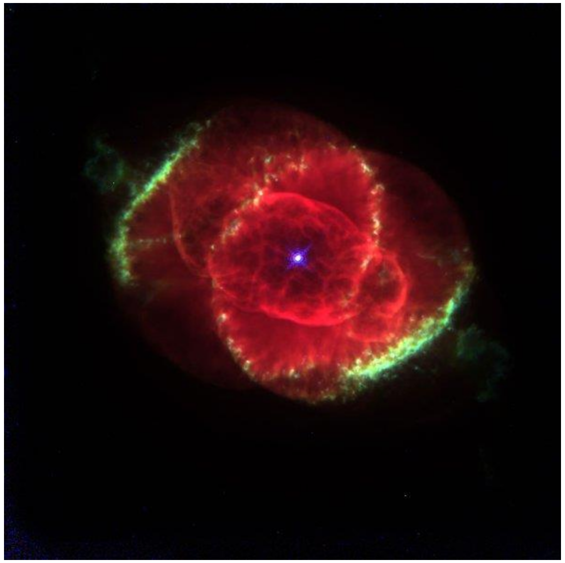
The end point: Stellar remnants

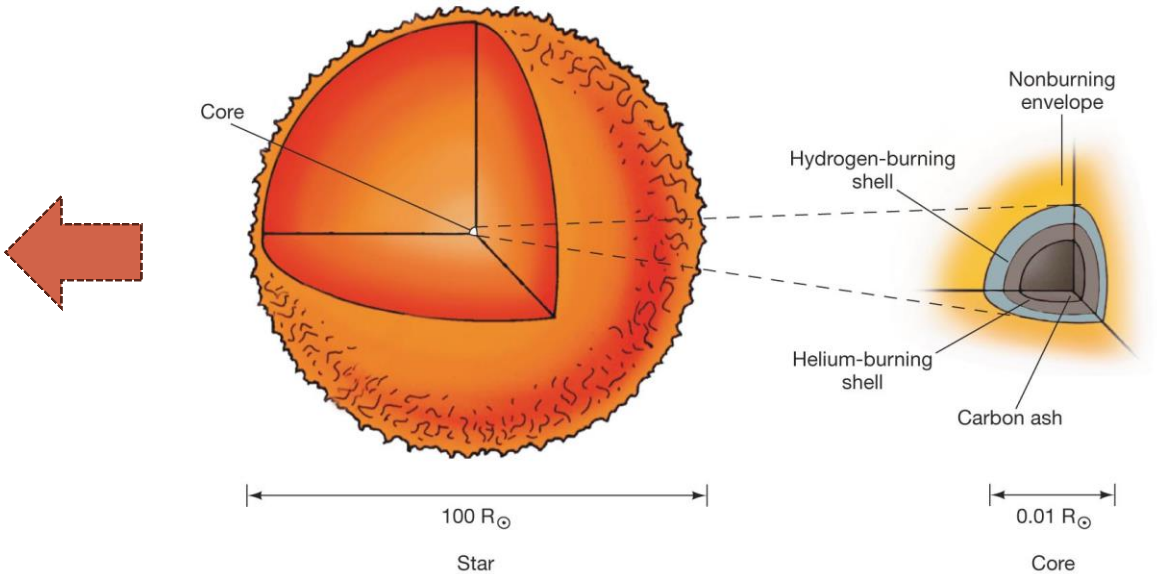
WHITE DWARFS
NEUTRON STARS
BLACK HOLES
SUPERNOVAE

White dwarfs

As mentioned in previous lectures, the end state of stars with masses $M < 8\text{–}10\ M_\odot$ is a white dwarf: a stellar remnant in which the pressure is provided by degenerate electrons and there is no significant nuclear burning. No fusion, no contraction, just cooling. For eternity.

