Lecture 15: Stellar evolution –

Massive stars and supernovae

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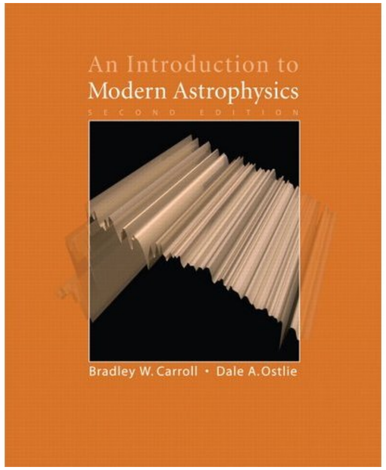
Chapter 15 of Carroll and Ostlie



Aims of lecture

Key concepts: endothermic processes and stellar core collapse

<u>Aims:</u>

- Understand how the evolution of massive stars differs from that of lower-mass stars

- Understand how endothermic processes doom the evolution of massive stars: photodisintegration, electron capture, and neutrino production

- Know how to calculate the amount of gravitational energy released in the collapse of the stellar core and how this drives a supernova

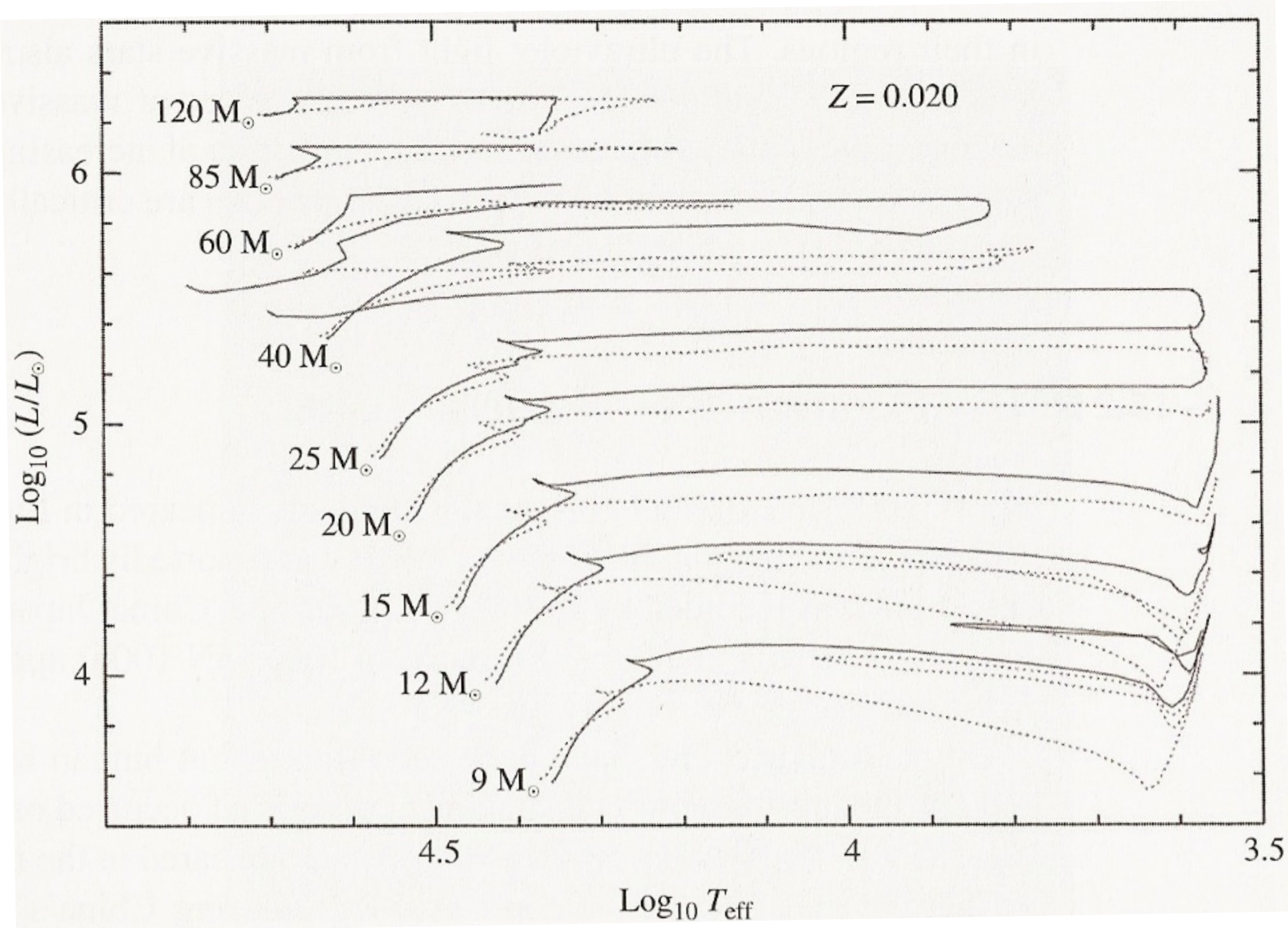
$$E = -\frac{3}{10}\frac{GM^2}{R}$$

Energy from gravitational collapse

- Be able to describe the basic properties of supernovae and their remnants

Evolution of the most massive stars

Stars of <8 solar masses will not fuse elements beyond Carbon and Oxygen (lecture 14). Now we will explore how high-mass stars of >8 solar masses evolve.



The higher core temperatures of massive stars mean that they can fuse beyond Carbon and Oxygen (see lecture 7). Their luminosities do not evolve as much as lower-mass stars since they are already close to their Eddington limit (where the star is close to destruction; see lecture 11)

