Physical Processes in Supernova Remnants
Evolution of Massive Stars

Stars with masses less than $9\,M_{\odot}$ do not burn carbon – Stars with masses near $9\,M_{\odot}$ develop a degenerate carbon core and have a “C-flash”, due to C-burning in a non-degenerate shell.

Stars having masses higher than $9\,M_{\odot}$ do not develop degenerate cores, burn carbon up to the formation of an iron core.

If $T_c > 5 \times 10^9\,K$, statistical equilibrium is destroyed and photo-disintegration of iron dominates.

\[ \gamma + Fe^{56} \rightarrow 13He^4 + 4n - 2.2\text{MeV/nuc} \]

This process absorbs too much thermal energy, destroying hydrostatic equilibrium and producing the gravitational collapse of the star.
The explosion mechanism

The photo-disintegration of iron destabilizes the star – the core collapses first since $t_{\text{col}} \propto (G\rho)^{-1/2}$ and the beta capture process forms a neutron rich core having a mass close to the Chandrasekhar limit (1.4 $M_\odot$).

$$X(A,Z) + e^- \rightarrow X(A,Z-1) + \nu_e$$

The energy released under the form of neutrinos (URCA and thermal), having an average energy of 2 MeV, is of the order of the potential energy of the neutron core with a radius of about 100 km

$$\frac{GM_c^2}{R_c} \approx 5 \times 10^{52} \text{erg} \quad \Rightarrow \quad N_\nu \approx 2 \times 10^{58}$$

Once the core is formed (timescale around few ms) the outer envelope falls into the core and bounces, absorbing the neutrinos that transfer momentum to the matter, producing ejection.

If the transfer conditions are not adequate, there is no ejection and the envelope falls back, being accreted by the core, which collapses to form a black hole (case of stars with masses higher than $\sim 50 M_\odot$)
The explosion mechanism

The momentum carried by each neutrino is \( E_{\nu} / c \) and the efficiency of each transfer is \( f \). Since each neutrino suffers on the average \( N_s \) elastic scatterings inside the envelope, the total momentum transferred is

\[
\Delta P_{\nu} \approx f \left( \frac{E_{\nu}}{c} \right) N_{\nu} N_s \approx 2.3 \times 10^{45} f \text{ g.cm.s}^{-1}
\]

Since the total number of scatterings is of the order of the square of the neutrino optical depth

\[
N_s \approx \tau_{\nu}^2 = \left( \frac{\sigma_{\nu}}{m_n} \Sigma \right)^2 \approx 1100 \quad \text{with } \sigma_{\nu} \approx 9.5 \times 10^{-45} \left( \frac{E_{\nu}}{\text{MeV}} \right) \text{ cm}^2 \quad \text{and } \Sigma \approx 10^{23} \text{ g / cm}^2
\]

Observed momentum \( \rightarrow \quad M_{\text{eje}} V_{\text{eje}} = 6.0 \times 10^{42} \left( \frac{M_{\text{eje}}}{10 M_\odot} \right) \left( \frac{V_{\text{eje}}}{3000 \text{km/s}} \right) \)

Required neutrino transfer efficiency \( \rightarrow \quad f \approx 2 \times 10^{-3} \)
Tycho–Brahe SNR – image composite: radio, optical and X-rays obtained by the satellite Chandra

IC 433 – SRN – image taken with an H-alpha filter using a 15cm refractor and a modified Canon 1200D camera. Non-thermal X-rays are emitted from this SNR
Sketch of the structure of the SNR shell

R.c. acceleration by Fermi mechanism

\[ \Delta R = \eta R \]

Ejected shell

\[ (E_0, \mu n_0) \]

shocked gas

\[ (m_0) \]

Interstellar Medium

X-rays (photofon production)

\[ \rightarrow V_s \]

synchrotron emission (radio, soft-X rays)
Phases of Expansion

• **Phase I** – “free-expansion” – short phase in which the shell velocity is constant – valid when the ejected mass is less than the mass swept by expansion through the interstellar gas.

• **Phase II** – adiabatic or Sedov phase – the cooling timescale is longer than the expansion timescale.

