- We bid a fond farewell to black holes and start a new topic…

supernova and supernova remnants

"Thank you, Blake, for that riveting presentation on black holes."

Why Study Supernova Remnants?

Supernova explosion:
How is mass and energy distributed in the ejecta?
What was the mechanism of the supernova explosion?
What and (how much) elements were formed in the explosion, and how?
What are the characteristics of the compact stellar remnant?

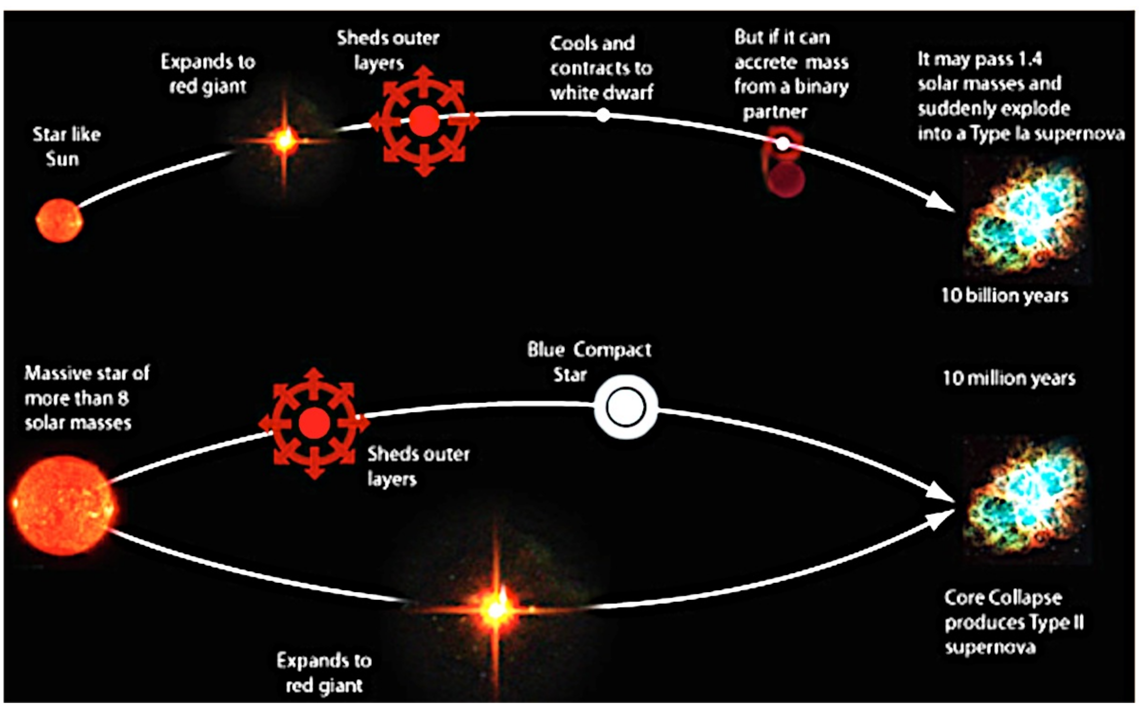
Shock physics:
How is energy distributed between electrons, ions, and cosmic rays in the shock?
How do electrons and ions share energy behind the shock?

Interstellar medium:
What is the structure of the interstellar medium, and how does the shock interact with that structure?
How is the ISM enriched and ionized- how are the metals created and distributed

