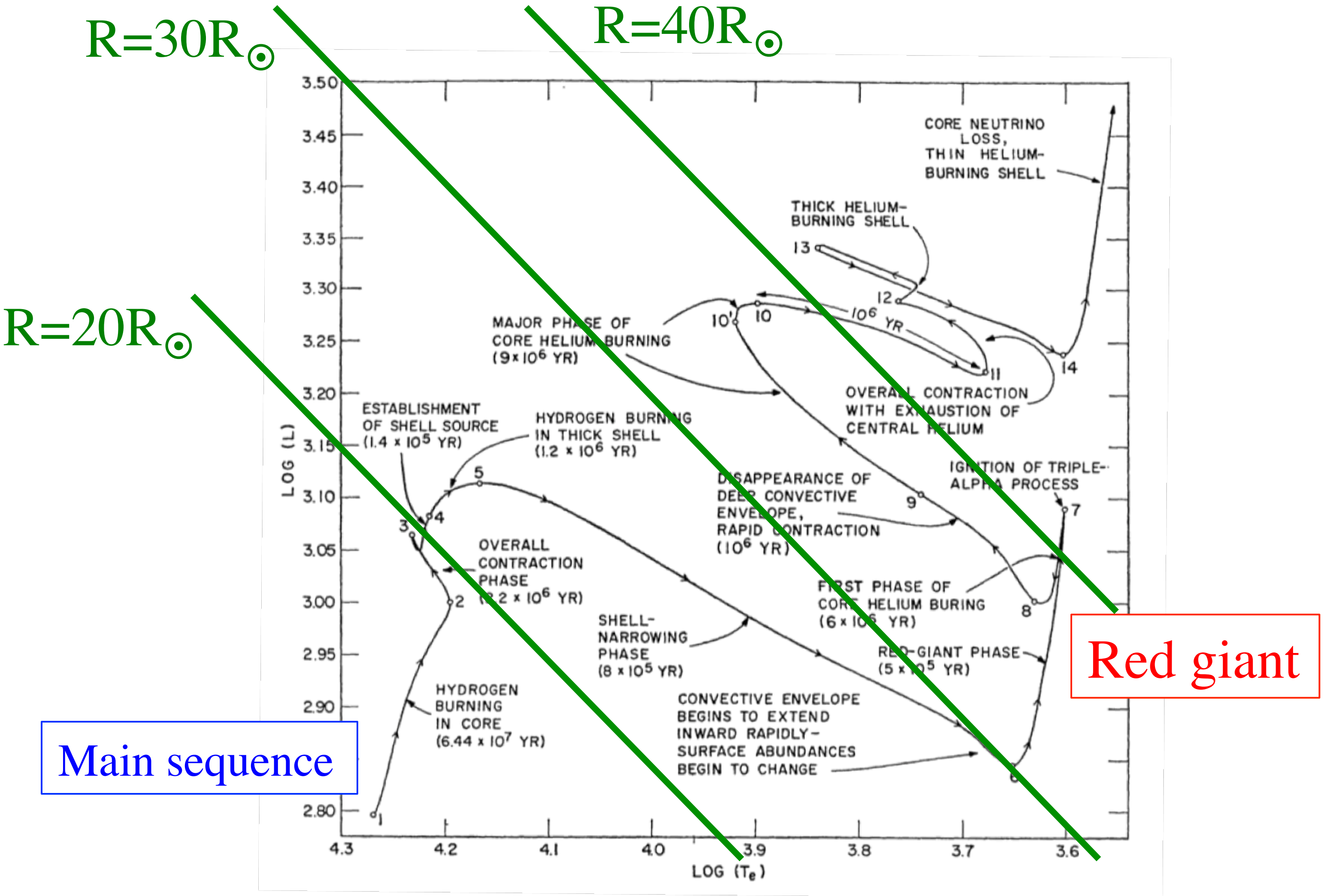
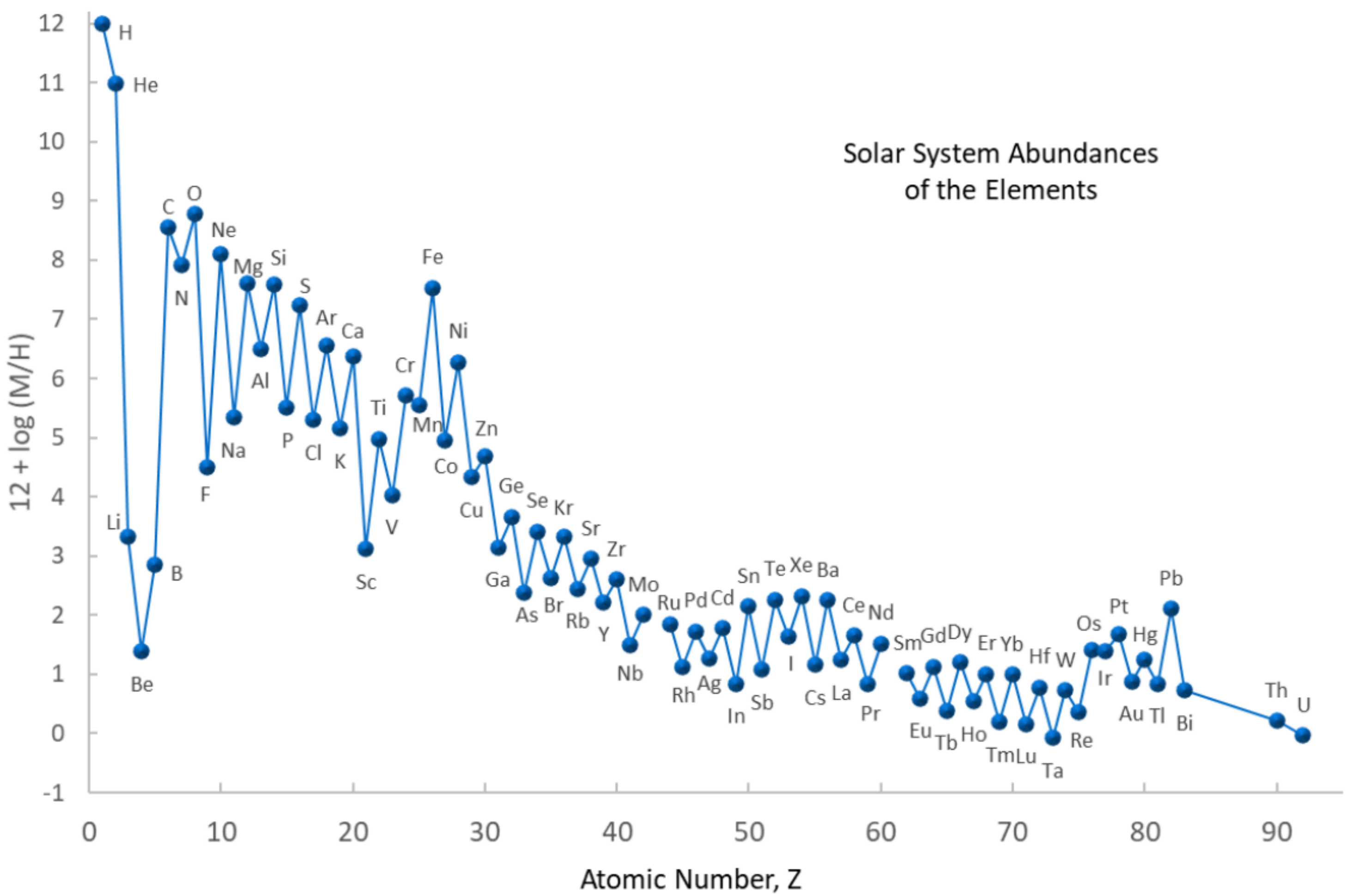
Evolution of a Massive Star