• **Phase III** – the expansion timescale becomes longer than the cooling – the shell expands according to the momentum conservation law.
The motion of the shock front – Phase II (Sedov)

Using the Hugoniot-Rankine equations:

\[
\begin{align*}
P_s &= 2 \frac{\rho_l V_s^2}{(\gamma + 1)} + \frac{(\gamma - 1)}{(\gamma + 1)} P_l \\
\rho_l &= \frac{(\gamma - 1)}{(\gamma + 1)} + \frac{2\gamma}{(\gamma + 1)} \frac{P_l}{(\rho_l V_s^2)}
\end{align*}
\]

For a strong shock \( \rightarrow \) \( P_s \gg P_l \) and \( P_l \ll \rho_l V_s^2 \)

Consequently \( \rightarrow \) \( \frac{\rho_l}{\rho_s} \approx \frac{1}{4} \) and \( P_s \approx \frac{3}{4} \rho_l V_s^2 \) \( \Rightarrow \) also \( \frac{P_s}{\rho_s} = \frac{kT_s}{\mu m_p} \approx \frac{3}{16} V_s^2 \)

But \( \rightarrow \) \( P_s = \frac{2}{3} \frac{E_{th}}{(4\pi R_s^3 / 3)} = \frac{E_{th}}{2\pi R_s^3} \Rightarrow V_s = \frac{dR_s}{dt} = \left( \frac{2E_{th}}{3\pi \rho_l} \right)^{1/2} R_s^{-3/2} \)

Integrating \( \rightarrow \) \( R_s = A t^{2/5} \) with \( A = \left( \frac{25}{6\pi} \frac{E_{th}}{\rho_l} \right)^{1/5} \) and \( V_s = \frac{2}{5} \frac{R_s}{t} \)
Shock motion in Phase III

Gas has cooled – the thermal pressure is no longer important – eq. motion is simply

\[ \frac{d}{dt} (M_s V_s) = 0 \Rightarrow \frac{4\pi}{3} \rho_1 R_s^3 \frac{dR_s}{dt} = K \]

Integrating → \( R_s \approx Bt^{1/4} \) with \( B = \left( \frac{3K}{\pi \rho_1} \right)^{1/4} \) and \( V_s = \frac{1}{4} \frac{R_s}{t} \)

The constant \( K \) can be estimated by assuming that the transition from phase II to phase III occurs at the cooling timescale

Then → \( At_c^{2/5} \approx Bt_c^{1/4} \) \( \Rightarrow K = \frac{\pi}{3} \rho_1^{1/5} \left( \frac{25E_{th}}{4\pi} \right)^{4/5} t_c^{3/5} \)

Where → \( t_c = E_{th} / L_B \) and \( L_B \) is the radiation rate of the shell due to line and bremsstrahlung emission
Some difficulties with phase II

Let \( \nu_{II} \) the rate at which type II supernovae are formed in the Galaxy. Then the number of SNR with radius less or equal \( R_s \) is given by

\[
\frac{dN_{SN}}{dt} \frac{dN_{SN}}{dR_s} \frac{dR_s}{dt} = \nu_{II}
\]

Using the previous results for \( V_s \) and integrating

\[
N(<R_s) = \frac{3}{5} \frac{\nu_{II}}{A^{5/2}} R_s^{5/2}
\]

Plot of the quantity \( N(<R_s) \) vs the shell radius using data from the Green catalog. The best data fit gives

\[
N(<R_s) = (4.92 \pm 1.99) R_s^{(1.11 \pm 0.13)}
\]

A similar result was obtained for SNR in the Large Magellanic Cloud, excluding uncertainties in the distance scale as a possible explanation for such a discrepancy.
Synchrotron Emission from the Shell

Shell luminosity → $4\pi D^2 f_\nu = L_\nu = B_\gamma K_e H^{(\gamma+1)/2} (4\pi\eta R_s^3)\nu^{-\alpha}$

where the shell thickness = $\Delta R_s = \eta R_s$ and $\alpha = (\gamma - 1)/2$

Emission coefficient: $B_\gamma = \frac{3}{16\pi} \left( \sqrt{\frac{27}{32\pi^2}} \right)^{(\gamma-3)/2}$

Emission coefficient: $\sigma_T c^{(\gamma-1)/2} (mc^2)^{(5-3\gamma)/2} e^{(\gamma-3)/2}$

Relativistic electron density: $W_e = \int_0^\infty EN(E)dE = \int_0^\infty E \frac{K_e}{(E+mc^2)^\gamma} dE = \frac{K_e}{(\gamma-2)(\gamma-1)(mc^2)^{\gamma-2}}$