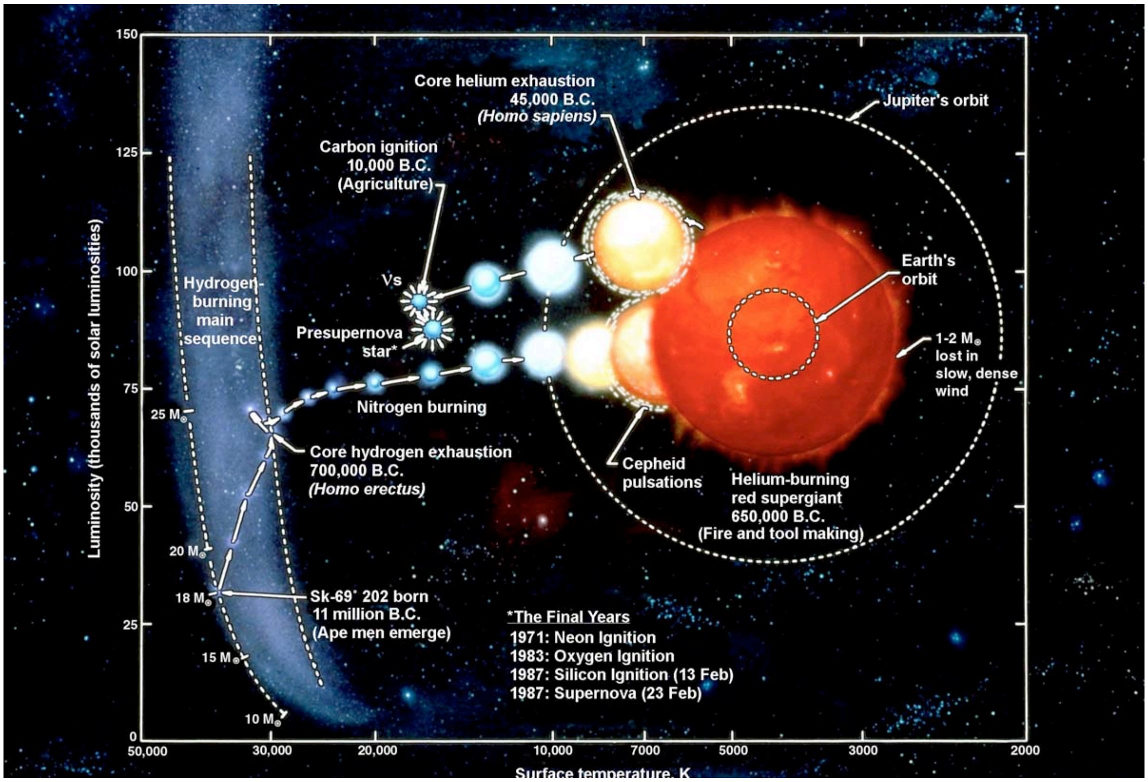
Supernova- See ch 13.1 of Longair

- Supernova come in two types (I and II)
  - Type Ia is the explosion of a white dwarf pushed over the Chandrasekar limit- details are not understood
    - However they are used as a 'standard candle' for cosmology
  - Type Ib and II is the explosion of a massive star after it has used up its nuclear fuel- massive $M>8M_\odot$ star
- Type I supernovae do not show hydrogen in their spectra. Type Ia supernovae reach peak luminosities of about 2×10^{43} erg/s (e.g. $10^{10}L_\odot$)
- Type II supernovae show hydrogen in their spectra. Their light curves are diverse, with peak luminosities $\sim 10^{42}$ erg/s

Two Paths to a SNe



The Life of SN1987A- AKA SK-69-202



How to Get to a Type I

- Route to a type I is very complex and not well understood
- There maybe several evolutionary paths

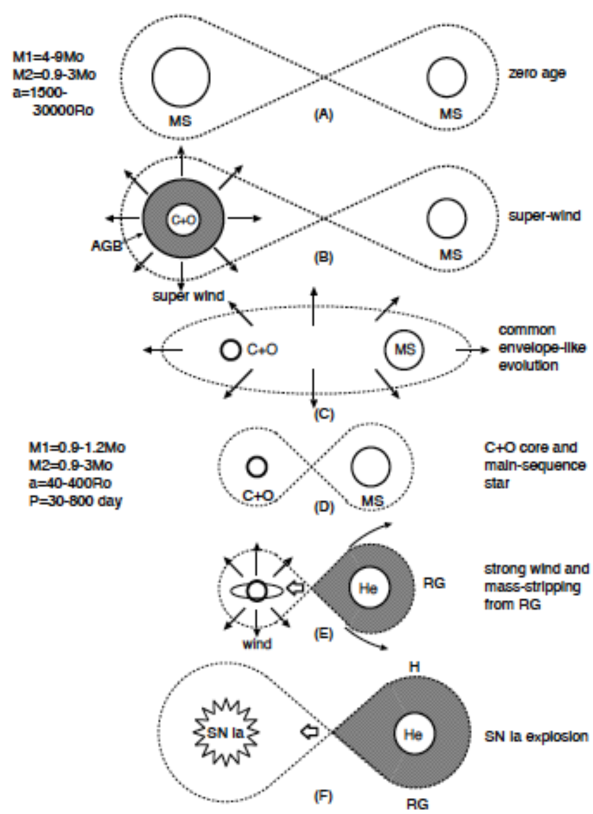


FIGURE 2. An illustration of the WD+RG (symbiotic) channel to Type Ia supernovae.

Formation of Black Holes in SN Explosions

- The formation of BHs occurs at the end of the nuclear burning phase in massive stars and can proceed via two routes.
  – For the lower mass end of BH formation, a meta-stable proto-neutron star (NS) is produced, followed by the formation of a BH through accretion of the part of the stellar envelope that was not expelled in the supernova explosion.
- Direct collapse (sometimes called failed supernova) into a BH occurs in the case of the most massive stars.

The mass of the remnant is determined by the mass of the star at the moment of collapse, and the explosion energy

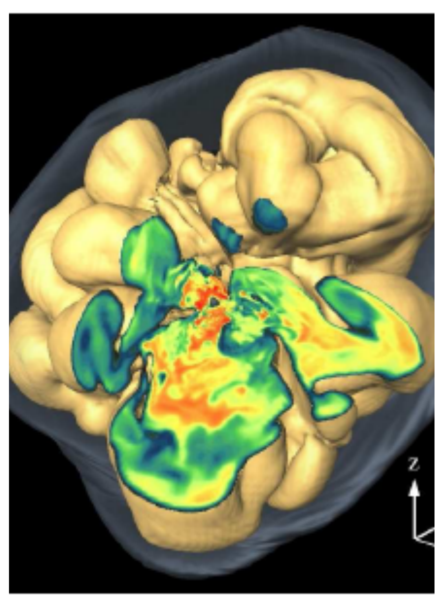
It Ain't Simple

- Two basic scenarios of stellar death:
  – thermonuclear runaway at

degenerate conditions (drives the destruction of white dwarf stars in Type Ia Sne)

  – implosion of stellar cores (associated with what is called core-collapse supernovae (CCSNe) of Types II, Ib/c,
- Violent, large-scale nonradial mass motions are generic in supernova cores
- For a detailed discussion see **Explosion Mechanisms of Core-Collapse Supernovae**