- Post main sequence evolution of a $5M_{\odot}$ star. Iben, I., ARAA **5**, 571 (1967).

Solar System Elemental Abundances



- From Lodders, K. 2020, Solar Elemental Abundances (Oxford University Press) [arXiv.org/1912.00844]

• Convective action can mix elements so that abundances of rarer elements such as lithium can change near the surface.

• The star subsequently becomes fully convective, transporting large amounts of energy outwards. This causes a rapid expansion of the envelope, and an increased luminosity accompanied by greater core production rates. This is the onset of the **red giant phase** (locus point 6), where the star moves vertically in the HR diagram.

Plot: Structural Evolution Diagram of Kippenhahn

• At the peak of the red giant branch (locus point 7), the temperature is hot enough to seed the triple alpha process in a short-lived, explosive **helium core flash**. The star then evolves its helium core into carbon and oxygen as it progresses blueward along the **horizontal branch** (locus points 7–11).

∗ The convection zone retreats to nearer the surface, and the outer envelopes can develop instabilities leading to pulsations; such variables are discussed in the next Chapter.

• After helium burning is exhausted, the evolution replicates the subgiant phase for hydrogen burning depletion, and the star expands and reddens, eventually moving up the **asymptotic giant branch** (AGB).

∗ AGB stars are inherently unstable to helium shell burning, leading to so-called helium-shell flashes and epicyclic stellar pulsation.