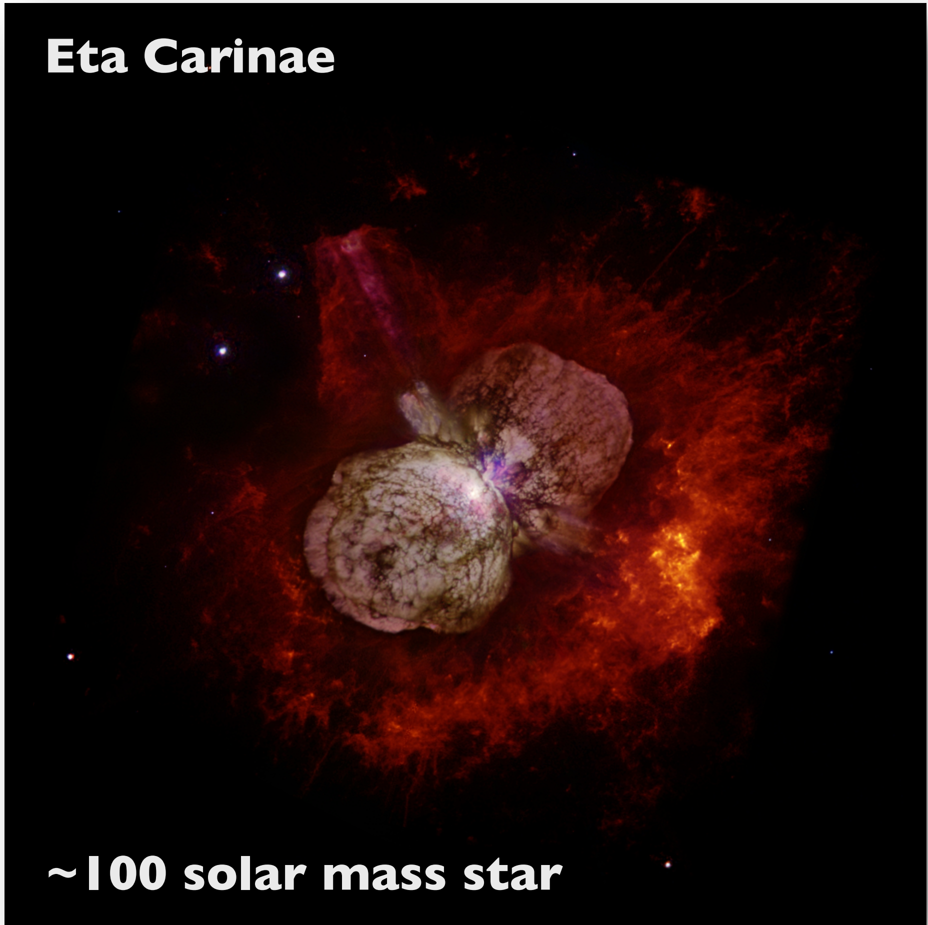
Main-sequence stars of different masses

Massive stars on the MS are blue and will have radii ~5-35x larger than the Sun:
But they are substantially rarer: only 10^{-6} stars have >100 solar masses
Their main-sequence lifetimes are of the order ~10^7-10^8 years

$$L = 4\pi R^2 \sigma T_e^4$$

Typical massive stars are luminous blue variables, Wolf-Rayet stars, O and B type stars

Eta Carinae: an extreme example



Eta Carinae has a luminosity ~5×10^6 times that of the Sun. It doesn't look particularly stable!

It is losing mass at a rate of ~10^{-3} solar mass/ year – material in the lobes has v~650 km/s!