H.-Thomas Janka **arXiv:1206.2503**

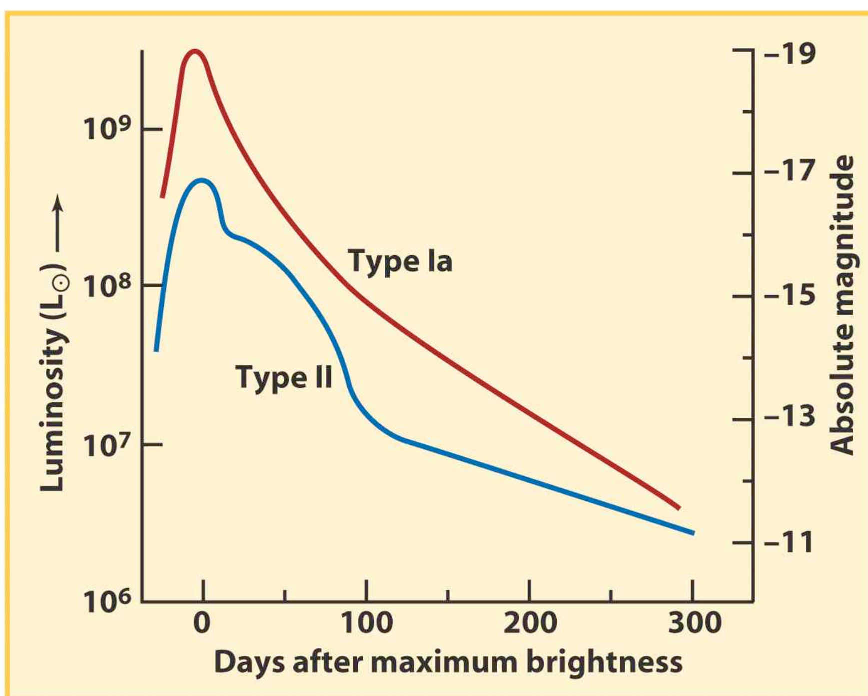


Types of Supernovae table 13.1 of Longair

Type Ia	Type II
• No H, He in spectrum	Both H, He in spectrum
• No visible progenitor (WD)	Supergiant progenitor
• Kinetic Energy: 10^{51} erg	Kinetic Energy: 10^{51} erg
• Total EM Radiation: 10^{49} erg	Total EM Radiation: 10^{48-49} erg
• Likely no neutrino burst	Neutrinos: 10^{53} erg
• Rate: 1/300 yr in Milky Way Rate:	1/50 yr in Milky Way
• Occur in spirals and ellipticals	Occur mainly in spiral galaxies
• No remnant	NS or BHs
• most of the explosion energy is in heavy element synthesis and kinetic energy of the ejecta	vast majority of the energy is in neutrino emission ,

Type II events occur during the regular course of a massive star's evolution. a Type Ia supernova, needs several very specific events to push the white dwarf over the Chandrasekhar limit.(adapted from Type Ia Supernovae and Accretion-Induced Collapse Ryan Hamerly) 9

