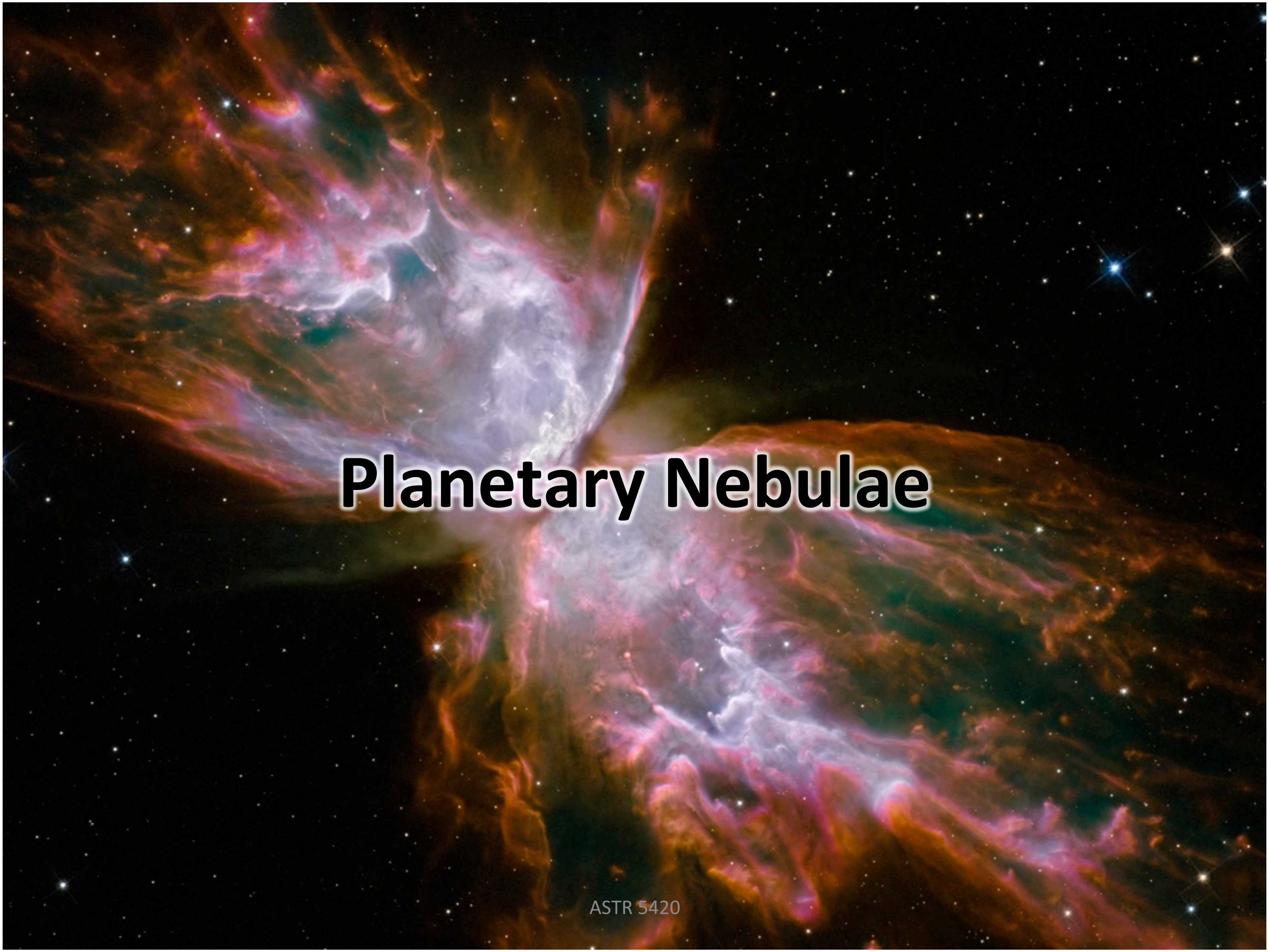
Stellar Deaths

Planetary Nebulae &
Supernovae

ASTR 5420



Planetary Nebulae

Mass Loss

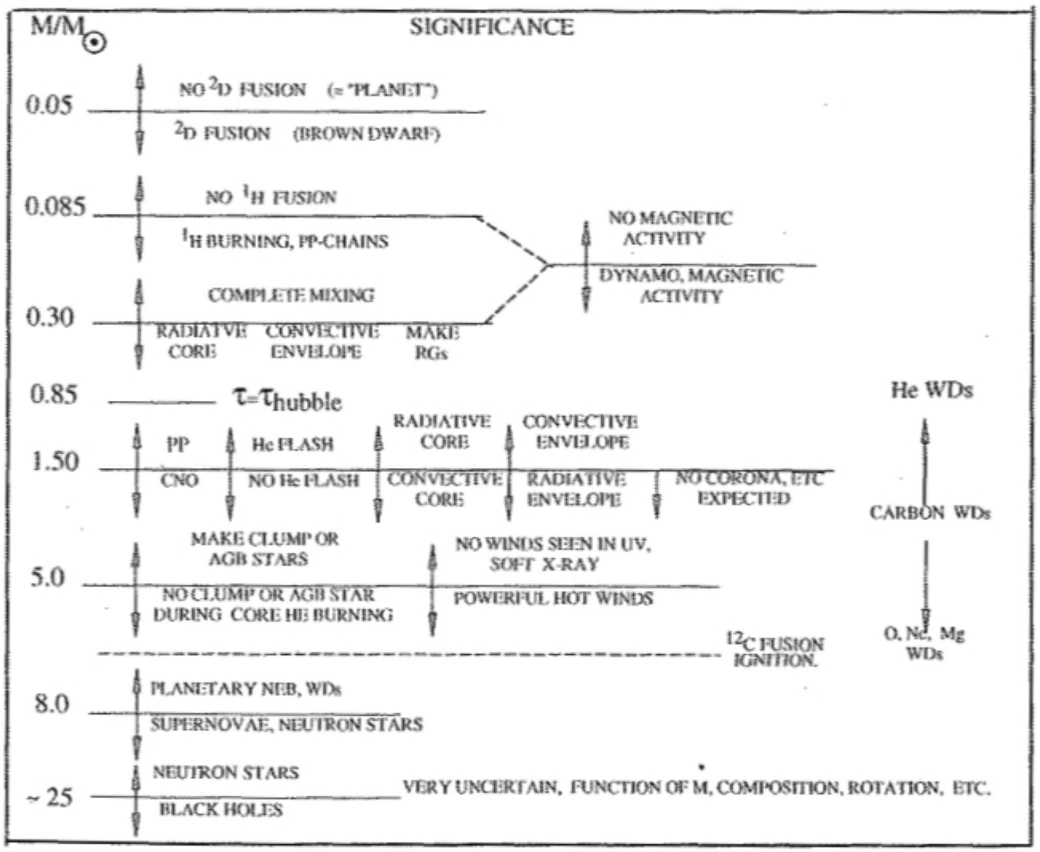
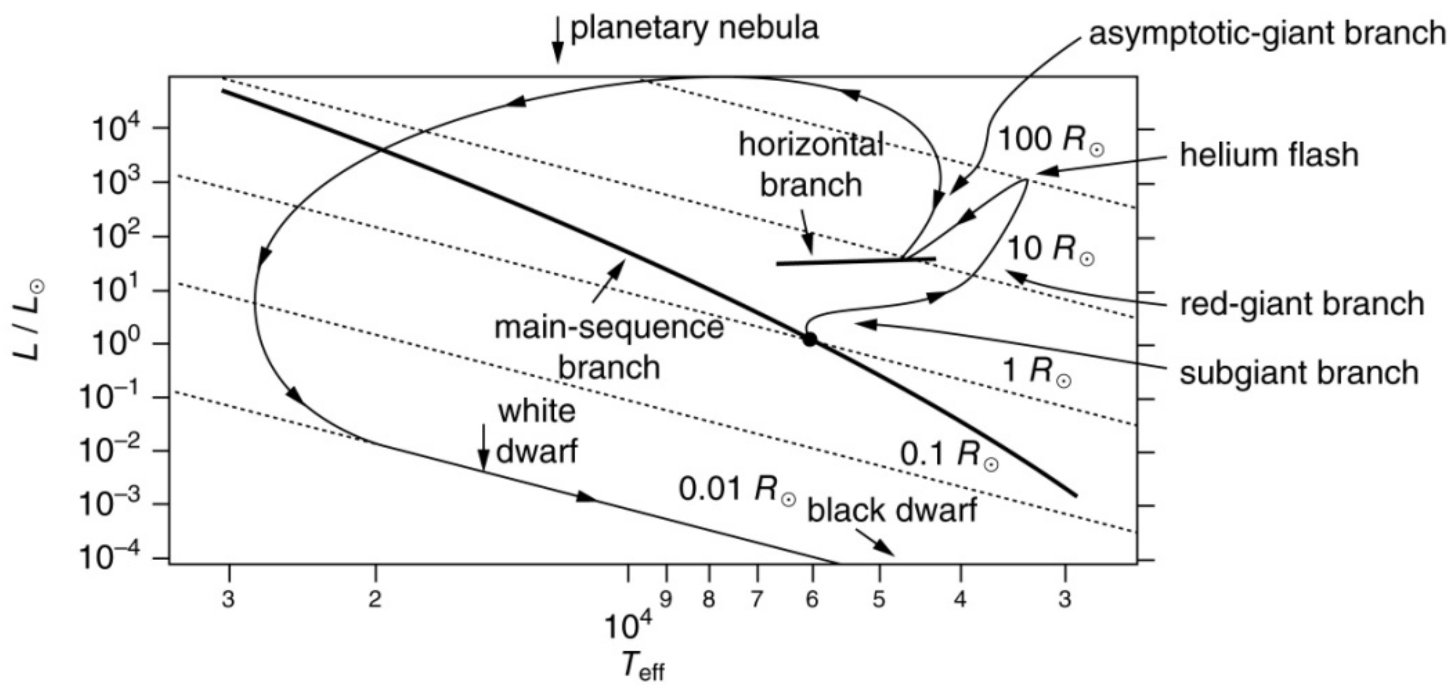


Fig. 2.4. Our "Mass Cut" diagram showing the fate of single stars in various mass classes. See text.

- White dwarfs
  - < 1.4 Msun
- Neutron stars
  - >1.4 Msun
  - <2-4 Msun
- Black Holes
  - > 2-4 Msun

Evolution of a 1 M_{sun} star

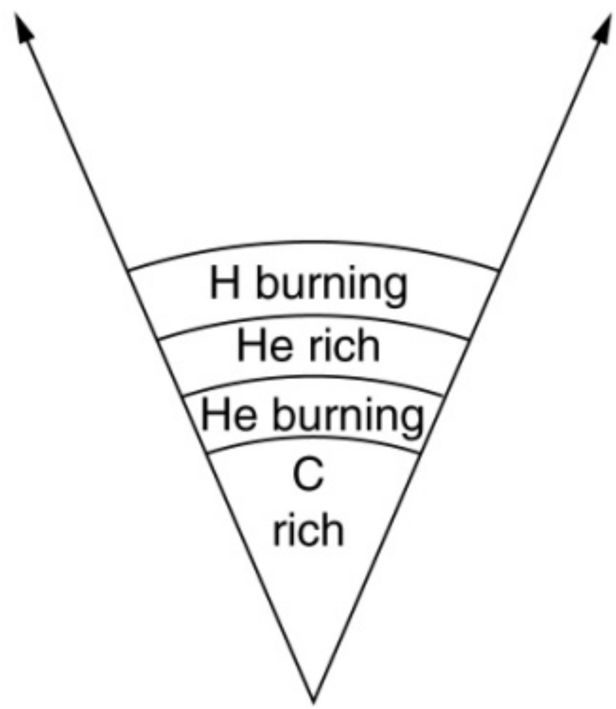


LeBlanc, 2010

Video of star sizes

- http://www.youtube.com/watch?v=7T1LO6nOUdw

Interior of a late-stage AGB star



LeBlanc, 2010

What drives Mass Loss?