Eta Carinae varies in luminosity and in the 1850s was the second brightest star in the sky after Sirius, despite being ~1000x more distant (~2.3 kpc)!

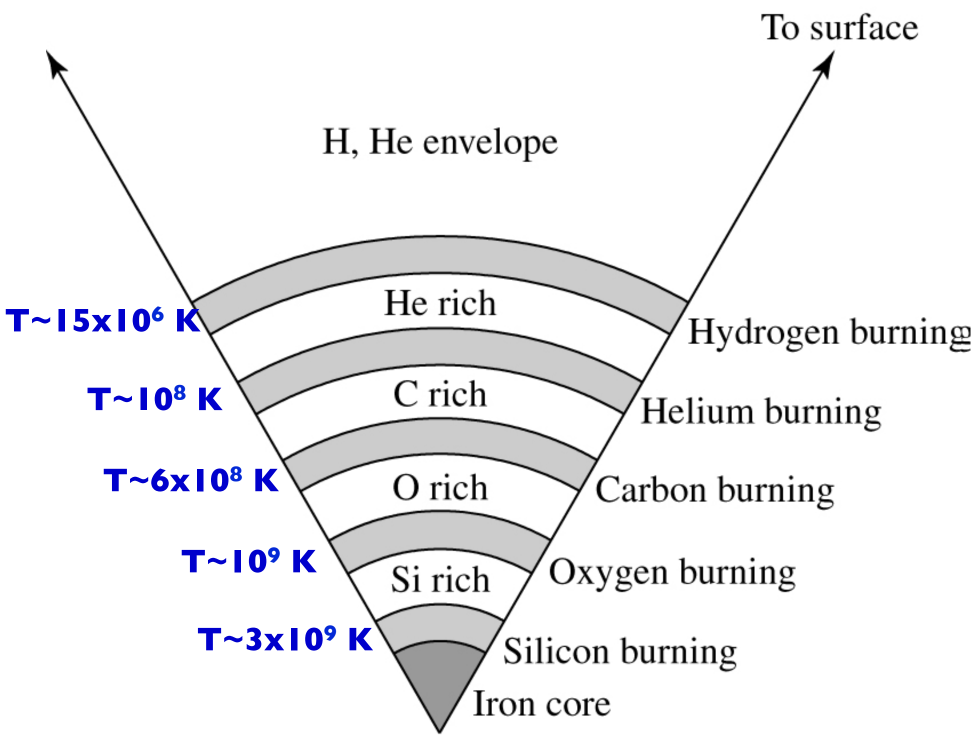
Recall the Eddington limit for stars, where radiation pressure balances gravity:

$$L_{Edd} = \frac{4\pi c G M}{\kappa}$$

Massive stars suffer significant mass loss, particularly during the later nuclear fusion phases when there are huge temperature dependencies on the reaction rates and significant radiation pressure. A large fraction of the star is therefore lost during their short lives, revealing the chemistry and fusion products in their inner regions.