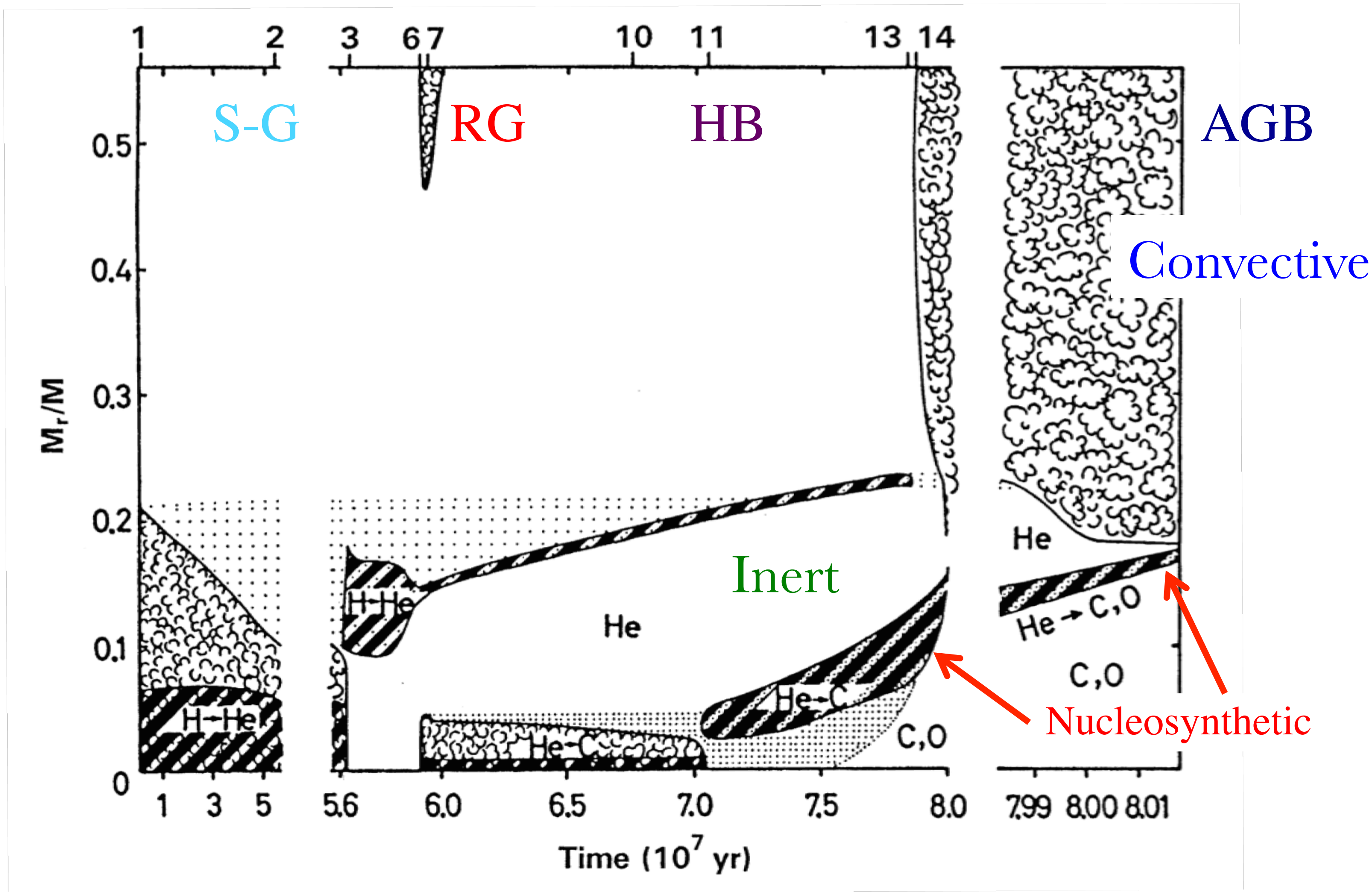
∗ Sequential heating and expansion of the helium shell followed by cooling to partial degeneracy and contraction accompanies the flashes.

Plot: Helium Flash Lightcurves

• Stellar pulsation can lead to extensive mass loss via stellar winds. These winds can be highly non-uniform, and be lit up by the radiation from the dying star, which is the phenomenon known as a **planetary nebula**.

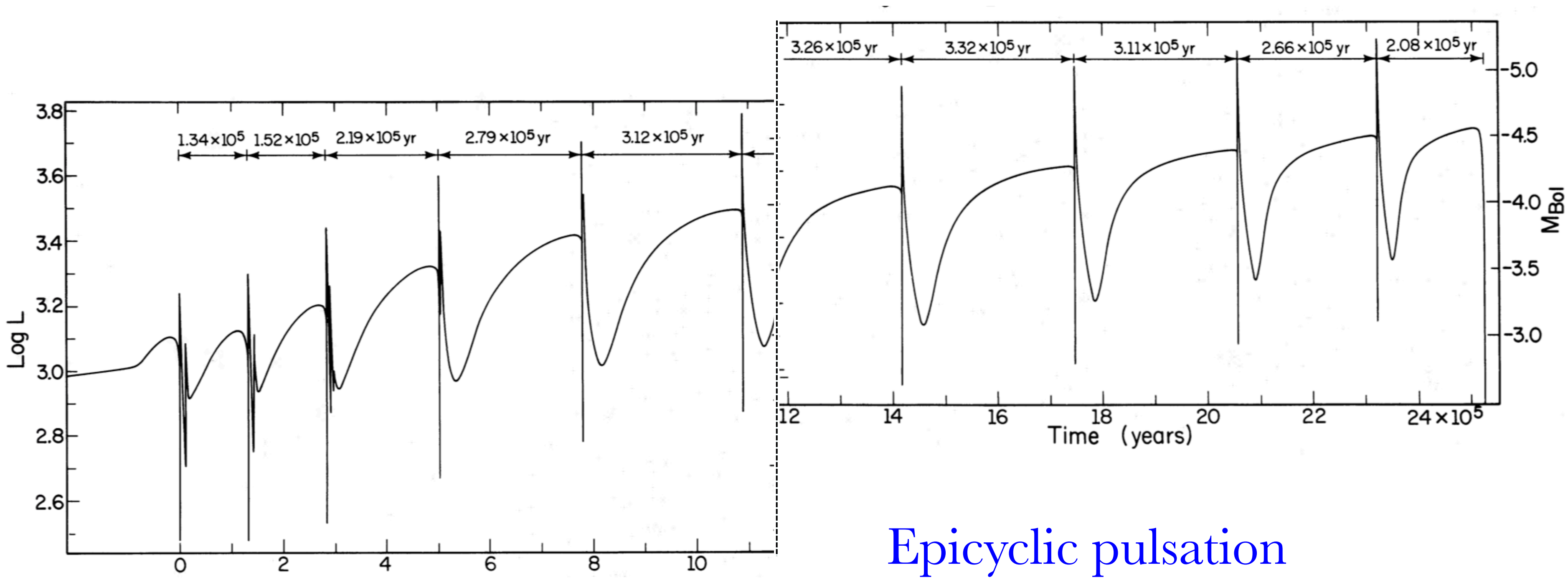
Plot: Planetary Nebula NGC 6543

Structural Evolution of a Massive Star



- Evolution of a $5M_\odot$ star. Kippenhahn, R., et al., Z. Astrophys. **61**, 241 (1965).