- Two classes of light curves



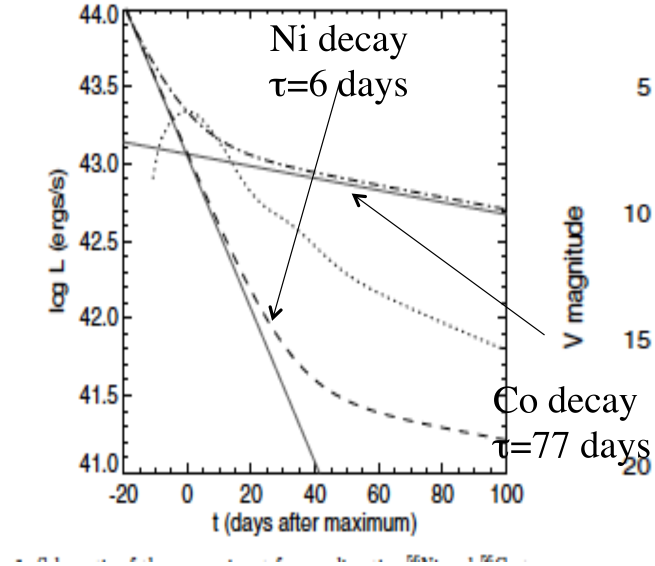
Rosswog and Bruggen fig 4.3

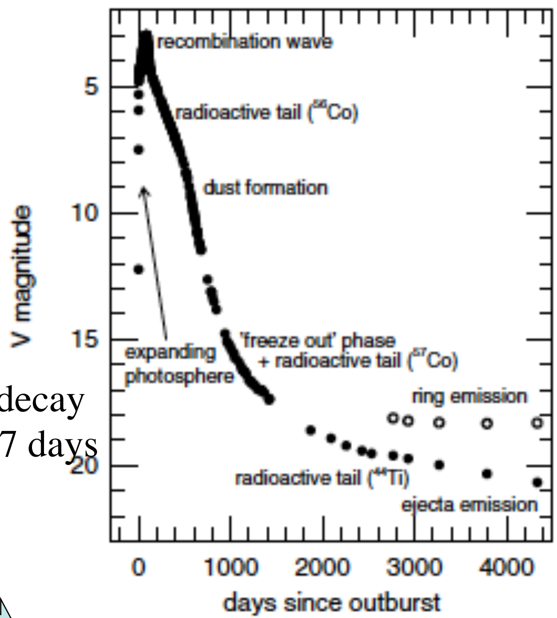
SN Light Curves

Type Ia

Bruno Leibundgut

Type II



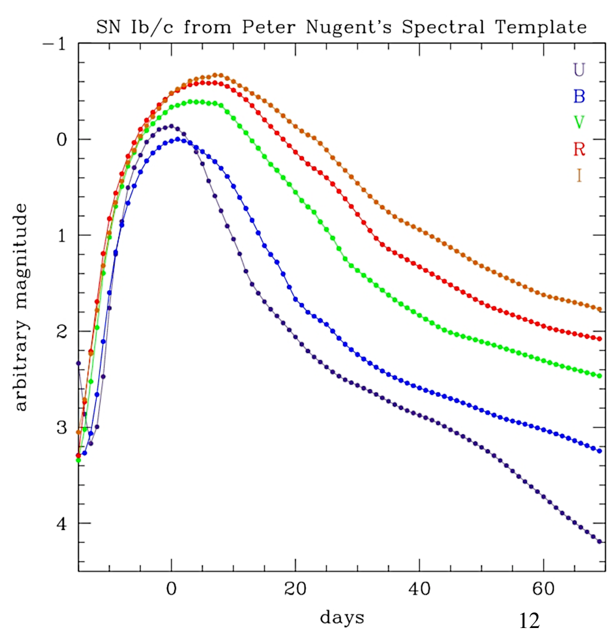


$^{56}Ni + e^-$ → $^{56}Co + \nu$; $^{56}Co + e$ → $^{56}Fe + \nu$

Fig 13.5 of Longair

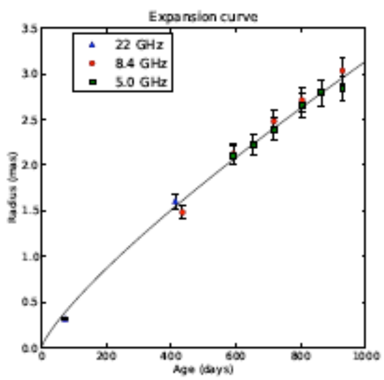
Technical Issue

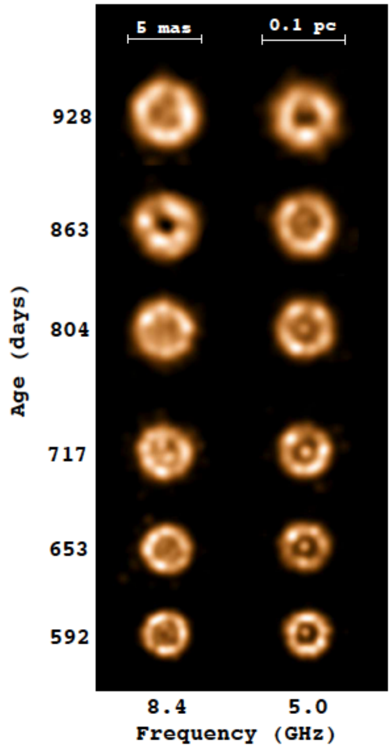
- Optical light curve depends on color due to radiative transfer effects in SN atmosphere



Super Nova and Super Nova Remnants

- Types of Super Nova
- Explosions
- Nucleosynthesis
- Physics of Supernova remnants
- Particle Acceleration
- Cosmology?

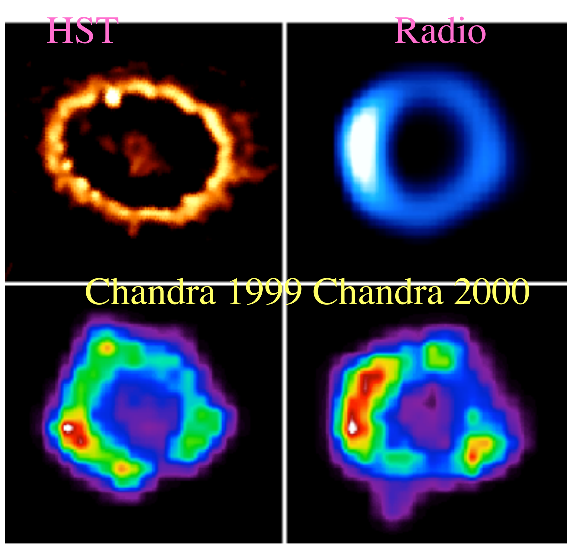




Radio images of SN2008 in M82 -Size vs time

SuperNova Remnants

- We will distinguish between
  - SN explosions (the actual events and the next few years) and
  - Remnants - what happens over the next few thousand years.



SN 1987A observed in 1999, 2000

SNRs enrich the ISM by dispersing material produced both during the star's life and at the moment of the SN event.

~2 per century for Milky Way (all types)

Supernova Remnants

SNRs are probes both of their progenitor star (and of their pre-supernova life) and of the medium into which they explode (the ISM)

They are also cosmic accelerators (cosmic rays).

Birth places of neutron stars and stellar mass black holes.

laboratories for study of magnetic fields, shock physics, jets, winds, nuclear physics etc

- SNR evolution (and their appearance now) depends on many factors:
  - age
  - environment (density)
  - total energy of the explosion
  - progenitor star (mass, type of SN associated..)

