Supernova

Historical Supernovae

Designation	Year	Distance	Type	Height
	1006	2.4	I	0.6
Crab	1054	2	I/II	0.2
	1181	8		0.43
Tycho	1572	6	I	0.15
Kepler	1604	10	1	1.2
Cas A	1667	3	II	0.11
	1987	600	II	---

Miscellaneous Important “Facts”

- Rate: 1 per 30 - 100 years in the Milky Way
- $M_V \sim -19$
- $L \sim 10^{10} L_{\odot}$
- Total Integrated Light Output: 10^{49} ergs
- Note that the gravitational energy release of 1 $M_{\odot}$ collapsing from 700000 km to 2000 km is about 10^{51} ergs.

Type I Supernovae

Basic Classification is on Light Curve and Spectra

- Rise Time: Several days – decline rapidly for about 30 days – then go into an essentially exponential decay: $L = L_0 e^{-t/\tau}$ where τ the time constant is about 70 days.
- There appears to be little variation in the shape of the light curve except scaling to the maximum brightness – this allows them to be used as a standard candle.
- They occur in all galaxy types with a comparable rate in spirals and ellipticals drawn from an older population.

Type I SN

- Note that the ones seen today must be formed from low mass stars. However, the SN of the original population of the galaxy did not necessarily have low mass.
- H lines are not observed.

Type II Supernovae

- Same rise time as Type I
- Initial decline covers about 25 days then the brightness hits a plateau where it stays for about 50 - 100 days. After this there is a further rapid decline and then a gradual decrease.
- The light curves do not repeat well and vary from object to object.
- They occur only in spirals and are found in the arms (not the bulge). If they originated in the arms then they are of age 10^7 years 10 $M_{\odot}$.

Supernovae Rate and Comparison

- The rate of SN is somewhere in the range 1 every 30 to 300 years / galaxy – this is independent of type.
- Note that Type I's did not occur/become common until "late" in the history of the Universe. Scenario is mass deposition onto a WD causing a carbon deflagration. Therefore must evolve to a WD in a close binary system.
- Type II are brighter that Type I by about a magnitude, but the integrated light is less.

SN Spectra

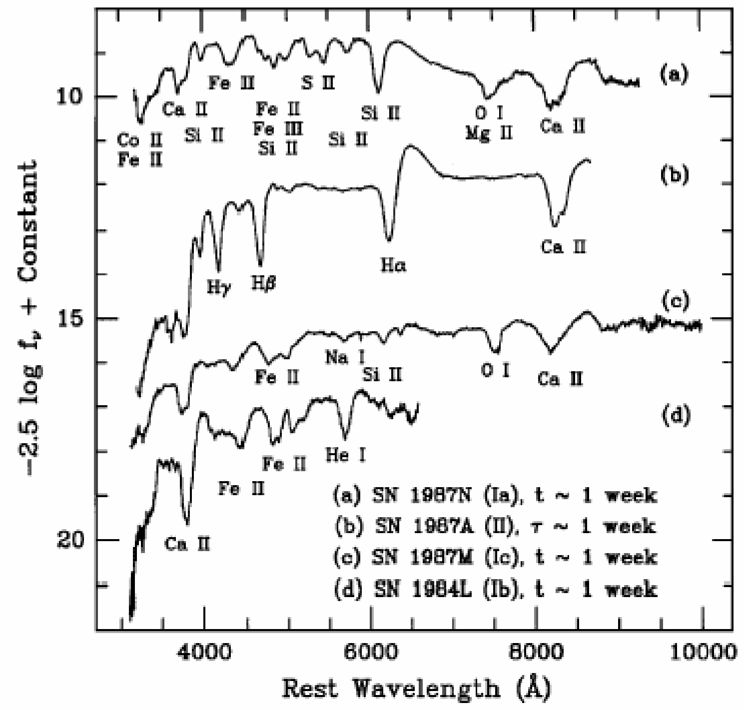

Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables *t* and τ represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

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- Early spectra (near maximum) have a nearly BB distribution with features imposed.
- Lines are broad: both absorption and emission.
- The absorption widths indicate velocities of ejection of 10^4 km/s.

