23 On the Deaths of Massive Stars

23.1 *Useful References*

- Prialnik, 2nd ed., Ch. 10
- Kippenhahn, Weiger, and Weiss, 2nd ed., Chap. 36
- Hansen, Kawaler, and Trimble, Secs. 2.6–2.8

23.2 *Introduction*

Stars with initial masses $\lesssim 6M_\odot$ will end their days as the degenerate white dwarfs we came to know and love in Sec. 20. But more massive stars will suffer new and different evolution and final fates: in **core-collapse supernovae**.

The most famous such event in living memory was the infamous SN1987A, which occurred "right next door" in the Large Magellanic Cloud (just 50 kpc away) in Feb. 1987. It was the first core-collapse supernova whose progenitor star could be uniquely identified and characterized (from archival data) – it was Sanduleak, a 14,000 K supergiant with mass of $\approx 18M_\odot$ (probably rather more at formation) and pre-collapse luminosity of $\approx 10^5 L_\odot$. Its light curve is shown in Fig. 44.

23.3 *Eddington Luminosity*

One interesting point is that stars with initial masses $\gtrsim 5M_\odot$ never ascend a giant branch. Instead they start much hotter and evolve to the right on the H-R diagram at roughly constant luminosity. This constant L is because the stars are emitting at roughly the maximum permissible luminosity, the so-called **Eddington Luminosity**.

To derive this maximum luminosity, $L_{\rm Edd}$, we need three ingredients: hydrostatic equilibrium, radiation energy transport, and radiation pressure. Recall that for a stable star in hydrostatic equilibrium, Eq. 239 says that its pressure gradient must be

$$\frac{dP}{dr} = \rho(r) g(r).$$

For intense radiation fields (i.e., energy transported by radiation not convection) the thermal profile (Eq. 282) is

$$\frac{dT}{dr} = -\frac{3\rho\kappa L(r)}{64\pi\sigma_{SB} T^3 r^2}.$$

And finally, radiation pressure is given by (Eq. 305)

$$P_{rad} = \frac{1}{3}\left(\frac{4}{c}\right)\sigma T^4.$$

An object (whether star or accreting supermassive black hole) has its maximum luminosity, $L_{\rm Edd}$, when the radiation pressure gradient just balances the hydrostatic gradient. Taking the derivative of P_{rad}, we have

(503)
$$\frac{dP_{rad}}{dr} = \frac{16\sigma}{3c} T^3 \frac{dT}{dr}$$
(504)
$$= \frac{16\sigma}{3c} T^3 \left(-\frac{3\rho\kappa L(r)}{64\pi\sigma_{SB} T^3 r^2} . \right)$$
(505)
$$= -\frac{\rho\kappa L}{4c\pi r^2}$$
(506)

This last expression must just equal $-\rho g$; setting $g = GM/R^2$ we then have

(507)
$$L_{\text{Edd}} = \frac{4\pi c G M}{\kappa}$$
(508)
$$\approx (3.5 \times 10^4 L_\odot) \left(\frac{M}{M_\odot} \right)$$
(509)

for an approximate value of $\kappa \approx 0.34$ cm^2 g^{-1}.

23.4 *Core Collapse and Neutron Degeneracy Pressure*

As we saw in Fig. 43, the most massive stars will undergo successive layers of shell burning, each shorter-lived than the last. Eventually the core is composed of ^{56}Fe (up to around $1.5 M_\odot$ for $M_* \gtrsim 20 M_\odot$), which is inert from a fusion standpoint (just like every other inert core which preceded it during the evolution process).

Two factors cause the core to collapse. First, as we saw in Sec. 21.6, photodisintegration of the Fe nuclei will set in once $T_c \gtrsim 3 \times 10^9$ K; this absorbs the photons that were previously providing radiation pressure support. Second, electron degeneracy pressure will also eventually drop: the degenerate electrons are forced into ever-higher energy states until they can initiate inverse beta decay:

(510) $e^- + p \rightarrow n + \bar{\nu}_e$.

The star is undergoing **neutronization** and emitting copious neutrinos. The number of free electrons declines and so electron degeneracy pressure will decrease.

Core collapse

The core is collapsing. What, if anything, can halt the collapse?

The answer is **neutron degeneracy pressure**. This is the same phenomenon we first encountered in Sec. 20.3, but provided by the neutrons instead. The physics is true but the names have been changed to protect the innocent; all relevant scales are all now $m_n/m_e \approx 1800\times$ smaller. We can estimate the size of a neutron star using the same arguments in Eq. 404:

(511) $N_n \lambda_D^3 \approx R^3$

where the de Broglie wavelength of the relativistic neutrons is

(512) $\lambda_D \approx \frac{h}{m_n c} \approx 1.3 \times 10^{-15}$ m

and so

(513) $N_n \approx 1.5 M_\odot / m_n \approx 1.8 \times 10^{57}$.

