mu_e^5 \propto (\rho Y_e)^{5/3}$$

Deleptonization stops around $\rho \approx 5 \times 10^{11}\,\mathrm{g\,cm^{-3}}$:

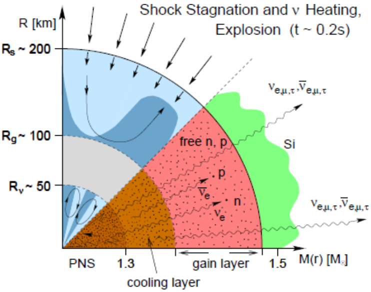
- Neutral-current scattering of neutrinos on nuclei $\nu A \to \nu A$
- Gray scattering opacity $\kappa_s \propto \rho \langle A \rangle \mu_e^2$
- Diffusion time-scale $\tau_{\mathrm{diff}} = \kappa R^2/c$ decreases faster than collapse time-scale (free-fall) $t_{\mathrm{ff}} \propto \sqrt{\rho}$.
- For $\tau_{\mathrm{diff}} < \tau_{\mathrm{ff}}$: equilibration of ν_e, e^-, p, n; co-advection of ν_e, no lepton number loss
- Final $Y_e \approx 0.27$
- $\to$Self-similarly collapsing *inner core* is small ($\sim 0.5 M_\odot$).

Bounce, Shock Breakout, Neutrino Burst



- Inner core bounces after reaching supranuclear densities (as P increases fast with ρ).
- Initial shock energy $\sim 10^{51}\,\mathrm{erg}$
- Shock stalls after a few ms:
  - needs to propagate through $0.9 M_\odot$ of the outer iron core
  - Dissociation losses: $1.7 \times 10^{52}\,\mathrm{erg}/M_\odot$ of shocked material for $Fe, Ni \rightarrow n, p$
  - For post-shock density $\lesssim 10^{11}\,\mathrm{g\,cm^{-3}}$: rapid deleptonization from $Y_e \approx 0.5$ to hot beta-equilibrium ($\Rightarrow$ neutrino losses)
- Phase of strongest neutrino emission: luminosity peaks at $\approx 4 \times 10^{53}\,\mathrm{erg\,s^{-1}}$ for $\sim$5 ms

The Accretion Phase

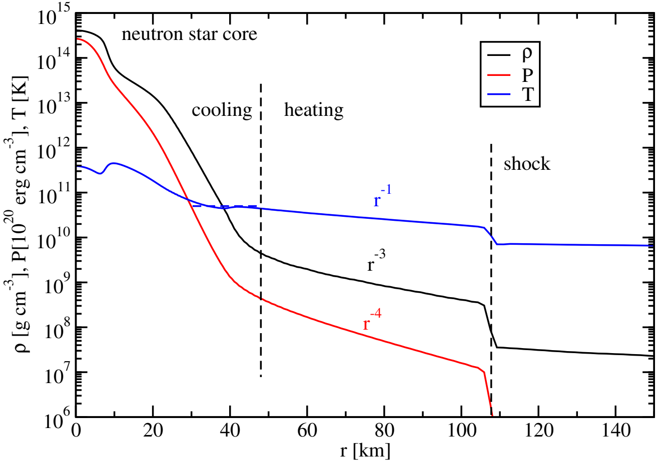


Sketch of the supernova core during the accretion phase: Waiting for the explosion...

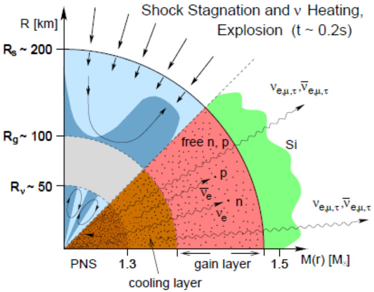
After the shock has stalled, the following structure develops in the supernova core:

- Proto-neutron star core ($\rho \gtrsim 10^{14}\,\mathrm{g\,cm^{-3}}$, $R \approx (10\ldots15)\,km$, nuclear forces dominate)
- Neutron star mantle and atmosphere (thermal pressure of baryons dominates ($P \propto \rho T$), cooled by neutrinos)
- Gain region (radiation pressure from photons and relativistic electron/positrons dominates ($P \propto T^4$), heated by neutrinos)
- Shock at $\sim 50\ldots200\,\mathrm{km}$

The Accretion Phase



How to Explode Massive Stars



Sketch of the supernova core during the accretion phase: Waiting for the explosion...