Total cosmic ray energy density: $W_{CR} = W_p + W_e = \beta W_e$ with $\beta = \left( \frac{m_p}{m} \right)^{(\gamma-1)/2}$

From these eqs.: $\beta L_\nu = B_\gamma (\gamma - 2)(\gamma - 1)(mc^2)^{\gamma-2} W_{CR} H^{(\gamma+1)/2} \Omega_{sh} \nu^{-\alpha}$
Using the previous eqs., the energy under the form of cosmic rays is:

\[ E_{CR} = W_{CR} \Omega_{sh} = \frac{\beta L_v}{(\gamma - 2)(\gamma - 1)B_\gamma (mc^2)^{\gamma - 2} H^{(\gamma + 1)/2}} = \frac{C_{CR}}{H^{(\gamma + 1)/2}} \]

The total energy inside the shell \( \longrightarrow \) cosmic rays + magnetic field

\[ E_T = \frac{C_{CR}}{H^{(\gamma + 1)/2}} + \frac{H^2}{8\pi} \Omega_{sh} \]

- Assume that the value of the H-field minimizes the energy

\[ \frac{\partial E_T}{\partial H} = 0 \Rightarrow H_{\text{min}} = \left[ \frac{2\pi(\gamma + 1)C_{CR}}{\Omega_{sh}} \right]^{2/(\gamma + 5)} \Rightarrow E_{CR} = \frac{4}{(\gamma + 1)} E_{\text{mag}} \]

Catalogs of SNR provide besides position, the energy flux at frequency \( \nu \), the spectral index \( \alpha \) and the angular diameter \( \theta_s \). Since \( \gamma = 2\alpha + 1 \), from observations, the magnetic field (minimum) can be derived if the distance \( D \) is known

\[ H_{\text{min}} = \left[ \frac{16\pi(\gamma + 1)\beta}{(\gamma - 2)(\gamma - 1)B_\gamma (mc^2)^{\gamma - 2}} \right]^{2/(\gamma + 5)} \left( \frac{\nu^\alpha f_\nu}{\eta \theta_s^3 D} \right)^{2/(\gamma + 5)} \]

Then, previous eqs. give the cosmic ray energy inside the shell
Mass under the form of filaments – 2 M⊙; mass of the pulsar – 1.4 M⊙; possible losses from the wind of the progenitor – 3 to 4 M⊙; estimated progenitor mass around 6.4 – 7.4 M⊙, less than the minimal mass for C-burning

Estimated distance 1.9 kpc; average shell radius $R_s = 1.53$ pc; spectral index $\alpha = 0.55$; CR power spectrum - $\gamma = 2\alpha+1 = 2.1$

Mean magnetic field – $H = 157$ mG and mean magnetic+CR energy density = $2.2 \times 10^{-7}$ erg/cm³

Observed acceleration of filaments:
$$<\ddot{R}_s> = 7.3 \times 10^{-4} \text{ cm/s}^2$$

$$<M> <\ddot{R}_s> = \frac{4\pi}{3} (\omega_H + \omega_{CR}) R_s^2 \quad \Rightarrow \quad <M> = 14M_\odot$$
Distance Scale for SNR

Distances must be calibrated using observable parameters.

Define the reduced brightness:

\[ \Sigma_v = \frac{f_v}{\theta_s^2} \]

There is a relation between the radius of the shell and the reduced brightness.

Calibration of the \( \Sigma \times R \) relation using 30 SNR with distances derived with errors not larger than 50%:

\[ \log R = 0.780 - 0.283 \log \Sigma_v \pm 0.255 \quad c.r. = 0.805 \]
Shell parameters: H-field & CR energy

