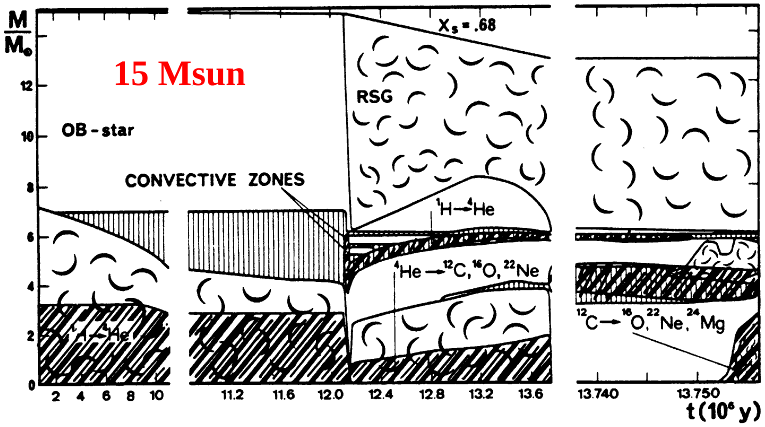
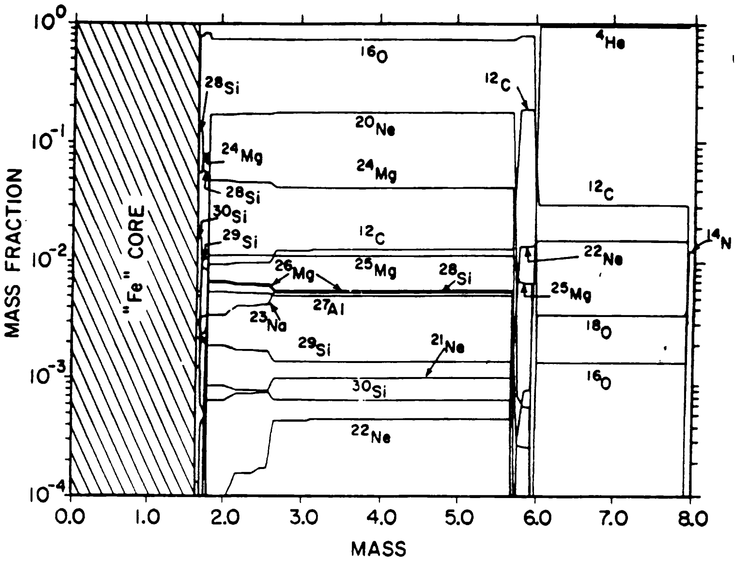
Evolution of Massive Stars



Maeder (1987)

Helium Core (8 Msun)



Itoh and Nomoto (1987)

EVOLUTION OF MASSIVE STARS $(M \gtrsim 13\,M_\odot)$

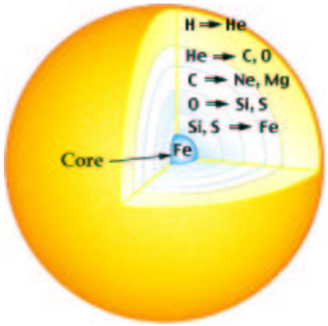
- massive stars continue to burn nuclear fuel beyond hydrogen and helium burning and ultimately form an iron core
- alternation of nuclear burning and contraction phases
  - ▷ carbon burning $(T \sim 6 \times 10^8\,K)$

$$\begin{aligned} {}^{12}C + {}^{12}C &\to {}^{20}Ne + {}^{4}He \\ &\to {}^{23}Na + {}^{1}H \\ &\to {}^{23}Mg + n \end{aligned}$$

  - ▷ oxygen burning $(T \sim 10^9\,K)$

$$\begin{aligned} {}^{16}O + {}^{16}O &\to {}^{28}Si + {}^{4}He \\ &\to {}^{31}P + {}^{1}H \\ &\to {}^{31}S + n \\ &\to {}^{30}S + 2\,{}^{1}H \\ &\to {}^{24}Mg + {}^{4}He + {}^{4}He \end{aligned}$$

