Ch. 15 - The Fate of Massive Stars

p518 §15.1 Post Main-Sequence Evolution of Massive Stars

(Google image search - Eta Carinae Hubble - on lecture computer)

Tell students to read η Car story in text.
Southern hemisphere star.
1600-1830 m~2, became more active, fluctuated between 0 & 1 for 20 years after 1837, -1 at one point (2nd brightest star after Sirius).
$d = 2300\,pc$ ($\gg d_{Sirius} = 2.64\,pc$)
>1856, m dropped to 8 by 1870. Lesser brightening 1887-1895.
Since then, gradual brightening, now m~6.
P Cygni - another MW star that has fluctuated similarly. (MW = Milky Way)

p.519 Luminous Blue Variables (LBV's)

Small # observed, incl. S Doradus in LMC.
Several names - S Doradus variables, Hubble-Sandage variables, LBV's.
(oh F15.1 or previous Google image)
2 lobes expanding outward at 650 $km\,s^{-1}$ (hollow) + equatorial disk.
(Mordecai simulated this in 2D in 1999 - "centrifugal force" significant.)
Composition of lobes ⇒ had undergone CNO cycle.
$\dot{M} = 10^{-3}\,M_\odot\,yr^{-1}$ probably ejected 1-3 $M_\odot$ during Great Eruption.
L (Great Eruption) ~ $2\times10^7\,L_\odot$, $L_{quiescent} \sim 5\times10^6\,L_\odot$, $T_{eff} \sim 30{,}000\,K$
LBV's are variable for a short period > leaving MS.
Various mechanisms have been proposed.
1) $L_{Ed} = \frac{4\pi G c}{\bar{\kappa}} M$. As star evolves to right (lower T) in HR diagram, $\bar{\kappa}\uparrow$ due to Fe lines etc., so $L_{Ed}\downarrow$ below L ⇒ mass loss.
2) Atmospheric pulsations as in Cepheids. But modeling is difficult.
3) High rotation ⇒ low effective gravity at equator (Mordecai's 1999 work).
4) LBV's may be members of binary systems: effects unclear.

p521 Wolf-Rayet (WR) stars

Characterized by strong emission (rather than absorption) lines.
$T_{eff} \sim 25{,}000 - 100{,}000\,K$, $\dot{M} > 10^{-5}\,M_\odot\,yr^{-1}$, wind speed = 800-3000 $km\,s^{-1}$, + rotation.
$M_{LBV} > 85\,M_\odot$, $M_{WR} > 20\,M_\odot$
Not as variable as LBV's.
(oh F15.2)
Subclasses WN, WC, + WO based on prominent emission lines of N, C, O.
Spectra due to loss of H envelope + convection bringing fusion products to surface.
Upper portion of HR also contains blue + red supergiants (BSG's, RSG's), + Of (O-star w/ emission lines)

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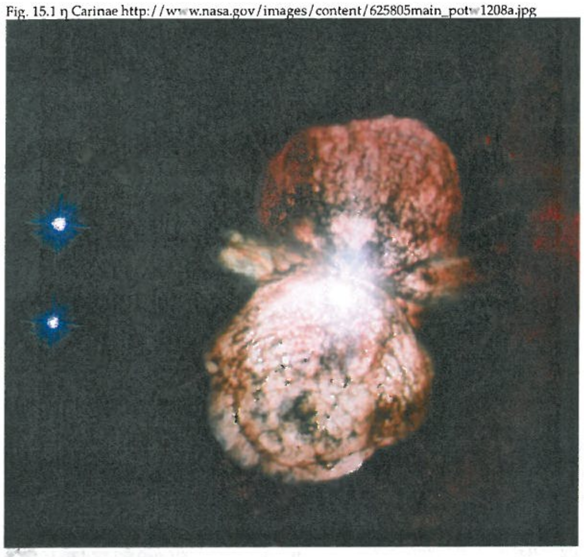

Fig. 15.1 η Carinae http://www.nasa.gov/images/content/625805main_potw1208a.jpg

Fig. 15.2 nebula M1-67 around Wolf-Rayet star WR 124 https://upload.wikimedia.org/wikipedia/commons/c/c6/M1-67_%26_WR124.png

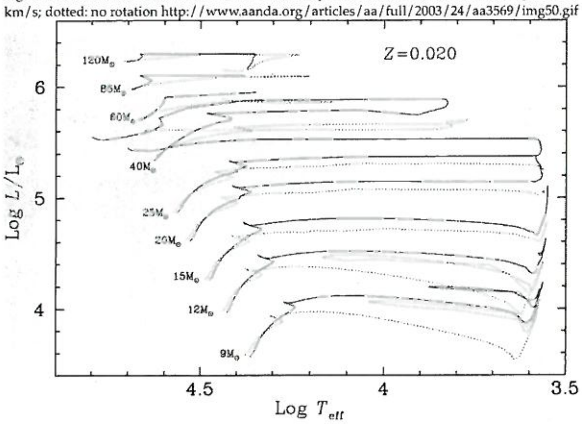

Fig. 15.3 Evolution of massive stars w/ Z = 0.02 Meynet & Maeder. solid: rotational speed 300 km/s; dotted: no rotation http://www.aanda.org/articles/aa/full/2003/24/aa3569/img50.gif