Helium Flash Light Curves



Epicyclic pulsation

- Surface luminosity as a function of time for a $0.6M_{\odot}$ AGB star undergoing helium shell flashes. Iben, ApJ 260, 821 (1982)

Planetary Nebula NGC 6543

- Helium burning in the shell deposits more carbon and oxygen onto the core until eventually electron degeneracy pressure can no longer support the core. It collapses catastrophically, the resulting explosion is called a **supernova**.

∗ If the core is less than $1.4M_\odot$ (the Chandrasekhar limit) in mass, it can form a **white dwarf** star; if it is more massive, it will form a **neutron star** or a **black hole**.

1.1 Massive Stars

Stars greater than about 8–10 $M_\odot$ suffer a different evolutionary sequence, due largely to their greater core temperatures. Core shrinking is more impressive, leading to temperatures far in excess of 10^8 K. This permits burning of more massive elements. **C & O, pp. 530–3**

- Oxygen will readily burn after the subgiant phase, and in quick succession, neon, sodium, magnesium can burn as the temperature rises. Then the temperature can reach $\gtrsim 2 \times 10^9$ K and silicon and sulphur burning can proceed, in a sequence all the way to the $^{56}_{26}Fe$ peak:

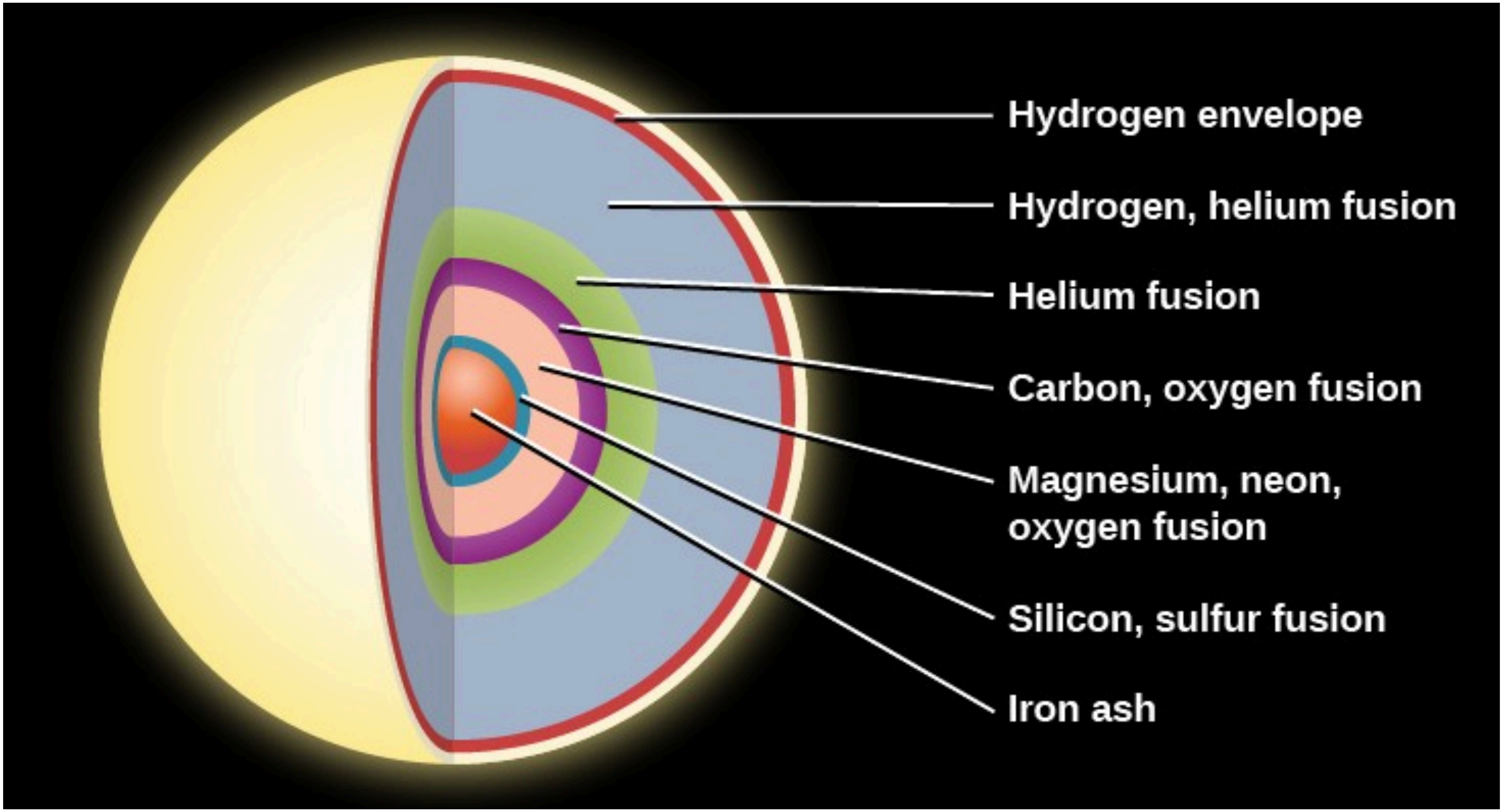
$$\begin{aligned} ^{28}_{14}Si + ^{4}_{2}He &\leftrightarrow ^{32}_{16}S + \gamma \\ ^{32}_{16}S + ^{4}_{2}He &\leftrightarrow ^{36}_{18}Ar + \gamma \\ &\vdots \\ ^{52}_{24}Cr + ^{4}_{2}He &\leftrightarrow ^{56}_{26}Fe + \gamma \end{aligned} \tag{1}$$

∗ Since burning to greater masses is endothermic, the fusion process stops here. A sequence of *onion shells* of burning of successively heavier elements forms, with an iron core.