  - ▷ silicon burning: photodisintegration of complex nuclei, hundreds of reactions → iron

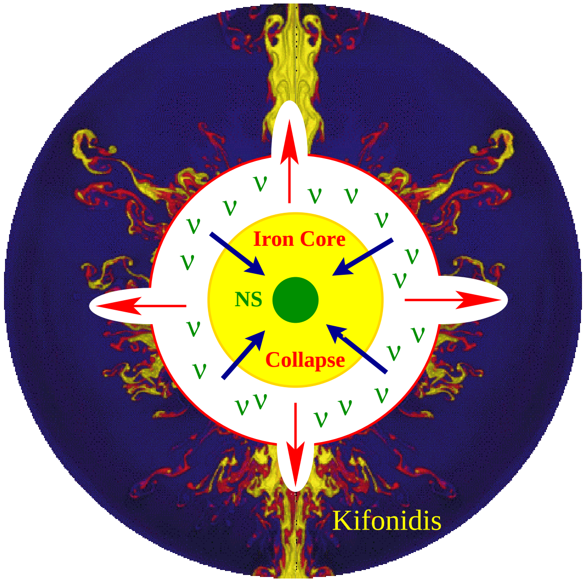


- ▷ form iron core
- ▷ iron is the most tightly bound nucleus → no further energy from nuclear fusion
- ▷ iron core surrounded by onion-like shell structure

EXPLOSION MECHANISMS

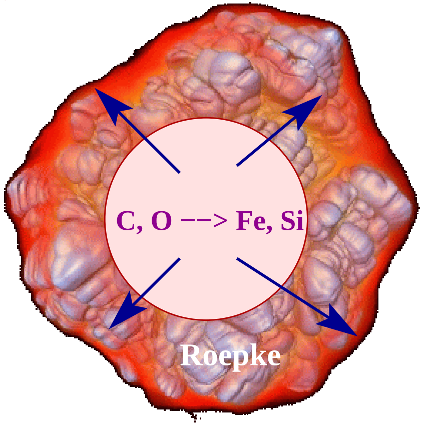
- two main, completely different mechanisms

Core-Collapse Supernovae



- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass > Chandrasekhar mass
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{46}$ J)
- most of the energy comes out in neutrinos (SN 1987A!)
  - ▷ unsolved problem: how is some of the neutrino energy deposited ($\sim 1\,\%$, 10^{44} J) in the envelope to eject the envelope and produce the supernova?
- leaves compact remnant (neutron star/black hole)

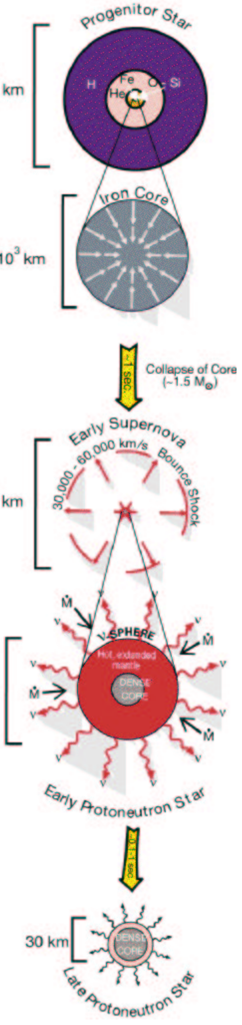
Thermonuclear Explosions



- occurs in accreting carbon/oxygen white dwarf when it reaches the Chandrasekhar mass
  - → carbon ignited under degenerate conditions; nuclear burning raises T, but not P
  - → thermonuclear runaway
  - → incineration and complete destruction of the star
- energy source is nuclear energy (10^{44} J)
- no compact remnant expected
- main producer of iron
- standard candle (Hubble constant, acceleration of Universe?)