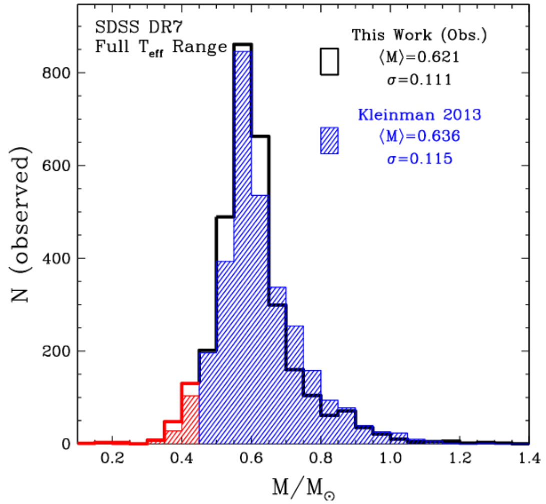
Simply speaking, white dwarfs are the remnants of former stellar cores supported by electron degeneracy pressure and left behind by stellar envelopes dissipated as planetary nebulae.





White dwarfs

Observed WD masses are mostly in a narrow range around 0.6 $M_\odot$, which corresponds to the mass of the C-O cores of low-mass ($\lesssim$2 $M_\odot$) AGB progenitors.



The great majority of white dwarfs are indeed composed of C and O.

White dwarfs with $M > 1.2\ M_\odot$, on the other hand, are mostly O-Ne or O-Ne-Mg white dwarfs. They form from stars with $M \approx 8$–$10\ M_\odot$ the core temperature of which is sufficient to fuse carbon but not neon.

Stars of very low mass will be unable to fuse helium; hence, a helium white dwarf should form, and they are indeed discovered.

However, the formation of known He WDs is not expected to happen in single stars, but can result by mass loss from binary interaction and indeed most low-mass WDs are found in binary systems.

Why?

White dwarfs

White dwarfs are very well described as polytropes.

In lecture 11 we obtained the Chandrasekhar mass limit – the **maximum mass possible** for a white dwarf.

$$M = M_{Ch} = \frac{5.826}{\mu_e^2} M_{\odot}$$

For a highly relativistic electron gas, there is only a **single** possible mass which can be in hydrostatic equilibrium. White dwarfs are typically formed of helium, carbon or oxygen, for which $\mu_e = 2$ and therefore $M_{Ch} = 1.456\, M_{\odot}$.

Thus, stars with masses $M < 8–10\ M_{\odot}$ never develop a degenerate core more massive than the Chandrasekhar limit (and even for such massive stars, this requires a lot of mass loss).

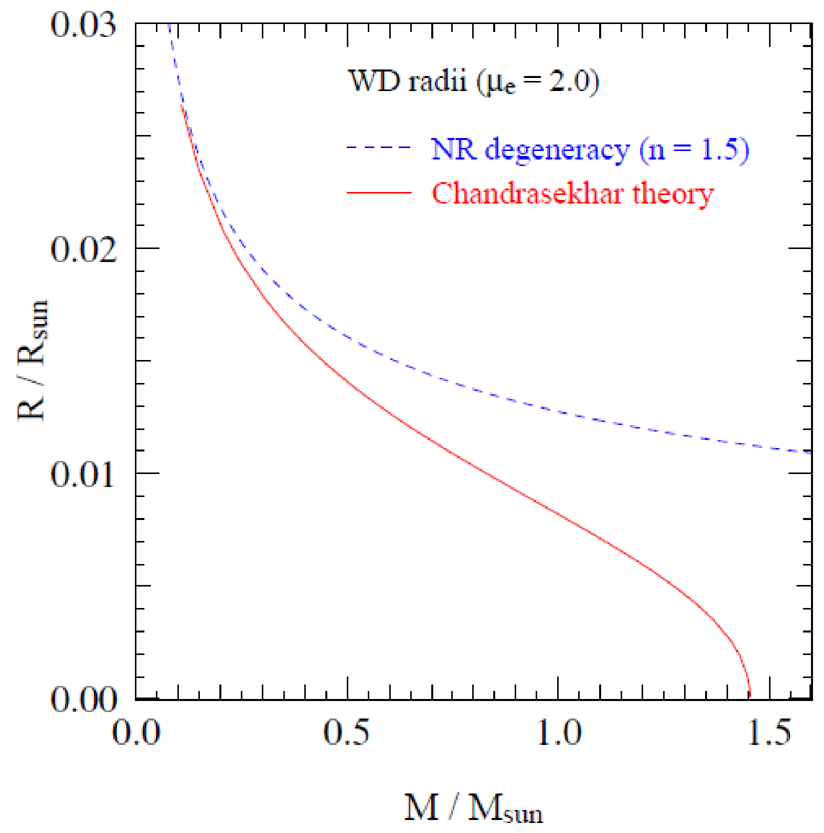
A further increase of the mass (e.g., due to accretion from a companion star) leads to the loss of stability and collapse. This is the cause of supernovae type Ia explosions (will discuss later).