That's a lot of neutrons! At that scale, the expected size is roughly

(514) $R_{NS} \approx \frac{h}{m_n c} N^{1/3} \approx 12$ km.

Contrast this with the size of a white dwarf (or of the initial degenerate core), which is *roughly* 1800× larger (but actually a bit less, because the composition is more complicated) – $R_{WD} \approx R_\oplus = 6400$ km.

Thus once hydrostatic support is lost, the core collapses from a size of $\approx R_\oplus$ to $\approx$ 12 km in a free-fall timescale:

(515) $\tau_{ff} \sim (G\rho)^{-1/2}$

which is $\lesssim 3$ s for the initial core, and a much shorter timescale by the end of the collapse.

Energy Release

The total gravitational energy liberated by this collapse is considerable:

(516)
$$\Delta E \approx \frac{3}{5}\frac{GM^2}{R_f} - \frac{3}{5}\frac{GM^2}{R_i}$$

(517)
$$\approx \frac{3}{5}\frac{GM^2}{R_f}$$

(518)
$$\approx 3 \times 10^{53} \text{ erg} = 3 \times 10^{46} \text{ J}$$

which is all released in of order a second.

Contrast this with the Solar luminosity, $L_\odot \approx 4 \times 10^{33}$ erg s^{-1}. This collapse (which has now become a **core-collapse supernova**) is over $10^{20}\times$ more luminous than the present-day Sun. Even over the Sun's entire lifetime of 10^{10} yr, it will emit $\sim 10^{51}$ erg. So in a few seconds, a core-collapse supernova releases 100× more energy than the Sun will in its entire life.

Where does all that energy go?

Photodisintegration captures a bit of it. The destruction of ^{56}Fe releases about 125 MeV per nucleus, or about ∼2 MeV per nucleon. There are roughly $N_{Fe} \approx 1.4 M_\odot / 56 m_p \approx 3 \times 10^{55}$ Fe nuclei in the core at collapse, so this absorbs roughly 6×10^{51} erg, or roughly 6% of the total.

Observed outflows from supernovae have velocities of $v_{ej} \sim 10^4$ km s^{-1}, far above the necessary escape speed. With an envelope mass of order $10 M_\odot$, these will carry away an energy roughly equal to

(519)
$$K = \frac{1}{2} M_{env} v_{ej}^2$$
(520)
$$\approx \frac{1}{2}(10 \times 2 \times 10^{33})(10^9)^2$$
(521)
$$\approx 10^{51} \text{ erg}$$

or roughly 1% of the total.

Ejection of the envelope only uses a smidgen, despite the considerable envelope mass. Even if all that mass were at the core radius, we would still have

(522)
$$\Delta U \approx \frac{G M_{env} M_c}{R_c}$$
(523)
$$\approx \frac{(2/3 \times 10^{-7})(10 \times 2 \times 10^{33})(2 \times 10^{33})}{7 \times 10^{10}}$$
(524)
$$\approx 4 \times 10^{51} \text{ erg}$$

so as much as 4% (and probably a bit less, since some mass started at larger radii).

Supernovae are almost always discovered via their optical/infrared emission, which rises rapidly (see Fig. 44 but persists for weeks to months. Very roughly, assuming one year of emission at a typical supernova luminosity of

$3 \times 10^{10} L_{\odot}$ gives

(525)
$$L_{SN} \approx (3 \times 10^{10})(4 \times 10^{33})(3 \times 10^{7})$$
(526)
$$\approx 4 \times 10^{51} \text{ erg}$$

which is again just a few percent of the total energy release.

Neutrino Luminosity

Most of the energy actually goes into neutrinos. Despite their *weak* interactions with baryonic matter, these fleeting leptons are created in sufficient numbers (and the collapsing star achieves such high densities) that enough neutrino opacity results to help eject the envelope. In 1987, ∼20 electron neutrinos were observed from SN1987A.

During neutronization, the entire Fe core is converted into a neutron core — the precursor to a **neutron star** — via inverse beta decay. The total number

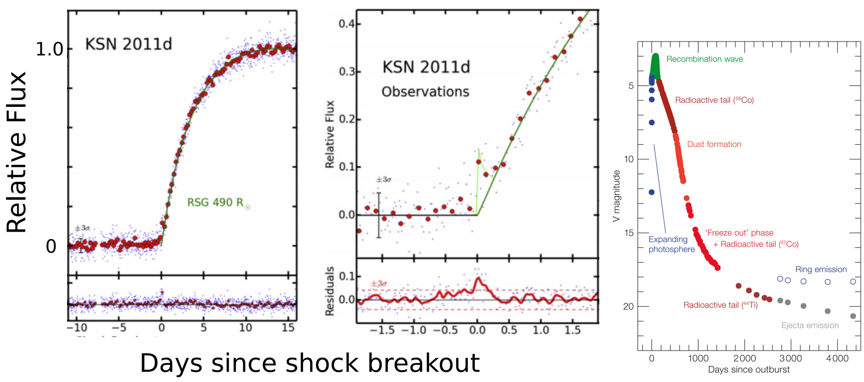

Figure 47: Supernova light curves at visible wavelengths. *Left*: Early phase of a supernova outburst captured by the *Kepler* space telescope (Garnavich et al. 2016). *Right:* Multi-year light curve of SN1987A (`https://www.eso.org/public/images/eso0708c/`).