Further nuclear fusion phases for massive stars

Last days of fusion in a massive star



The higher core temperatures of massive stars mean that they can start to fuse Carbon in the nuclear core - the evolutionary cycle is similar to before but now with Hydrogen and Helium fusion shells and an Oxygen rich core

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Carbon fusion leads to Oxygen fusion and, ultimately, if the star is massive enough, to Silicon fusion producing Iron (see lecture 7)

Recall from lecture 6 that to produce heavier elements than Iron requires more energy input than is available from the fusion process (endothermic)

Between the fusion shells there are regions where no fusion is occurring because the temperature/density is not high enough (given the chemical composition of the region)

The last days in the life of a massive star

The table below gives the temperature and duration of the fusion phase in a massive star of 20 solar masses

Fusion process	Temperature (K)	Duration
Hydrogen burning	15 million	10 million years
Helium burning	100 million	1 million years
Carbon burning	600 million	300 years
Oxygen burning	1 billion	200 days
Silicon burning	3 billion	2 days

The duration of the nuclear fusion phases becomes shorter and shorter as less energy is released per nucleon from the fusion of heavier elements. The last nuclear fusion phase lasts just 2 days!

Why are the later fusion processes so short?

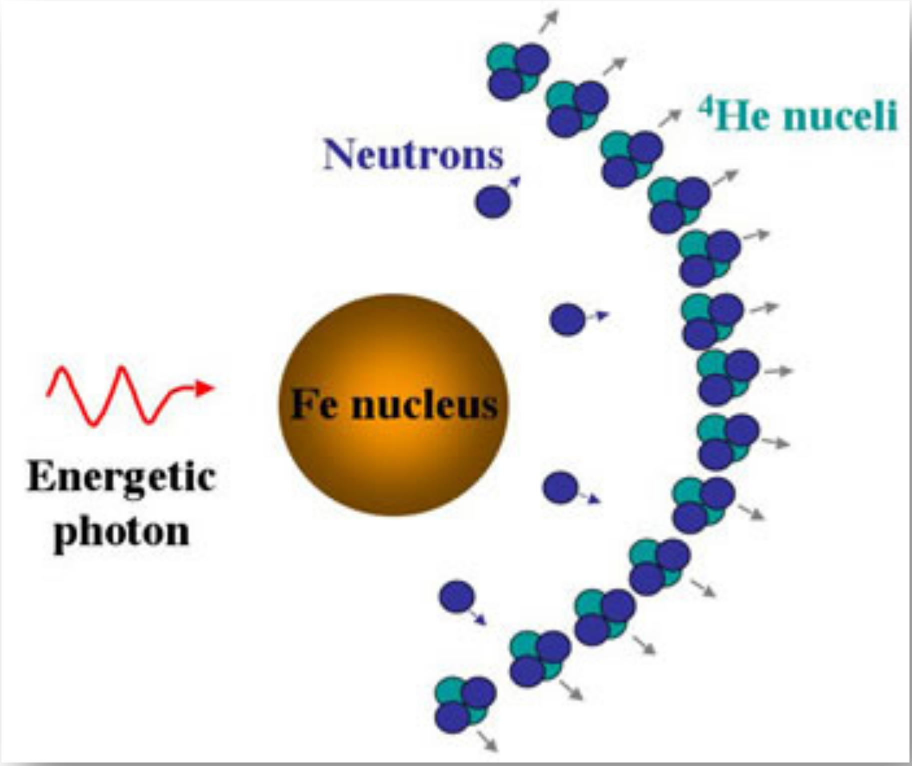
Photodisintegration weakens the stellar core

In the last nuclear fusion phase of Silicon producing Iron and Nickel, the temperatures get so high at the core (~(3-10)x10^9 K) that the thermal photons produced in the plasma are at MeV energies and so can disintegrate the heavy elements (recall lecture 7), undoing much of the work of the previous nuclear fusion phases.