Radius—Mass relation for WDs

White dwarfs are very well described as polytropes with n=1.5, and also in Lecture 11 we obtained that for n=1.5, $R \sim M^{-1/3}$, i.e. the stellar radius is inversely proportional to the mass.

In reality, a proper theory for WDs should take into account that the most energetic electrons in the Fermi sea can move with relativistic speeds, even in fairly low-mass white dwarfs. This means that the EOS is generally not of polytropic form but has a gradually changing n between 1.5 and 3. The pressure in the central region is therefore somewhat smaller than that of a purely non-relativistic electron gas.

Thus, WD radii are smaller than given by the polytropic relation, the difference growing with increasing mass (and increasing central density).

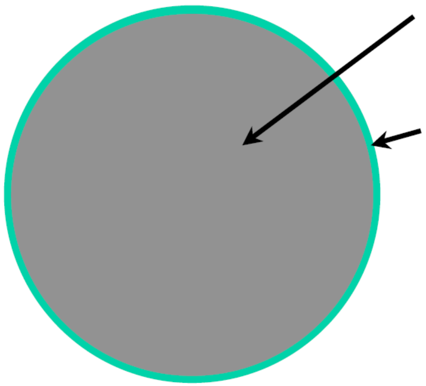


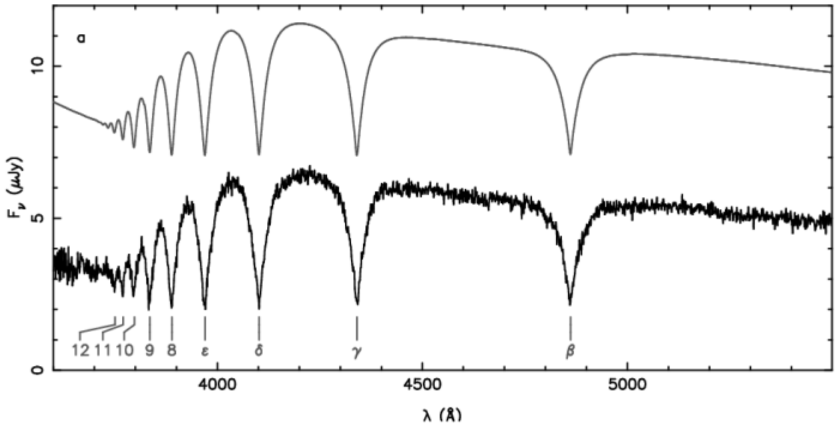
Structure of white dwarfs

The surface composition of white dwarfs is usually completely different than their interior composition.

The strong surface gravity has resulted in separation of the elements, such that any hydrogen left is found as the surface layer while all heavier elements have settled at deeper layers.

Most white dwarfs, regardless of their interior composition, show spectra completely dominated by H lines and are classified as DA white dwarfs.
A minority of white dwarfs show only helium lines and have spectroscopic classification DB. These have lost all hydrogen from the outer layers during their formation process, probably as a result of a late or very late thermal pulse.

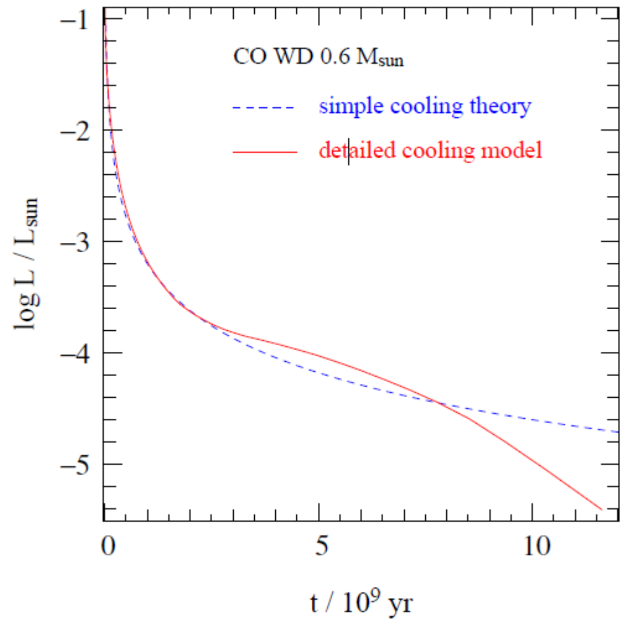




He and CO WDs also usually appear to be **pure** hydrogen. Only distinguishable by mass.

