Supernovae
C+O Chapter 15

A supernova is one of the most energetic events in the universe. The energy comes from the explosion of a star, but there are actually two main types: the explosion of a high-mass star at the end of its life and the explosion of a $\sim$ Solar mass white dwarf after accreting matter from a companion. A SN leaves behind a neutron star or a black hole.

Famous SN

Compared to a star's entire history, a supernova is very brief (visible for perhaps only a couple months).

From Wikipedia:
Early discoveries The earliest possible recorded supernova, known as HB9, could have been viewed by unknown prehistoric people of the Indian subcontinent and then recorded on a rock carving, since found in Burzahama region in Kashmir and dated to 45001000 BC.
Later, SN 185 was documented by Chinese astronomers in AD 185.
The brightest recorded supernova was SN 1006, which occurred in AD 1006 in the constellation of Lupus. This event was described by observers in China, Japan, Iraq, Egypt, and Europe.
The widely observed supernova SN 1054 produced the Crab Nebula.

Supernovae SN 1572 and SN 1604, the latest Milky Way supernovae to be observed with the naked eye, had a notable influence on the development of astronomy in Europe because they were used to argue against the Aristotelian idea that the universe beyond the Moon and planets was static and unchanging Johannes Kepler began observing SN 1604 at its peak on 17 October 1604, and continued to make estimates of its brightness until it faded from naked eye view a year later. It was the second supernova to be observed in a generation, after Tycho Brahe observed SN 1572 in Cassiopeia.

There is some evidence that the youngest Galactic supernova, G1.9+0.3, occurred in the late 19th century, considerably more recently than Cassiopeia A from around 1680. Neither supernova was noted at the time. In the case of G1.9+0.3, high extinction from dust along the plane of our galaxy could have dimmed the event sufficiently for it to go unnoticed. The situation for Cassiopeia A is less clear; infrared light echos have been detected showing that it was not in a region of especially high extinction.

The most famous SNR, however, is SN 1987A in the Large Magellanic Cloud. This SN went off in 1987 (thus the name) and is only 50 kpc distant. We have been observing it ever since. The progenitor was a blue supergiant. https://www.nasa.gov/feature/goddard/2017/the-dawn-of-a-new-era-for-supernova-1987a

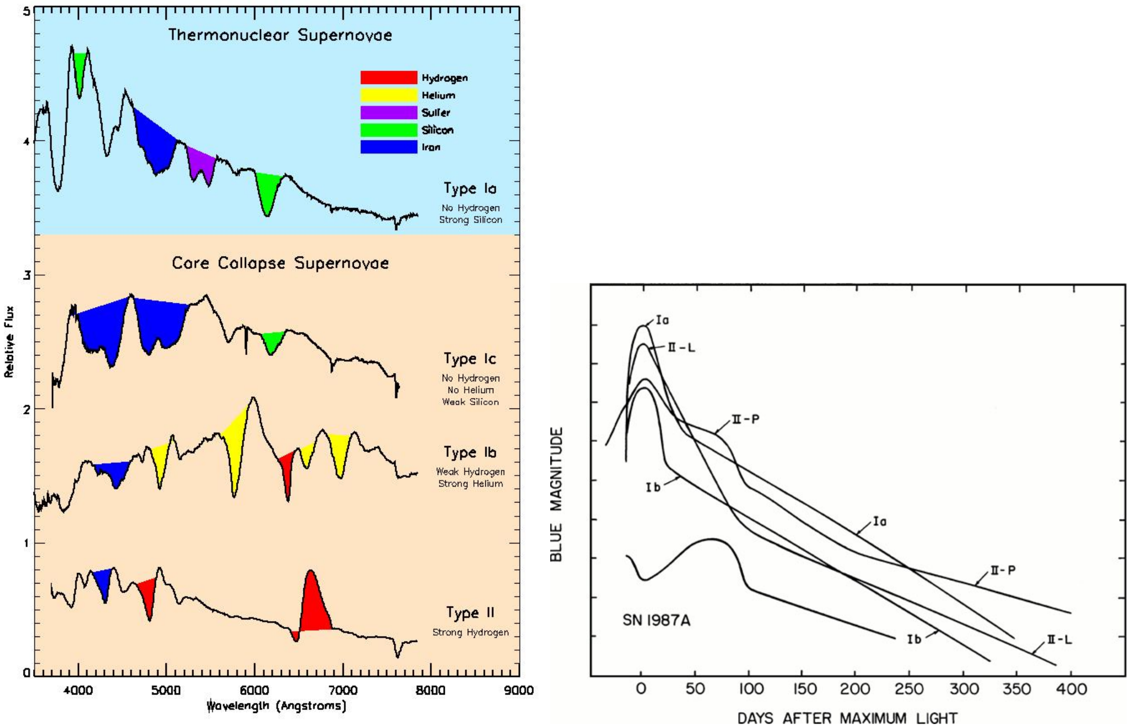

Figure 1: SN spectra and light curves.