Two of the particularly important photodisintegration phases are:

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

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



These photodisintegration phases are <u>endothermic</u> (more energy goes in than is gotten out) so this <u>critically</u> weakens the core, removing much of the energy that was holding up the rest of the star!

Rapid collapse of the stellar core: electron capture

Without sufficient pressure the core will collapse. Collapse could be partially supported by electron degeneracy pressure (lecture 16). However, the free electrons are captured (electron capture: due to extreme density) by the photodisintegration products:

$$p^{+} + e^{-} \Rightarrow n + \nu_e$$

This leads to a colossal release of energy in neutrinos: for a 20 solar mass star ~3x10^{38} W of energy is released as neutrinos, as compared to ~4x10^{31} W from photons during Silicon burning!

This process ultimately leads to a degenerate remnant: a neutron star or black hole.

The core is now unable to support the star. The catastrophic removal of pressure means that the core collapses astonishingly quickly (up-to v~70,000 km s^{-1}) in (nearly) free fall:

$$t_{ff} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}$$

The core (approximately the size of the Earth) is crushed to just 20 km in <1 second: the free-fall equation gives ~0.02s for a density of ~10^{13} kg m^{-3} as the collapse is not quite in free fall.

Rebound of the stellar core

The core collapses until it reaches a density of ~8x10^{17} kg m^{-3}, ~3x greater than the density of an atomic nucleus. At this point there is repulsion due to the nuclear strong force, causing the core to rebound with tremendous energy, sending out a pressure wave which becomes a shock front when the local sound speed is exceeded.

The shock loses energy when it encounters the **outer layers of the star**. Further photodisintegration and electron capture occurs, which produces a colossal abundance of neutrinos (more than before). Gas density so high that ~5% of the neutrinos are deposited into the material which accelerates the gas. This tremendous energy release produces a **supernova!**

Heaviest elements (beyond Iron) are fused in this shock-gas interaction (endothermic)

A vast amount of gravitational energy is released in the collapse: can the collapse provide the energy to power the supernova? The energy release can be calculated as (recall from lecture 5 the derivation for gravitational collapse):

$$E \sim -\frac{3GM^2}{10}\left[\frac{1}{R} - \frac{1}{R_{initial}}\right] \quad \text{which is} \quad E \sim -\frac{3}{10}\frac{GM^2}{R} \text{ when } R << R_{initial}$$

For example, down from $R_{initial}$~6300 km to R~20 km, ~3x10^{46} J of energy is produced from the gravitational collapse of a core of 2.5 solar masses, the total energy of the supernova but almost all of this energy is released as neutrinos!

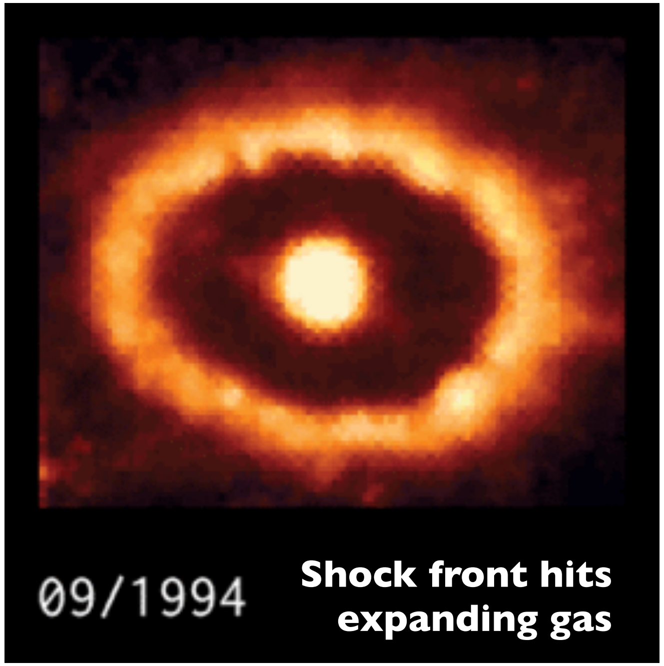
Supernova!