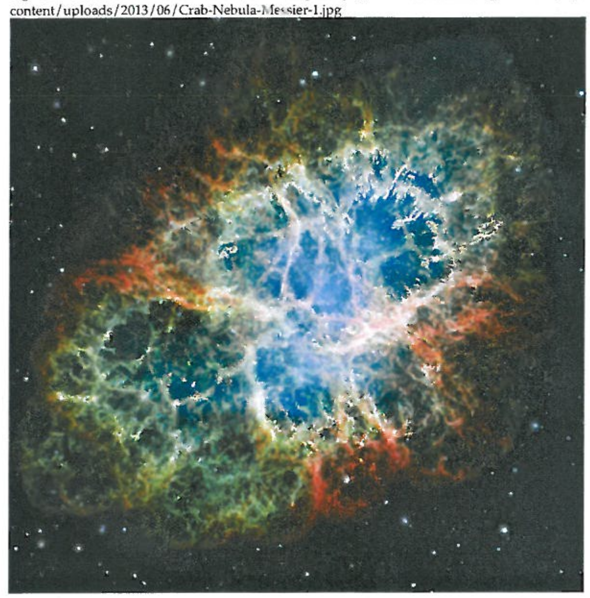

Fig. 15.4 Crab sn remnant in Taurus, d = 2000pc http://www.constellation-guide.com/wp-content/uploads/2013/06/Crab-Nebula-Messier-1.jpg

p. 522 Evolutionary scheme for massive stars

$M > 85\ M_\odot$: O → Of → LBV → WN → WC → SN

$40\ M_\odot < M < 85\ M_\odot$: O → Of → WN → WC → SN

$25\ M_\odot < M < 40\ M_\odot$: O → RSG → WN → WC → SN

$20\ M_\odot < M < 25\ M_\odot$: O → RSG → WN → SN

$10\ M_\odot < M < 20\ M_\odot$: O → RSG → BSG → SN

p. 522 A General Evolutionary Scheme for Massive Stars

(evolutionary scheme from p. 522)

This scheme is supported by detailed numerical models (F15.3 p. 523)

p. 523 The Humphreys-Davidson Luminosity Limit - skip

§15.2 The Classification of Supernovae (SNe)

AD 1006 SN w/ $M_V \sim -9$ observed in Europe, China, Japan, Egypt, & Iraq; bright enough to read by at night, faded after 1 year (M(Full Moon) $= -12.7$).

AD 1054 - Crab supernova (F15.4) (now contains a pulsar).

Next 2 observed = Tycho's SN (1572) & Kepler's SN (1604)

Kepler's was the last SN in the Milky Way (observed - probably some obscured)

The next "nearby" SN was SN 1987A in LMC (F15.5).

By looking at old photos, it was determined that the progenitor was BSG (Sanduleah) Sk -69 202

p. 526 Classes of SNe

SNe are classified by their spectra & light curves.

Over 1000 SNe have now been observed, now ~100/year.

(F15.6) Type I: no H lines ⇒ stripped of H envelope.

Ia: strong Si II line

Ib: strong He lines

Ic: no strong He lines

Type II: strong H lines

Other clues to mechanism comes from environments

(ex: Ib & Ic found only in active star formation regions)

(F15.7) Composite SN I blue light curve.

SN II have peak brightness ~1.5 mag dimmer than SN Ia.

SN II are classified as Type II-P or II-L if they do or don't have a plateau from ~30-80 days after peak (F15.8)

(F15.9) Decision tree for classifying SNe.

We will see (§15.3) that Types Ib, Ic, & II are core-collapse SN, while (§18.5) Type Ia's involve detonation of accreting white dwarf star.

p529 §15.3 Core-Collapse SNe

SNe II release ~10^{46} J of energy; 1% in KE of ejecta, 0.01% in photons, & the rest in ν's. Types Ib & Ic are similar.

p. 530 Core-Collapse SN Mechanism

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Fig. 15.5 SN 1987A in LMC (from sci.esa.int)

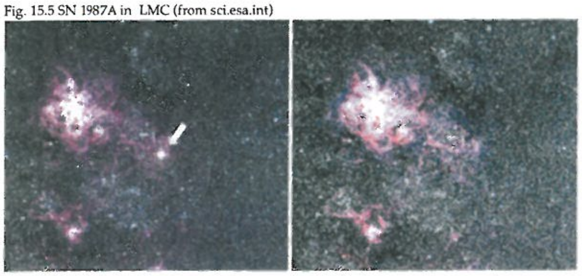


Figure 3: Apparition of SN1987A
In the left-hand image you can see the Tarantula Nebula after the supernova exploded. An arrow points to the supernova. The right-hand image shows the Tarantula Nebula in the LMC before the explosion of Supernova 1987A on February 23rd 1987.