- Winds (radiation pressure, magnetic fields)
- Pulsation
- Helium flash
- Cyclical burning

Planetary Nebulae

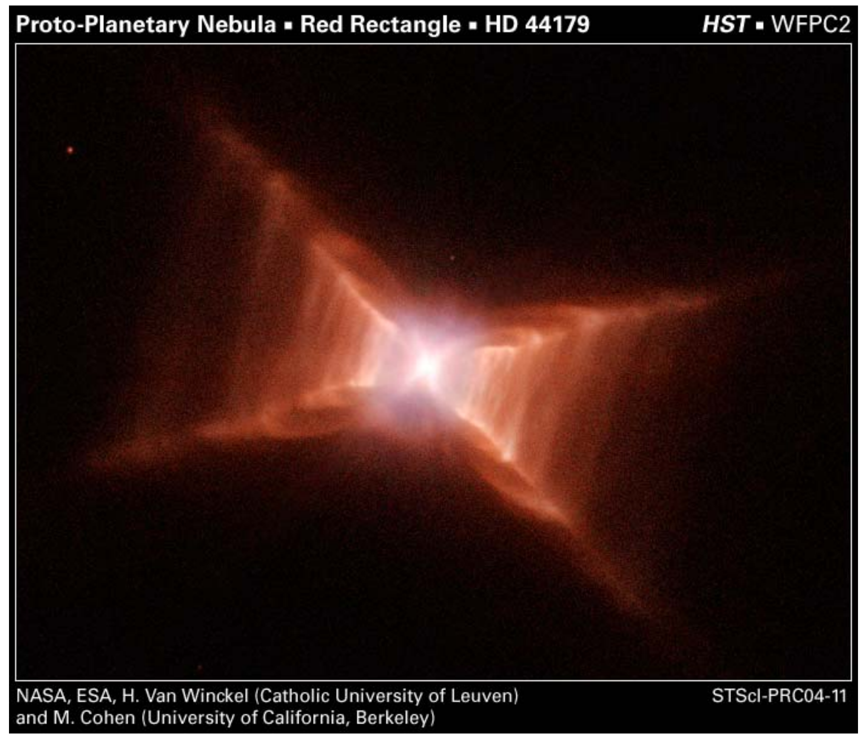
Butterfly Nebula (HST)

Cat's Eye Nebula (HST)

Planetary Nebulae

Helix Nebula (Spitzer)

Red Rectangle (HST)

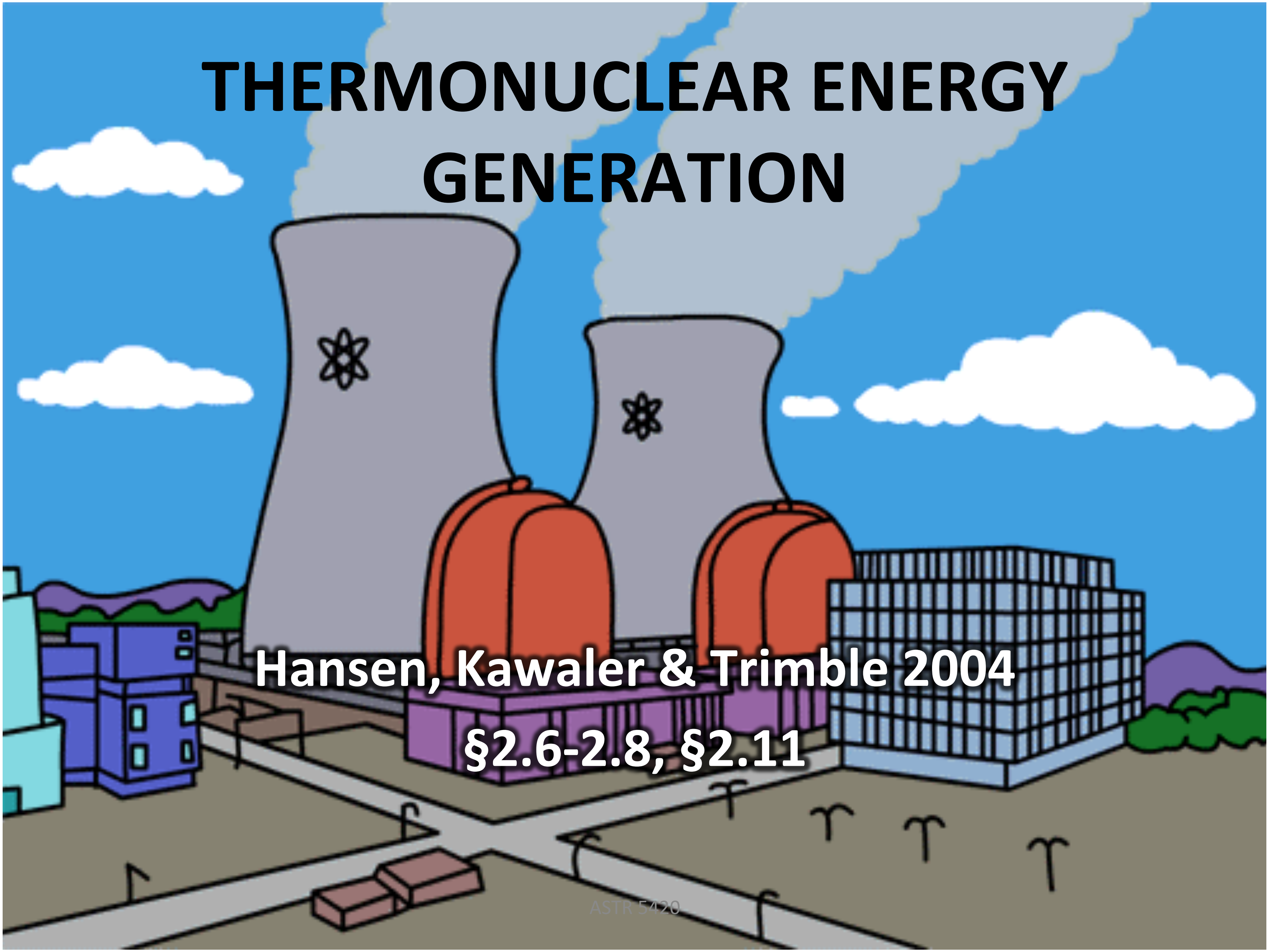


Planetary Nebulae

Shaped by:

- Spin
- Binary Companions
- Earlier mass loss
- Outflows
- Magnetic fields
- Orientation