- For first ~1000 days the luminosity is driven by radioactive decay (type Ia)

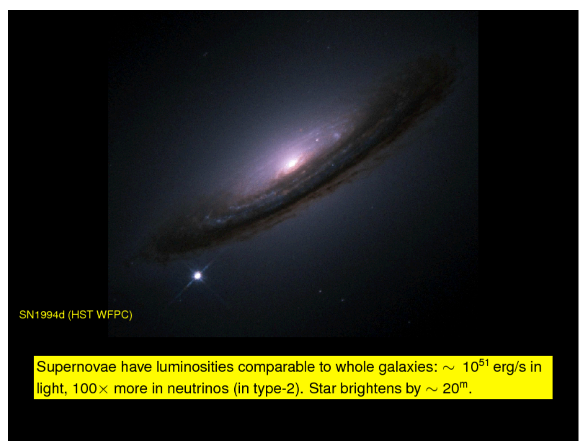
Ni^{56} → Co^{56} → Fe^{56} (77 day 1/2 life)

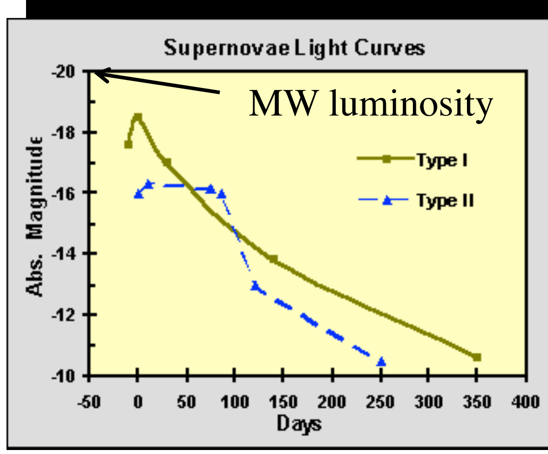
Velocities of gas seen in the optical is ~10^4 km/sec

$E \sim 1/2Mv^2 \sim 10^{51}\, M_\odot v_4^2$ ergs

Luminosity of SN ~ that of the host galaxy- can be seem to z>1

v_4 in units of 10^4 km/sec





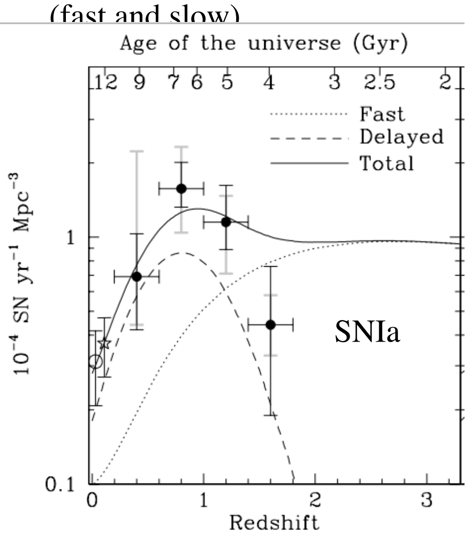
Supernovae and Supernova Remnants

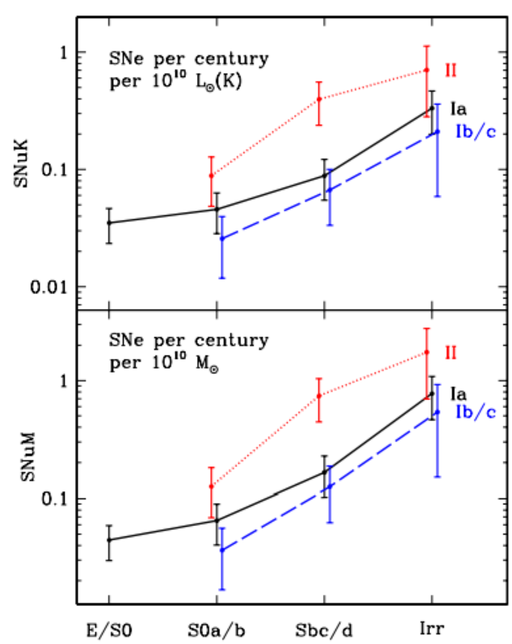
Supernovae
T~ 5000 K characteristic kT of photospheric emission during early period
characteristic emission is optical and infrared
timescale ~ year

Supernova remnants
powered by expansion energy of supernova ejecta,
dissipated as the debris collides with interstellar material
generating shocks
T ~ 10^{6-7} K
characteristic thermal emission is X-rays
timescale ~100-10,000 years (youngest SN in MW is ~110years old)

SN Rate vs Time and Galaxy Properties

- the Ia SN rate per unit mass changes with galaxy morphology , colors and cosmic time
- it increases by a factor of about 4 from E/S0 to Sbc/d, up to a factor of about 17 in Irr galaxies
- Argues for 2 populations of SNIa (fast and slow)