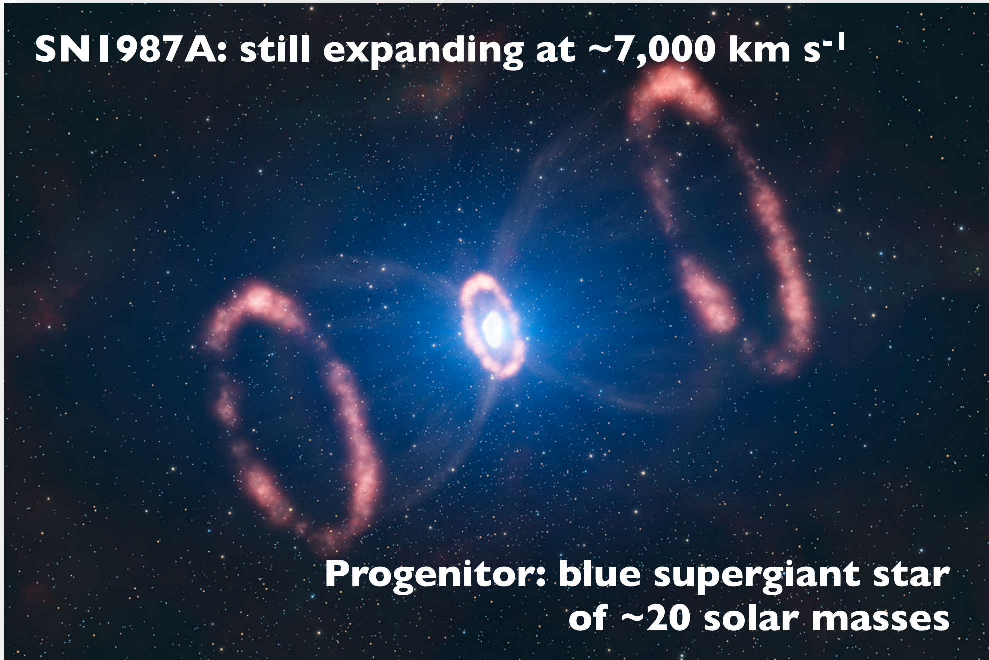
A huge amount of kinetic energy drives the expansion of the plasma (~10^{44} J), more emission than the entire energy produced by a typical galaxy of ~10^{11} stars

The optical photons (the emission we see in the image above) only provide ~0.01% of the total energy of the supernova (~10^{42} J), which is dominated by neutrinos!

The properties of SN1987A

SN1987A occurred in the large-magellanic cloud (satellite galaxy at a distance of 168,000 light years) in 1987 and was the brightest supernova witnessed in recent times: the last supernova in our own galaxy was in 1604.