but: progenitor evolution not understood

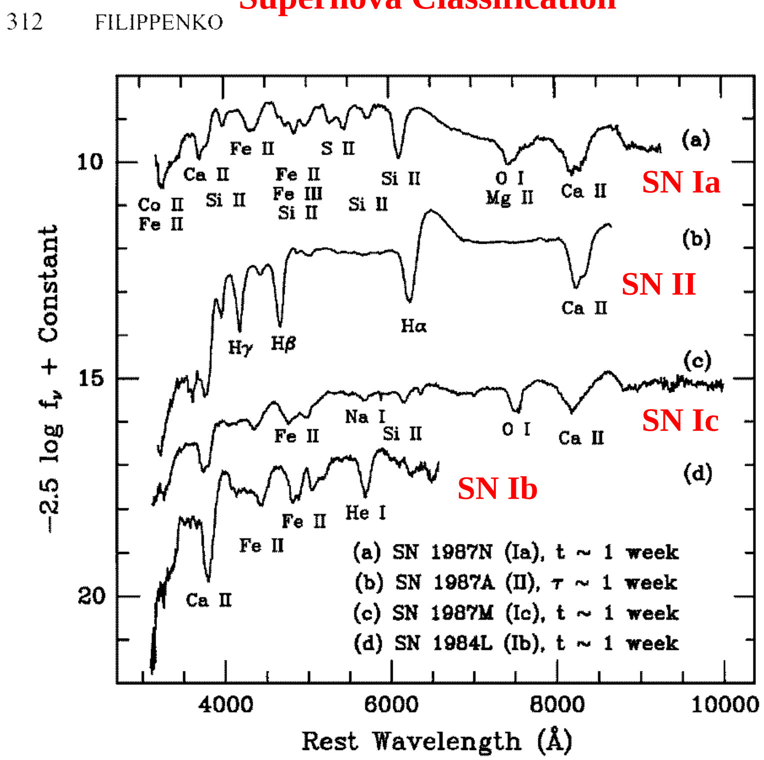
- ▷ single-degenerate channel: accretion from non-degenerate companion
- ▷ double-degenerate channel: merger of two CO white dwarfs