Basic idea: somehow increase pressure (thermal, turbulent, magnetic...) behind the shock:

- Neutrino heating: heat post-shock matter by partial absorption of neutrinos emitted from the proto-neutron star surface
- Magnetohydrodynamic mechanism: Generate magnetic stresses by field winding and magneto-rotational instability.
- Other mechanisms have been proposed, but these two have been studied best and appear most viable

Accretion Phase – Neutron Star Core

- Density $\rho \gtrsim \rho_{nuc} = 2.7 \times 10^{14}\,\mathrm{g\,cm^{-3}}$
- Internal energy $\sim GM/(Rc^2)$
- temperature of several tens of MeV, large neutrino chemical potential
- Neutrinos remain trapped, diffusion time-scale $t_{\mathrm{diff}} > t_{evol} \approx 0.5\,\mathrm{s}$ evolution time-scale
- Neutrinos escape only at *neutrinosphere* at densities of $< 10^{14}\,\mathrm{g\,cm^{-3}}$
- Emitted neutrino mean energies therefore lower ($\sim 15 \ldots 20\,\mathrm{MeV}$)
- Neutron star core radius ($10 \ldots 15\,\mathrm{km}$) is important as inner boundary for the accretion problem ($\rightarrow$ nuclear equation of state)

Neutrino-Driven Mechanism: Neutrino Emission

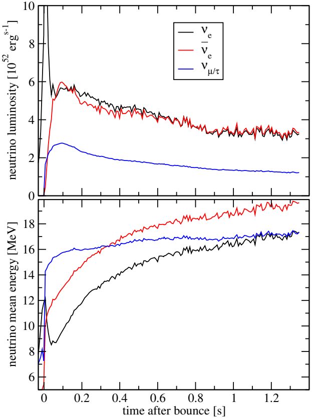
Electron neutrinos and antineutrinos

- are mostly produced by charged-current reactions $p + e^- \to \nu_e$ and $n + e^+ \to \bar{\nu}_e$,
- are produced throughout the cooling region and take away most of the thermal (=liberated potential) energy of the accreted matter as accretion luminosity $L_\mathrm{acc} \approx GM\dot{M}/2R_{cooling\ \ region}$ (M: neutron star mass, $\dot{M}$: accretion rate).

Heavy flavor neutrinos (ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$)

- are predominantly produced by bremsstrahlung (cooling term $Q_\mathrm{brems} \propto \rho^2 T^{11/2}$) or pair proccess ($e^+ e^- \to \nu\bar{\nu}$ or $\nu_e \bar{\nu}_e \to \nu\bar{\nu}$, $Q_\mathrm{pair} \propto T^9$),
- are only produced at high densities in the mantle,
- luminosity $L_{diff} \sim R_\nu^2 T_\nu^4$ (Stefan-Boltzmann law) supplied by the diffusive flux from the neutron star core and mantle.

Neutrino-Driven Mechanism: Formation of Gain Region



Time evolution of neutrino luminosities and mean energies, $15 M_\odot$ star.

For larger r neutrino absorption/emission is slow and the accreted mater undergoes *almost* adiabatic contraction, resulting in a stratification

$$T \propto r^{-1}, \quad \rho \propto r^{-3}, \quad P \propto r^{-4}.$$

The resulting charged-current heating and cooling rates ($\nu_e + n \rightleftharpoons e^- + p$, $\bar{\nu}_e + p \rightleftharpoons e^+ + n$) scale as

$$\begin{aligned} \dot{q}_{\mathrm{heat}} &\propto \frac{L_\nu \langle E_\nu^2 \rangle}{4\pi f r^2} \propto r^{-2}, \\ \dot{q}_{\mathrm{cool}} &\propto T^{-6} \propto r^{-6} \end{aligned}$$

As the cooling rate decreases faster with radius, a region of net heating (*gain region*) eventually develops.