Cooling of white dwarfs

- In the interior of a white dwarf, the degenerate electrons provide a high thermal conductivity. This leads to a very small temperature gradient, especially because L is also very low. The degenerate interior can thus be considered to have a constant temperature.
- However, the outermost layers have much lower density and are non-degenerate, and here energy transport is provided by radiation. Due to the high opacity in these layers, radiation transport is much less effective than electron conduction in the interior. The non-degenerate outer layers thus act to insulate the interior from outer space, and here a substantial temperature gradient is present.
- It can be shown that more massive WDs evolve more slowly, because more ionic thermal energy is stored in their interior.
- Simple cooling law, shown in Figure for a $0.6\ M_\odot$ CO WD, predicts cooling times greater than 1Gyr when $L < 10^{-3}\ L_\odot$, and greater than the age of the Universe when $L < 10^{-5}\ L_\odot$.
- A more detailed WD cooling model show that white dwarfs that have cooled for most of the age of the Universe cannot have reached luminosities much less than $10^{-5}\ L_\odot$ and should still be detectable.
- Observed WD luminosities thus provide a way to derive the age of a stellar population.



Exceeding the Chandrasekhar mass

Suppose we add mass to a white dwarf, for example in a mass transfer binary system, to bring it up to the Chandrasekhar limit. What happens?

Possibility 1:

- A further increase of the mass leads to the loss of stability – the pressure of degenerate electrons can no longer hold the star up – and collapse. If this accretion-induced collapse occurs, the end state would be a neutron star (see below).
- The collapse would produce very little in the way of observable phenomenon.

Possibility 2:

- As M approaches M_{Ch}, the temperature and density in the core ignite fresh nuclear reactions. Unlike in the case of ordinary stellar nuclear reactions, this is devastating to the star.

Recall: $$P_e = K_{NR}\left(\frac{\rho}{\mu_e}\right)^{5/3}$$ ...no temperature dependence

- Hence, large energy release from nuclear reactions heats the material up without changing the pressure or density. This is the cause of supernovae type Ia explosions, production of $\sim 1 M_\odot$ of radioactive nickel.

Neutron stars (1)

- When a star's total mass is above around $8 - 10\ M_{\odot}$, the mass around the core will be larger than the Chandrasekhar limit. In this case after helium fusion ends and the core temperature is not hot enough for carbon fusion to occur, the gravitational pressure will overwhelm the electron degeneracy pressure and the core will collapse past the white dwarf stage.
- The further compression heats up the core, allowing the remaining stages of fusion to occur, making elements up to iron. After these stages finish, the star collapses again.
- As the core collapses its temperature becomes so high, $T > 10^{10}$ K, that the photons are energetic enough to break up heavy nuclei into lighter ones their constituent protons and neutrons (photodisintegration):

$$^{56}\mathrm{Fe} \rightarrow 13\ ^{4}\mathrm{He} + 4\ \mathrm{n}$$

  Since this is an endothermic reaction that costs energy, rather than produces it, the core quickly cools and the collapse accelerates.
- the protons smash into the electrons producing neutrons and neutrinos:

$$p + e^{-} \rightarrow n + \nu$$

  This reaction is energetically favorable because the neutrinos stream out of the star relieving some of the pressure. Ultimately, only neutrons are left.

Neutron stars (2)

Neutrons are fermions, and the core of neutrons in a neutron star is a Fermi gas, like a WD.

- Once the core reaches nuclear densities ($\rho \sim 10^{15}$ g cm^{-3}), degeneracy pressure of neutrons provides the pressure support against gravity.
- Formation of a proto-neutron star stops the collapse and produces a bounce which sends a shock wave back out into the star.