Late SN Spectra

- Type I have no H but Type II do is the most basic criteria.

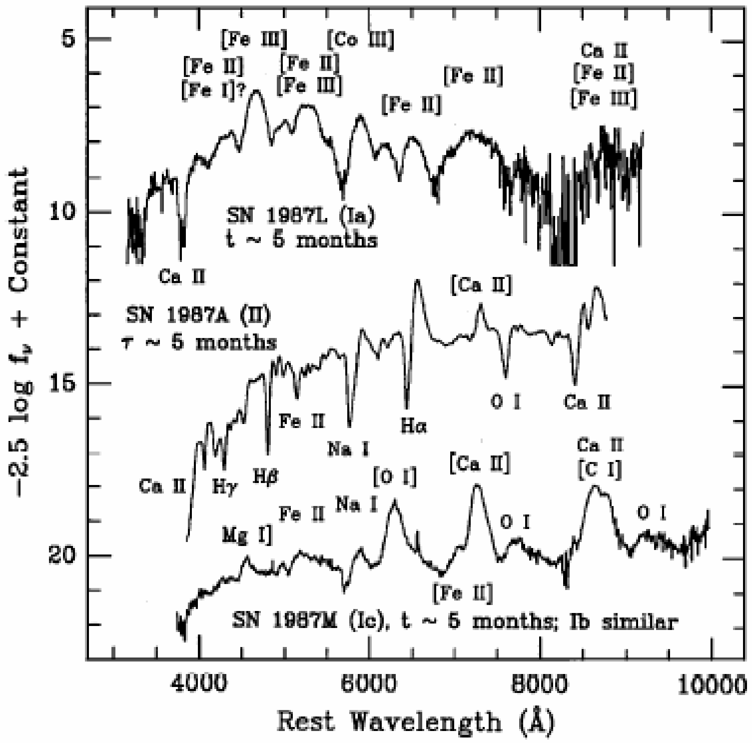


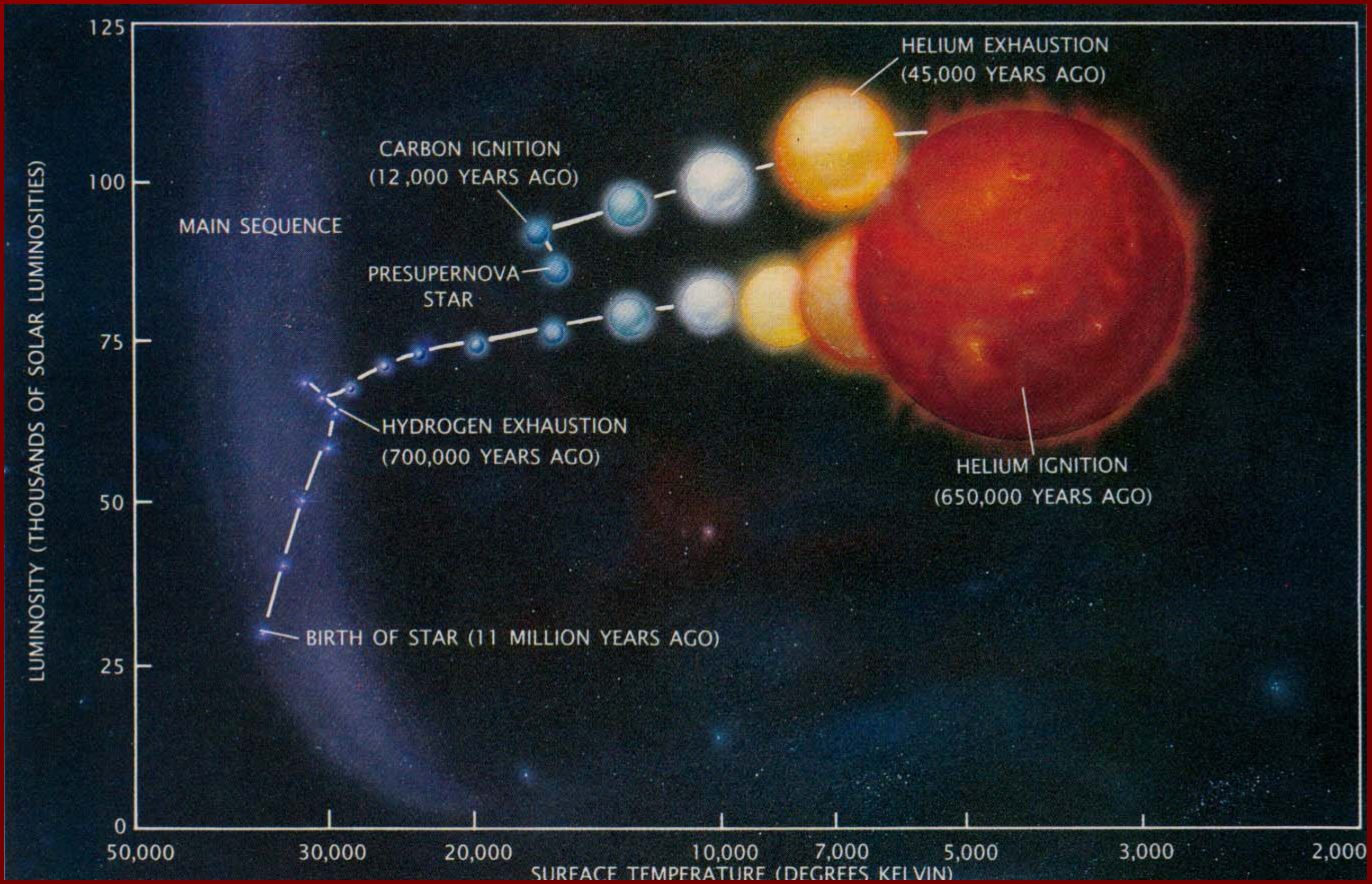
Figure 2 Spectra of SNe, showing late-time distinctions between various types and subtypes. Notation is the same as in Figure 1. The parent galaxy of SN 1987L is NGC 2336 (cz = 2206 km s^{-1}); others are listed in the caption of Figure 1. At even later phases, SN 1987A was dominated by strong emission lines of Hα, [O I], [Ca II], and the Ca II near-IR triplet, with only a weak continuum.

The Evolution of 15 and 25 M Supernovae of Type II

Stan Woosley

- Evolutionary Stages
- The Last Years of A Massive Star
  - Neutrino Energy Loss
- Once the Fe core has formed no further burning is possible
  - Once the energy sources have died the core concentration and heating leads to photodisintegration of Fe. This is a major energy sink for the star. It leads to the gravitational collapse of the core.
- Pre-SN composition.

Evolution through Si Burning I.



Evolution through Si Burning II.