We also detect SN in other galaxies, and these have proven key to our understanding of the Universe (most on this next semester if you take ASTR368).

Types of SN

Just like many things in astronomy, the designations of SNe are based on observed characteristics, and we later determined that this scheme was not intuitive. Oh well.

We have two primary tools for classifying SNs: light curves and spectra. Light curves are just the intensity as a function of time. Spectra can tell you which elements are in the SN explosion.

Type I SN have no H in their spectra. Type II do. The lack of H indicates that Type I SN come from stars that lack H envelopes.

Type Ia have strong Si II lines at 615 nm.
Type Ib SN have He lines.
Type Ic do not have Si or He lines.

Type I SN have light curves that reach maximum a few days after explosion. After maximum, they decline in brightness rapidly for 20 days, then decline slower for 50 days.

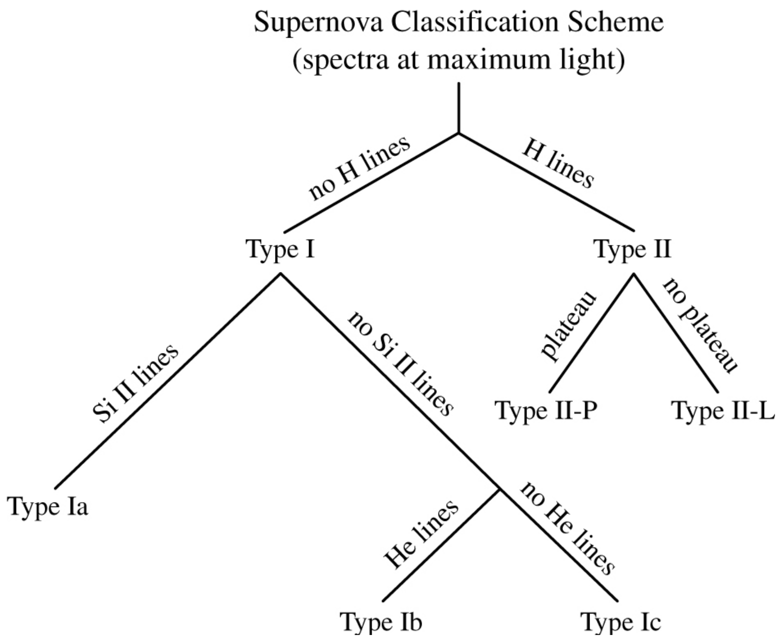

Figure 2: SN decision tree.

The lightcurves of Type II SNs are similar to those of Type Is, although Type II-Ps “plateau” and Type II-Ls are linear.

Confusingly, Type 1a are from white dwarfs. All others are core collapse of massive stars.

Runaway Fusion

A white dwarf star may accumulate sufficient material from a stellar companion to raise its core temperature enough to ignite carbon fusion, at which point it undergoes runaway nuclear fusion, completely disrupting it. There are three avenues by which this detonation is theorised to happen: stable accretion of material from a companion, the collision of two white dwarfs, or accretion that causes ignition in a shell that then ignites the core. The dominant mechanism by which type Ia supernovae are produced remains unclear. Despite this uncertainty in how type Ia supernovae are produced, type Ia supernovae have very uniform properties and are useful standard candles over intergalactic distances.

Core-Collapse SN

A typical Type II SN releases 10^{53} erg (10^{46} J) of energy. Interestingly, only about 1% of this goes into the energy of the ejected material, and 0.01% is released as photons. How does the rest of the energy get out? Neutrinos!

As an interesting aside, SN1987A was first detected in neutrinos, before any photons from the explosion. This neutrino burst took place over 12.5 seconds. How could this have happened? The neutrinos travel at essentially the speed of light. The light was impeded by the dense shell around the progenitor, and therefore we had to wait until the shell became optically thin.