Plot: Onion-Shell Interior of an Evolved Massive Star

∗ Sequential burning toward the iron peak becomes rapidly faster: for a $20M_\odot$ star, hydrogen burning takes 10^7 years, helium burning takes 10^6 years, carbon burning 300 years, oxygen burning 200 days, and silicon burning just 2 days!

Onion Shell Model of Massive Star Interiors



Credit: Lumen Learning

• Note that at such temperatures, the gamma-rays can seed **photodisintegration of the nuclei**, generating copious neutrons.

$$\begin{aligned} {}^{56}_{26}Fe + \gamma &\leftrightarrow 13\,{}^{4}_{2}He + 4n \\ {}^{4}_{2}He + \gamma &\leftrightarrow 2\,{}^{1}_{1}H + 2n \end{aligned} \qquad (2)$$

∗ Such endothermic processes are in detailed balance indicated in the reactions of Eq. (1). These rapidly cool the core and hence soon cease.

Plot: Woosley & Weaver Abundance/Radius Model for a Massive Star

• Electron capture in the iron core plus photodisintegration readily removes electron degeneracy pressure to the point that the core can no longer support itself. The collapse is rapid and **homologous** (i.e. with virtually no mixing of layers), reaching speeds of around $c/5$.

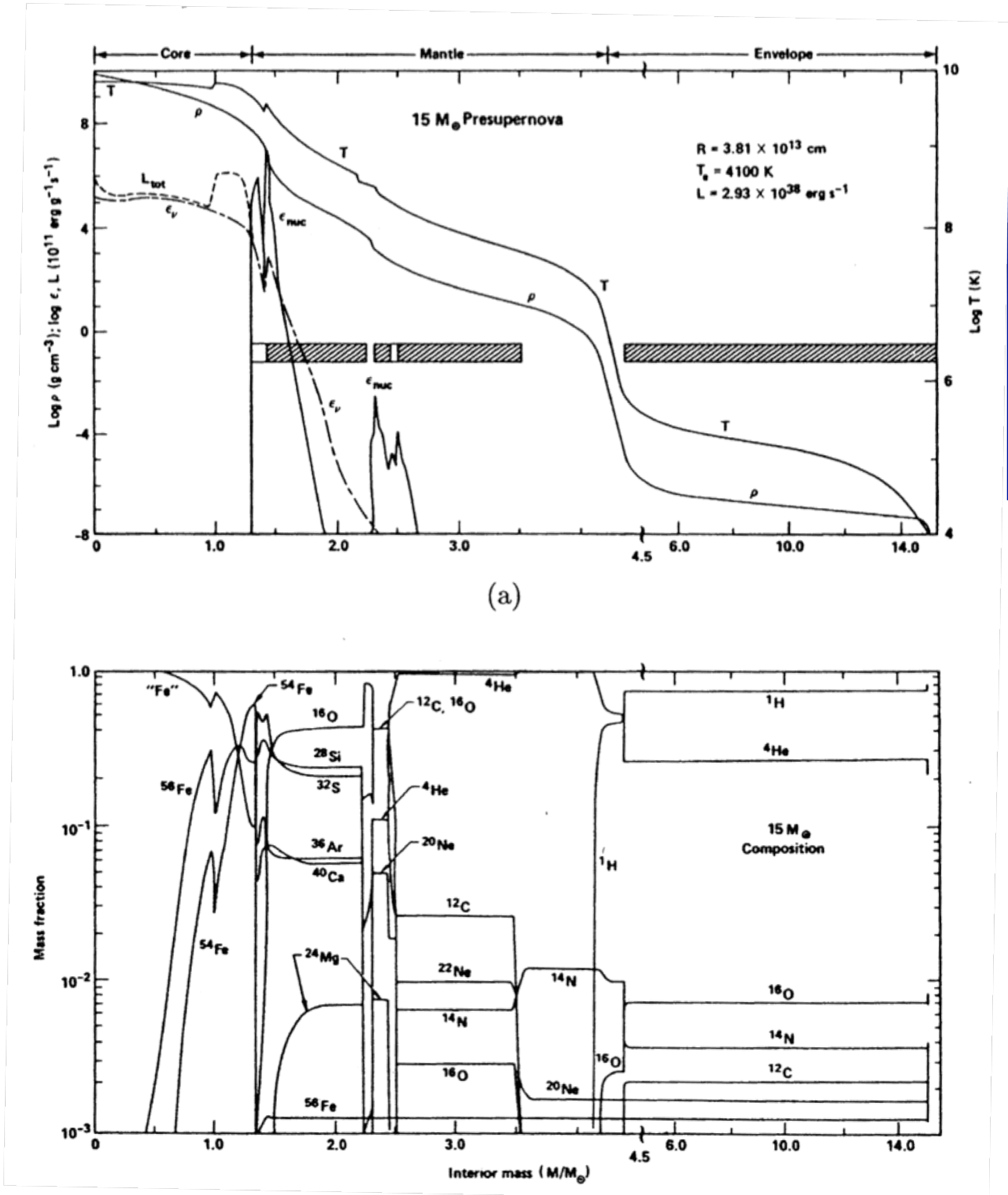
∗ The outer layers are temporarily "suspended" above the supersonically collapsing core, and the core reaches supernuclear densities in about a second.