of neutrinos produced will be roughly

(527)
$$N_\nu = N_p$$
(528)
$$\approx \frac{1.5 M_\odot}{2 m_p}$$
(529)
$$\approx (2 \times 10^{33})(6 \times 10^{23})$$
(530)
$$\approx 10^{57}$$

The neutrinos produced are highly relativistic, and despite their minuscule masses ($\lesssim 0.1$ eV) they have typical energies of $\sim$30 MeV. Thus they carry away $\gtrsim 5 \times 10^{52}$ erg, and so transport the bulk of the energy liberated by the core's collapse. A wee bit of the copious neutrino flux couples to the dense stellar material; this is still an active area of SN research.

23.5 *Supernova Nucleosynthesis*

Although core fusion has ceased in our dying massive star, nucleosynthesis has not. Given the colossal neutron fluxes present in these final moments, new nuclear pathways open up that were unavailable before; recall that the neutron has no charge, and so can proceed without needing to overcome the strong Coulomb repulsion that hindered us in Sec. 18.3.

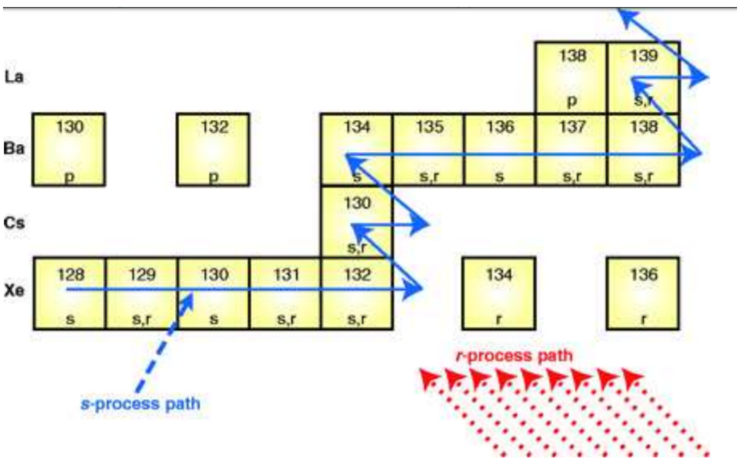

Figure 48: Nucleosynthesis via the s-process and r-process. Only a subset of the possible nuclei (and only the stable isotopes) are shown. Letters indicate which process can form which isotopes. From `http://www.astro.sunysb.edu/lattimer/PHY521/nucleo.pdf`.

As long as stable isotopes are formed, neutron capture can lead to a continuous path of isotopes:

(531)
$$^{A}_{Z}X + n \rightarrow ^{A+1}_{Z} X$$

(532)
$$^{A+1}_{Z}X + n \rightarrow ^{A+2}_{Z} X$$

and so forth. But sooner or later an unstable isotope will be formed. What happens next depends on the relative timescales of neutron capture and beta decay. Fig. 45 depicts the two possible paths; so long as neutron captures occur, the nucleosynthesis track moves steadily to the right.

If neutron captures are relatively infrequent, then the isotope will beta-decay before another neutron can be jammed into the nucleus. This is the **s-process** ("s" for the **s**low neutron capture rate). This occurs, for example, in the cores of asymptotic giant branch (AGB) stars, where the H-shell burning provides the neutrons and large-scale instabilities lead to dredge-up. The beta decay follows its usual course:

(533) $$^{A+N}_{Z}X \rightarrow ^{A+N}_{Z+1} Y + e^{-} + \bar{\nu}$$

and it could either be followed by more beta decays if the daughter nucleus $^{A+N}_{Z+1}Y$ is unstable

(534) $$^{A+N}_{Z+1}Y \rightarrow ^{A+N}_{Z+2} \Omega + e^{-} + \bar{\nu}$$

(thus moving one step up and one to the left in Fig. 45) or by resuming the train of neutron captures if $^{A+N}_{Z+1}Y$ is stable

(535) $$^{A+N}_{Z+1}Y + n \rightarrow ^{A+N+1}_{Z+1} Y$$

(and thus moving steadily to the right again in Fig. 45). One of the more unusual s-process products is Technetium, which has no stable isotopes but is still seen in stellar spectra of evolved, late-type stars.