Fig. 15.6 spectra of 4 types of supernovae (Fillipenko 1997) http://www.pha.jhu.edu/~bfalck/SNSpectra.png

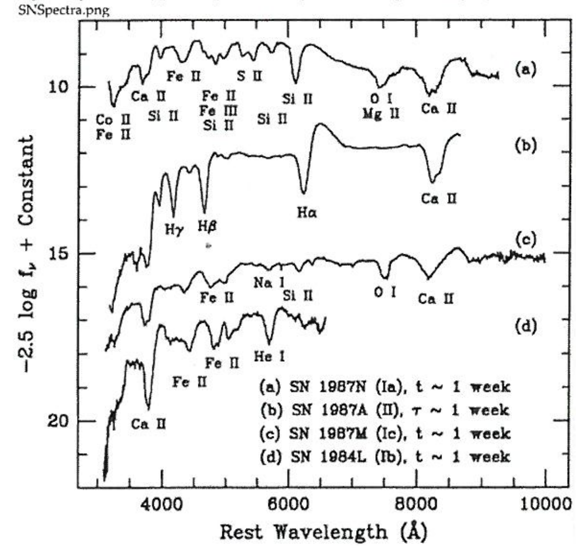


Fig. 15.7 Composite light curve for Type I SNe at blue wavelengths (adapted from Cadonau 1987) https://ned.ipac.caltech.edu/level5/Branch2/Figures/figure2.jpeg

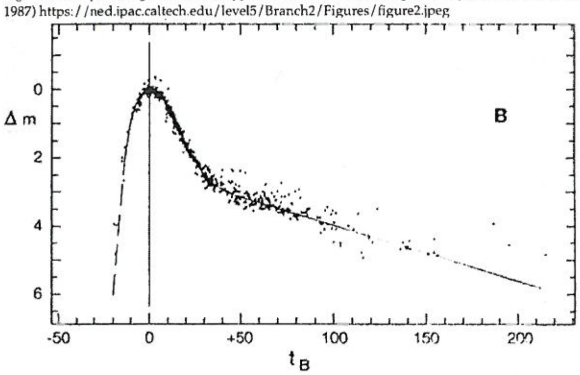
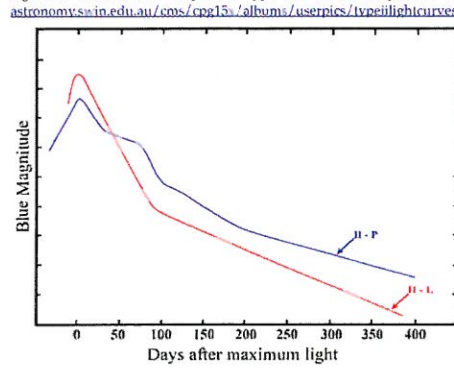


Fig. 15.8 characteristic shapes of Type II-P & II-L supernova light curves http://astronomy.swin.edu.au/cms/cpg15x/albums/userpics/typeiilightcurves1.gif



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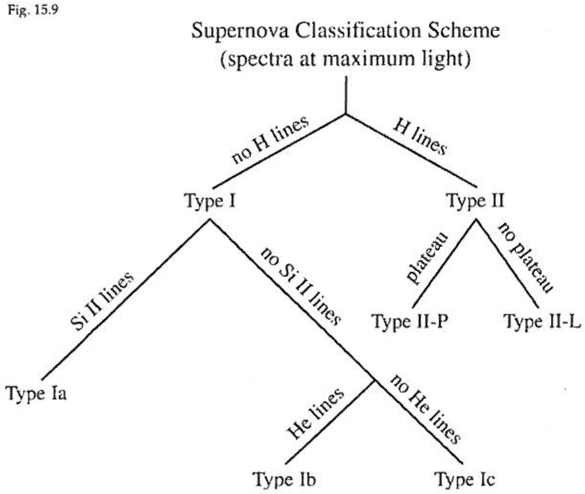