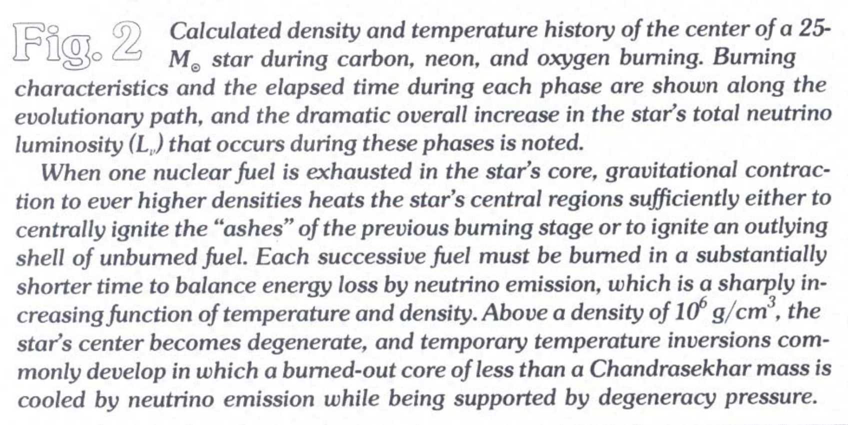
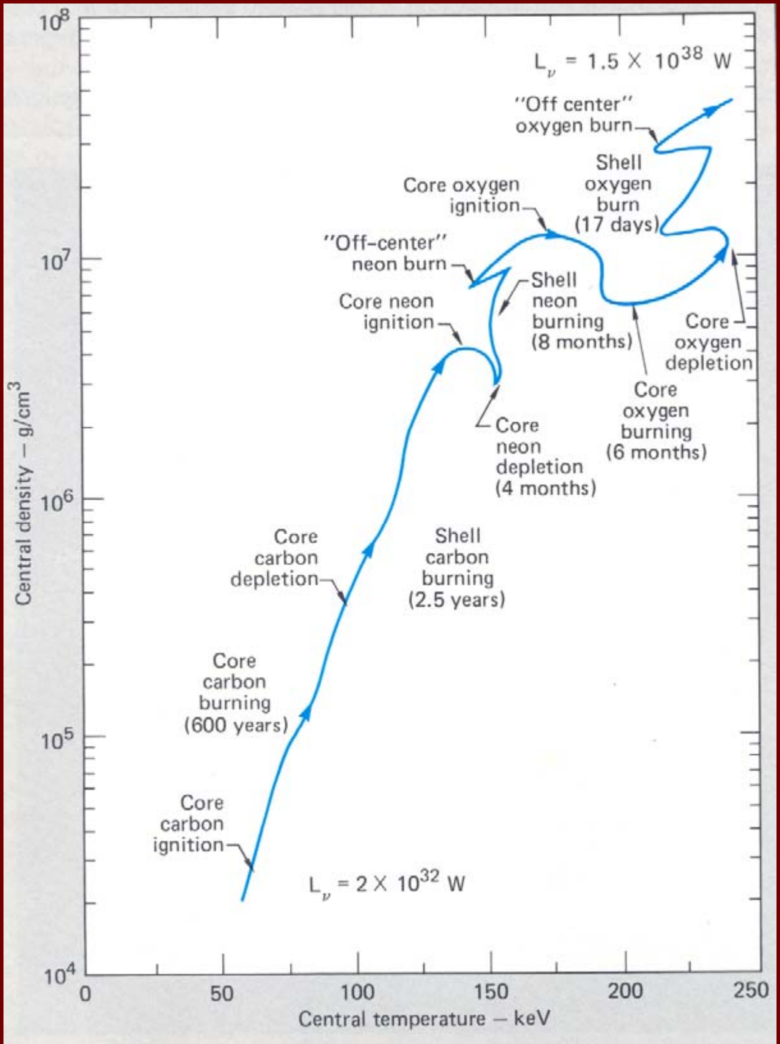


Fig. 2 *Calculated density and temperature history of the center of a 25-$M_\odot$ star during carbon, neon, and oxygen burning. Burning characteristics and the elapsed time during each phase are shown along the evolutionary path, and the dramatic overall increase in the star's total neutrino luminosity (L_ν) that occurs during these phases is noted.*