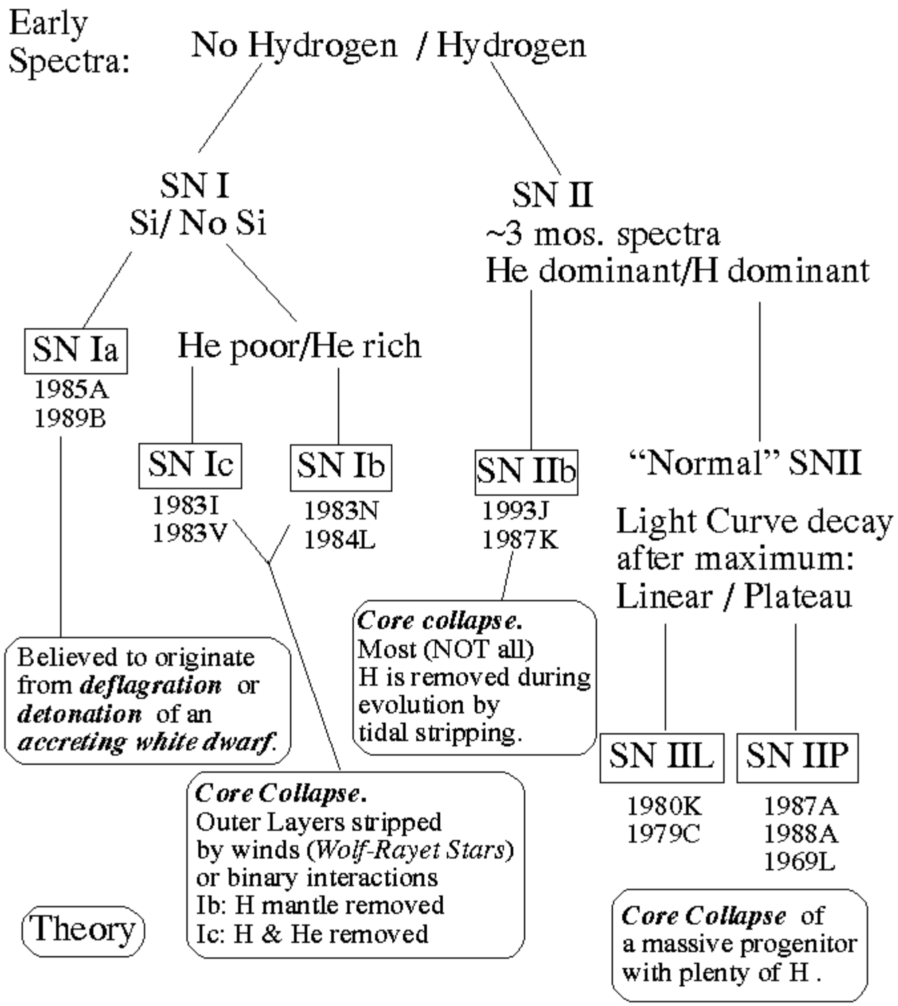


Core Collapse

- central properties at the beginning of core collapse: for $\mathrm{M_{core}} = 1.5\,\mathrm{M_\odot}$, $\mathrm{T_c} \simeq 8\times10^9\,\mathrm{K}$, $\rho_c \simeq 4\times10^{12}\,\mathrm{kg\,m^{-3}}$
- instabilities in the contracting core lead to essentially free-fall collapse
- photodissociation of nuclei
  - ▷ $\mathrm{T_c} \sim 10^{11}\,\mathrm{K}$: $\gamma + {}^{56}\mathrm{Fe} \rightleftharpoons 13\,\alpha + 4\,\mathrm{n} - 124\,\mathrm{Mev}$
  - ▷ endothermic reaction (requires heat) → temperature increases less rapidly than pressure → rapid contraction
  - ▷ $\mathrm{T_c} \sim 2\times10^{11}\,\mathrm{K}$: $\gamma + {}^{4}\mathrm{He} \rightleftharpoons 2\,\mathrm{p} + 2\,\mathrm{n} - 28\,\mathrm{Mev}$
- note: all of these reactions occur in both directions; maximization of entropy favours right-hand sides (larger number of particles)
- these reactions essentially undo all of the previous nuclear fusion reactions
- neutronization
  - ▷ electron capture reactions (reduce the number of electrons and electron degeneracy pressure)
    $\mathrm{e^-} + (\mathrm{Z},\mathrm{A}) \rightarrow \nu_\mathrm{e} + (\mathrm{Z}-1,\mathrm{A})$
    $\mathrm{e^-} + \mathrm{p} \rightarrow \nu_\mathrm{e} + \mathrm{n}$ (also: $\mathrm{n} \rightarrow \bar{\nu}_\mathrm{e} + \mathrm{p} + \mathrm{e^-}$)
- most of the energy is lost by neutrino emission (10 % of the rest mass energy of the neutron star)
- energy source: gravitational energy

Supernova Classification





SUPERNOVA CLASSIFICATION

observational:

- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

theoretical:

- thermonuclear explosion of degenerate core
- core collapse → neutron star/black hole