Fig. 15.9

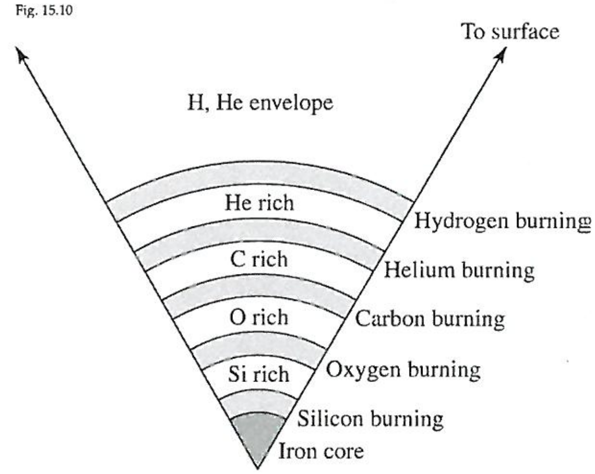


Fig. 15.10

Fig. 15.11 Radioactive decay of Ni-56 with half-life 6.1 days

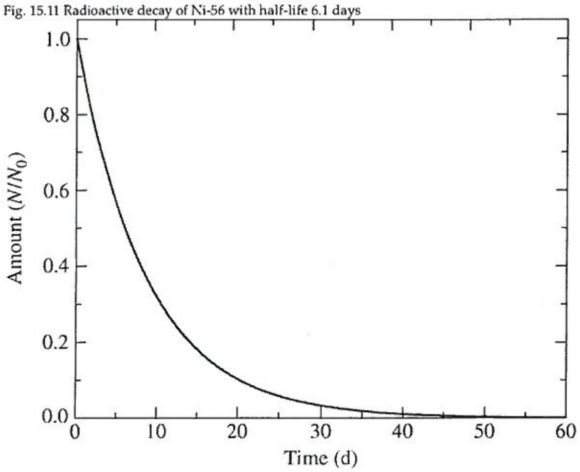
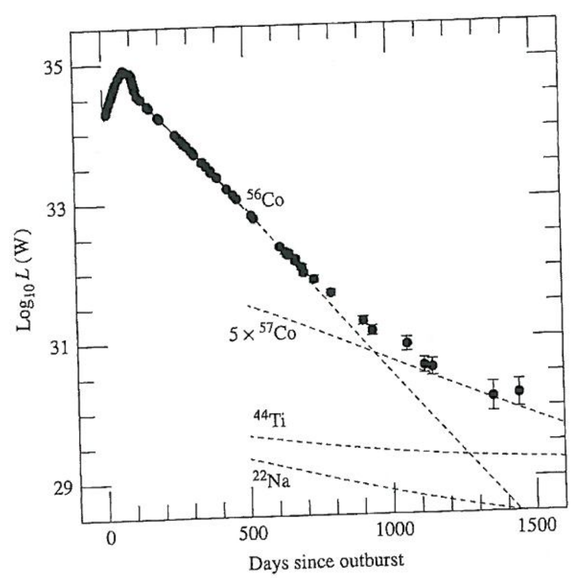


Fig. 15.12 bolometric light curve of SN 1987A http://callisto.ggsrv.com/imgsrv/FastFetch/UBER1/ZI-2PLZ-2012-APR00-IDSI-24-1



For $M > 8 M_\odot$, C + O can burn,
Star attains an onion-like structure (F 15.10)
The final exothermic reaction, at $T \sim 3\times10^9$ K is Si-burning.

$${}^{28}_{14}Si + {}^{4}_{2}He \rightleftharpoons {}^{32}_{16}S + \gamma$$

$${}^{32}_{16}S + {}^{4}_{2}He \rightleftharpoons {}^{36}_{18}Ar + \gamma$$

(reverse arrows due to photodisintegration)

⋮

$${}^{52}_{24}Cr + {}^{4}_{2}He \rightleftharpoons {}^{56}_{28}Ni + \gamma$$ (+ other nuclei near the Fe-56 peak).

("iron core" means elements near the Fe-56 peak).

Not much energy is produced per reaction near the Fe peak, so (for $M = 20 M_\odot$) ms (H burning) takes 10^7 yr, core He burning 10^6 yr, C burning 300 yr, O 200 days, Si 2 days!

At high T, γ's have enough energy to photodisintegrate Fe + He:

$${}^{56}_{26}Fe + \gamma \rightarrow 13\,{}^{4}_{2}He + 4n$$

$${}^{4}_{2}He + \gamma \rightarrow 2p^+ + 2n$$

$U = \frac{3}{2}NkT$, $P = \frac{NkT}{V} = \frac{2U}{3V}$, $U\downarrow \Rightarrow P\downarrow$

$\Rightarrow$ removal of thermal energy + pressure supporting ($1.3-2.5 M_\odot$) core.

Core contracts + heats up to $T_c \sim 8\times10^9$ K + $\rho_c \sim 10^{13}$ kg m^{-3}.

$p^+ + e^- \rightarrow n + \nu_e$ (p's capture e's which were providing degeneracy pressure, + ν's remove energy).

Si burning in $20 M_\odot$ model: $L_{photons} = 4.4\times10^{31}$ W, $L_\nu = 3.1\times10^{38}$ W!

Core collapses! Speed $\sim 70{,}000$ km s^{-1}! Earth volume compressed to 50 km in ~ 1 second!

<u>Ex. 15.3.2 p.532</u> How much mass would have to collapse from Earth radius $R_\oplus$ to $R_f \sim 50$ km for gravitational energy to provide $E_{II} = 10^{46}$ J?

As in Ex. 10.3.1, p.297, $\Delta E = -\frac{3}{10}\frac{GM^2}{R} \Rightarrow$

$$M \simeq \sqrt{\frac{10}{3}\frac{E_{II} R_f}{G}} \simeq 5\times10^{30}\text{ kg} \simeq 2.5 M_\odot \text{ — yes!}$$

Core collapses to $\rho_c \sim 8\times10^{17}$ kg m^{-3}, at which point it stiffens due to neutron degeneracy.

Pressure wave moves outwards, becoming shock wave when it reaches v_{sound}.

Shock wave encounters infalling outer iron core $\Rightarrow$ photodisintegration $\Rightarrow$ shock loses energy + stalls.

Below the shock, neutrinosphere develops.

Neutrinos deposit ~5% of their energy, perhaps allowing the shock to move out.