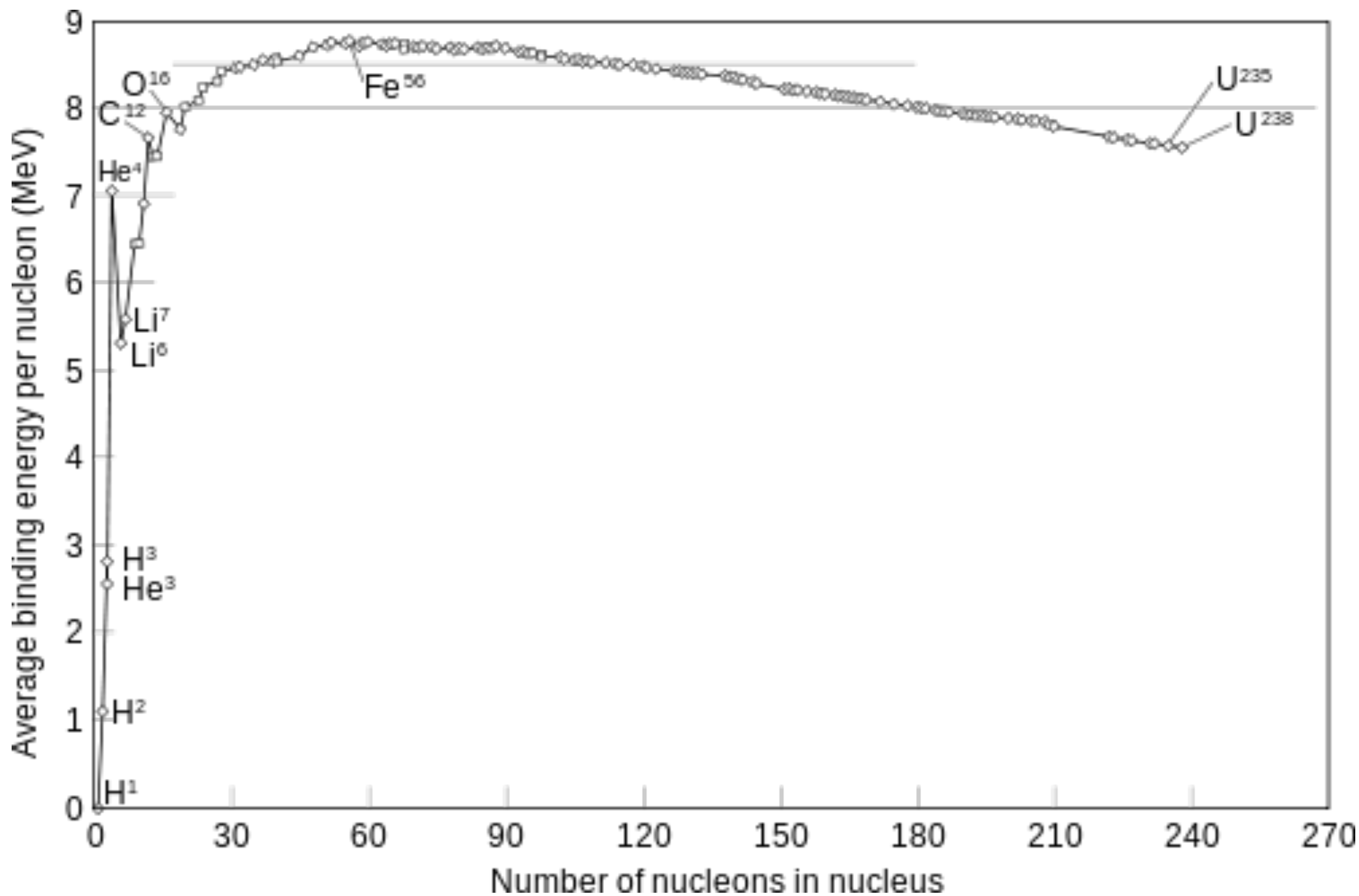
THERMONUCLEAR ENERGY GENERATION



Hansen, Kawaler & Trimble 2004

§2.6-2.8, §2.11

Average binding energy



Double shell burning

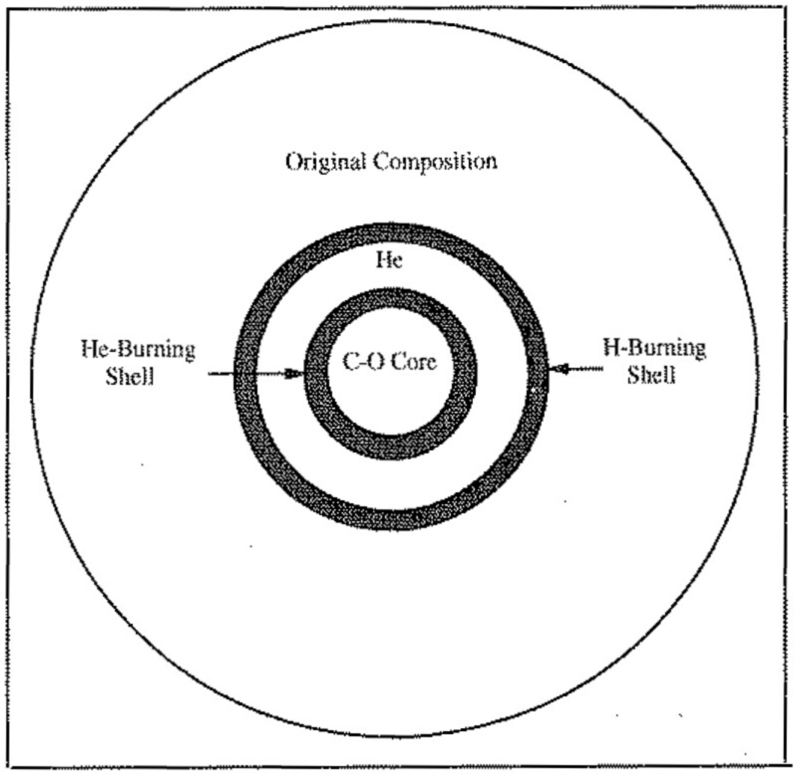


Fig. 2.14. Double shell burning. Not to scale (by quite a bit) because the outer envelope is huge, while shells and core are much smaller in real life.

Hansen, Kawaler & Trimble 2004

Layered composition of the core of a massive star

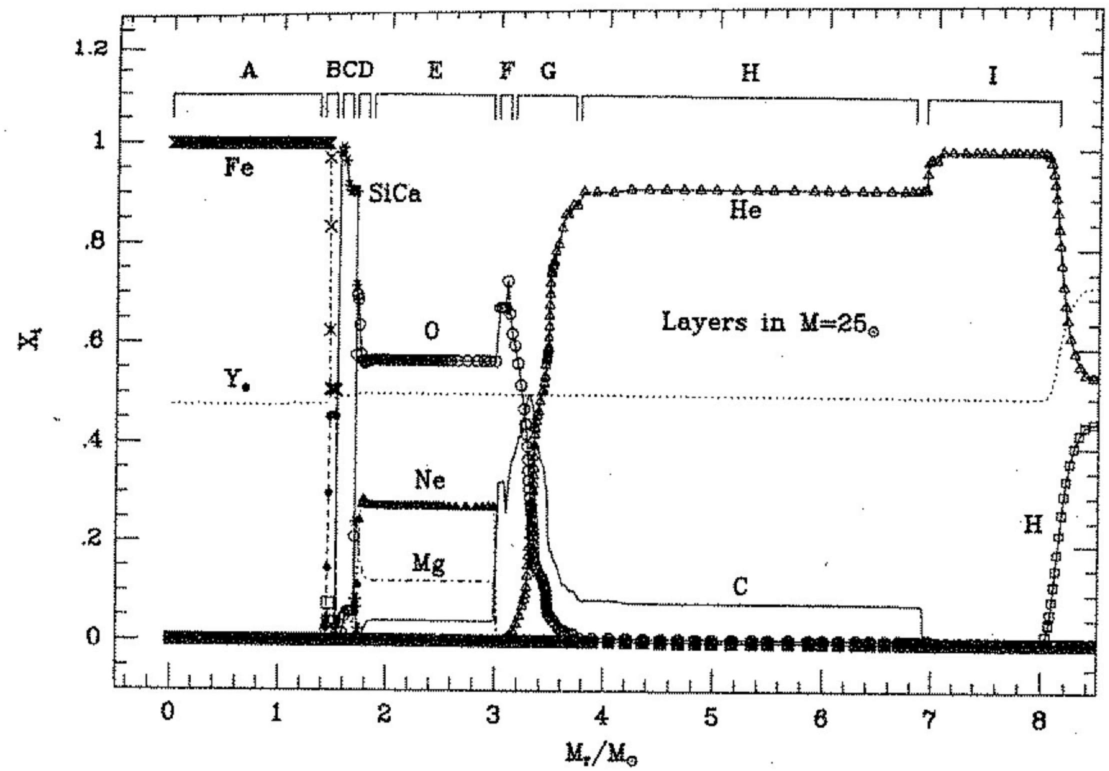


Fig. 2.17. The compositional layering in the inner core of a 25 $\mathcal{M}_\odot$ pre-supernova model versus interior mass. X_i is the mass fraction. See text for an explanation and further commentary. Reprinted with permission from Arnett (1996, his Fig. 10.8), ©1996 by Princeton Univerity Press.

Hansen, Kawaler & Trimble 2004

Nucleosynthesis progression

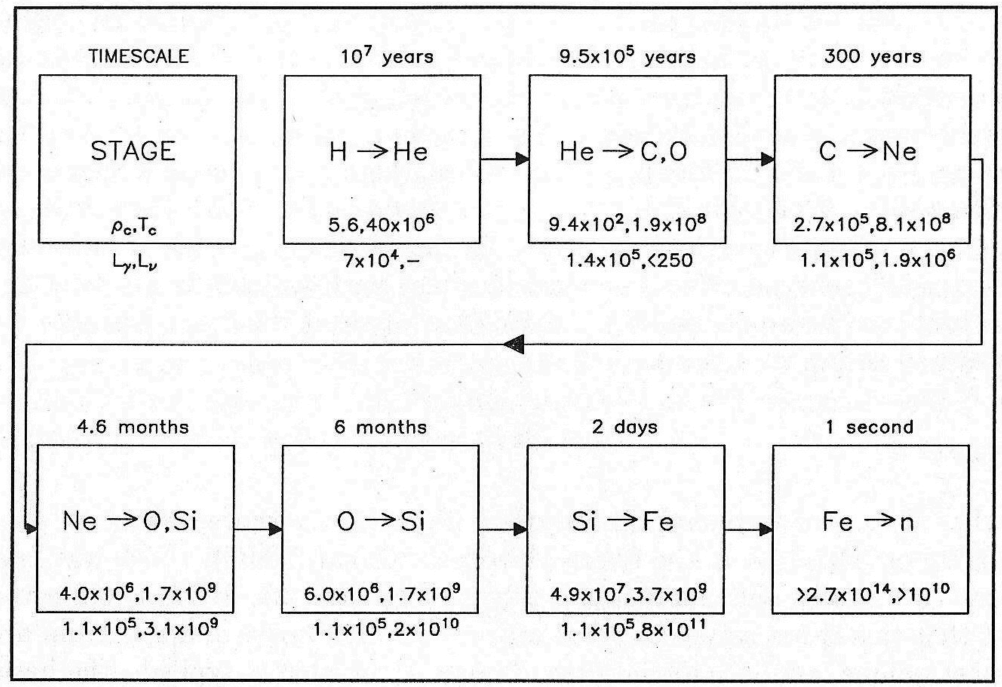


Fig. 2.30. A representation of the thermonuclear burning stages of a star similar to SN1987A. The first box is a key to the notations in the boxes following—each of which represents a stage. Central density is in the units of g cm^{-3}, T_c in K, and photon and neutrino luminosities are in the units of $\mathcal{L}_\odot$. The progression of arrows indicates the arrow of time. The figure is adapted from Table 1 of Arnett et al. (1989).

Hansen, Kawaler & Trimble 2004

“Onion-skin” model for a pre-supernova star

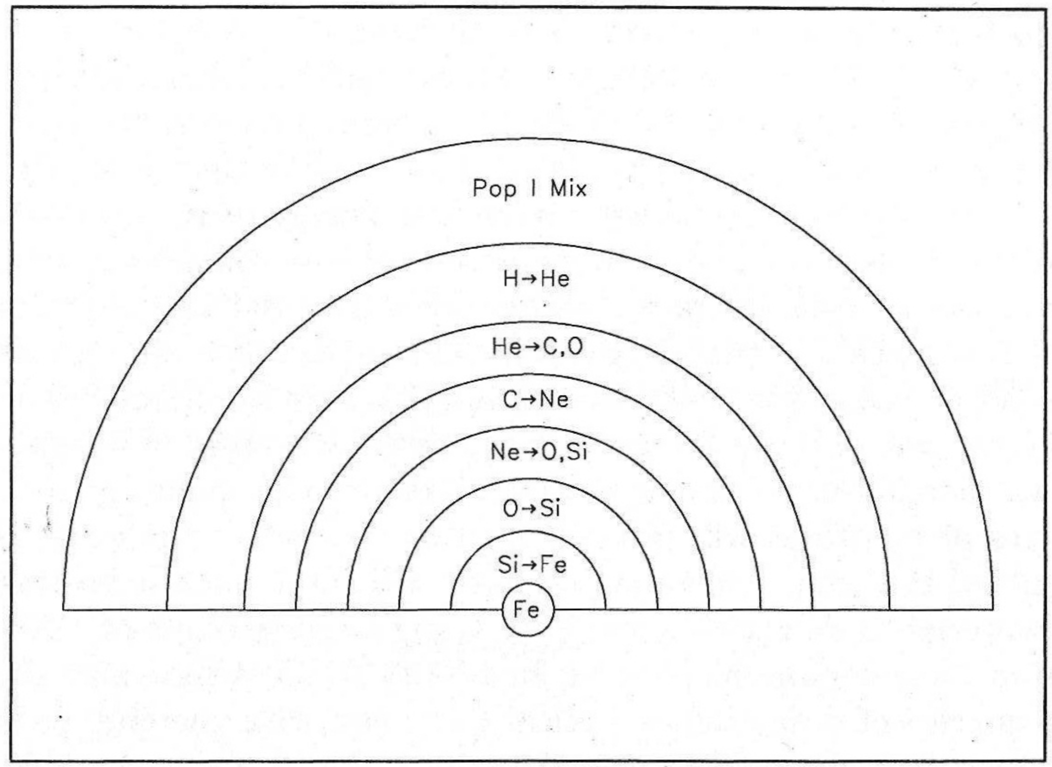


Fig. 2.31. An onion-skin diagram for the last stage of Type II presupernovae. The thickness of the layers is not to scale.