∗ The repulsive degeneracy pressure associated with neutrons kicks in and causes the core to *bounce*, sending a shock wave out into the overlying shells before they have had time to collapse.

• Photodisintegration robs the shock of its energy. Depending on the size of the core, the shock can stall and become an **accretion shock**. Neutrino heating of the shocked material can eventually push the shock outwards again.

∗ Simulations are extremely sensitive to assumed boundary conditions such a dimensionality (1D codes often failed to explode).

Interior Structure of a $15M_\odot$ Star



- Woosley & Weaver ARAA 24, 205, (1986)

2 Supernovae

• The subsequent explosion is a **Type II supernova**. Examples are the Crab supernova (AD 1054), SN1987a in the LMC, and Cassiopeia A. They occur around once every 50 years in the galaxy. **C & O, Sec. 15.3**

Plot: Crab Nebula: X-ray/Optical Montage

• Talk a little about SNRs.

Plot: Chandra Image of Cassiopeia A

* Observationally, there are prominent hydrogen lines in Type II supernovae, indicating the presence of hydrogen envelopes in the progenitors. **Type I supernovae** (from carbon-oxygen white dwarfs; they are used as cosmological distance calibrators) do not exhibit such hydrogen line emission.

• If the ZAMS progenitor has a mass less than around $25M_\odot$, the supernova generates a neutron star; greater initial masses inevitably yield a black hole since even the neutron degeneracy pressure is not sufficient to stabilize the core against collapse.

2.1 Lightcurves of Supernovae

• The light curves of supernovae exhibit exponential decay epochs (subsequent to normally rapid rises; exception is SN1987a), characteristic of radioactive decay. The slopes couple directly to the decay constant:

$$\frac{dN}{dt} = -\lambda N \;\Rightarrow\; \frac{dm_{bol}}{dt} = 1.086\lambda \quad . \tag{3}$$

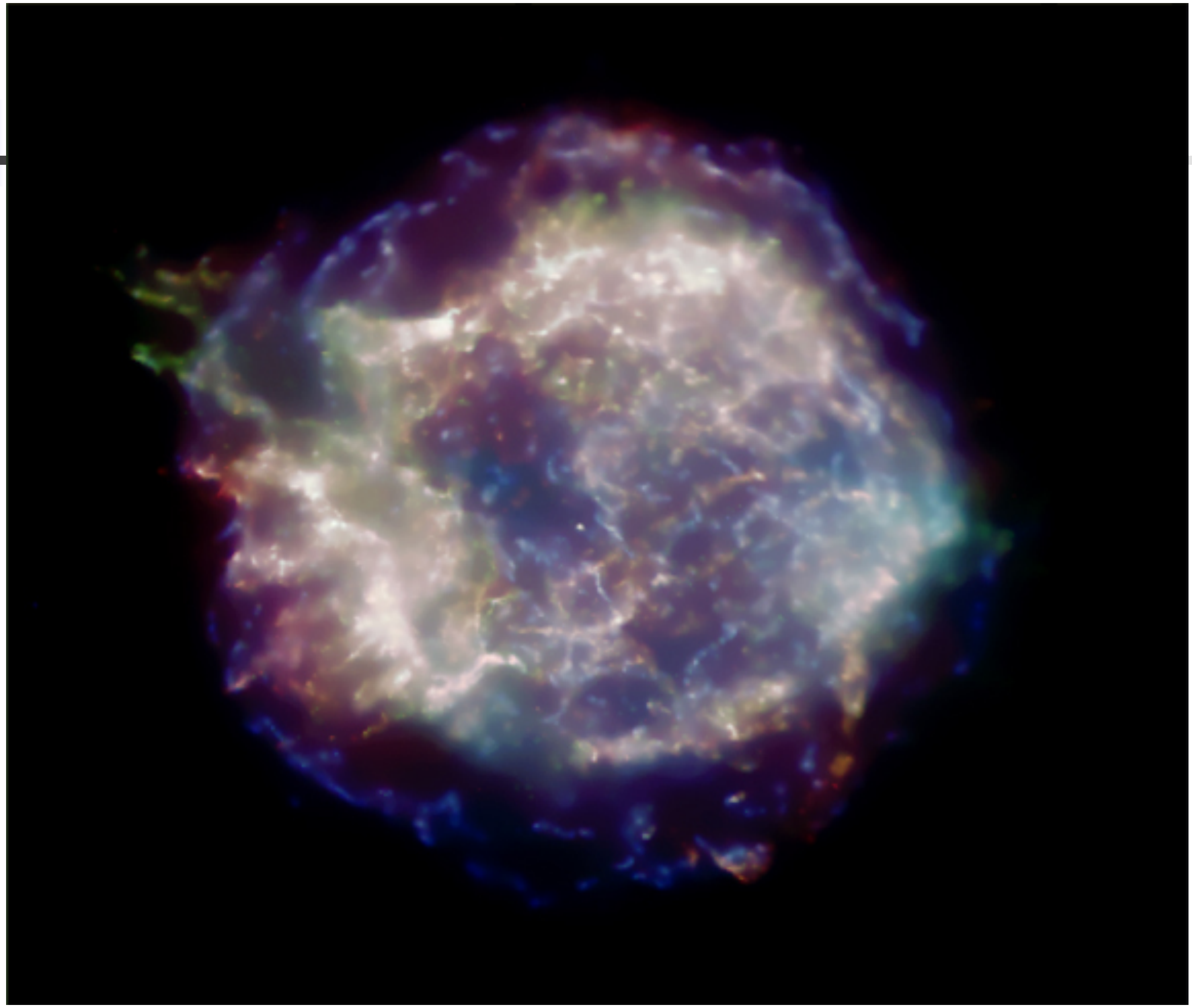
Here, $\lambda = \log_e 2/\tau_{1/2}$.