This process is very difficult to simulate even on modern supercomputers.
Need to treat 3D convection, ν's, many grid points...
But if shock is able to move outwards, it pushes envelope outwards, releases $\sim 10^{42}$ J of γ's when it becomes optically thin, peak $L \sim 10^9 L_\odot \sim L_{galaxy}$.

This is the general mechanism for Types II, Ib, & Ic, with differences being masses & composition of envelopes.
Type II = RSG
Ib's & Ic's have lost some of envelope prior to SN:
maybe Ib's & Ic's come from WN & WC Wolf-Rayet's.

<u>p.534 Stellar Remnants of Core-Collapse SN</u>
If $M_{ZAMS} \lesssim 25 M_\odot$, after SN, core becomes ns. (ZAMS = zero-age ms) (ch.16)
$M_{ZAMS} \gtrsim 25 M_\odot \Rightarrow$ bh (ch.17)
Energy emitted by ν's $\sim 3\times10^{46}$ J = huge ($\sim E_{binding}$ of ns (grav))

<u>Light Curves & Radioactive Decay of the Ejecta</u>
II P is most common type of core-collapse SN.
Plateau caused by shock-ionized envelope slowly recombining.
Light curve also supported by radioactive decay of ${}^{56}_{28}Ni$ ($\tau_{1/2} = 6.1$ days), as well as ${}^{57}_{27}Co$ (271d), ${}^{22}_{11}Na$ (2.6 yr), & ${}^{44}_{22}Ti$ (47 yr).
Rate of decay $\propto$ # of atoms remaining:
$\frac{dN}{dt} = -\lambda N \Rightarrow N = N_0 e^{-\lambda t}$, $\lambda = \ln 2/\tau_{\frac{1}{2}}$ (F15.11 p.535)
One can show (prob. 15.9) that $\frac{d\log_{10} L}{dt} = -0.434\lambda$ & $\frac{dM_{bol}}{dt} = 1.086\lambda \Rightarrow$
slope of light curve $\Rightarrow$ identification of radioactive species.
SN1987A was unusual - subluminous, w/ slow (80 day) rise to maximum.
(F15.12 p.536) shows bolometric light curve of SN1987A along with contributions due to radioactive decay.

<u>p.537 The Subluminous Nature of SN1987A</u>
After SN1987A its progenitor was found to be a blue supergiant, which is much smaller & denser than the usual RSG $\Rightarrow$ much of the thermal energy was converted into mechanical energy (ejecting the H envelope at 0.1c) rather than light.

<u>SN Remnants</u> (SNRs)
Many SNR's have been observed - expanding explosion remnants.

(F15.4 from before) Crab Nebula, remnant of SN 1054 in Taurus, expanding at 1450 km s^{-1}, $L = 8\times10^4 L_\odot$ (energy source = pulsar).

(F15.13) 15,000 year old Cygnus Loop, 800 pc from Earth. Shock fronts expanding from left to right, ionizing the ISM.

(F15.14) Rings around SN 1987A, 0.42 pc diameter
Central ring ejected by stellar winds 20,000 yrs ago.
Outer rings mechanism unsure, possibly jets from precessing ns or bh "painting" hourglass-shaped mass distribution.

(F15.15) shows expanding nebula inside inner ring, + lumps of matter in inner ring beginning to glow as they are overtaken by expanding shock.

<u>p539 Detection of ν's from SN 1987A</u>
ν burst lasted for $12\frac{1}{2}$ s, 3 hours <u>before</u> photons. 12 recorded at KamiokandeII (Japan) + 8 at IMB in Ohio.
Star became optically thin to ν's before γ's.
Due to facts that 1) ν's arrived before γ's + 2) high-E + low-E ν's arrived at same time ⇒ $m < 16$ eV (lab results $m < 2.2$ eV).

<u>p.540 Search for Compact Remnant of SN 1987A</u>
In grad school, we waited excitedly for a compact remnant (ns or bh) to reveal itself - but still nothing!
Perhaps after the nebula thins further something will be seen.

<u>p541 Chemical Abundance Ratios in the Universe</u>
(F15.16 p.541) Relative abundances in Sun's photosphere.
H + some He - primordial (Big Bang)
Lithium - under-abundant in Sun relative to meteorites ⇒ it has been destroyed collisions w/ H at $T > 2.7\times10^6$ K. But convection models say convection doesn't go deep enough for this.
Solve this <u>solar lithium problem</u> + get a PhD!

<u>p.542 s-Process + r-Process Nucleosynthesis</u>
Neutron-capture reactions which alter abundances for $A > 60$ - skip!