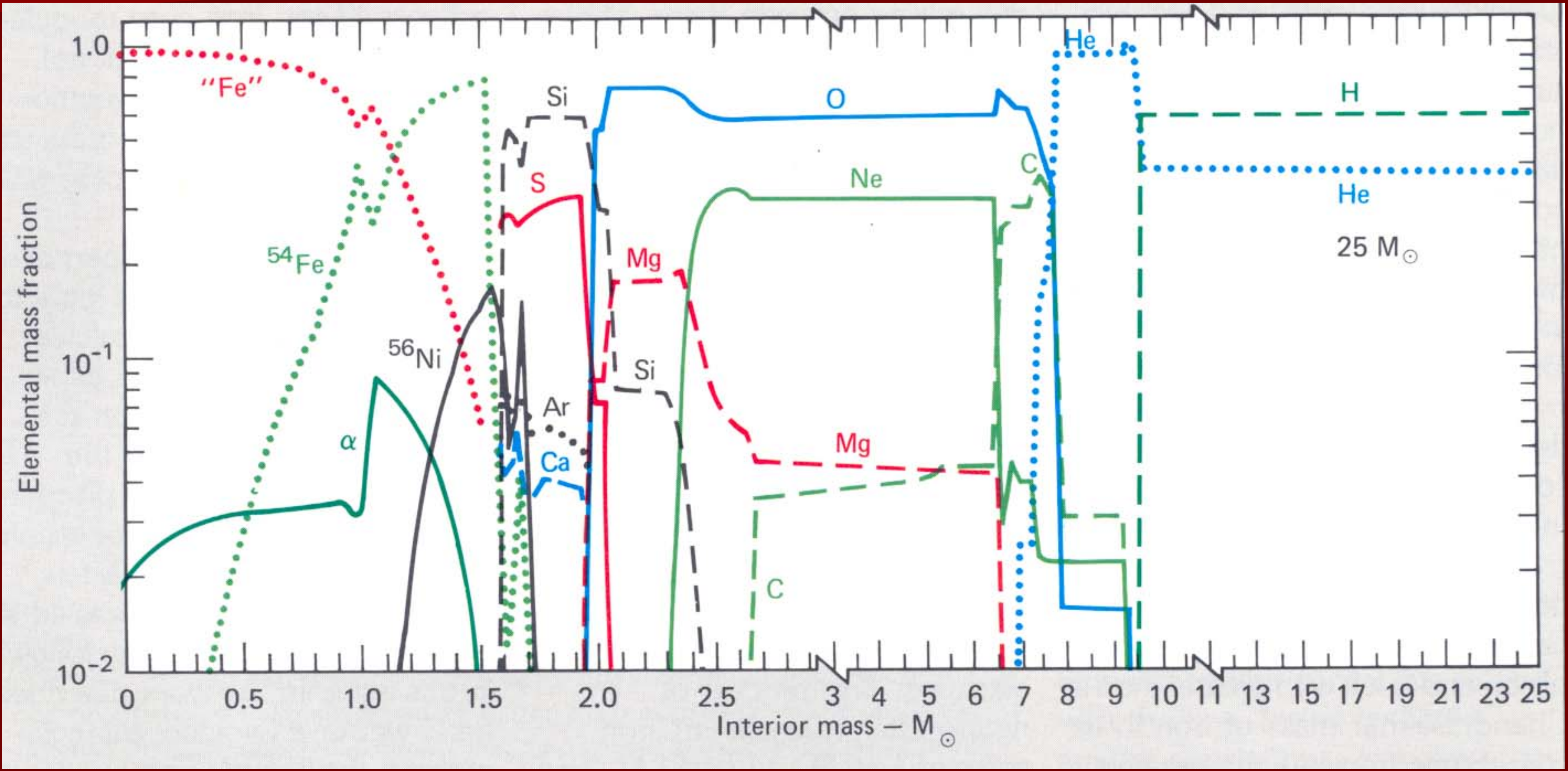
When one nuclear fuel is exhausted in the star's core, gravitational contraction to ever higher densities heats the star's central regions sufficiently either to centrally ignite the "ashes" of the previous burning stage or to ignite an outlying shell of unburned fuel. Each successive fuel must be burned in a substantially shorter time to balance energy loss by neutrino emission, which is a sharply increasing function of temperature and density. Above a density of 10^6 g/cm^3, the star's center becomes degenerate, and temporary temperature inversions commonly develop in which a burned-out core of less than a Chandrasekhar mass is cooled by neutrino emission while being supported by degeneracy pressure.



Evolution Through Si Burning III.