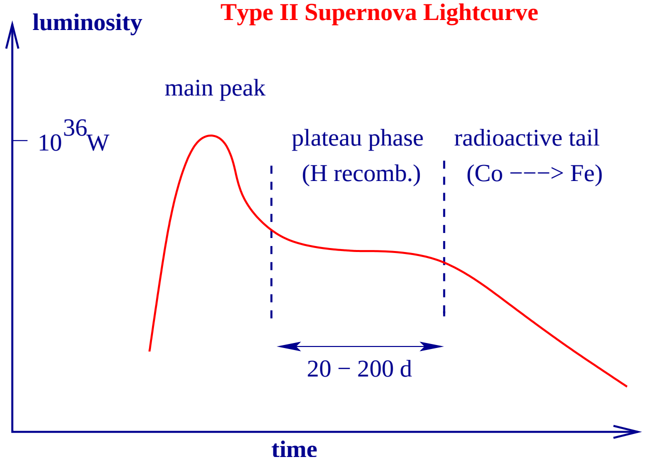
relation no longer 1 to 1 → confusion

- Type Ia (Si lines): thermonuclear explosion of white dwarf
- Type Ib/Ic (no Si; He or no He): core collapse of He star
- Type II-P: "classical" core collapse of a massive star with hydrogen envelope
- Type II-L: supernova with linear lightcurve (thermonuclear explosion of intermediate-mass star? probably not!)

complications

- special supernovae like SN 1987A
- Type IIb: supernovae that change type, SN 1993J (Type II → Type Ib)
- some supernova "types" (e.g., IIn) occur for both explosion types ("phenomenon", not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)

Supernova Lightcurves



- **Explosion energy:** $E \sim 10^{44}$ W ($\sim$ binding energy of Fe core $\sim GM_{Fe}^2/R_{Fe}$ with $M_{Fe} \sim 1\,M_\odot$, $R_{Fe} \sim 2 \times 10^6$ m)
- much larger than the binding energy of the envelope (for $R \sim 10^3\,R_\odot$)

→ kinetic energy $E \sim M_{env}v^2/2$

$$v \simeq \left(\frac{2E}{M_{env}}\right)^{1/2} \sim 3000\,\mathrm{km\,s^{-1}}$$

- energy diffuses out of the expanding ejecta (radius R)
- diffusion time, t_{diff}: $t_{diff} \simeq R^2/(lc)$, where the mean free path l is given by $l = \dfrac{1}{\kappa\rho} \simeq \dfrac{4R^3}{\kappa M_{env}}$ → $t_{diff} \sim \dfrac{M_{env}\kappa}{4Rc}$
- but: $R(t) \simeq vt$, substitute and solve for $t = t_{diff}$

$$\boxed{t_{diff} \simeq \frac{M_{env}^{3/4}\kappa^{1/2}}{2(2E)^{1/4}c^{1/2}} \simeq 150\,\mathrm{d}}$$

(for $E = 10^{44}$ J, $M_{env} = 10\,M_\odot$, $\kappa = 0.034\mathrm{m}^2/\mathrm{kg}$)

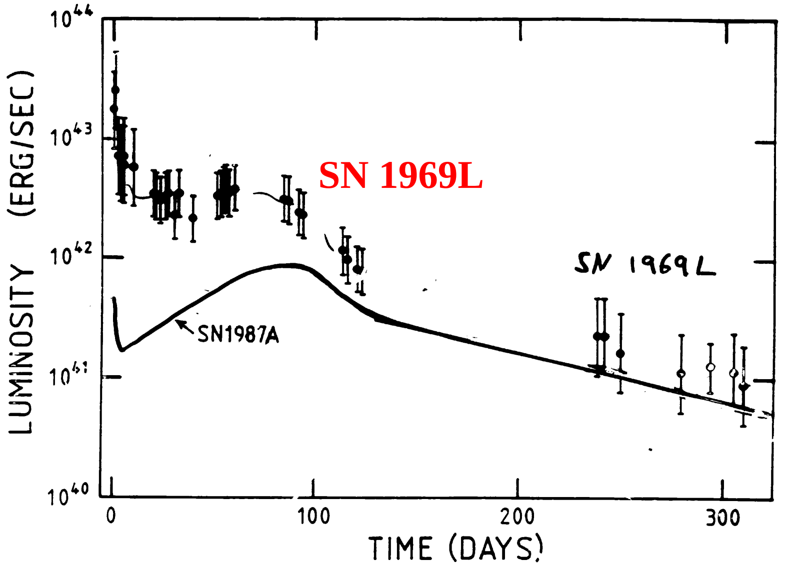
- peak luminosity: $L_{peak} \sim E/t_{diff} \sim 8 \times 10^{36}$ W (a bit high)
- late-time light curve is powered by radioactive decay of Ni and Co