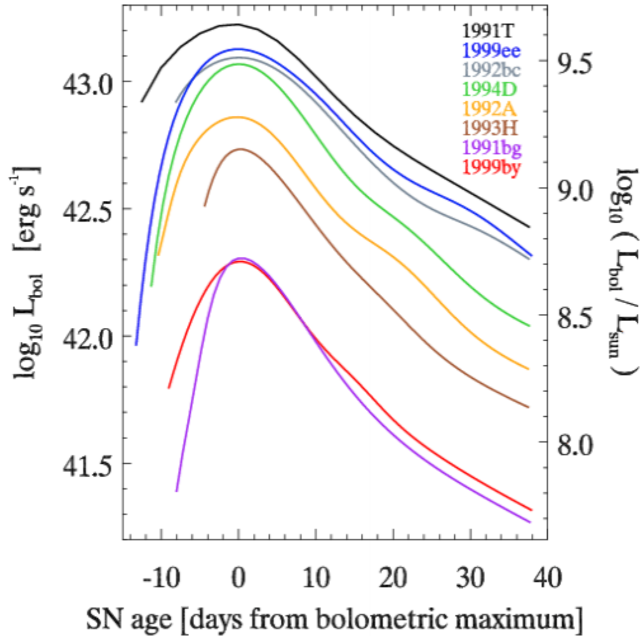




Mannucci 2005

- From total luminosity derive M_{Ni} that has been synthesized and thus the amount of Fe that has been produced.
- SNe Ia :the main producer of iron in the universe. Their progenitors have long life times.
- $L \sim 1.1 \times 10^{50}$ ergs= $0.6 M_{\odot}$ of Ni
- Light curves are rather homogenous- suggesting little variation in the nature of the progenitor (?)
  - Thought 2 possibilities
    - merger of 2 white dwarfs
    - or white dwarf collapse due to accretion

Type Is



Type Ia's

- Why a thermonuclear explosion of a white dwarf?
  - Kinetic energy of ejecta ~5×10^{17} erg/gm (~$1/2v^2$~$(10^4$km/sec$)^2$) is similar to nuclear burning energy of C/O to Fe (~1 Mev/ nucleon)
  - lack of remant (e.g. NS or BH)
  - occurance in elliptical galaxies with no star formation
- But (Rosswog and Bruggen pg 136)
  - No consensus on
    - mass of WD or its composition
    - origin of accreted material
    - exact explosion mechanism

Supernova Explosions

Ia Thermonuclear Runaway

• Accreting C-O white dwarf reaches Chandrasekhar mass limit, undergoes thermonuclear runaway- have to accrete matter at the right rate (too slow and get burning on WD surface and produce a novae; need $dm/dt > 4x10^{-8}$ M/yr)

•Type I supernovae: no hydrogen in their spectra- reach peak luminosities ~ 2 × 10^{43} erg/s

• Results in total disruption of progenitor (no remnant NS or BH)

• Explosive synthesis of Fe-group plus some intermediate mass elements (e.g., Si)

• Uncertain mechanism and progenitor: probably a delayed detonation (flame transitions from subsonic to supersonic speed) or deflagration

•Amount of Ni synthesized is not the same from object to object

- ➔**different ejecta mass**
- ➔**different explosion energies**
- ➔**asymmetries in the explosions**
- ➔**differences in the explosion physics**

Type Ia- How the Explosion Occurs

- Deflagration wave
- Deflagration-

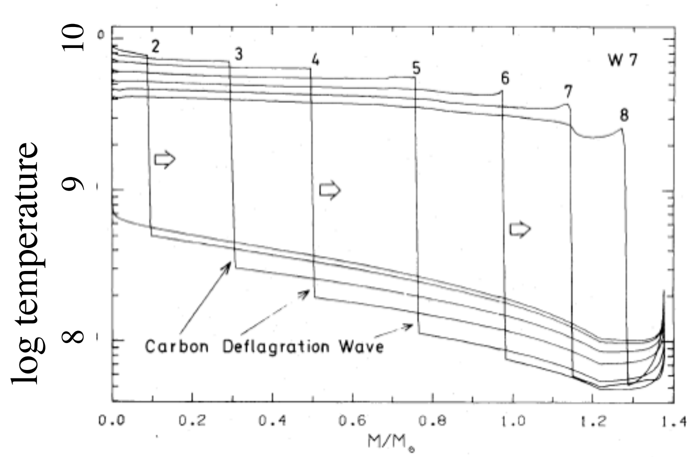
"Combustion" that propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat.

In main sequence stars $T_c \sim 10^8$ K to ignite helium core burning- in SNIa $T_{core} \sim 10^{10}$ K

Detailed physics is still controversial!

Fundamental reason: nuclear burning rate in SnIa conditions $\sim T^{12}$

'flame' ~ 1cm thick, White dwarf has $r \sim 10^8$cm

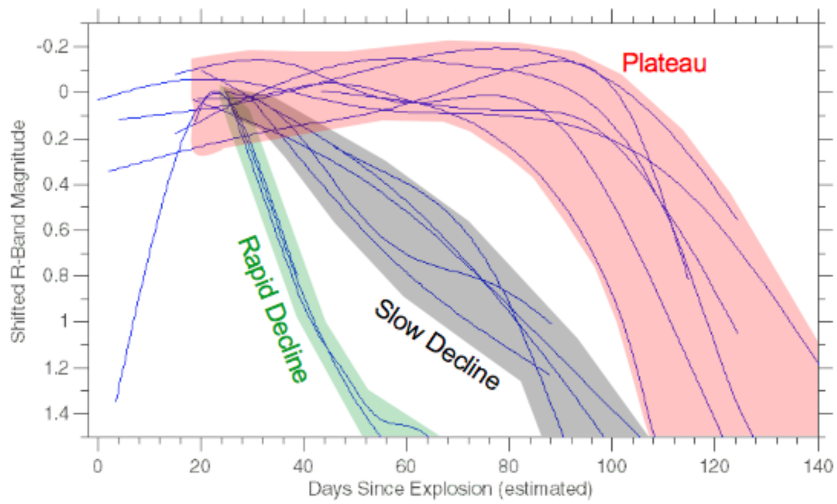


mass shell

Deflagration wave in WD
time steps are at 0, 0.6, 0.79, 0 .91, 1.03, 1.12, 1.18, 1.24 **sec**