Evolutionary Stages of a 25 Solar Mass Star			
Stage	Temperature (Kev)	Density (g/cm^3)	Time Scale
Hydrogen Burning	5	5	7(10^6) years
Helium Burning	20	700	5(10^5) years
Carbon Burning	80	2(10^5)	600 years
Neon Burning	150	4(10^6)	1 year
Oxygen Burning	200	10^7	6 months
Silicon Burning	250	3(10^7)	1 day
Core Collapse	700	3(10^9)	Seconds
Core Bounce	3000	10^{14}	Milliseconds
Explosive	100-600	Varies	0.1-10 seconds

Pre-SN Composition



Core Detachment

- Core evolution proceeds at such a rapid rate that the envelope cannot respond.
- The collapse generates a shock wave which detaches the mantle and envelope.
  - Inner boundary conditions are time dependent
    - Falls In – (collapse of core)
    - Accelerates Out – (bounce)
    - Rarefaction wave generated behind the shock as inner boundary collapses to the surface of the neutron star.

Explosive Nucleosynthesis

- The shock wave propagates outwards through the nuclear ash and causes more processing in the Si, O, and Ne layers.
- Core-explosion energies lead to a shock which is not strong with respect to the energy density of the mantle!
  - Most energy is internal, not in kinetic form after the shock has passed
  - The temperature and density behind the shock are roughly constant.
    - The shock is basically an expanding bubble of radiation containing most of the core explosion energy.

Shock Temperatures

- Peak temperatures:
- Persistence: ~ 0.1 s
- T > 400 keV (4.6 T_9)
  - Process to the Fe peak
    - 1 eV = 1.160485(10^4) K
- 300 < T < 400 keV
  - O and P produced
  - Ne Zones: during the pre SN there was a n flux in this zone which can r/s process to Pb. After the SN (during shock) this region photodisintegrates and r- processes more production of heavy species.

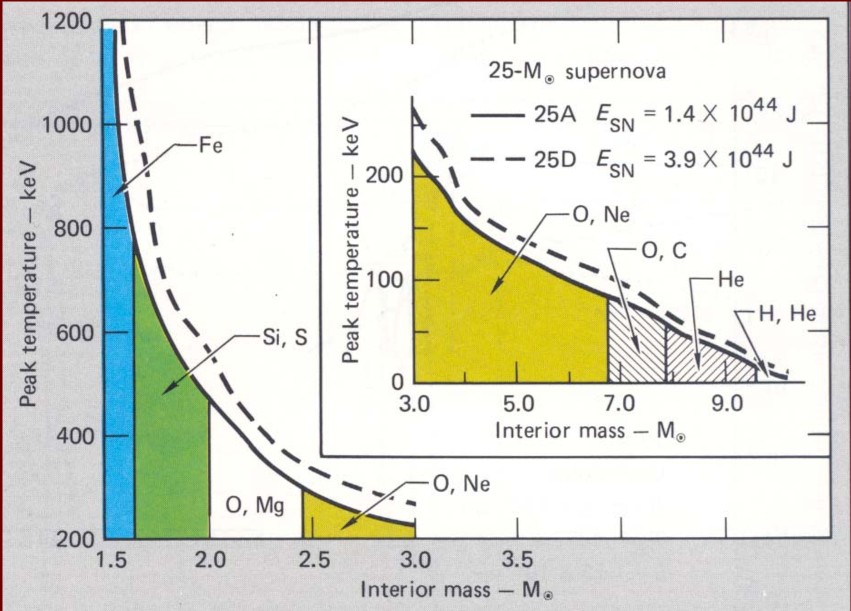
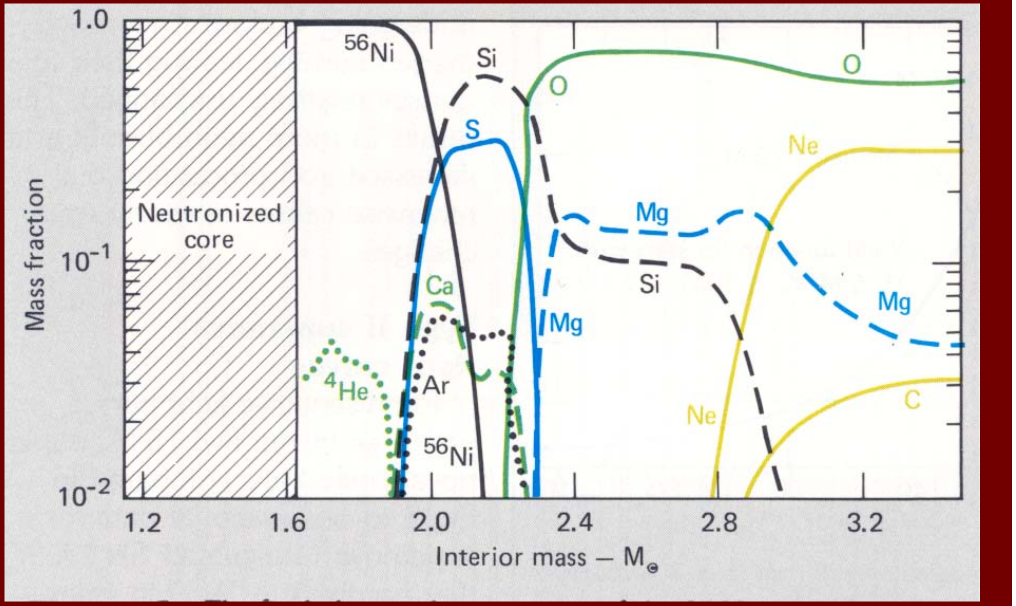