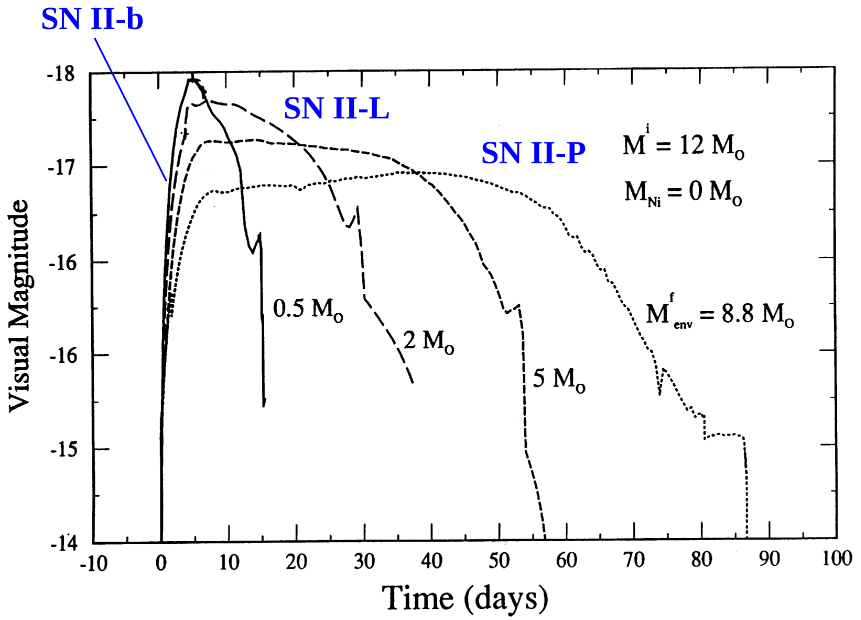
$${}^{56}\mathrm{Ni} \xrightarrow{t_{1/2}=6.1\,\mathrm{d}} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}=77.3\,\mathrm{d}} {}^{56}\mathrm{Fe},$$

- releasing 5.9×10^{41} J and 1.3×10^{42} J for each $0.1\,M_\odot$ of Ni
- radioactive luminosity: $L(t) = L_0 e^{-t/\tau}$, where $\tau = t_{1/2}/\ln 2 \simeq 112$ d
- $E_{tot} = \int_0^\infty L(t)\,dt = \tau L_0 = M_{Ni}c^2\,\varepsilon_{Co}$, $\varepsilon_{Co} \simeq 7 \times 10^{-5}$

→ $$L_{radioact} \simeq 1.3 \times 10^{35}\,\mathrm{W}\left(\frac{M_{Ni}}{0.1\,M_\odot}\right)\exp\left(\frac{-t}{112\,\mathrm{d}}\right)$$

Supernova lightcurves (core collapse)





Hsu, Ross, Joss, P.

LIGHTCURVES OF CORE-COLLAPSE SUPERNOVAE

- central explosion may be very similar in all cases (with $E \sim 10^{44}\,J$)
- variation of lightcurves/supernova subtypes mainly due to varying envelope properties
  - ▷ envelope mass: determines thermal diffusion time and length/existence of plateau
  - ▷ envelope radius: more compact progenitor → more expansion work required → dimmer supernova
- binary interactions mainly affect stellar envelopes
- a large fraction of all stars are in interacting binaries

→ binary interactions are, at least in part, responsible for the large variety of supernova (sub-)types