<u>p543 §15.4 Gamma-Ray Bursts</u> (GRBs) (CNTBT outlawed testing in space, underwater, or atmosphere)
Vela military satellites launched in 1960's to monitor compliance w/ 1963 nuclear test ban treaty with Soviet Union by looking for bursts of γ-rays.
By 1967 it was known that ~ once/day there was a gamma-

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Fig. 15.13 HST WF/PC 2 image of portion of Cygnus Loop http://archive.seds.org/hst/CygnusLoop.jpg

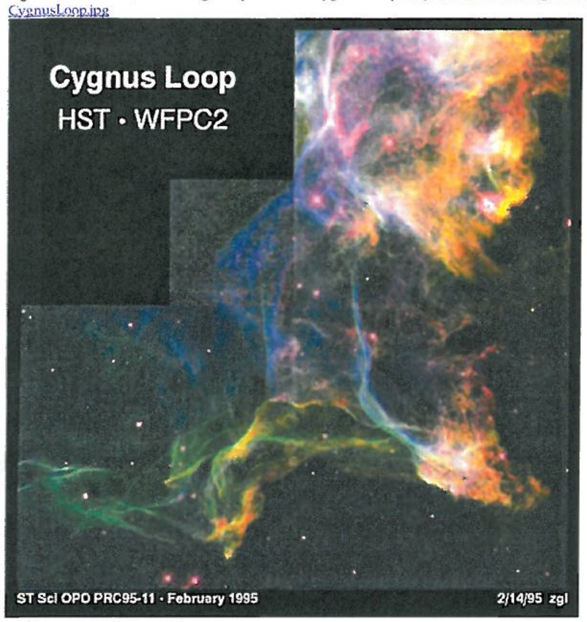


Fig. 15.14 Rings around SN 1987A Burrows ESA/STScI https://www.cfa.harvard.edu/sins/data/87A_skyt.jpg

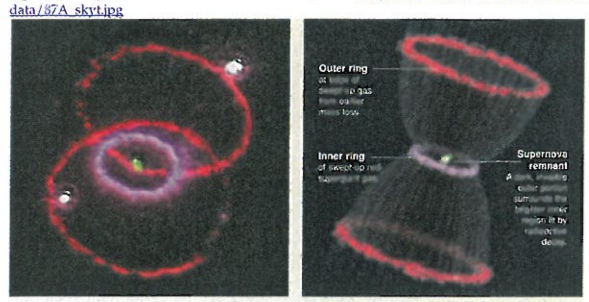


Fig. 15.15 Expanding nebula from 1987A Kirshner http://www.spacetelescope.org/static/archives/images/screen/opo0409b.jpg

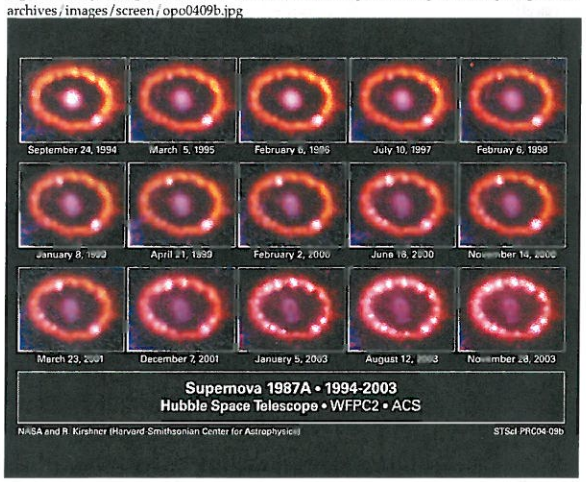
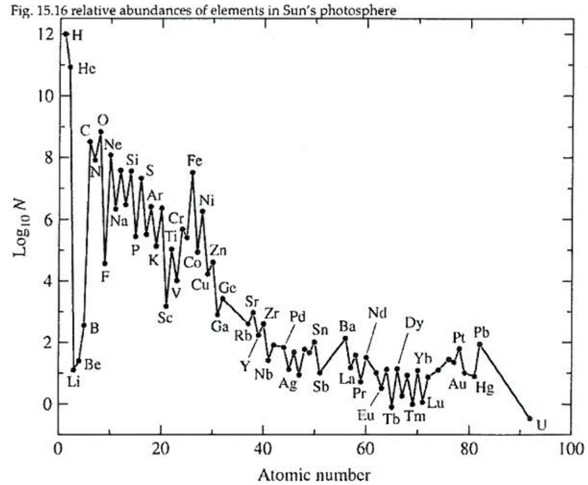


Fig. 15.16 relative abundances of elements in Sun's photosphere



ray burst (GRB) from above (not below) (info released to public in 1973).

E_γ = 1 keV → many GeV (incl. X-rays)

Rise time ≥ 10^{-4} s, duration $10^{-2} \to 10^{3}$ s, exponential decay.

(F15.17 p.543) 2 examples from BATSE (Burst + Transient Source Experiment) aboard CGRO (Compton γ-ray Observatory) (980922 means 9/22/98).

p.544 Are the Sources of GRB's Galactic or Extragalactic?

It was originally not known if GRB's came from solar system, galaxy, or universe. This has huge implications for the energies of the bursts.

Ex 15.4.1 p.544 Let S = fluence = time-integrated energy flux = 10^{-7} J m^{-2}.

Assume isotropic + r = 50,000 AU (Oort Cloud) ⇒

$$E = (4\pi r^2)S = 4\pi[50{,}000(1.50\times10^{11}\,m)]^2 10^{-7}\,J\,m^{-2} = 7\times10^{25}\,J$$

If r = 1 Gpc (distant galaxy), $E = 1\times10^{45}$ J ~ $E_{SN\,II}$.