Neutrino-Driven Mechanism: Runaway Criterion

How much neutrino heating is necessary to instigate an explosive runaway? A rough estimate is furnished by the comparison of two time-scales:

- the advection time-scale τ_{adv} (average time spent in the gain region by accreted matter)
- the heating time-scale $\tau_{heat} = E_{bind,gain}/Q_{heat}$ required to inject the binding energy $E_{bind,gain}$ into the gain region for a volume-integrated heating rate Q_{heat}
- $\tau_{adv}/\tau_{heat} \gtrsim 1$: gain region expands and pushes the shock out

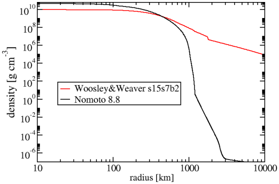
Using the Rankine-Hugoniot jump conditions at the shock, balance between heating and cooling at the gain radius R_{gain}, spherical symmetry, and a few other approximations, one can translate this into a condition on the neutrino luminosities and mean energies:

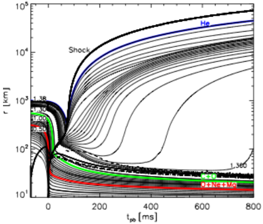
$$\frac{\tau_{adv}}{\tau_{heat}} \propto \frac{(L_\nu \langle E_\nu \rangle^2)^{5/3} R_{gain}^{2/3}}{\dot{M} M}$$

Neutrino-Driven Mechanism – Energetics

- Specific binding energy at gain radius
  $e_{bind} \approx 30\,\mathrm{MeV}/\mathrm{nucleon}$
- Electron flavor luminosity $L \sim 10^{53}\,\mathrm{erg\,s^{-1}}$
- Achievable heating efficiency (heating rate/luminosity)
  $\eta \sim 0.1$ ($\leftarrow$neutrino transport simulations)
- Heating for $t \sim 0.5\,\mathrm{s}$ (depends on explosion dynamics)
- Ejection of $M \approx \eta L t / e_{bnd} \approx 0.1 M_\odot$ of neutrino-heated material
- Neutrino heating mostly used to unbind material
- Residual explosion energy from nucleon recombination
  $n, p \rightarrow 56^{\mathrm{Ni}}, \alpha$ ($\sim 5 \ldots 8.8\mathrm{MeV}/\mathrm{nucleon}$)
  $E_{expl} \approx M \times 8.8\,MeV/m_{\mathrm{nucleon}} \lesssim 1.4 \times 10^{51}\,\mathrm{erg}$

Simulation Results – Spherical Symmetry

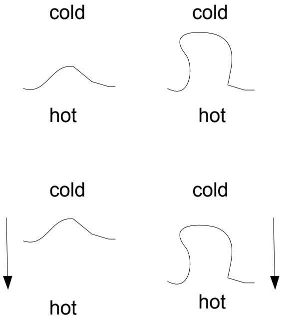




Density profile (top) and evolution of mass shells (bottom) for an exploding $8.8 M_\odot$ progenitor (Kitaura et al. 2006, Janka et al. 2008).

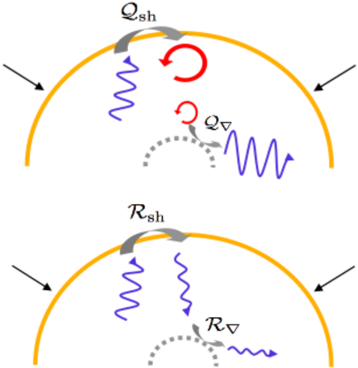
- Spherically symmetric simulations *fail* for most models
- Exception: low-mass "electron-capture" supernovae and low-mass iron core progenitors: $\dot{M}$ drops rapidly due to envelope structure
- Hence: Multi-D effects relevant for explosion mechanism

Multi-D Effects: Convection



- Heating in gain region results in an *entropy increase* as material is advected to the gain radius:
$$\frac{\mathrm{d}s}{\mathrm{d}r} < 0$$
- We can think of convection as a heat engine: heating $\rightarrow P\,dV$ work $\rightarrow$kinetic energy $\rightarrow$turbulent dissipation.
- In the non-linear phase energy input and dissipation balance each other, and the convective velocities reaches about (Müller & Janka 2015):
$$v_\mathrm{conv} \sim \left(\dot{q}_\mathrm{heat}(R_\mathrm{sh} - R_\mathrm{gain}\right)^{1/3}.$$