Plot: Type II SN Decay Lightcurves (Composite)

• Not all light curves exhibit clean exponential decays at all times. For example, consider GRB afterglows, which often have re-activation phases.

Crab Nebula: X-ray/Optical Montage

Cassiopeia A Supernova Remnant



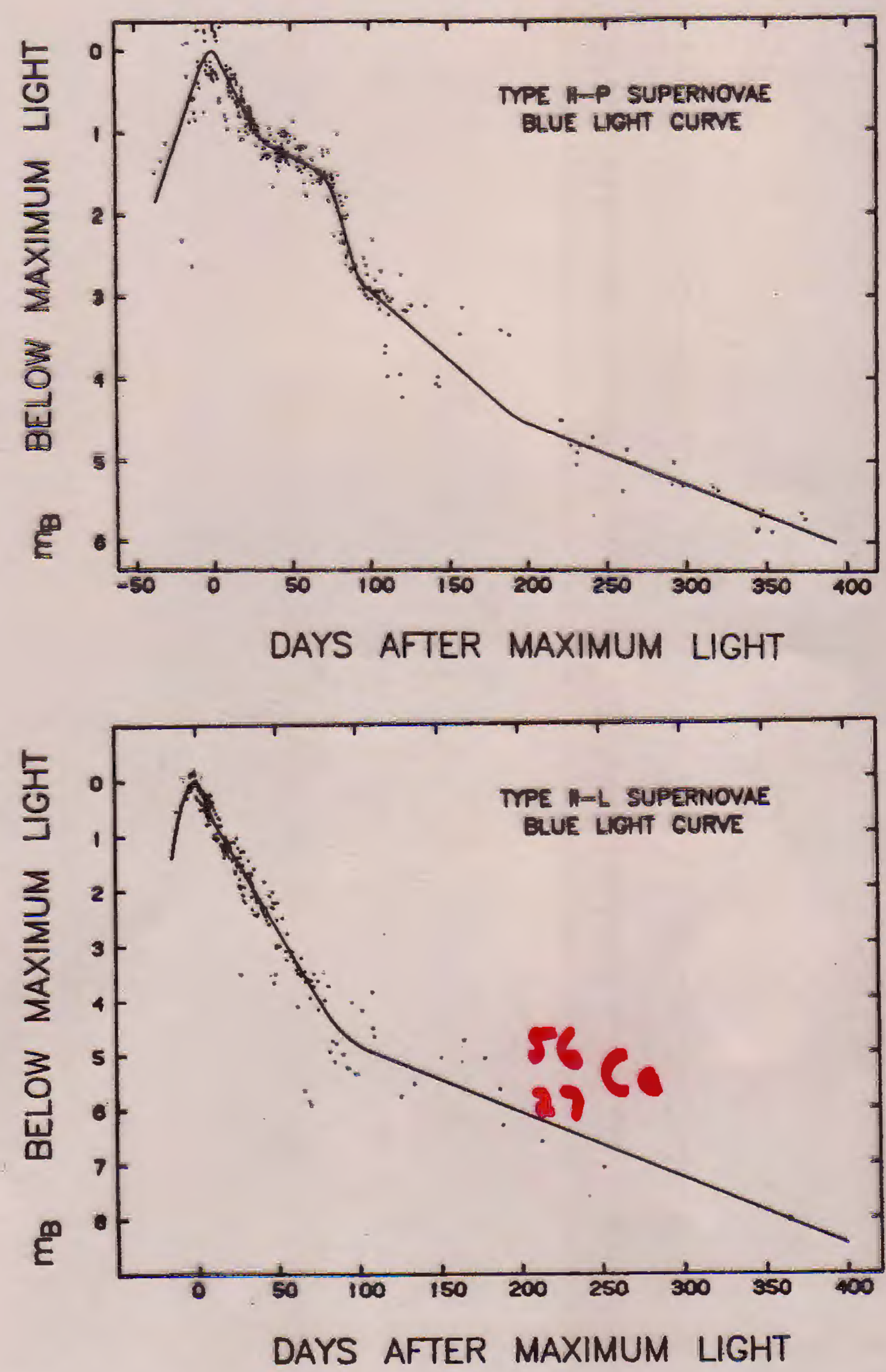


Figure 13.16 The characteristic shapes of Type II-P and Type II-L light curves. These are composite light curves, based on the observations of many supernovae. (Figures from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)

• Nickel is a lead-off player in the light curves, starting a *beta decay* chain with a half-life of 6.1 days:

$$ {}^{56}_{28}Ni \;\rightarrow\; {}^{56}_{27}Co + e^+ + \nu_e + \gamma \quad . \tag{4} $$

This lifetime does not secure a prominent decay signature in SN lightcurves: its short life leads to confusion with other temporal factors.