- recent: new-born pulsars (neutron stars) have large space velocities (median: $200 - 300\,\mathrm{km\,s^{-1}}$)
  → neutron-stars receive a large supernova kick
  - ▷ probably due to asymmetry in neutrino flux (1 %)
  - ▷ momentum balance:

$$M_{NS}\, v_{kick} = \epsilon\, \frac{E_\nu}{c} \quad \text{(neutrino momentum)}$$

$$\rightarrow \quad v_{kick} \simeq 350\,\mathrm{km\,s^{-1}} \left(\frac{\epsilon}{0.01}\right)$$

(ϵ: anisotropy factor, $M_{NS} = 1.4\,M_\odot$, $E_\nu = 3 \times 10^{46}\,J$)

http://www-supernova.lbl.gov/

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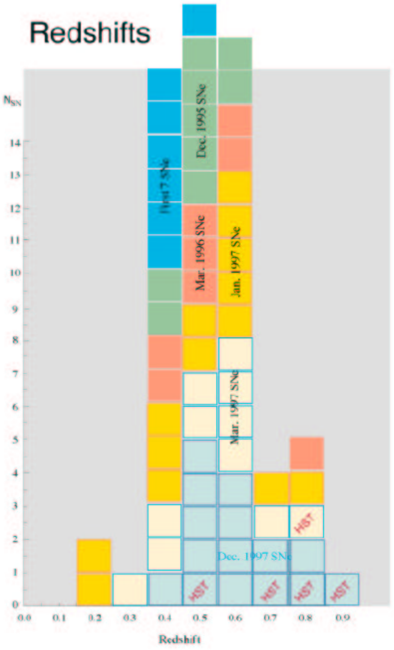
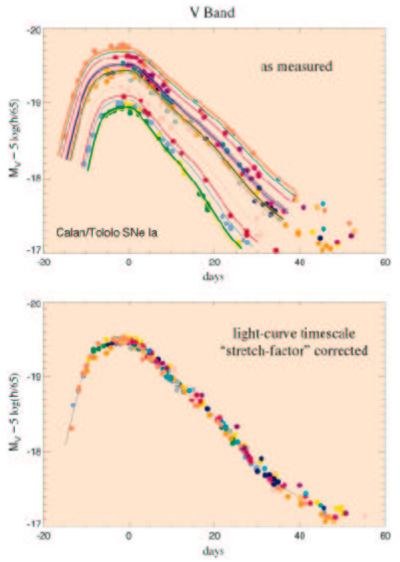


We have discovered well over 50 high redshift Type Ia supernovae so far. Of these, approximately 50 have been followed with spectroscopy and photometry over two months of the light curve. The redshifts shown in this histogram are color coded to show the increasing depth of the search with each new "batch" of supernova discoveries. The most recent supernovae, discovered the last week of 1997, are now being followed over their lightcurves with ground-based and (for those labeled "HST") with the Hubble Space Telescope.

Low Redshift Type Ia Template Lightcurves



Type Ia supernovae observed "nearby" show a relationship between their peak absolute luminosity and the timescale of their lightcurve: the brighter supernovae are slower and the fainter supernovae are faster (see Phillips, *Ap.J.Lett.*, 1993 and Riess, Press, & Kirshner, *Ap.J.Lett.*, 1995). We have found that a simple linear relation between the absolute magnitude and a "stretch factor" multiplying the lightcurve timescale fits the data quite well until over 45 restframe days past peak. The lower plot shows the "nearby" supernovae from the upper plot, after fitting and removing the stretch factor, and "correcting" peak magnitude with this simple calibration relation.