Fig. 5 *Peak explosion temperatures as a function of mass fraction and preexplosion composition for the 25-M⊙ model supernovae listed in Table 2. The peak temperature in each layer scales roughly as the fourth root of the explosion energy, as is expected from the simple radiation-dominated model described in the text. These temperatures are sufficient to cause a substantial amount of neon, oxygen, and silicon to be burned explosively, while the cooler outer layers of hydrogen, helium, and carbon are ejected without burning significantly.*

Cooler Zone

- T ~ 200 keV: material ejected with no large scale processing.
- What is the yield?
  - Relative to the median mass of a “SN” of 29 $M_{\odot}$ the 25 $M_{\odot}$ case is typical.
  - The absolute yield is high
    - 15 times original with respect to hydrogen and the proportions are good



SN Light Curves

Compare the 15 $M_{\odot}$ light curve to SN 1969 and the fit is good.

- Time Sequence
  - Initial sharp spike – breakout of the SN shock through the envelope
    - Should observe a 2000 s soft x-ray pulse at 150000 K with a peak luminosity of 10^{38} watts
    - After this there is a rapid cooling by radiative emission and dynamic expansion.
  - Material in mantle and envelope expands due to
    - Shock impulse
    - Adiabatic expansion of shock heated material
    - Expansion velocities reach terminal values after 2 - 4 days
    - Final velocities 3000 km/s average: 1000 km/s in mantle and 13000 km/s near the surface