But astronomers early on agreed that GRB's involve ns's:

c t_{rise} ~ 30 km, 511 keV photons red-shifted by 25%, cyclotron lines ⇒ $B \sim 10^8$ T (10^{12} G).

Angular distribution = isotropic (F15.18 p545) ⇒ not galactic disk ⇒ either very close or very distant.

But sources not homogeneous (in r).

$$S = E/4\pi r^2 \to r(S) = (E/4\pi S)^{\frac{1}{2}}$$

If all sources have same energy E + there are n sources/volume, then the number of sources w/ fluence > S = # within volume $\frac{4}{3}\pi r(S)^3 = N(S) = \frac{4}{3}\pi n(E/4\pi S)^{3/2} \Rightarrow N(S) \propto S^{-\frac{3}{2}}$

(F15.19 p546) (CGRO, uses max count rate instead of fluence)

Low-S cutoff ⇒ the distribution has a cutoff (r_{max}). (r_{min} → edge of universe?)

1997 distance question resolved by BeppoSAX (Italy + Netherlands) - detected by burst monitor, then wide-field x-ray camera localized to within 3′, then within a few hours narrow-field x-ray telescope + other ground + orbital telescopes located afterglow (x-ray + optical) in distant galaxy ⇒ S(E) cutoff is edge of observable universe.

⇒ E ~ E_{SN}

p.547 - 2 Classes of GRB's

Δt > 2s ⇒ long-soft GRB's, Δt < 2s ⇒ short-hard (soft ⇒ lower-E γ's)

Short-hard seem to be ns-ns or ns-bh mergers. Long-soft → SN

Fig. 15.17 Light curves of GRB 980922 & GRB 000526 BATSE

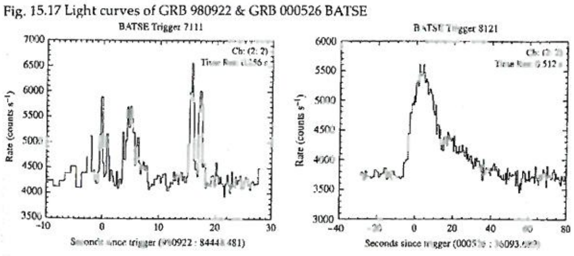


FIGURE 15.17 Light curves of two gamma-ray bursts, GRB 980922 and GRB 000526, in the energy range between 50 keV and 100 keV. The data were obtained by BATSE onboard the Compton Gamma-Ray Observatory. The dates of the two events are recorded in their designations; GRB 980922 occurred on September 22, 1998, and GRB 000526 occurred on May 26, 2000. GRB 0000526 was the last gamma-ray burst recorded by BATSE before the Compton Gamma-Ray Observatory was deorbited. (Courtesy of the BATSE Team – NASA.)

Fig. 15.18 Isotropic angular distribution of 2704 gamma-ray bursts seen by BATSE http://heasarc.gsfc.nasa.gov/docs/cgro/images/cgro/BATSE_2704.jpg

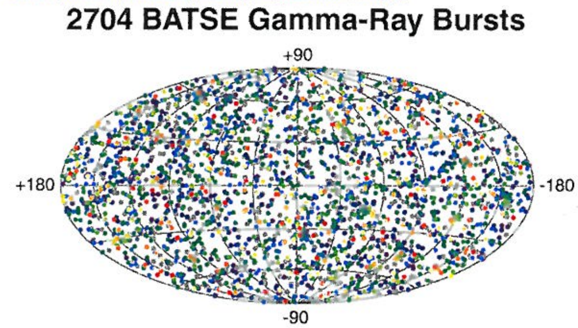


Fig. 15.19 Violation of the proportionality N ∝ $S^{-3/2}$ Meegan et al.

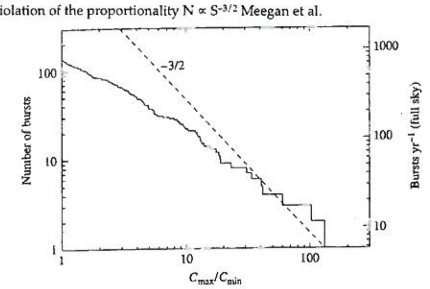


FIGURE 15.19 Violation of the proportionality $N \propto S^{-3/2}$, indicating an edge to the distribution of gamma-ray burst sources. The maximum gamma-ray count rate, C_{max}, is plotted instead of the fluence, S; C_{min} is the weakest burst the CGRO can confidently detect. (Figure adapted from Meegan et al., *Nature*, *355*, 143, 1992.)