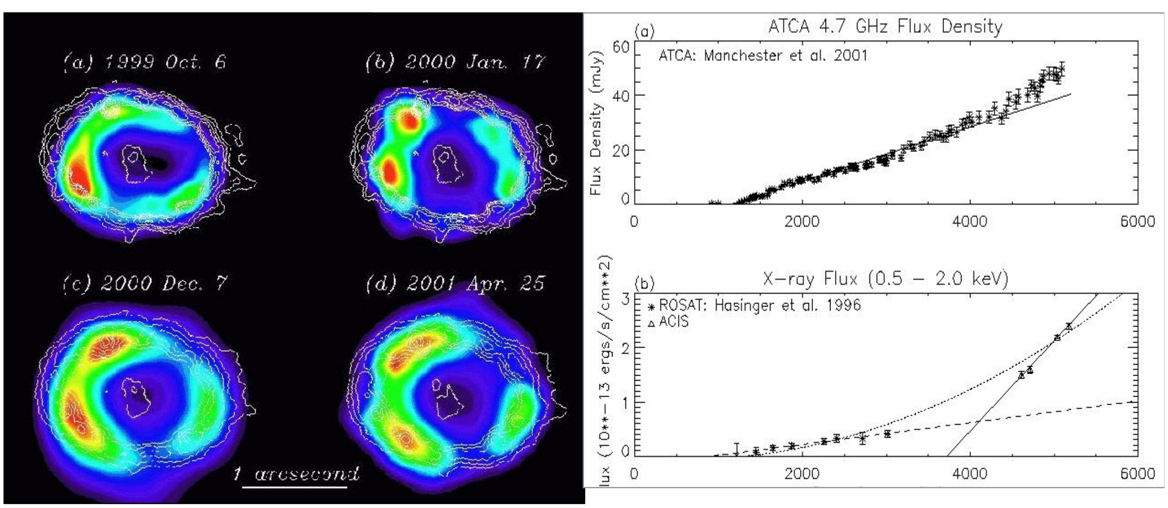
SN II

- Wide Variety of Light Curves- assume wide range of progenitors
- Type II supernovae - implosion-explosion events of a massive star. They show a characteristic plateau in their light curves a few months after explosion
- . This plateau is reproduced by models which assume that the energy comes from the expansion and cooling of the star's outer envelope as it is blown away



SNR 1987A in Large Magellanic Cloud-

Pre SN explosion images showed star that exploded



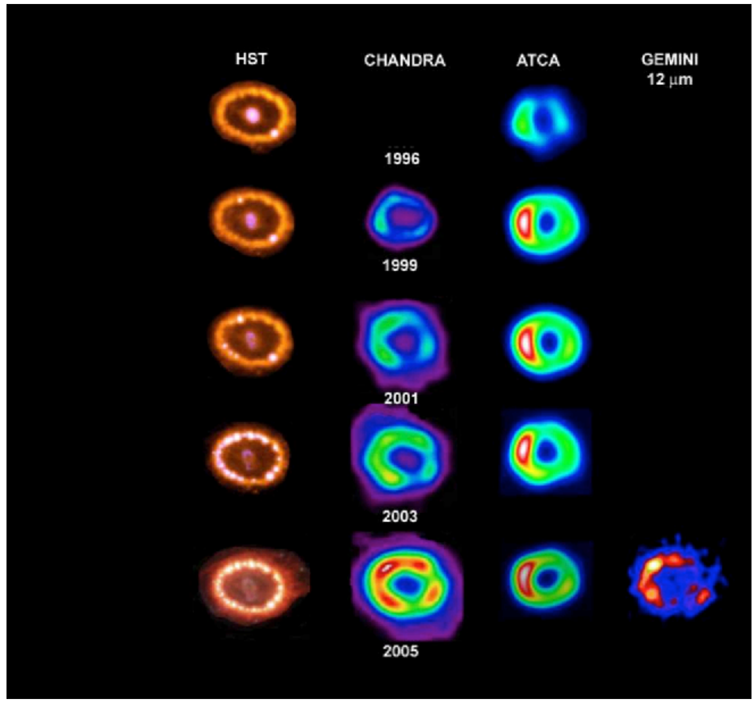
Park et al. 2002 , Burrows et al. 2001

days since explosion

X-ray emission is approaching inner circumstellar ring
X-rays correlate with radio

Young SN remnants evolve rapidly

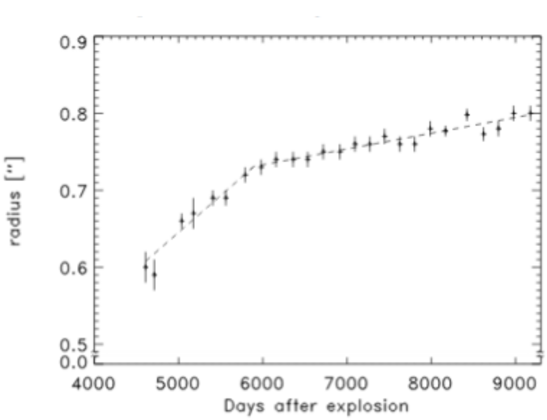
Some extragalactc SN have been followed for years