Hansen, Kawaler & Trimble 2004

s-process and r-process

s-process	r-process
neutron capture time is greater than beta decay time	neutron capture time is less than beta decay time
Add neutrons one by one. If nucleus is stable, it stays there. If unstable, beta decay to a stable nucleus	lots of neutrons added at once, beta-decay to stable nuclei
Occurs in massive post-main sequence stars	**Only** occurs in supernovae

Synthesis of heavy elements during a supernova

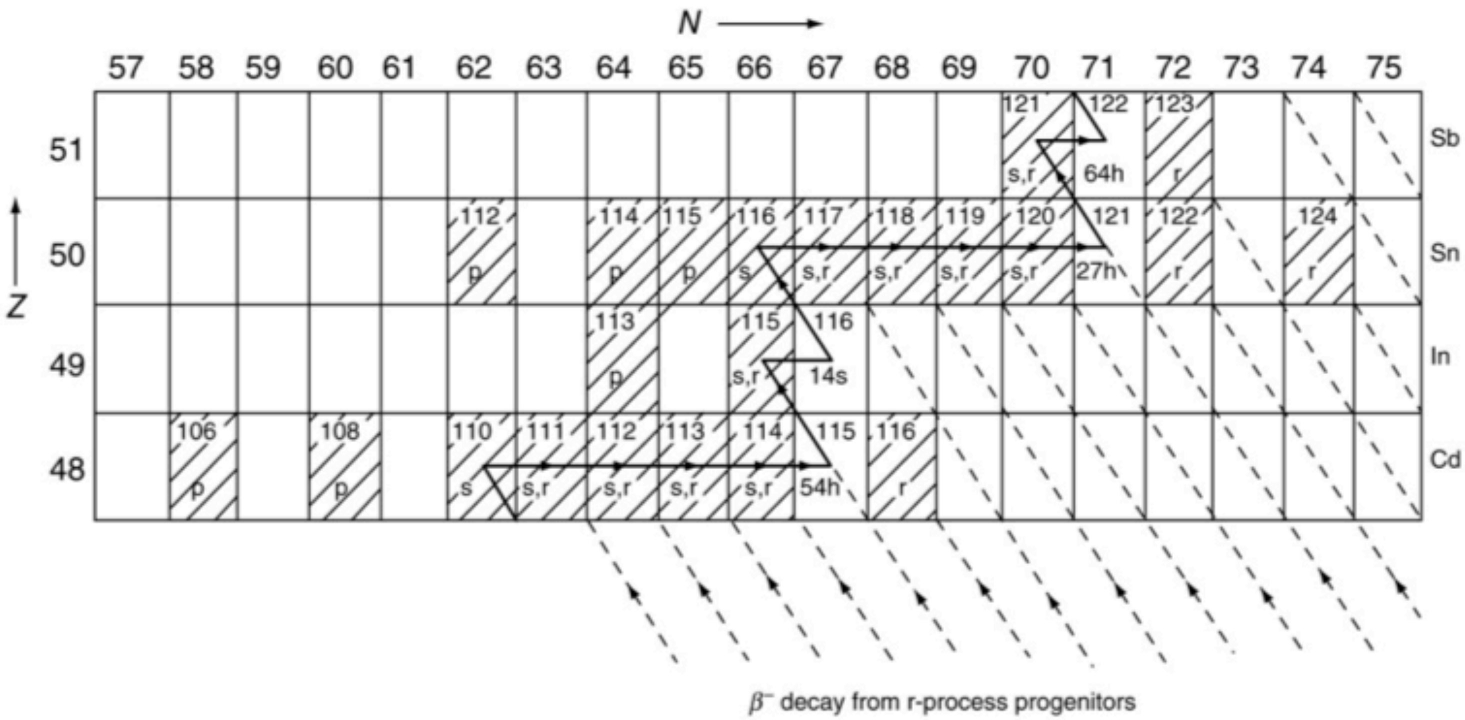


Figure 6.36 Synthesis of the elements Cd through Sb. The stable isotopes are hatched. The solid line shows the path of the *s* process. Figure reproduced and adapted with permission from Pearson, J.M., *Nuclear Physics: Energy and Matter*, Adam Hilger, Bristol (1986).

LeBlanc, 2010

s- and r-processes

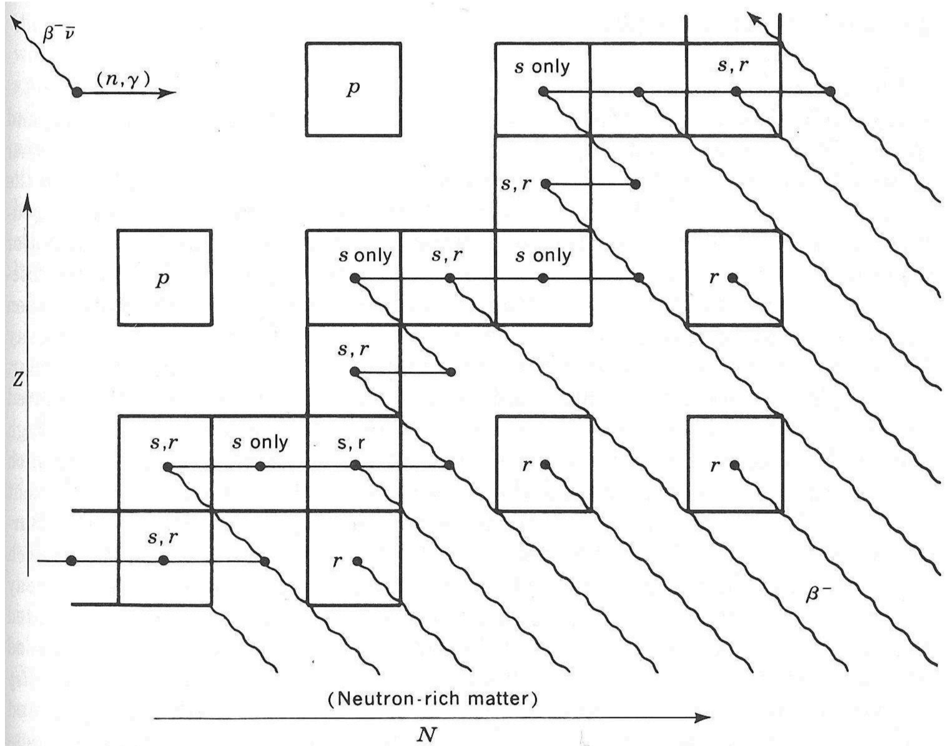


Fig. 7-14 A characterization of a portion of the chart of nuclides showing the assignment of nuclei to the classes *s*, *r*, and *p*. The *s*-process path of (n,γ) reactions followed by quick beta decays enters at the lower left and passes through each nucleus designated by the letter *s*. Neutron-rich matter undergoes a chain of beta decays terminating at the most neutron-rich of the stable isobars, which are designated by the letter *r*. Those nuclei on the *s*-process path which are shielded from *r*-process production are labeled "*s only*." The rare proton-rich nuclei which are bypassed by both neutron processes are designated by the letter *p*.

Clayton, 1983

Stable nuclei

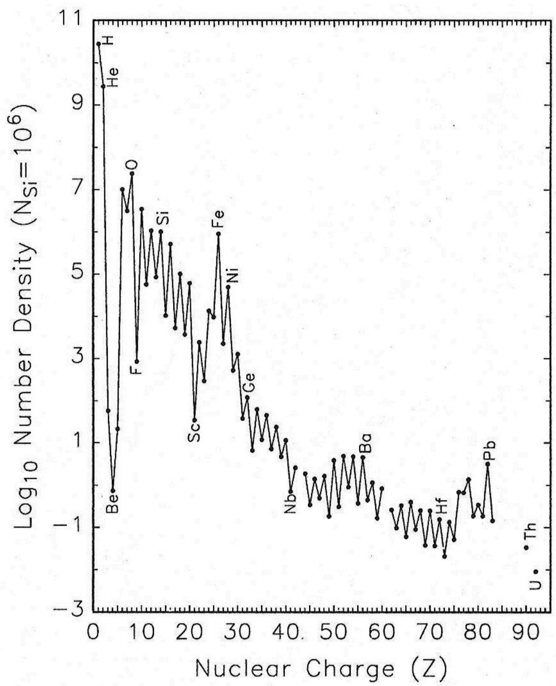


Fig. 2.19. "Solar" elemental abundances are plotted against nuclear charge, with some representative element names shown as a guide. These abundances, from Anders and Grevesse (1989), are derived from a combination of observed solar values, carbonaceous chondrite meteorites, and with some values folded in from ISM observations. The normalization used is that the number density of $\mathrm{Si} = 10^6$. Note that some elements are missing (e.g., technetium, promethium. polonium, etc.) because all their isotopes are radioactive with half-lives short compared to the age of the solar system.

Hansen, Kawaler & Trimble 2004

Stable nuclei

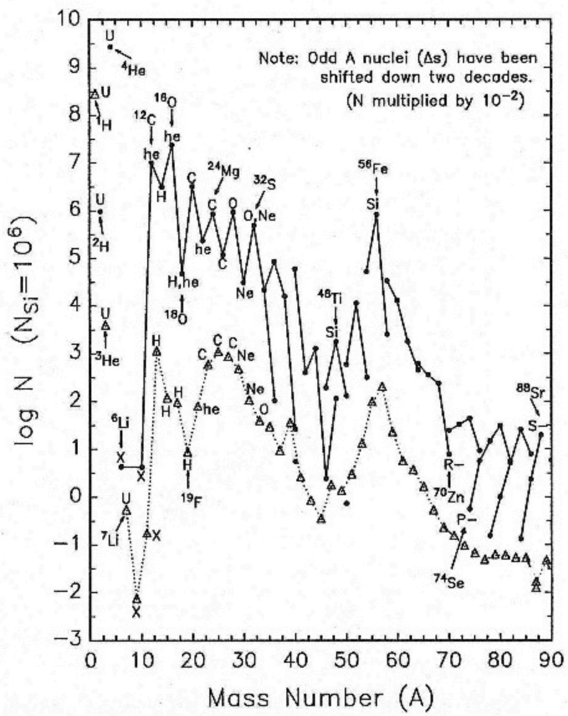
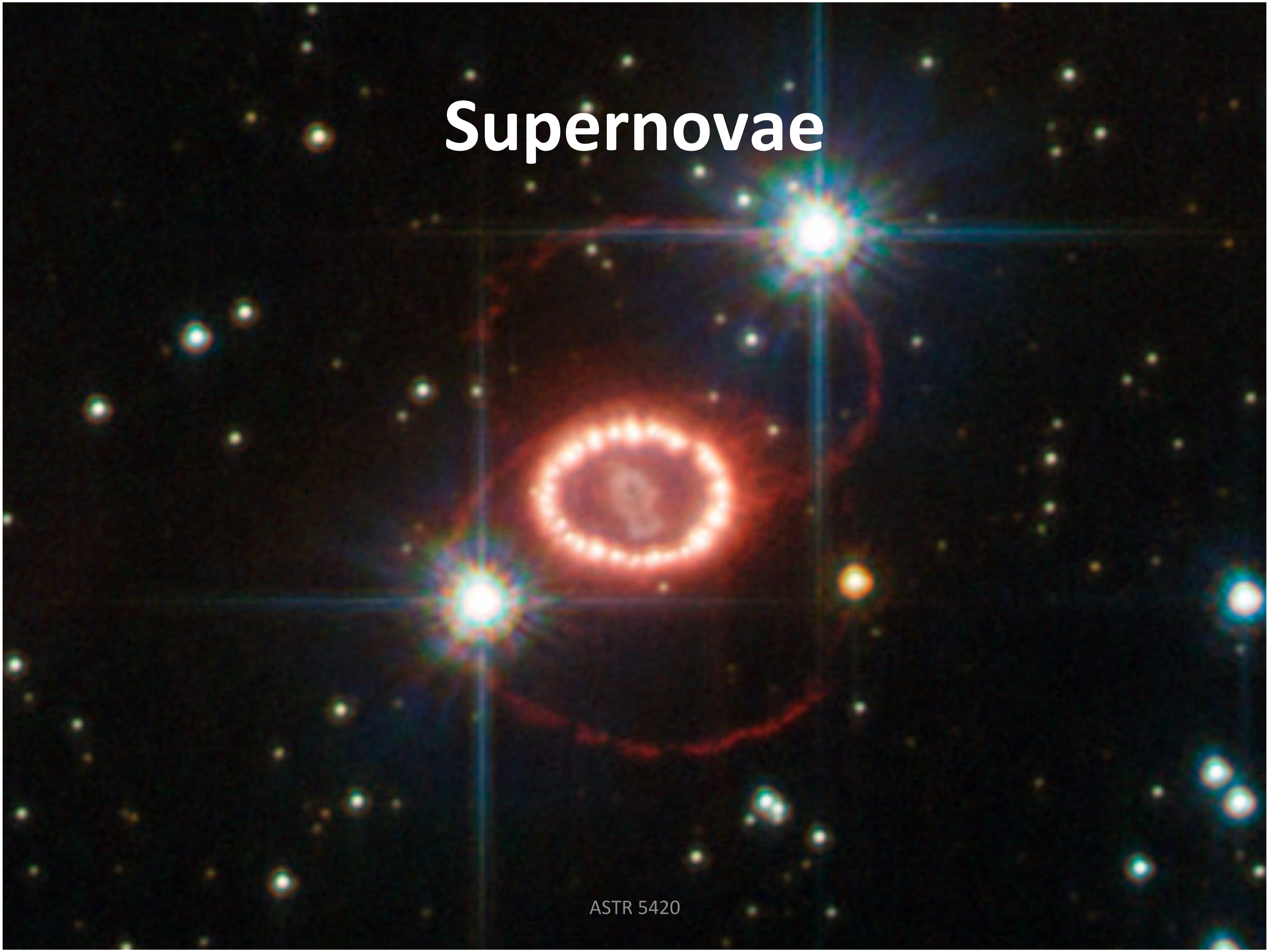