Multi-D Effects: Standing Accretion Shock Instability



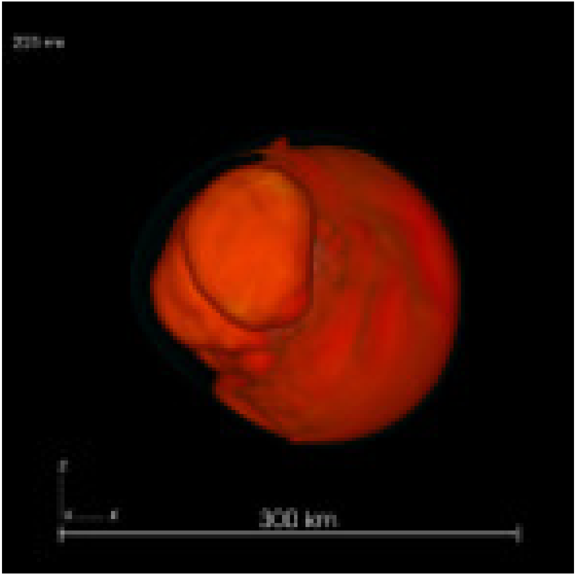
- "'Standing accretion shock instability" can grow even without convective instability
- Mediated by a feedback loop of vorticity and acoustic waves between the shock and the neutron star surface
- Low-ℓ instability: dipole and quadrupole mode dominate
- Oscillatory instability: regular periodicity, at least during linear phase.

A Table-Top Experiment

Credit: T. Foglizzo (CEA Saclay)

Visit the Palais de la Découverte in Paris or CEA Saclay to see the experiment.

Convection and SASI in Motion

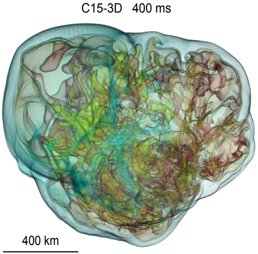


Why Are These Multi-D Effects Helpful?

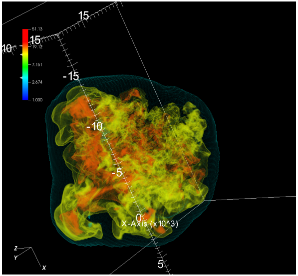
- Fluctuations in the velocity provide an additional "turbulent pressure" (or Reynolds stresses) that helps the shock expand. One can show this more formally by decomposing the flow into temporally and spherically averaged and fluctuating components (spherical Reynolds decomposition). They also increase the thermal pressure by mixing hot material towards the shock.
- Expansion of the shock then increases the mass that can be heated by neutrinos and the advection time-scale τ_{adv}.
- The critical time-scale ratio is thus higher for a given luminosity and accretion rate. One can derive that the increase depends roughly on the average squared Mach number of the convective/SASI motions (Mueller& Janka 2015),

$$\frac{\tau_{adv}}{\tau_{heat}} \propto \frac{(L_\nu \langle E_\nu \rangle^2)^{5/3} R_{gain}^{2/3}}{\dot{M} M} \times \left(1 + \frac{4}{3}\langle \mathrm{Ma}^2 \rangle\right).$$

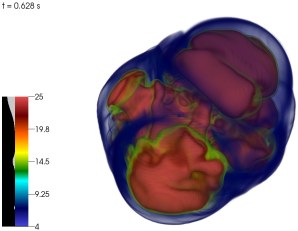
Success or Failure – Status of Supernova Modelling



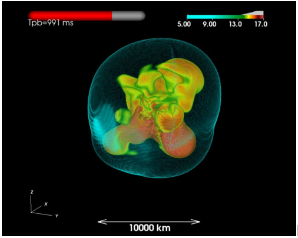
Lentz et al. (2015)



Müller et al. (2019)



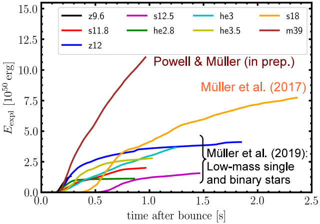
Burrows et al. (2020)

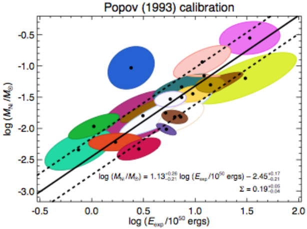


Nakamura et al. (2019)

Success or Failure – Status of Supernova Modelling

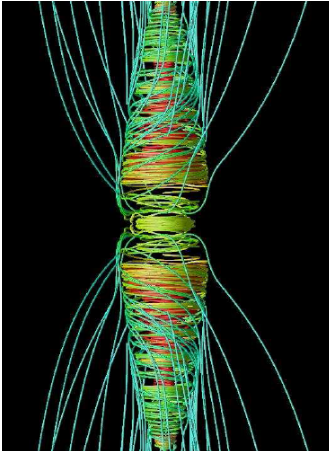
- We can now model the neutrino heating and cooling in supernovae with 3D multi-group neutrino transport.
- There are now over two dozen successful 3D explosion models by different groups, but others still do not show explosion.
- It is still difficult to account for the full range of observed explosion energies. Either the models are no yet sufficiently accurate, or some physics is still missing.