∗ Cobalt signatures feature prominently in SN lightcurves. For example, ${}^{56}_{27}Co$ has a *beta decay* half-life of 78 days in the reaction

$$ {}^{56}_{27}Co \;\rightarrow\; {}^{56}_{26}Fe + e^+ + \nu_e + \gamma \quad . \tag{5} $$

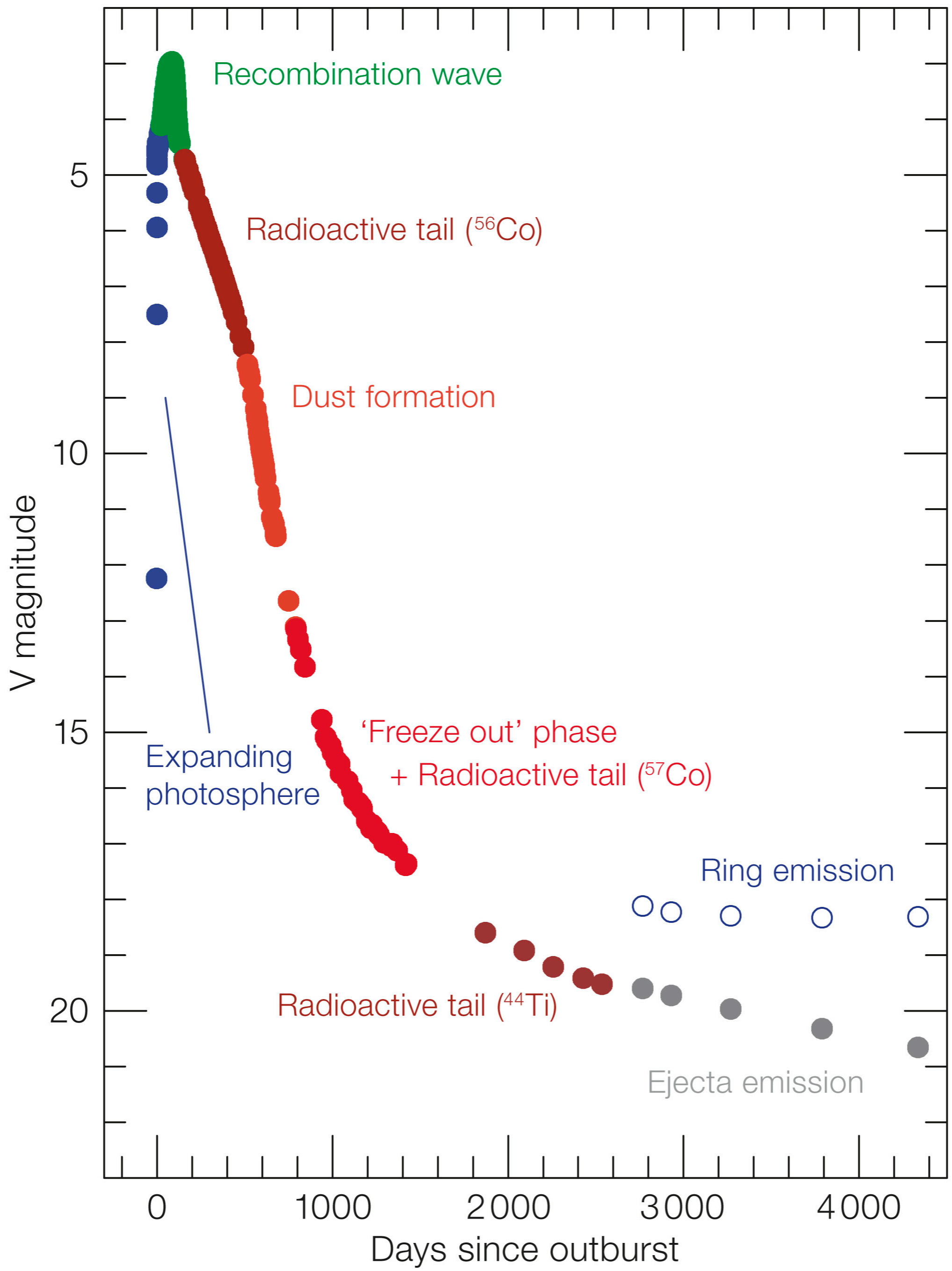
The gamma-rays so generated are absorbed by the expanding, optically-thick SN shell, and reprocessed into the optical band. ${}^{57}_{27}Co$ has a *beta decay* half-life of 271 days, and also features prominently:

Plot: SN 1987a Bolometric Light Curve

∗ However, the shell eventually becomes *optically thin* to the gamma-rays. SN 1987a was the first supernova where the 847 keV and 1238 keV gamma-ray lines for ${}^{56}_{27}Co$ were detected, after the shell had thinned (by CGRO).

[*Reading Assignment: Section 13.4 of Carroll & Ostlie: Stellar Clusters*].

• This reading material discusses, among other things, use of the peel-off point of the cluster population in the H-R diagram as a means of cluster age determination.



Light Curve of SN 1987a

Credit: ESO public images