Shock wave can explode the star (a supernova explosion), if it can propagate out through the infalling matter.

- Core may leave a neutron star, or if it is too massive, collapse further to form a black hole.

We can again use our polytropic equations to estimate parameters of a WD, but matters are complicated because nuclear forces are important. Exact EOS is still unknown.

- Masses of NSs are between 1.2 and 2.5 $M_\odot$ and radius is ~10 km.
- The maximum mass of a neutron star depends on the existence of a general-relativistic instability (interactions between nucleons), quite commonly accepted to be ~3 $M_\odot$.
- Most neutron star observations are in a very narrow range of masses $M_{NS} = 1.35 \pm 0.04\ M_\odot$.

Neutron stars (3)

Newly formed NSs are very hot and embedded within young supernova remnants. Rapidly cool due to neutrino emission (in the very early stages), then photon emission.

Neutron stars cool down faster than WDs.

Galactic population of NSs must be enormous - a very small number have been detected directly from this cooling radiation.

Idea that neutron stars might be formed in supernova explosions was suggested by Walter Baade & Fritz Zwicky in 1934.

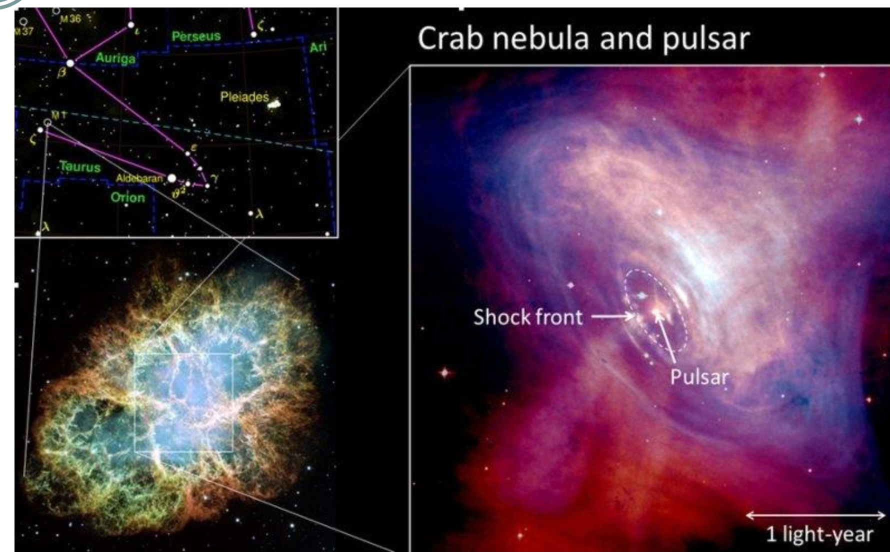
Detailed models for neutron stars were derived by Robert Oppenheimer and George Volkoff in 1939.

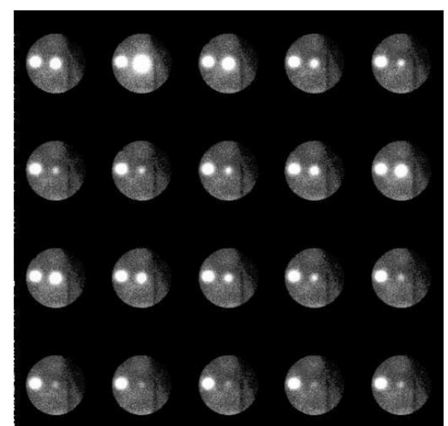
Obvious that isolated neutron stars would be very faint and hard to detect.

Neutron stars in binaries are extremely luminous, but only in X-rays which at the time were undetectable.

Surprisingly, first discovered by accident via pulsed radio emission - pulsars, by Jocelyn Bell in 1967.

Large number (~ thousand) of radio pulsars are now known, some of which also pulse in X-rays and even in optical





Golden et al., 2000, A&A, 363, 617

Stellar mass black holes

Maximum mass of a neutron star is unknown but is probably $\lesssim 3\ M_\odot$.

No known source of pressure can support a stellar remnant with a higher mass - collapse to a black hole appears to be inevitable.

Strong observational evidence for black holes in two mass ranges:

Stellar mass black holes: $M_{BH} = 5 - 100\ M_\odot$.