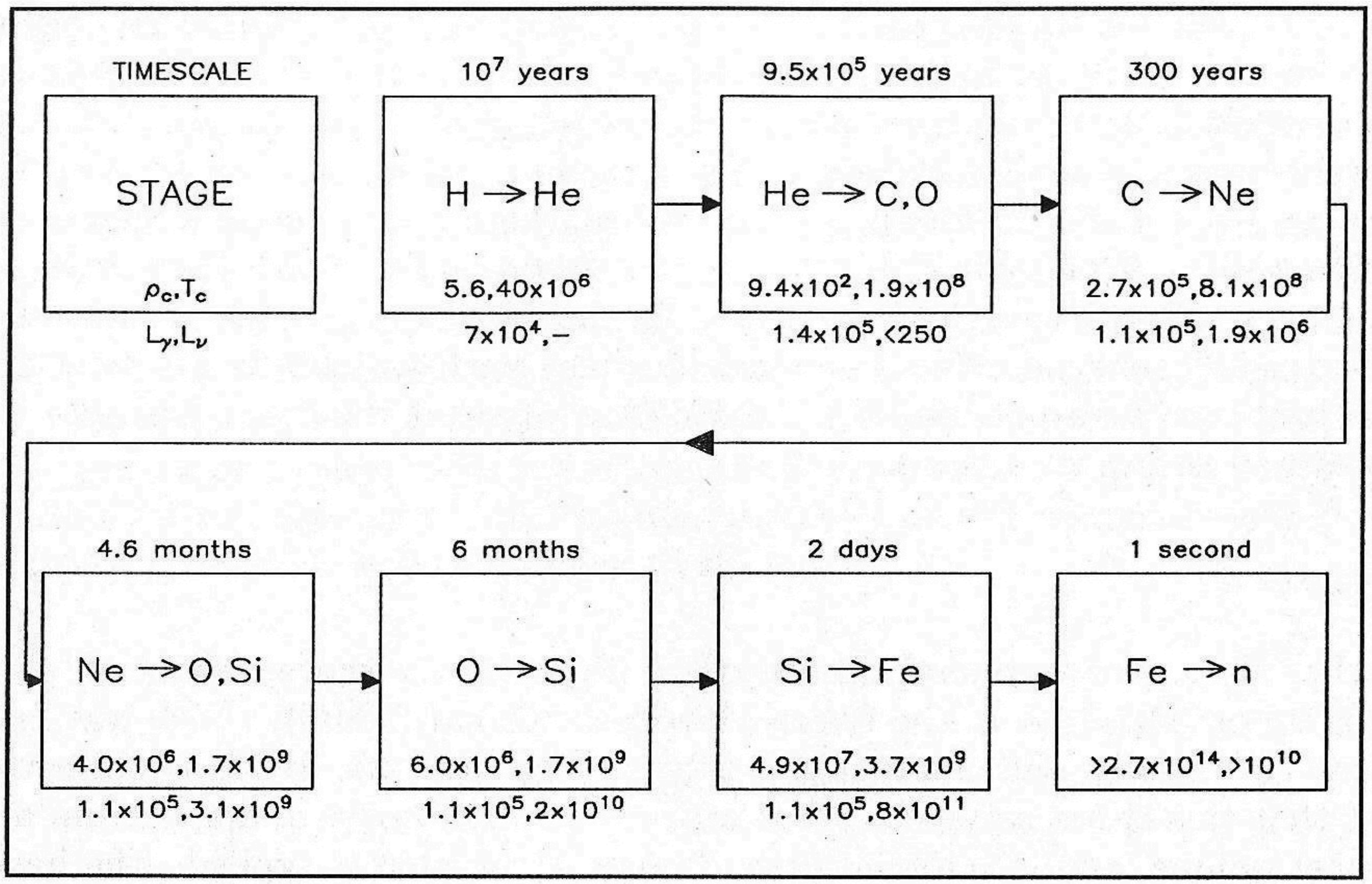
Fig. 2.20. Individual nuclide abundances for odd and even nuclides, taken primarily from Anders and Grevesse (1989). Triangles denote odd nuclides (which have been shifted down by two decades), whereas "dots" are for even. Some important nuclides are labeled. Sources (e.g., nuclear burning stages) are indicated for some nuclides: U means Big Bang; X from fragmentation of cosmic rays; H for hot (and hotter) hydrogen burning; he=helium burning; C, O, Ne, or Si=carbon, oxygen, neon, or silicon burning; and an occasional P-, S-, or R- for p-, s-, or r-process.

Hansen, Kawaler & Trimble 2004

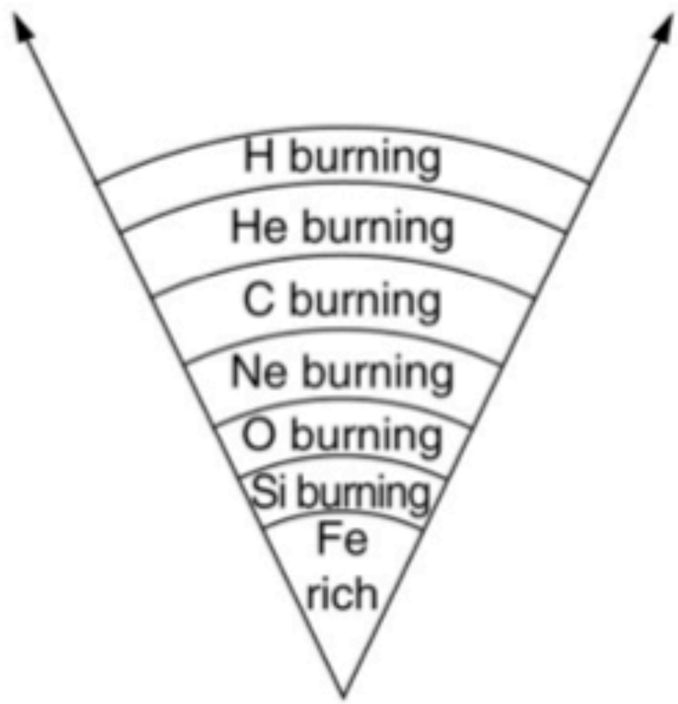
Supernovae



Supernovae (>8-10 M_{sun})