SNR from the Green catalog – Distances from the $\Sigma_y - R_s$ relation
The cosmic ray energy is correlated with the shell radius up $R_s \sim 40$ pc. For larger radii, the relativistic particles escape to the interstellar medium.
If each supernova releases about $10^{50}$ erg under the form of relativistic particles, then the expected cosmic ray energy density in the galactic disc is

$$w_{CR} \approx v_H \frac{E_{CR}}{V_d} T_{CR}$$

Since $E_{CR} \approx 10^{50}$ erg, the volume of the disc $V_d \approx 2.4 \times 10^{66} \text{ cm}^3$ and the lifetime of cosmic rays inside the confinement zone, fixed by the abundance ratio (Li+Be+B)/(C+N+O) in the cosmic ray chemical composition, is $T_{CR} \approx 1.2 \times 10^7 \text{ yrs}$ we have

$$w_{RC} \approx 313 v_H \ eV \text{ cm}^{-3}$$

With one SN every 240 yrs (see later) the resulting CR energy density is about $1.3 \ eV \text{ cm}^{-3}$, in good agreement with the observed value (1 $eV \text{ cm}^{-3}$).
X-rays from the shocked region

X-ray image of the SNR 1006 obtained with the satellite XMM Newton superposed to molecular CO emission.

The shock interacts with a dense molecular cloud, producing an asymmetric X-ray emission.
Bremsstrahlung emission from the shocked region

Thermal X-rays

The total X-ray luminosity from the shocked region is: \( L_x(\Delta \varepsilon) = \Lambda(\Delta \varepsilon, T_x)n_e n_i V_{sh} \)

where:
\[
\Lambda(\Delta \varepsilon, T_x) = \frac{64\pi^{3/2} Z e^6 g}{\sqrt{54}} \frac{kT_x}{hc^2 m} \left( \frac{kT_x}{mc^2} \right)^{1/2} \left( e^{-\frac{\varepsilon_1}{kT_x}} - e^{-\frac{\varepsilon_2}{kT_x}} \right)
\]

\[
n_e = n_p + 2n_{He} = 1.2n_p = 4.8n_0
\]

and
\[
T_s = 0.75 T_x^{1.03} \text{ if } T_x > 2\text{keV} \text{ and } T_s = T_x \text{ otherwise}
\]

If the distance is known, from the observed X-ray flux, the luminosity can be computed. The spectrum provides the temperature and these equations permit to derive the interstellar gas density as well as the thermal energy

\[
P_s = \frac{E_{th}}{2\pi R_s^3} = n_s kT \quad \Rightarrow \quad \frac{E_{th}}{n_0} = 8\pi R_s^3 kT_s
\]
The average thermal energy inside the shocked region of SNRs is

\[ \log E_{th} = 49.94 \pm 0.58 \]

On the average, the energy under the form of relativistic particles represents 40% of the thermal energy.

Distribution derived from data taken from the Green catalog – Distances estimated from the calibrated sigma-radius relation.
Thermal energy is correlated with the shock radius

$$\log\left(\frac{E_{50}}{n_0}\right) = (-1.498 \pm 0.129) + (2.278 \pm 0.117) \log R_s \pm 0.214 \quad r^2 = 0.967$$

This relation implies for the shock velocity $$V_s = K R_s^{-0.361}$$ and for the number of SNR less than a given radius. $$N(<R_s) = 550 \nu_{_II} R_s^{1.361}$$

Comparison with data implies a frequency of about one SN each 240 yrs.
The correlation between the thermal energy & the shell radius

The variation of the shell velocity with radius directly from line emission data by Dopita is consistent with the results derived from X-ray data. This indicates failure in the Sedov theory.

Simulations of shock models suggest that the shell kinetic energy could be converted into thermal energy, implying that the energy content is not constant. In other words, the adiabaticity condition is not satisfied.

\[ R_s > 5 \text{pc} \implies V_s = 806R_s^{-0.5} \text{ km/s} \]
Sedov model – inhomogeneous model
(thesis – Julien Frémeaux - 2002)

Simulations of the Green catalog – goal – to simulate the same number of SNR listed in the catalog with the same brightness distribution

- Random age from an uniform distribution \((0 < t < 50 000 \text{ yrs})\)

- Density of a three-phase IM: dense \((1 \text{ cm}^{-3})\); intermediate \((0.1 \text{ cm}^{-3})\) and rarefied \((0.01 \text{ cm}^{-3})\) - the birth probability is different for each phase

- Spectral probability according to the catalog distribution

- Explosion energy obeys a log normal distribution with a median \(\log E = 50.0\) and dispersion \(\sigma_{\log} = 0.60\)

- If \(t < t_{\text{crit}} = 3900n_0^{-1/3}E_{50}^{-1/2} \text{ yrs}\) free expansion and if \(t > t_{\text{crit}} \rightarrow \text{“Sedov”}\)