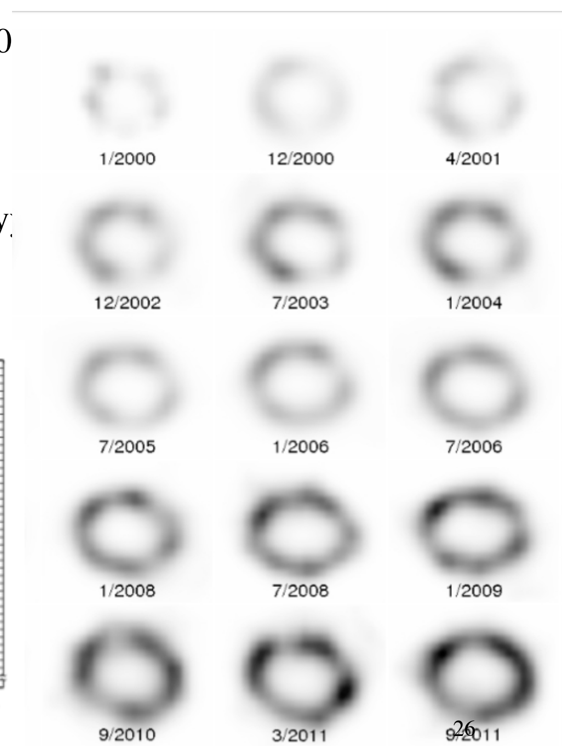


SN 1987A (Type II) Through Time in Different Wave Bands

Sn 1987A X-ray Evolution

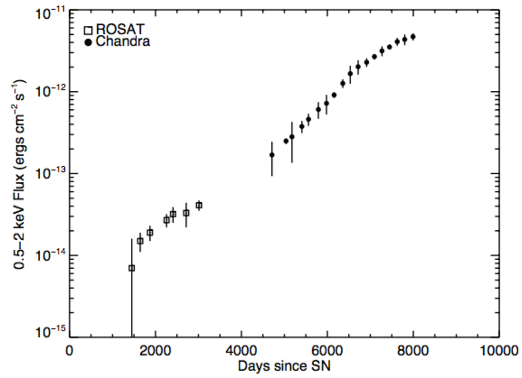
- a velocity of 8500 km/sec util day 590 then a slow down to 1820 km/sec
- consistent with the idea that the forward shock only fully started to interact with the equatorial ring at day ~600

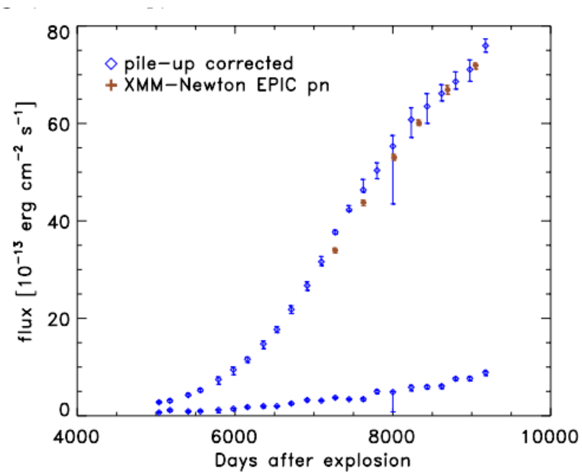




c morphology (corrected for the *Chandra* PSF) of SN 1987A at all epochs u

1987A - Latest X-ray Light Curves





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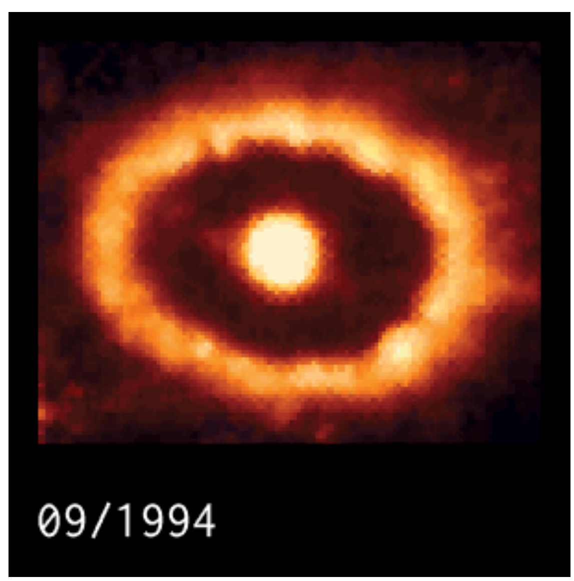
1987A

~24 neutrinos were detected within 12 hours before the optical light was detected-

confirmation that neutrinos carry most of the energy

Direct detection of ^{56}Co γ-ray lines



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1987A with HST

~

Evidence for Two Distinct Populations of Type Ia Supernovae

- Type Ia supernovae (SNe Ia) have been used as excellent standardizable candles for measuring cosmic expansion, but their progenitors are still elusive... the spectral diversity of SNe Ia is tied to their birthplace environments. ...SNIa with high-velocity ejecta are substantially more concentrated in the inner and brighter regions of their host galaxies than are normal-velocity SNe Ia ... and are in larger and more luminous hosts... suggesting that high-velocity SNe Ia originate from younger and more metal-rich progenitors and are only found in galaxies with substantial chemical evolution.

Explosive Nucleosynthesis-Type IIs

(Details see 13.1.4 of Longair)

Nuclear processing as the supernova shock wave propagates through the star (see Arnett 1996)

'α' products

C burning produces O, Ne, Mg, etc
T ~ 2 x 10^9 K

Ne burning produces O, Mg, etc
T ~ 2.3 x 10^9 K

O burning produces Si, S, Ar, Ca, etc
T ~ 3.5 x 10^9 K

Si burning produces Fe, Si, S, Ca, etc T ~ 5 x 10^9 K

stops at Fe