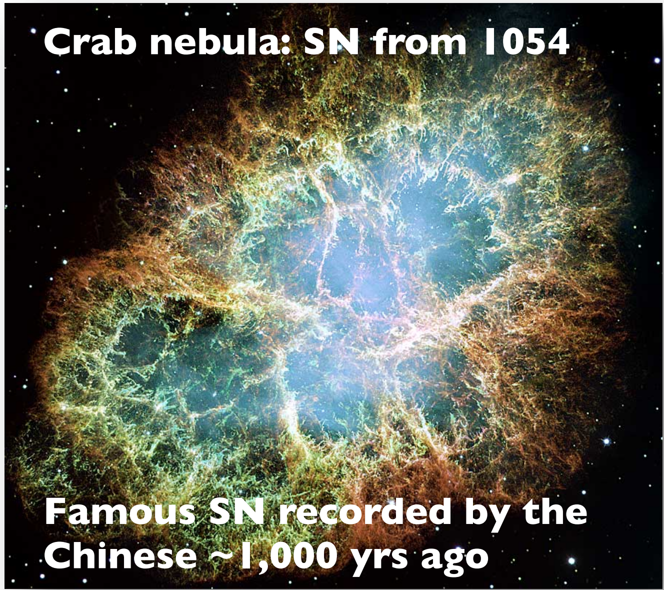


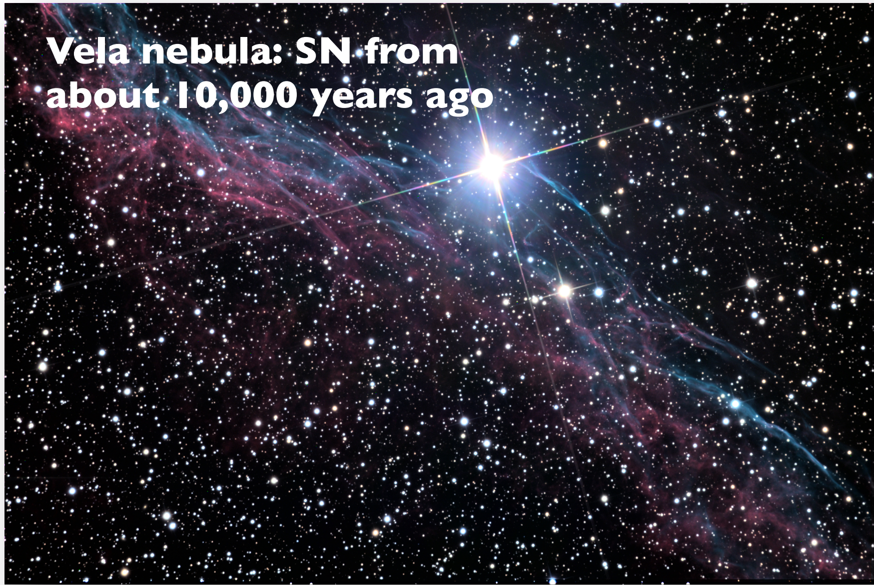


Neutrinos were detected from SN1987A. The neutrinos were actually detected ~3 hours before the optical emission was observed. However, the neutrinos didn't travel faster than the speed of light! The **large optical depth** of the accelerated gas means that the supernova was not witnessed in optical light until it had expanded.

Only ~20 neutrinos were detected but the implied luminosity was huge: ~10^{46} J, in good agreement with the predictions for core-collapse supernovae (as explored in this lecture).

Some supernova (SN) remnants in our galaxy





The velocity of the gas in the Crab nebula is still ~1500 km s^{-1}, even though it was originally ejected ~1000 yrs ago!

Supernova (SN) are a very destructive process. However, they seed the interstellar medium with heavy elements, which are needed for making planets, people, etc. Supernovae can also initiate star formation (i.e., lecture 13) – the life cycle of stars

Typical galaxies have ~1 SN every 100 yrs (last in our galaxy was 1604: Kepler SN) and ~1-3 solar masses/SN is lost. The average mass loss is therefore ~0.02 solar masses/yr/galaxy.

As we will learn in lecture 17 some of these host pulsars

Degenerate products of massive stars

What about the collapsed core? Its fate depends on its mass: if <2.5 solar masses then it becomes a neutron star; if >2.5 solar masses then nothing can stop the collapse and it becomes a black hole. It is possible that quark stars exist and are of intermediate mass between neutron stars and black holes; however, they are largely hypothetical.

In terms of the original mass of the star, a star with a mass of ~8-25 solar masses is likely to collapse to a neutron star while a star with a mass >25 solar masses is likely to collapse to a black hole.

We will explore the (exotic) degenerate properties of stars in the last two lectures: white dwarfs, neutron stars (and pulsars), and black holes.