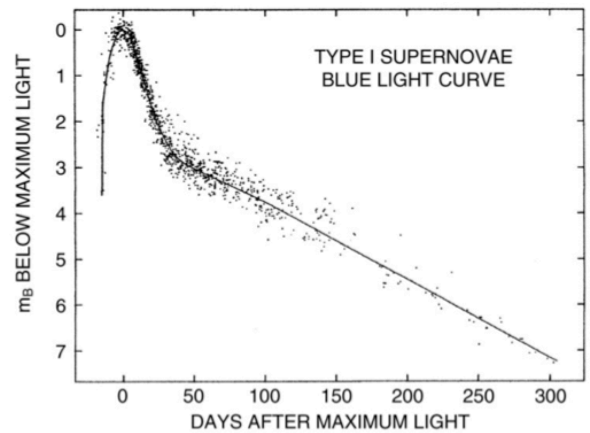


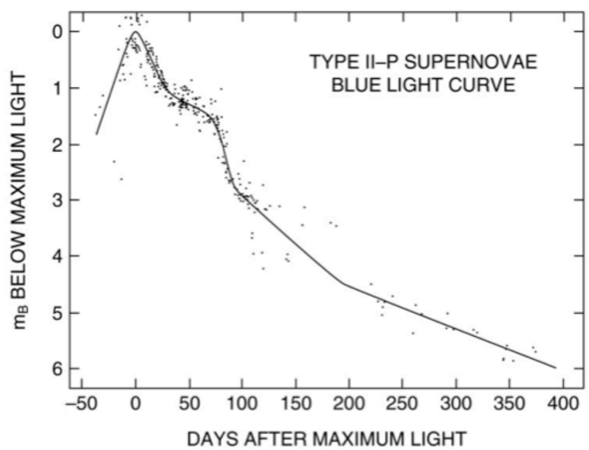
Interior of late stage massive star

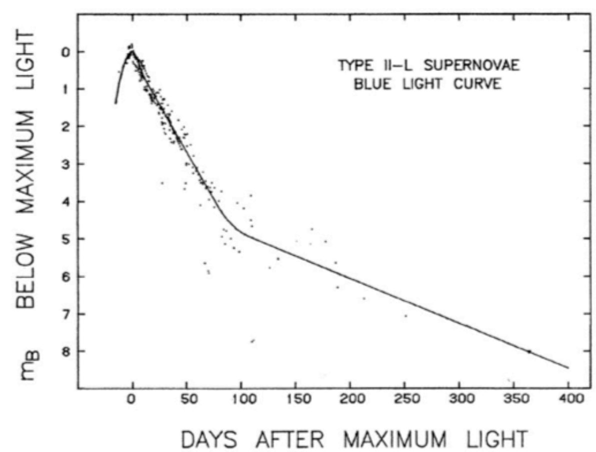


LeBlanc, 2010

Supernova Light Curves







LeBlanc, 2010

Supernova Types

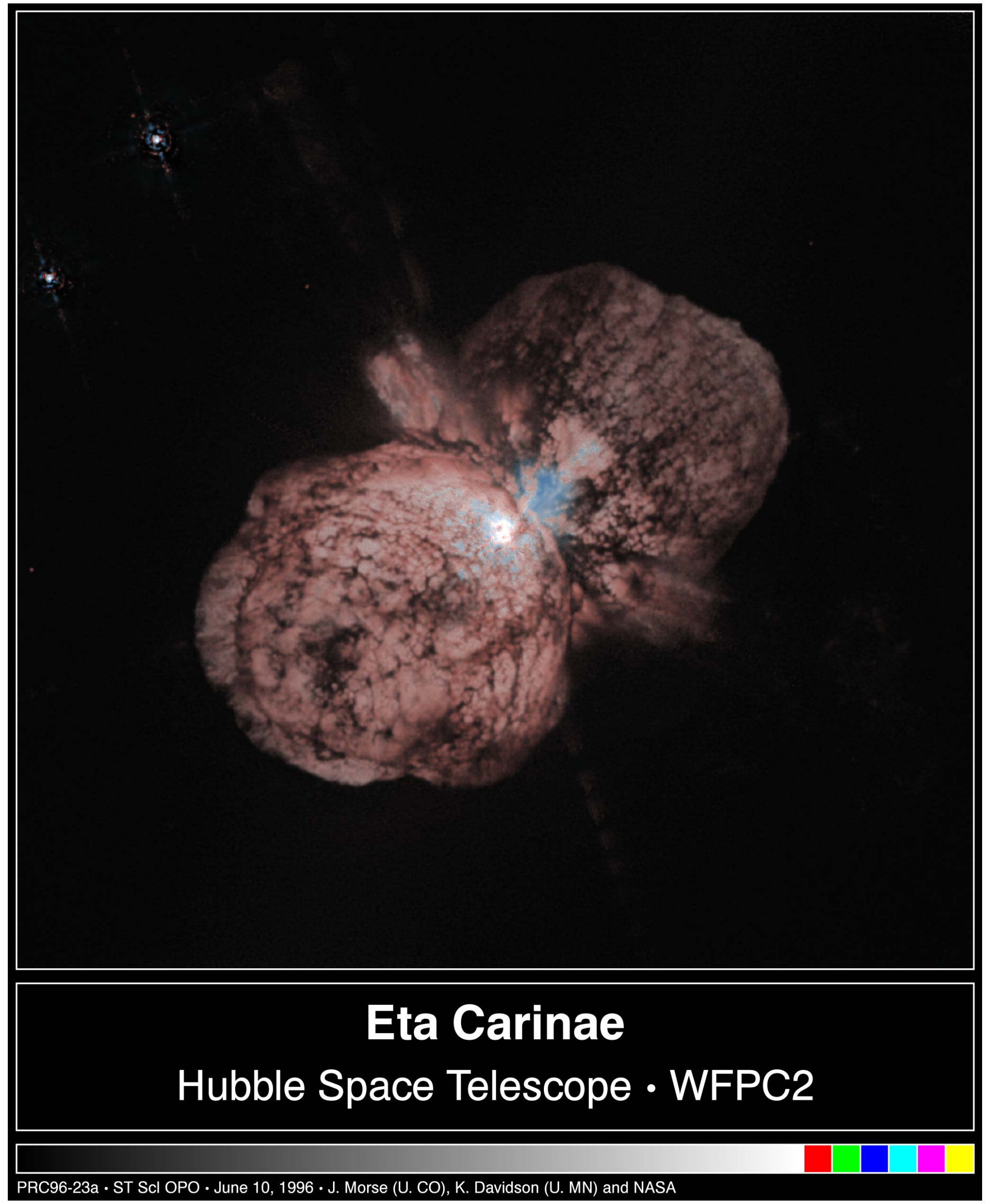
Type	Origin	Spectral features
SN Ia	white dwarf binary	No H lines, strong Si lines
SN Ib	core collapse	No H lines, no Si lines
SN Ic	core collapse	No H, lines no Si lines, no He lines
SN II	core collapse	Strong H lines

Pre-Supernova: Eta Carinae

~100 M_{sun}

Outburst in 1830s, making it one of the brightest stars in the southern sky – since faded