Fig. 15.20 relativistic jet of material will appear to observer to have cone half-angle ~1/γ

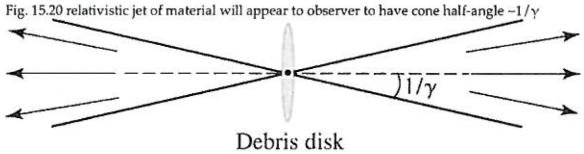


Fig. 15.21 collapsar model of formation of GRB Zhang & Woosley

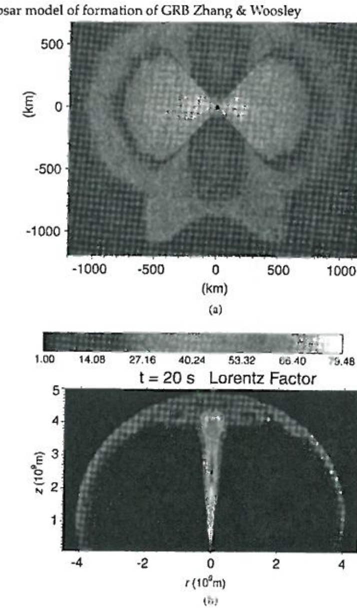


FIGURE 15.21 A collapsar model of the formation of a gamma-ray burst event. (a) The central region of the star following the formation of a black hole and debris disk. (b) The emerging relativistic jet. (Figures courtesy of Weiqun Zhang and Stan Woosley.)

p547 Core-Collapse SNe + Long-Soft GRB's

SN 1998bw (at $v = 40$ Mpc) detected at same location as GRB 980425.
Also SN 2003dh = GRB 030329.

p.548 Models of Long-Soft GRBs

Most models involve beaming of relativistic matter (relativistic jets) (F15.20 p548)
Ch.4 - A light ray emitted at 90° in frame moving w/ matter moving at u towards observer is at $\theta = \gamma^{-1} = \sqrt{1-u^2/c^2} \Rightarrow$ headlight effect.
May have $\gamma \sim 100$, + total E reduced by $\gamma^2 = 10^4$
Collapsar (hypernova) model of Stan Woosley (F15.21 p549)
High-mass (possibly Wolf-Rayet) star has core-collapse SN, resulting in bh + debris disk. Disk + B-field ⇒ 2 relativistic jets (we see them only if pointing towards us).
Or - supranova model. M_{max} for nonrotating ns = 2.2 $M_\odot$, rotating = 2.9.
$M > 2.2 M_\odot$ ns formed in SN, slows down over weeks or months due to B-fields ⇒ collapse to bh (debris disk, relativistic jets, GRB)

p.550 §15.5 Cosmic Rays

1912 Victor Hess + 2 colleagues went up 5 km in a balloon w/ an electroscope, found that radiation levels increase w/ altitude.
Charged particles from space (called cosmic "rays") 10^7 eV < E < 3×10^{20} eV
e, e^+, p, ν, nuclei (F15.22 p551)

Sources of Cosmic Rays

solar cosmic rays: E < 10 MeV
Up to "knee" ($\sim 10^{16}$ eV) - probably from shocks in SNRs.
Magnetic force qvB → moves in circle of radius (Larmor radius, gyroradius) $r = \gamma mv/qB$
Ex. 15.5.1 p552 B (typical interstellar space) $\sim 10^{-10}$ T ⇒
r (proton) = 3×10^{16} m = 1 pc = size of SNR
⇒ particle accelerated by collision w/ approaching shock, then curves around + collides again, repeatedly, till it gets enough energy to escape from the SNR. (Called Fermi acceleration - he thought of it).
(F15.23 p553) (shows shocks in SNR?)
"knee" to "ankle" ($\sim 10^{19}$ eV) possibly different mechanism - acceleration in vicinity of ns or bh.
E > 10^{19} eV possibly collisions involving intergalactic shocks, or near supermassive bh's at galactic centers.

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Fig. 15.22 flux of cosmic rays as function of energy Cronin, Gaisser & Swordy 1997 http://www-astro.physik.tu-berlin.de/files/Bilder/dbres3f1.jpg

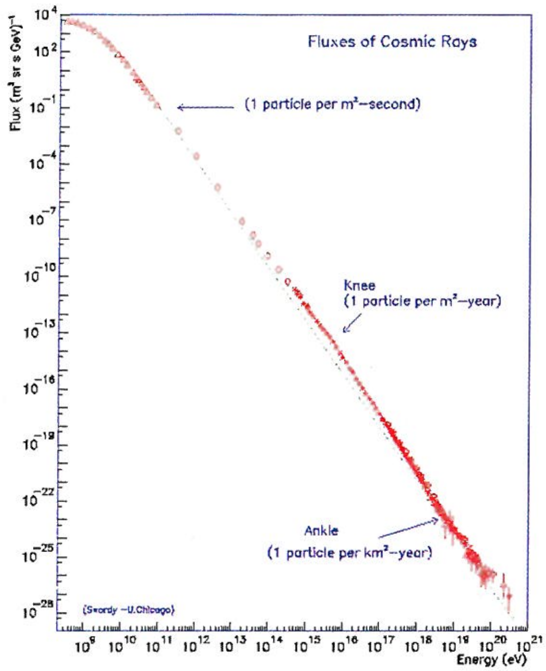

Fig. 15.23 X-ray image of SN 1006 from ASCA https://heasarc.gsfc.nasa.gov/Images/objects/heapow/nebulae/sn1006.jpg