An iron core cannot release energy via fusion. In extremely high temperatures, iron can be gotten rid of through photodisinegration. This process strips iron down into protons and neutrons, and in the process absorbs energy in the form of photons. This is bad for the stability of the star. Furthermore, the protons themselves can capture electrons in the nearly 10^{10} K core, leading to the creation of neutrons and neutrinos:

$$p^+ + e^- \rightarrow n + \nu_e \,. \tag{1}$$

This releases tremendous energy.

Because of these endothermic reactions, and because the electrons are removed during electron capture, the star loses its support and rapidly collapses. During collapse, the outer layers are falling slower than the inner ones ($\tau \propto \rho^{-0.5}$), and when the collapse is progressing at the sound speed, the inner core decouples from the outer core. The outer core is now in free fall, suspended above a more rapidly collapsing (mostly iron) core. This probably won't end well.

The core has blown through its electron degeneracy pressure, but neutron degeneracy can resist the freefall (neutrons are also fermions, and obey the Pauli exclusion principle). The core rebounds slightly, and this sets up a shock wave. The details of what happens next depend on the model, but in essence the shock wave must travel outwards to the stellar surface, blowing those layers into the local medium.

What is left behind depends on the mass of the star. The most massive stars will become black holes, whereas less massive ones will become neutron stars. Your book notes that the cutoff mass is about 25 $M_\odot$.

Radioactive Decay

The chaotic fusion processes in the last few moments of a star's life lead to the creation of numerous radioactive isotopes. Your book notes $^{57}_{27}$Co and $^{44}_{22}$Ti, for example. Many of these decay through beta decay, releasing an electron, a neutrino electron, and radiation. These elements provide clocks that astronomers can use, since the decay will proceed as an exponential decay:

$$N(t) = N\_0 e^{-\lambda t} \tag{2}$$

Nucleosynthesis within SNe

SNe also create elements and this is how the Universe can make all elements more massive than iron (neutron star collisions may also play a large role).

Fusion reactions are impeded by the high Coulomb barrier, but neutrons can penetrate this barrier and hence initiate fusion reactions. For example:

$$^{A}_{Z}X + n \rightarrow ^{A+1}_{Z} X + \gamma \, . \tag{3}$$

If beta decay is slow compared to neutron capture this is called the rapid or “r-process.” If the decay is fast compared to neutron capture, it’s called the slow or “s-process.” We can have s-process during normal stellar evolution, but r-process can only occur in a SN when large neutrino fluxes exist. The end result of the s- and r-processes is neutron-enriched elements.

Gamma Ray Bursts

Gamma-ray bursts (GRBs) are extremely energetic explosions that have been observed in distant galaxies. They are the brightest electromagnetic events known to occur in the universe. Bursts can last from ten milliseconds to several hours. After an initial flash of gamma rays, a longer-lived “afterglow” is usually emitted at longer wavelengths (X-ray, ultraviolet, optical, infrared, microwave and radio).

The intense radiation of most observed GRBs is thought to be released during a supernova or superluminous supernova as a high-mass star implodes to form a neutron star or a black hole. A subclass of GRBs (the “short” bursts) appear to originate from the merger of binary neutron stars.

The sources of most GRBs are billions of light years away from Earth, implying that the explosions are both extremely energetic (a typical burst releases as much energy in a few seconds as the Sun will in its entire 10-billion-year lifetime) and extremely rare (a few per galaxy per million years). All observed GRBs have originated from outside the Milky Way. It has been hypothesized that a gamma-ray burst in the Milky Way, pointing directly towards the Earth, could cause a mass extinction event.

GRBs were first detected in 1967 by the Vela satellites, which had been designed to detect covert nuclear weapons tests; this was declassified and published in 1973. In 1997 the first X-ray and optical afterglows were detected from a GRB and direct measurement of their redshifts using optical spectroscopy, and thus their distances and energy outputs. These discoveries, and subsequent studies of the galaxies and supernovae associated with the bursts, clarified the distance and luminosity of GRBs, definitively placing them in distant galaxies.

Cosmic Rays

SN also produce cosmic rays, charged particles that travel through space at incredible speeds.The Sun also produces cosmic rays, although Solar cosmic rays particles are comparably low energy.

Because they are charged, cosmic rays interact with magnetic fields.

Cosmic rays are responsible for heating in the interstellar medium. If fact, they are the only source of heating that can penetrate dense molecular clouds.

Cosmic rays are a serious impediment to long-distance human travel. The Earth is surrounded by its magnetic field, which diverts cosmic rays around it. Once astronauts leave this protected region, they can be exposed to cosmic rays, which can damage their internal organs.