TYPE IA SUPERNOVAE

- recently: Type Ia supernovae have been used as standard distance candles to measure the curvature of the Universe → accelerating Universe?
- Type Ia supernovae are no good standard candles! (peak luminosities vary by a factor up to 10)
- but they may be standardizable candles, i.e. there appears to be a unique relation between peak luminosity and the width of the lightcurve which can be used to derive good distances

Caveats:

- the relation between lightcurve shape and peak luminosity is not well understood (depends on diffusion time and probably opacity)
- the progenitors of Type Ia supernovae are not known
- many progenitors models
  - ▷ Chandrasekhar white dwarf accreting from a companion star (main-sequence star, helium star, subgiant, giant)
    Problem: requires fine-tuning of accretion rate
  - ▷ merging of two CO white dwarfs with a total mass > Chandrasekhar mass (probably not, more likely to lead to formation of neutron star)
  - ▷ sub-Chandrasekhar mass white dwarfs (helium shell flash leading to a detonation of the white dwarf; extremely unlikely!)

IMPORTANT STELLAR TIMESCALES

- dynamical timescale: $t_{\rm dyn} \simeq \dfrac{1}{\sqrt{4G\rho}}$

$$\sim 30\,{\rm min}\,\left(\rho/1000\,{\rm kg\,m^{-3}}\right)^{-1/2}$$

- thermal timescale (Kelvin-Helmholtz): $t_{\rm KH} \simeq \dfrac{GM^2}{2RL}$

$$\sim 1.5\times10^{7}\,{\rm yr}\,(M/M_\odot)^2\,(R/R_\odot)^{-1}\,(L/L_\odot)^{-1}$$

- nuclear timescale: $t_{\rm nuc} \simeq \underbrace{M_c/M}_{\text{core mass}}\;\underbrace{\eta}_{\text{efficiency}}\;(Mc^2)/L$

$$\sim 10^{10}\,{\rm yr}\,(M/M_\odot)^{-3}$$

Example	$t_{\rm dyn}$	$t_{\rm KH}$	$t_{\rm nuc}$
main-sequence stars			
a) $M = 0.1\,M_\odot$, $L = 10^{-3}\,L_\odot$, $R = 0.15\,R_\odot$	4 min	10^9 yr	10^{12} yr
b) $M = 1\,M_\odot$, $L = 1\,L_\odot$, $R = 1\,R_\odot$	30 min	15×10^6 yr	10^{10} yr
c) $M = 30\,M_\odot$, $L = 2\times10^5\,L_\odot$, $R = 20\,R_\odot$	400 min	3×10^3 yr	2×10^6 yr
red giant ($M = 1\,M_\odot$, $L = 10^3\,L_\odot$, $R = 200\,R_\odot$)	50 d	75 yr	
white dwarf ($M = 1\,M_\odot$, $L = 5\times10^{-3}\,L_\odot$, $R = 2.6\times10^{-3}\,R_\odot$)	7 s	10^{11} yr	
neutron star ($M = 1.4\,M_\odot$, $L = 0.2\,L_\odot$, $R = 10$ km, $T_{\rm eff} = 10^6$ K)	0.1 ms	10^{13} yr	

END STATES OF STARS

Three (main) possibilities

- the star develops a degenerate core and nuclear burning stops (+ envelope loss) → degenerate dwarf (white dwarf)
- the star develops a degenerate core and ignites nuclear fuel explosively (e.g. carbon) → complete disruption in a supernova
- the star exhausts all of its nuclear fuel and the core exceeds the Chandrasekhar mass → core collapse, compact remnant (neutron star, black hole)

Final fate as a function of initial mass (M_0) for $Z = 0.02$

$M_0 \lesssim 0.08\,M_\odot$	no hydrogen burning (degeneracy pressure + Coulomb forces)	planets, brown dwarfs
$[0.08, 0.48]\,M_\odot$	hydrogen burning, no helium burning	degenerate He dwarf
$[0.48, 8]\,M_\odot$	hydrogen, helium burning	degenerate CO dwarf
$[8, 13]\,M_\odot$	complicated burning sequences, no iron core	neutron star
$[13, 80]\,M_\odot$	formation of iron core, core collapse	neutron star, black hole
$M_0 \gtrsim 80\,M_\odot$	pair instability? complete disruption?	no remnant
also (?) $[6, 8]\,M_\odot$	degenerate carbon ignition possible (but unlikely), complete disruption	no remnant