- produced from the collapse of very massive stars ($\gtrsim 25\ M_\odot$).
- lower mass examples could be produced from the merger of two neutron stars.

Supermassive black holes: $M_{BH} = 10^6 - 10^9\ M_\odot$.

- present in the nuclei of most galaxies
- formation mechanism unknown

Other types of black hole could exist too (intermediate mass black holes: $M_{BH} \sim 10^3\ M_\odot$).

Basic properties of black holes (1)

Black holes are solutions to Einstein's equations of General Relativity. Numerous theorems have been proved about them, including, most importantly:

The 'No-hair' theorem:

A stationary black hole is uniquely characterized by its:

- Mass M
- Angular momentum J
- Charge Q

} Conserved quantities

Remarkable result: Black holes completely 'forget' how they were made – from stellar collapse, merger of two existing black holes, etc…

Astrophysical black holes are highly unlikely to have any significant charge.

Basic properties of black holes (2)

Astrophysical black holes are highly unlikely to have any significant charge, so $Q=0$.

Then there are 2 interesting cases:

$J=0$: Schwarzschild black hole

Spherically symmetric. Most important property – existence of an event horizon at a radius:

$$R_s = \frac{2GM}{c^2} \qquad \text{(Schwarzschild radius)}$$

No matter, radiation, or information can propagate outwards through this radius.

For $M_{BH} = 7\ M_\odot$: $R_s = 20$ km - very similar to the size of a neutron star. Unless we can measure the mass, hard to observationally distinguish between stellar mass black holes and neutron stars…

Basic properties of black holes (3)

Astrophysical black holes are highly unlikely to have any significant charge, so $Q=0$.
Then there are 2 interesting cases:

J = arbitrary: Kerr black hole

Axisymmetric solution – black hole has a preferred rotation axis.

Let's define the amount of angular momentum via a dimensionless spin parameter:

$$a = \frac{cJ}{GM^2}$$

Maximum angular momentum of a Kerr black hole corresponds to a spin parameter $a = 1$. A Kerr black hole cannot spin up beyond this limit.

For comparison, $J_\odot = 1.6 \times 10^{48}$ g cm^2 s^{-1}, $M = 1.99 \times 10^{33}$ g, so for the Sun $a = 0.185$.

Event horizon $\rightarrow \frac{GM}{c^2}$ as a tends to maximal value.

Black holes

Stellar mass black holes in mass transfer binaries are the best studied systems. Show many very complex phenomena.

Best hope for studying fundamental physics of black holes is probably to observe gravitational radiation as they either form, or as pre-existing black holes in a binary merge.

Axisymmetric systems do not emit gravitational radiation (e.g. pulsars, or Kerr black holes) at all, so need to look for:

- inspiral or merging of black hole binaries
- merger of neutron stars (binary pulsar will merge in a few hundred million years, so we know for certain such events occur)
- signals from black hole formation in core collapse supernovae - **if** the collapse is not axisymmetric…

Supernovae and Supernova remnants

Explosion ejects outer layers of the star with $v \sim 10^4$ km s^{-1}.

This gas expands and collides with the circumstellar medium producing a supernova remnant.

Supernovae are classified according to the spectral lines seen in their spectra:

- Type I: no lines of hydrogen in the spectrum
- Type II: lines of hydrogen seen in spectrum

Overwhelming observational evidence that Type II supernovae are associated with the endpoints of massive stars. Thought to represent core collapse of massive stars with
$M > 8\text{–}10\ M_\odot$.

Type I is further divided into subclasses (Ia, Ib and Ic) again based on their spectral properties:

- Type Ia supernovae are believed to result from the explosion of Chandrasekar mass white dwarfs.
- Type Ib and Type Ic are thought to result from the collapse of massive stars that have lost their outer hydrogen envelopes prior to the explosion.

Note: classification predates any physical understanding, and so is potentially confusing!

Summary of Star Lifecycles

- The formation, evolution and death of stars is a cyclical process.
- Starts off with big cloud of gas.
- Cloud collapses under gravity until it becomes hot enough to burn and shine.
- When the fuel runs out the star dies.
- Massive stars end in supernova explosions which returns material to the interstellar medium.
- This is recycled into new stars!

Stellar Mass