Alternatively, in a high-neutron-flux environment (such as our collapsing, massive star) neutron captures happen more rapidly than beta decays. This is the **r-process** (for **r**apid) and it occurs to some extent in core-collapse supernovae and perhaps reaches its greatest heights in neutron star-neutron star mergers (as were touched upon in Sec. 9). In this case, the chain of neutron captures may continue to quite high atomic mass even given a dearth of protons – i.e., into highly unstable nuclei. But when the neutron flux drops off, it's closing time: the isotopes can't go home and they "can't stay here" – they will undergo a series of beta decays, moving steadily up and to the left in Fig. 45 until a stable isotope is reached.

23.6 *Supernovae Observations and Classification*

The observation and classification of supernovae go back over 1000 years, making this one of the oldest branches of observational astronomy. The name "nova" had been given to "new stars" (actually outbursts from accreting white dwarfs), and "super"-novae were that much brighter. The names are similar in other cultures; e.g., Chinese records refer to them as *kexing*, or "guest stars."

Before the modern era began, there were $\sim$8 supernovae visible without telescopes. The brightest of these, SN 1006, is estimated to have had $m_V \approx -7.5$ mag, roughly 3 mag brighter than Venus and visible even in the daytime. Another famous example is SN 1054, whose ejecta now span a radius of $\approx$1.7 pc – this is the famous Crab Nebula[9] The two most famous, local (i.e., in the Milky Way) supernovae in "recent" times are Tycho's and Kepler's supernovae; these occurred "only" 30 years apart, in 1572 and 1604, and in Europe helped break down beliefs in a static, unchanging heavens and to unleash the modern astronomical revolution. No SN have been seen in the Milky Way since, although we think there should be 1–3 per year.

Like the classification of stars (discussed in Sec. 3), supernovae were classified into groups first and only later associated with underlying physical mechanisms. The observationally-motivated nomenclature comes from optical spectra of the supernova near peak luminosity (when it's easiest to observe), and it is:

- **Type I:** No H-α line seen.
- **Type II:** H-α line seen.

As simple as that! But this was subsequently clarified:

- **Type Ia:** No H-α, but Si lines seen.
- **Type Ib:** No H-α, but He lines seen.
- **Type Ic:** No H-α, and not much else.
- **Type II:** H-α line seen.

There are also multiple types of Type II supernovae, classified on the basis of their light curve morphology. E.g. SN1987A (lightcurve shown in in the rightmost panel of Fig. 44) was classified as Type IIpec, for "peculiar."

A **Type Ia supernova** is caused by fusion detonation on a degenerate white dwarf. Once the main source was thought to be mass transfer from a nearby binary companion onto the white dwarf, until the WD's degeneracy pressure can no longer support itself. But we now know that there are many pathways leading to SNe Ia; different pathways lead to different chemical abundances in the SN ejecta, and these studies now indicate that most SNe Ia (at least in dwarf galaxies) occur from white dwarfs of roughly $\sim 1 M_\odot$, well below the Chandrasekhar Mass of $1.4 M_\odot$. These SNe Ia are typically brighter — less

[9] Note that its ejecta have moved $\sim$5 light years over the past millennium, implying an *average* speed of 0.5% c – and presumably higher (and more relativistic) at earlier times.

total energy is released, but more of the energy here goes into photons rather than into neutrino luminosity.

Types II, Ib, and Ic are all different flavors of core-collapse supernovae probably resulting from progenitor stars with different initial masses and evolutionary histories.

In many supernovae, many of the photons we see actually come from the radioactive decay of unstable isotopes produced in the explosion. The most important pathway comes from the decay of ^{56}Ni, which was itself produced from fusion of Si with a succession of α particles:

(536) $^{28}_{14}\mathrm{Si} + 7^{4}_{2}\mathrm{He} \rightarrow^{56}_{28} \mathrm{Ni}$

or by direct, Si-Si fusion:

(537) $2^{28}_{14}\mathrm{Si} \rightarrow^{56}_{28} \mathrm{Ni}.$

The decay pathway after the supernova is over and nucleosynthesis has ceased is

(538)
$$^{56}\mathrm{Ni} \rightarrow^{56} \mathrm{Co} + e^{+} + \nu_e + \gamma \quad (6.1 \text{ day half} - \text{life})$$
(539)
$$^{56}\mathrm{Co} \rightarrow^{56} \mathrm{Fe} + e^{+} + \nu_e + \gamma \quad (78 \text{ day half} - \text{life})$$
(540)

Note that the ^{56}Co phase of SN1987A is indicated in Fig. 44. That SN was estimated to produce just $0.075 M_\odot$ of ^{56}Ni, but others produce as much as $\sim 1 M_\odot$ — these are extremely luminous.