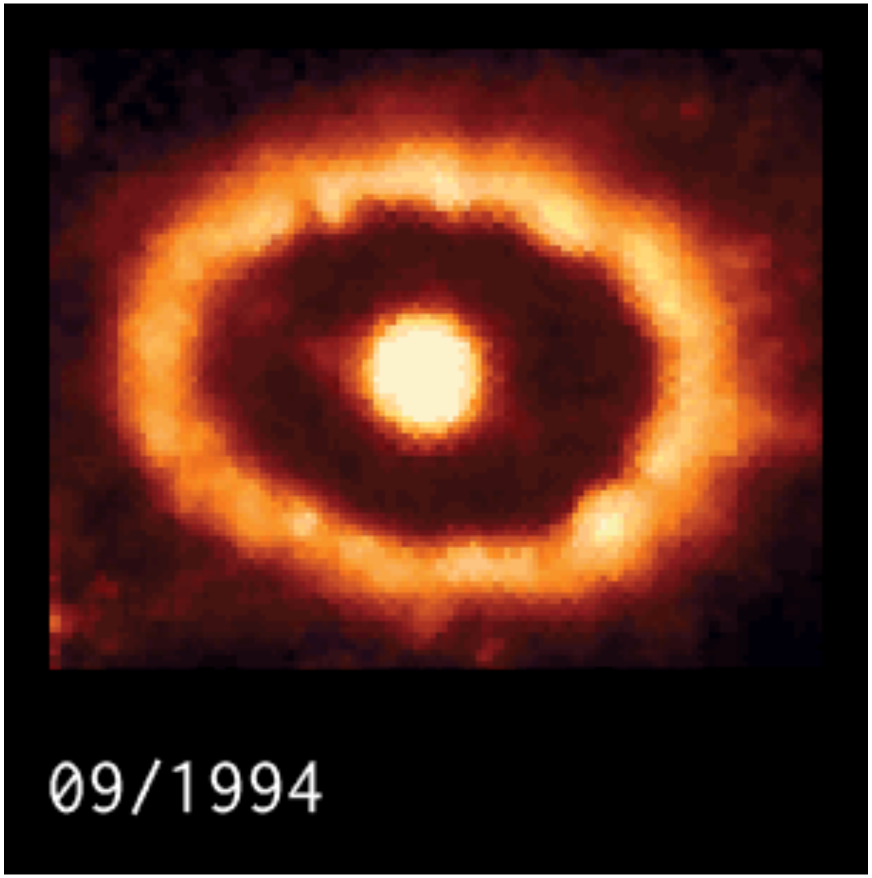
May go supernova any day



SN 1987A

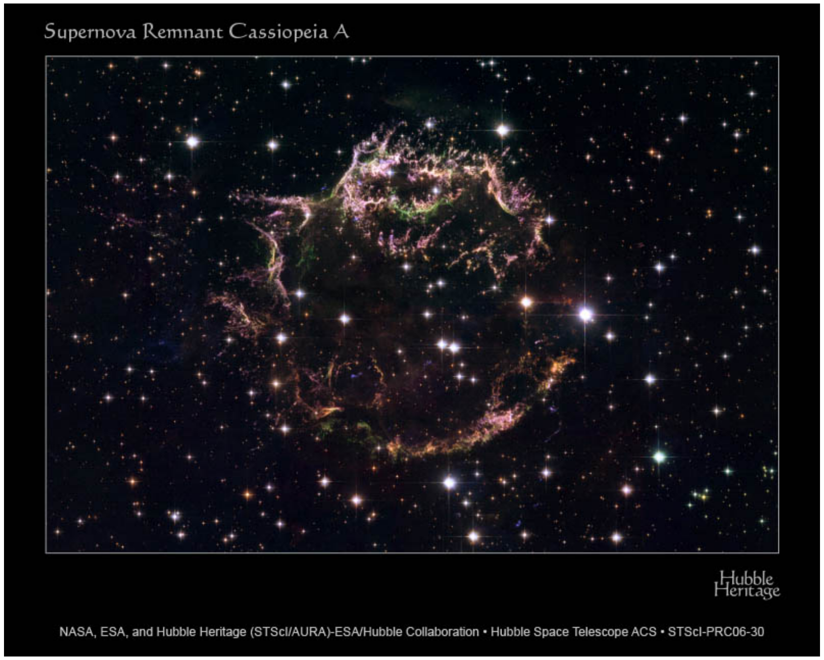
Type II supernova

HST observations over time

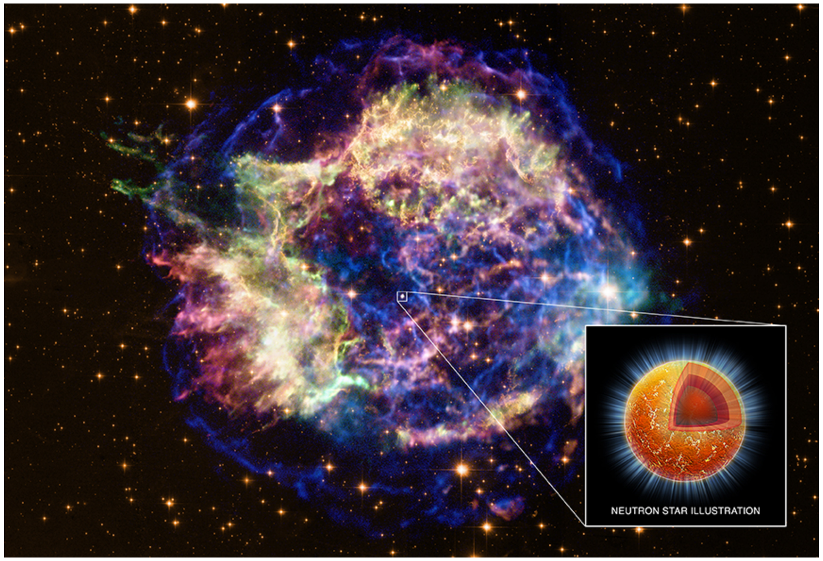


Cassiopeia A

HST: optical



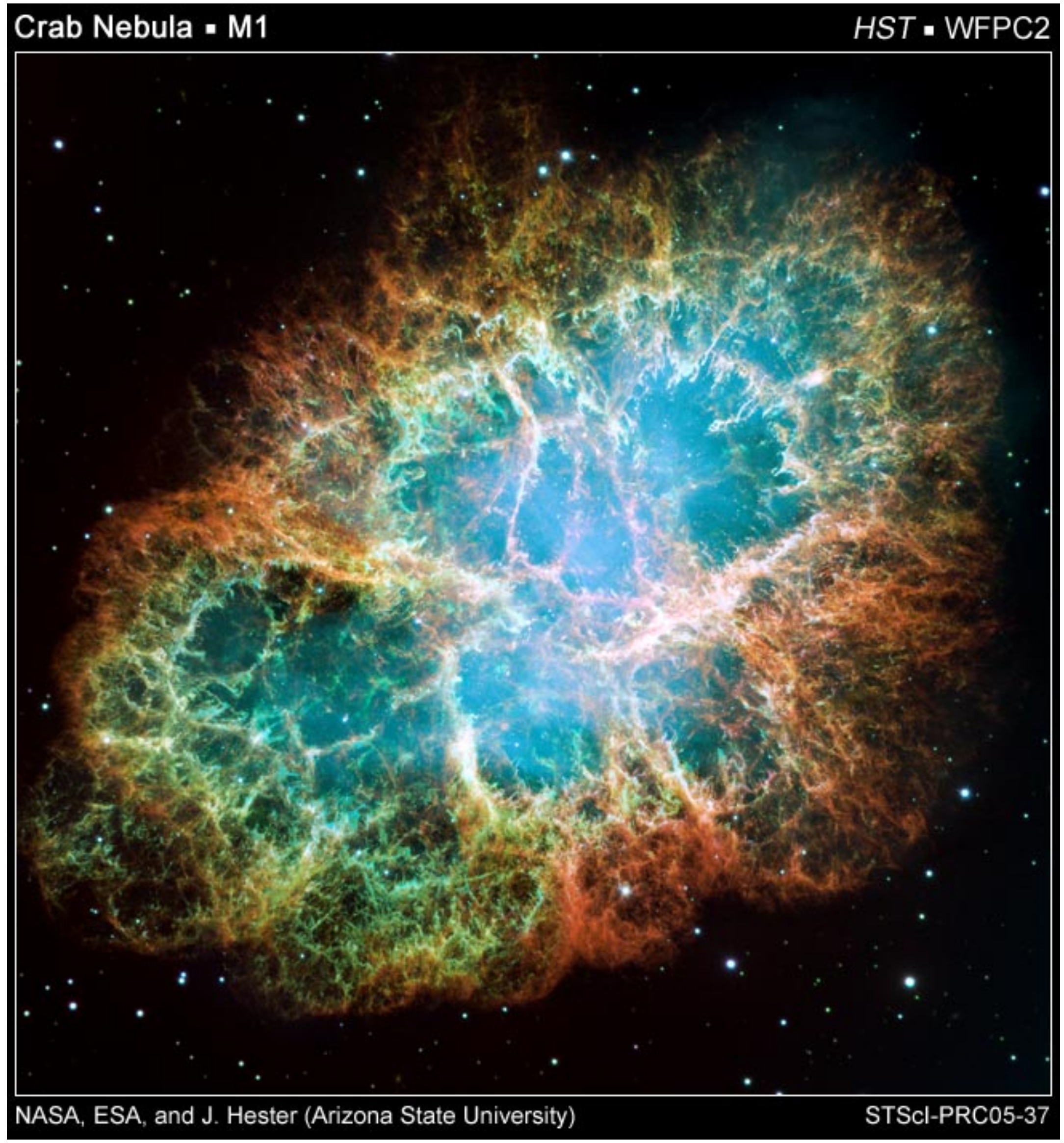
Chandra: X-rays



Supernova observed in Galileo's time: 1667 or 1680

Crab Nebula

Supernova observed by Japanese and Chinese astronomers in 1054.

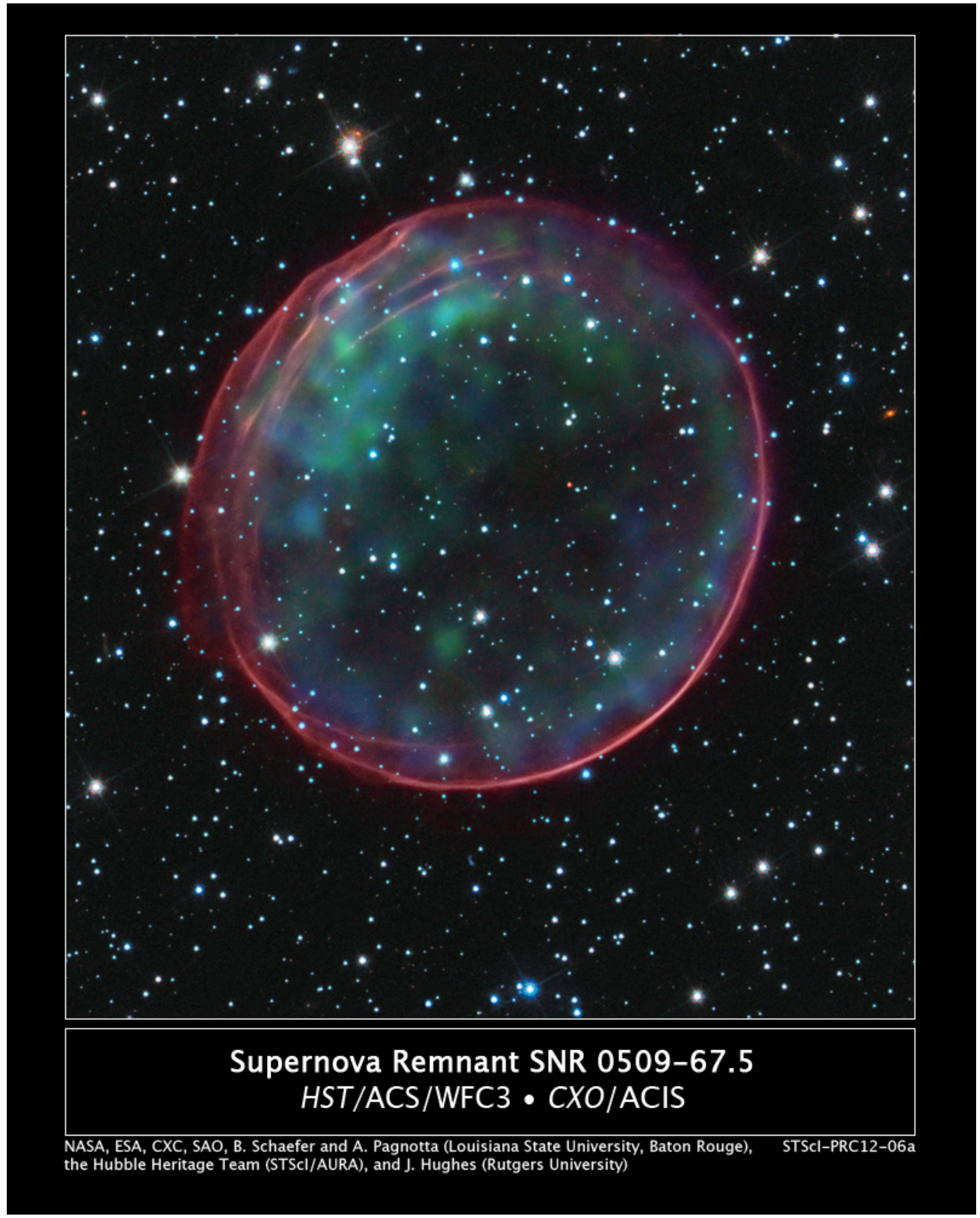


Crab Nebula in X-rays

SNR 0509-67.5

Hubble/Chandra composite

Type Ia supernova, 400 years ago



The Solar Neutrino Problem

Solar Neutrino Problem

- Neutrinos are a direct probe of hydrogen burning
- They interact weakly, so they have a very small cross-section of interaction
- The sun is basically transparent to neutrinos, so they freely escape

Solar Neutrino Problem

- PP chains:
  - $^{1}H + ^{1}H \rightarrow ^{2}H + e^{+} + \nu_e$
  - $^{7}Be + e^{-} \rightarrow ^{7}Li + \nu_e\ (+\gamma)$
  - $^{8}B \rightarrow ^{8}Be + e^{+} + \nu_e$
- CNO Cycle:
  - $^{13}N \rightarrow ^{13}C + e^{+} + \nu_e$
  - $^{15}O \rightarrow ^{15}N + e^{+} + \nu_e$
  - $^{17}F \rightarrow ^{17}O + e^{+} + \nu_e$
  - $^{18}F + e^{-} \rightarrow ^{18}O + \nu_e$
- Additional reactions:
  - $p + p + e^{-} \rightarrow H + \nu_e + \nu_e$ (pep)
  - $^{3}He + p + e^{-} \rightarrow ^{4}He + \nu_e + \nu_e$ (hep)

Neutrino Energies

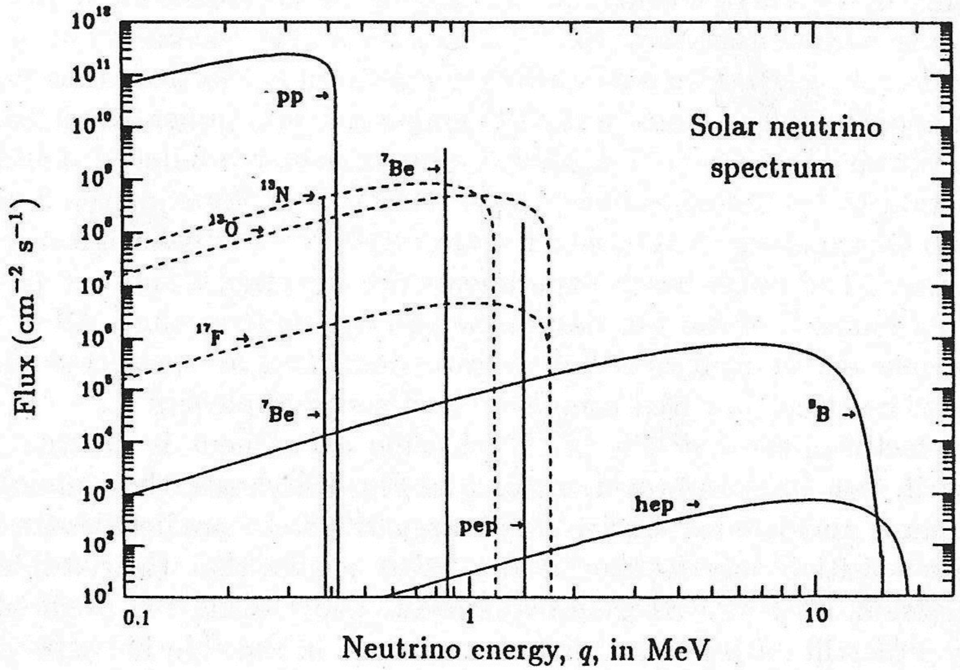


Fig. 9.7. The energy spectrum of electron neutrinos predicted from a standard solar model. The solid (dashed) lines are pp-chain (CNO) reaction neutrinos. The units for continuum neutrinos are cm^{-2} s^{-1} MeV^{-1} and, for line neutrinos, cm^{-2} s^{-1}. The fluxes are what should be observed at 1 AU. Reproduced with permission from Bahcall (1989).