- \(H\)-field results from the empirical \(H - n_0\) relation
Model that provides the best fit of the brightness distribution of the catalog:

dense medium: 10%

intermediate medium: 30%

rarefied medium: 60%

\[ N(< R) \propto R^{1.4} \]

An inhomogeneous medium can explain the cumulative counts even if the expansion is described by the Sedov theory!
High energy emission from SNR Crab remnant
Photo-pion production in SNRs

Pions are produced in SNR by CR interactions with the shell matter via

\[ p + p \to p + p + a\pi^0 + b(\pi^+ + \pi^-) \]

cross section \(\to \sigma_{pp}(E_p) = \sigma_0 E_p^\beta = 25.7 E_p^{0.08} \text{mb}\)

multiplicity \(\to \xi(E_p) = \xi_0 E_p^\delta \quad \delta = 0.22 \quad \text{and} \quad \xi_0 = 3.39 \quad \text{valid for} \quad E_p \geq 1\text{GeV}\)

Mean energy of pions \(\to \bar{E}_\pi \approx \frac{E_p^{1-\delta}}{3\xi_0}\)

Pion production rate: \(q_\pi(E_\pi) = n_H \int N(E_p) \cdot c \cdot \xi(E_p)\sigma_{pp}(E_p)\delta(E_\pi - \bar{E}_\pi) dE_p\)

where \(\to N(E_p)dE_p = \frac{K_p}{E_p^\gamma}dE_p\)

and \(\to d\bar{E}_\pi = \frac{(1-\delta)}{(3\xi_0)^{1/(1-\delta)}} \bar{E}_\pi^{-\delta/(1-\delta)} dE_p \quad \text{replace this into the integral and integrate}\)
$$q_\pi(E_\pi) = \sigma_0 n_H c K_p \frac{K_\pi}{E_\gamma^{\gamma_\pi}} \text{ pions/cm}^3\text{s.GeV}$$

where

\[
K_\pi = \frac{\xi_0}{(1-\delta)(3\xi_0)^{\gamma_\pi-1}} \quad \text{with} \quad K_\pi^0 = \frac{K_\pi}{3} \quad \text{and} \quad K_\pi^\pm = \frac{2K_\pi}{3}
\]

\[
\gamma_\pi = \frac{(\gamma - \beta - 2\delta)}{(1-\delta)}
\]

**Example:**

\[
\gamma = 2.5 \Rightarrow \gamma_\pi = 2.54 \quad K_\pi = 0.122 \quad K_\pi^0 = 0.041 \quad K_\pi^\pm = 0.081
\]

**Production of gamma-rays due to pion decay:**

\[
\pi^0 \rightarrow 2\gamma
\]

\[
q(\epsilon_\gamma) = 2 \int_{f(\epsilon_\gamma)}^{\infty} q_\pi^0(E_\pi^0) \frac{dE_\pi^0}{\sqrt{(E_\pi^0)^2 - 4\epsilon_0^2}} \quad \text{with} \quad f(\epsilon_\gamma) = \epsilon_\gamma + \frac{\epsilon_0^2}{\epsilon_\gamma} \quad \text{and} \quad \epsilon_0 = 67.5\text{MeV}
\]

**Numerical solution:**

\[
q(\epsilon_\gamma > 100\text{MeV}) = 5.28 \times 10^{-16} n_H K_p \text{ ph/cm}^3\text{s}
\]

**Luminosity gamma:**

\[
L_\gamma(> 100\text{MeV}) = q(> 100\text{MeV}) V_s = 1.65 \times 10^{37} n_H \left(\frac{E_{RC}}{10^{50}\text{erg}}\right) \text{ ph/s}
\]
\( \varepsilon_\gamma \gg 2 \text{GeV} \implies f(\varepsilon_\gamma) \propto \varepsilon_\gamma^{-2.54} \)

Spectrum calculated for a proton power law \( \gamma_p = 2.5 \)
Muon production from pion decay \[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \]

Mean energies: \[ < E_\mu > = 0.79 E_\pi \quad < E_{\nu_\mu} > = 0.21 E_\pi \quad < E_{\nu_\mu} > = 0.30 E_\mu \]