The Comparison

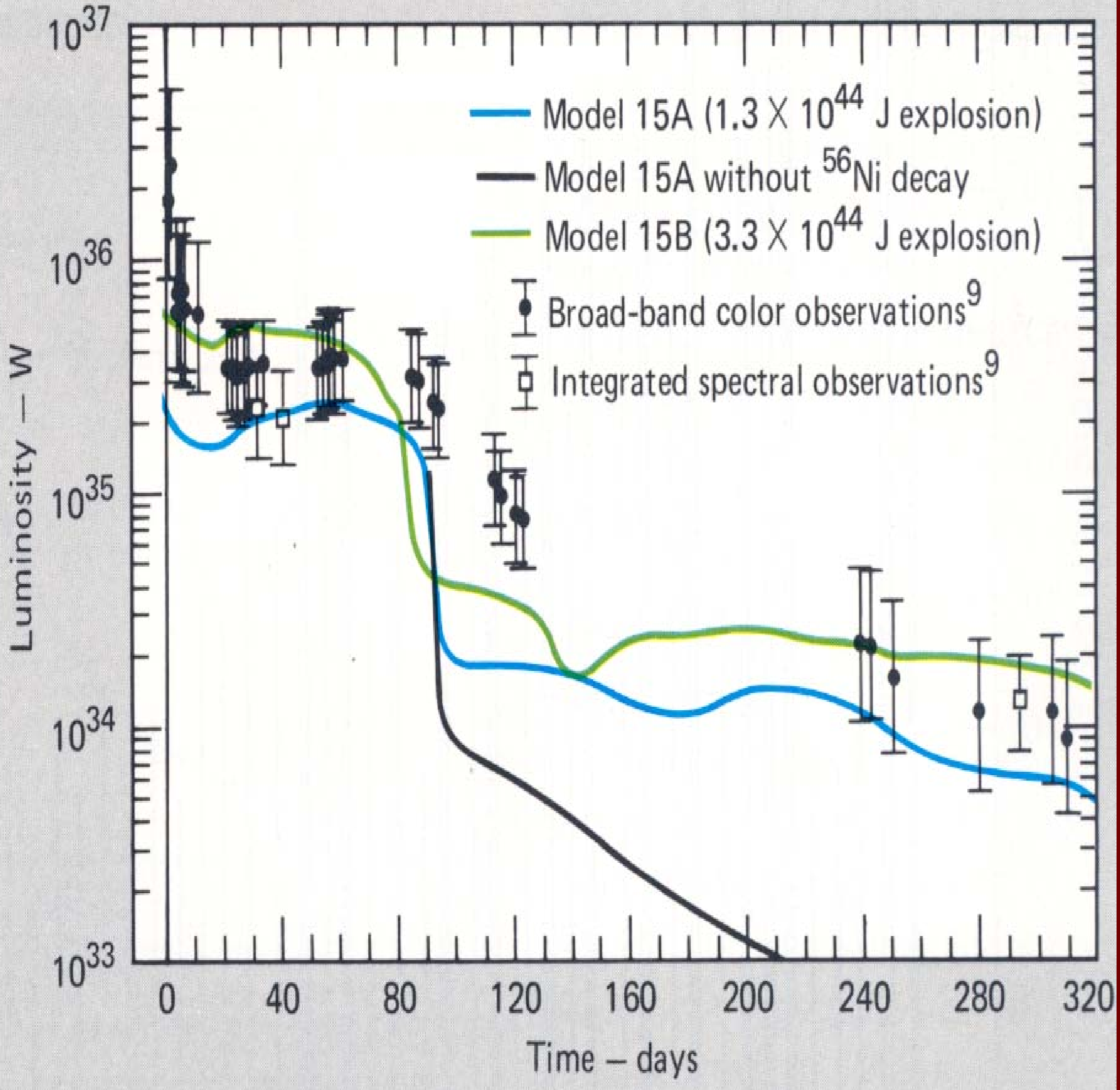


Fig. 9 *Light curve of Type II supernova 1969ℓ compared to 15-$M_\odot$ theoretical models. Here, time is measured with respect to core*

Kinetic Energy

- The SN has sufficient opacity to convert 99% of the "total" energy to kinetic energy.
- The SN becomes optically thin when R reaches about 10^{10} km (10-30 times original radius).

Photosphere Evolution

- Photosphere in 20 days has cooled to about 6000 K and Hydrogen has recombined to form a low density optically thin gas (AKA as an F supergiant!)
  - This allows radiative cooling of the lower levels to proceed – they then recombine also.
  - This effect propagates downwards over a period of 2 months and the effective temperature remains at about 6000 K (photosphere remains relatively constant in R, inward cooling (in mass) balanced by outward flow of material. This is the plateau phase.
  - Eventually the "wave" gets to the mantle and cooling ceases
  - The luminosity during the latter phase is generated by the decay of Ni^{56} to Fe^{56}.

Temperature History