Hansen, Kawaler, Trimble

Detecting Neutrinos

- Earth is transparent to neutrinos – how to detect them?
- $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$
- ${}^{37}Ar$ has a half-life of 35 days
- Homestake Mine Experiment
  - Kellogg, SD
  - Raymond Davis, Jr.
  - Filled a 100,000 gallon tank with 600 tons C_2Cl_4 (tetrachloroethylene – cleaning fluid)
  - Sensitive to neutrinos >0.814 MeV
  - Measured neutrino fluxes from 1970-1988

Davis Experiment

- SNU = solar neutrino units = 10^{-36} captures per second per target (less than one detection per day)
- Expected 7.6 +/- 1.2 SNU
- Measured 2.1 +/- 0.9 SNU
- Initially blamed on experimental error, bad technique, errors in models

Additional Experiments

- GALLEX – gallium, >0.23 MeV ($^{71}Ga + \nu_e \rightarrow$ $^{71}Ge + e^-$)
- SAGE – gallium
- Kamiokande – Cherenkov radiation in water, >6.5 MeV
- Super-Kamiokande – (Cherenkov)

- All detect a deficit of electron neutrinos

Sudbury Neutrino Observatory

- 1999-2006
- Deuterium dissociation in heavy water
- $\nu_e + {}^2H \rightarrow {}^1H + {}^1H + e^-$
- Can measure all neutrinos
- $\nu_x + {}^2H \rightarrow \nu_x + {}^1H + n$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
  - Neutron scattering, electrons create Cherenkov radiation
- Verified neutrino oscillations by detecting the "missing" neutrinos

Neutrino Oscillations

- There are three flavors of neutrinos: electron, mu, tau – corresponding to three flavors of leptons
- The flavors convert into each other, so that by the time they reach the earth, there are equal numbers of each.
- Also, neutrinos have mass

- Nobel Prize in Physics 2002 to Davis & Koshiba

Main sequence Stellar Structure

Central Temperature

Kippenhahn & Weigert 1990

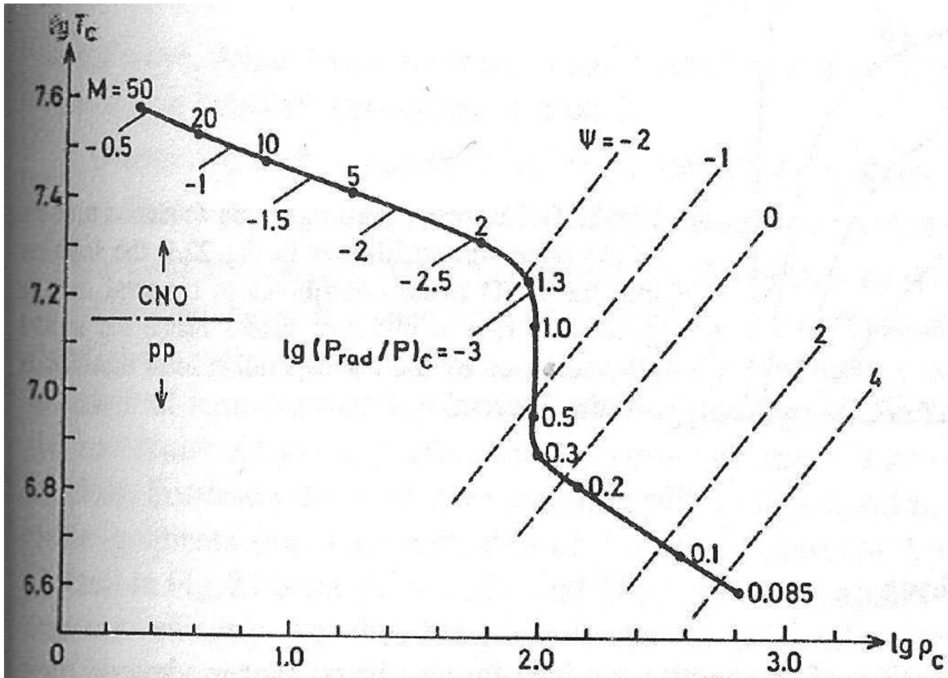


Fig. 22.5. The heavy solid line gives the central temperature T_c (in K) over the central density ϱ_c (in g cm^{-3}) for the same zero-age main-sequence models as in Fig. 22.1. The dots give the positions of some models with masses between $M = 0.085$ and $M = 50$ (in solar masses). The labels below the curve indicate the fractional contribution of the radiation pressure P_{rad} to the total pressure in the centre. The dot-dashed line at the left gives roughly the border between dominating CNO-cycle and dominating pp-chain reactions. The dashed lines give the constant degeneracy parameter ψ of the electron gas

Convective Zones

Kippenhahn & Weigert 1990

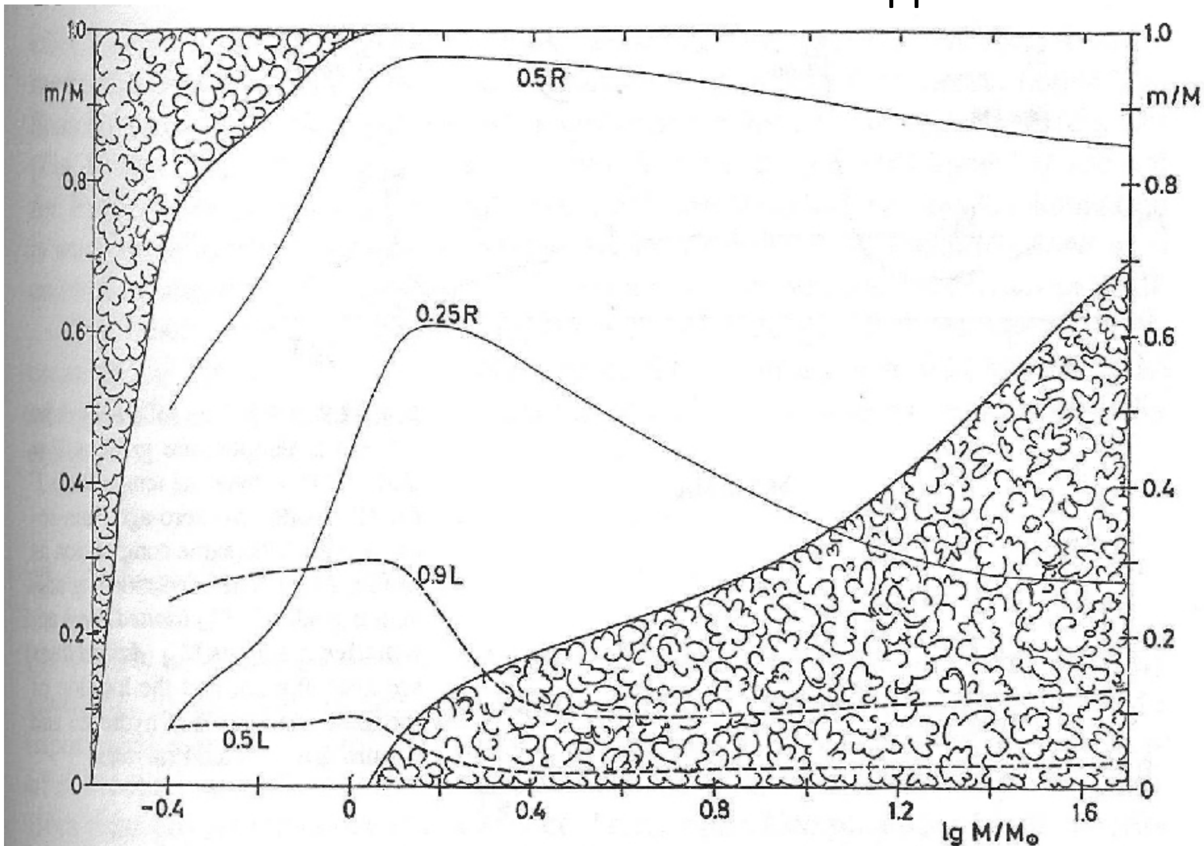


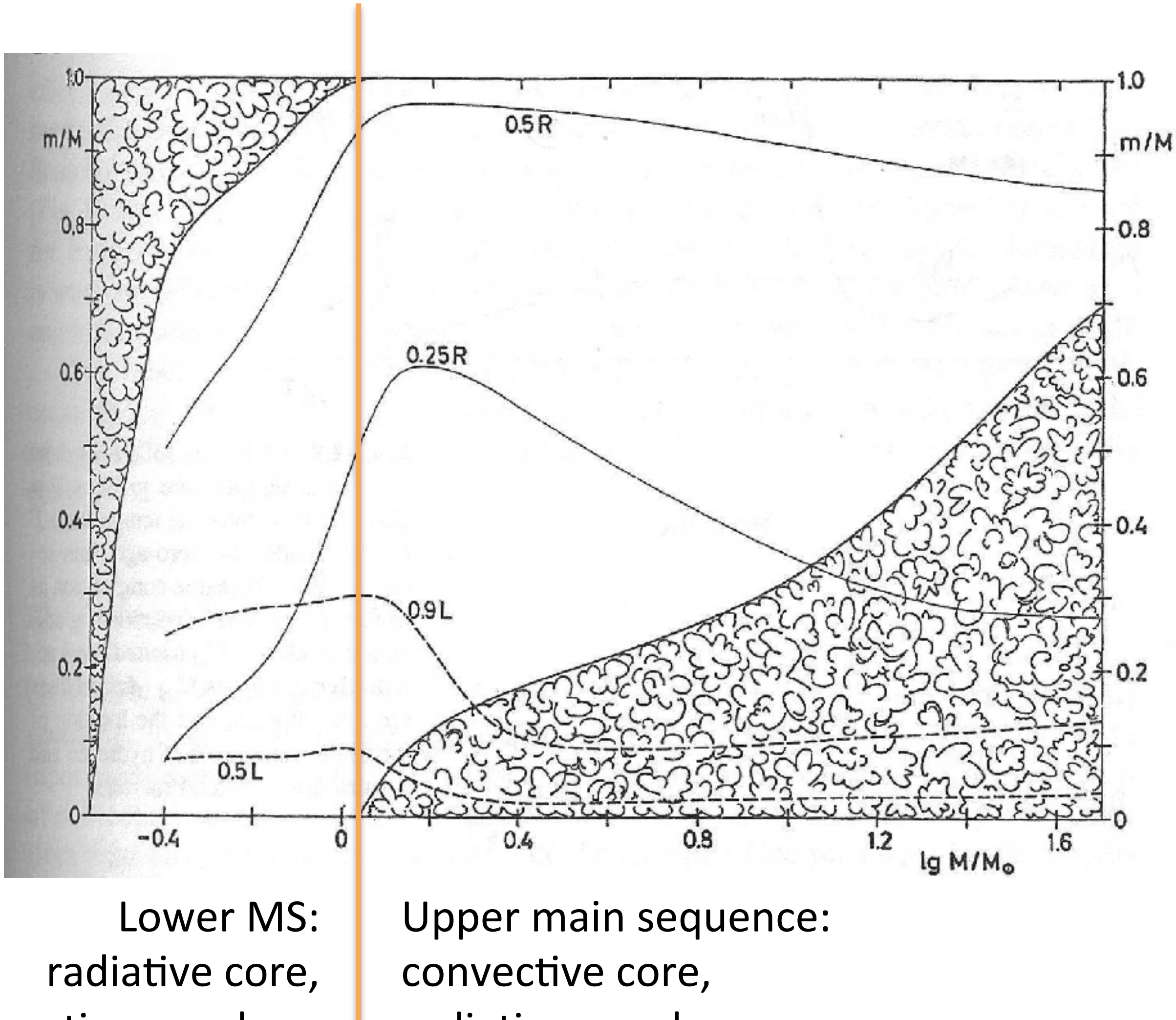
Fig. 22.7. The mass values m from centre to surface are plotted against the stellar mass M for the same zero-age main-sequence models as in Fig. 22.1. "Cloudy" areas indicate the extension of convective zones inside the models. Two solid lines give the m values at which r is 1/4 and 1/2 of the total radius R. The dashed lines show the mass elements inside which 50% and 90% of the total luminosity L are produced

Schwarzchild criteria:

$$\nabla < \nabla_{ad}$$

$$\left(\frac{dT}{dz}\right)_{ad} > \left(\frac{dT}{dz}\right)$$

Convective Zones



Lower MS:
radiative core,
convective envelope

Upper main sequence:
convective core,
radiative envelope