Production rate of charged pions and neutrinos

\[ q_{\pi^\pm} (E_{\pi^\pm}) = 6.24 \times 10^{-17} \frac{K_p n_H}{E_{\gamma\pi}} \quad \rightarrow \quad q_{\nu_\mu}^{(1)} = 5.7 \times 10^{-18} \frac{K_p n_H}{E_{\gamma\pi}} \text{ cm}^{-3} \text{s}^{-1} \text{GeV}^{-1} \]

Neutrinos from muon decay \[ \mu^\pm \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \bar{\nu}_\mu (\nu_\mu) \]

Average neutrino energy: \[ \bar{E}_{\nu_\mu} = 0.3 E_\mu \simeq 0.24 E_{\pi^\pm} \]

Neutrino production rate:

\[ q_{\nu_\mu}^{(2)} (E_{\nu_\mu}) = 6.93 \times 10^{-18} \frac{K_p n_H}{E_{\gamma\pi}} \text{ cm}^{-3} \text{s}^{-1} \text{GeV}^{-1} \]

Total production rate:

\[ q_{\nu_\mu}^{(1)} (E_{\nu_\mu}) + q_{\nu_\mu}^{(2)} = 1.3 \times 10^{-17} \frac{K_p n_H}{E_{\gamma\pi}} \text{ cm}^{-3} \text{s}^{-1} \text{GeV}^{-1} \]

Expected muon-neutrino flux:

\[ f_\nu = \frac{q_\nu V_{sh}}{4\pi D^2} \]
Some examples

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<tr>
<th>Supernova</th>
<th>$\gamma$</th>
<th>Log $E_{CR}$ (erg)</th>
<th>D (kpc)</th>
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SN 1987A – LMC – already 30 years!

- February 1987
- 22.4 UT: the progenitor – Sand -69°.202 (B2l) detected at V =12.2
- 23.12 UT: 5 neutrino pulses \((E_\nu > 7 \text{ MeV})\) detected by Mont Blanc detector
- 23.316 UT: 11 neutrino events \((7.5 < E_\nu < 36 \text{ MeV})\) detected by Kamiokande II (Mont Blanc neutrinos were not seen)
- 23.316 UT: 8 neutrino events with \(E_\nu < 50 \text{ MeV}\) detected at Irvine-Michigan-Brookhaven experiment
- 23.316 UT: 3 neutrino events seen at Baksan with \(E_\nu \sim 20 \text{ MeV}\)
- 24.23 UT: discovery by I. Shelton the “optical” SN at V \(\sim 5.1\)
- 26.8 UT: beginning of the observations at LNA
Exponential Decay
Radioactive powering
First spectra obtained at LNA – these spectra are dominated by broad absorption bands. The envelope was still opaque.

Fit of the continuum permitted an estimation of the color temperature of the expanding atmosphere.

The radius of the expanding atmosphere was estimated from

\[ f_\lambda = \left( \frac{R_*}{D} \right)^2 \pi B_\lambda(T_c) \]

First results – MNRAS 240, 179, 1989
Color temperature – derived from black body fits of the continuum.

Evolution of the apparent photospheric radius calculated as explained before – the time derivative gives the expansion velocity of the photosphere.

\[
\frac{dR_{ph}}{dt} = V_{exp} = 6800 \text{ km/s}
\]
Proposed identification of the observed absorption features: a difficult task caused by the blending of the broad lines.

Line profiles modeled by the Sobolev theory

Derived abundances

\[
\frac{Na}{Fe} = 0.1 (0.045) \quad \frac{Mg}{Fe} = 0.55 (0.66) \\
\frac{Sc}{Fe} = 4.6 \times 10^{-4} (4.1 \times 10^{-5}) \\
\frac{Ba}{Fe} = 3.5 \times 10^{-6} (2.2 \times 10^{-6})
\]

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Emission features begin to appear
LINE FLUXES
(in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$)

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What SN1987A has taught us

• The detection of neutrino pulses confirms the gravitational collapse scenario in which a neutron core is formed

• However, no pulsar was detected up to now. This means that whether the beam does not sweep the Earth or a fraction of the envelope has fallen back leading to a BH formation

• The late evolution of the light curve is due to the radioactive decay of $^{56}\text{Co}$ – Nuclear lines of cobalt (0.847 and 1.238 MeV) were detected confirming powering of the envelope by radioactivity. A cobalt mass of 0.07 M☉ was present in the ejecta.

• Ejected oxygen and iron masses are in agreement with the “onion model” envelope