Explosion energies: models (top) vs. observations (bottom, compiled by Pejcha & Thompson 2015).

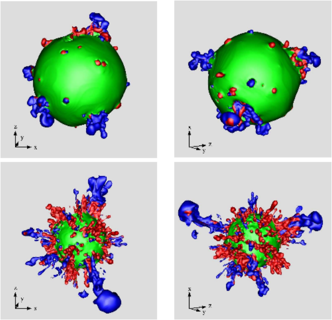
Alternatives – Magnetohydrodynamically-Driven Supernovae



Visualisation of field lines for an MHD-driven supernova explosion (Burrows et al. 2007)

- Neutrino-driven explosions inherently limited to $\sim 10^{51}\,\mathrm{erg}$
- Explanation for hypernova explosions with $\sim 10^{52}\,\mathrm{erg}$ needed
- For fast rotation: tap rotational energy reservoir ($\sim 10^{52}\,\mathrm{erg}$ for neutron star with rotation period $P = 1\,ms$)
- Estimates: $10^{52}\,\mathrm{erg}\,s^{-1}$ can be channelled into outflow for $B \sim 10^{15}\,G$ and $P = 1\,ms$
- Higher efficiency than neutrino-driven mechanism ($10^{53}\,\mathrm{erg}$ binding energy $\rightarrow$ $10^{51}\,\mathrm{erg}$ explosion energy)
- Critical parameters: Seed fields, stellar rotation rates, amplification mechanisms of magnetic fields

The Aftermath

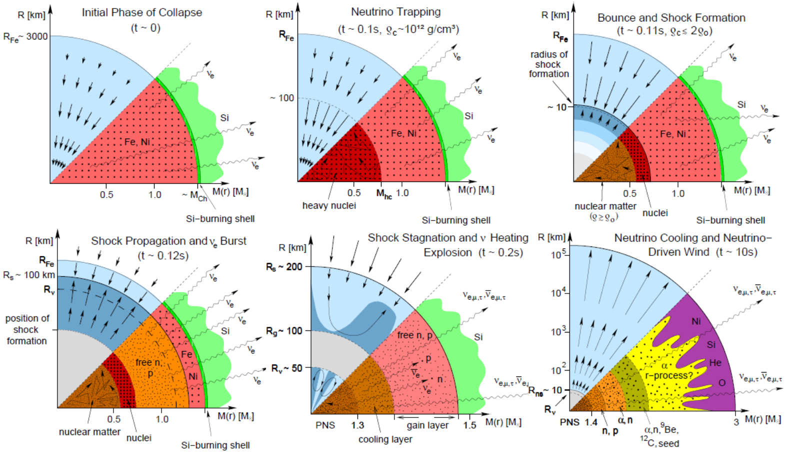


Mixing of Nickel into the H shell (Hammer et al. 2010). Blue: Ni, Green: C, Red: O.

- After shock revival, it takes several hours for the shock to reach the surface (which is when we start to see an electromagnetic signal).

- As the shock propagates through the envelope, mixing due to Rayleigh-Taylor instability can occur. Spectra of SN1987A show, e.g., Nickel clumps clumps that have penetrated into the hydrogen shell with extremely high velocities.
- The outer shells are also partially reprocessed by explosive nuclear burning (due to high post-shock temperatures).
- If the mass ejection is asymmetric, a considerable kick can be imparted onto the neutron star (up to $\sim$1000 $\mathrm{km\ s^{-1}}$.

Summary – Back to the Overview Slide



from Janka et al. (2007)

A very non-exhaustive list of further references

- Janka H.-T., Langanke K., Marek A., Martínez-Pinedo G., Müller B, Physics Reports 442, 38 (2007)
- Janka H.-T., 2012, Annual Review of Nuclear and Particle Science, 62, 407
- Müller B., 2016, Publications of the Astronomical Society of Australia 33, e048