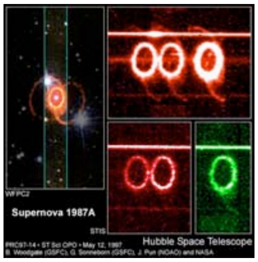
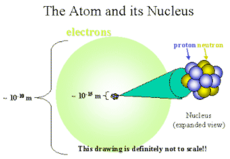
Astronomy 102.
October 13, 2005.



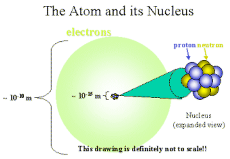
The atom.

- In order to understand stellar evolution, we need to have some basic understanding of the composition of atoms.
- The diameter of the atom (about 10^{-10} m) is determined by the size of the orbit of the outer electrons.
- Most of the mass of the atom is concentrated in its nucleus, which has a diameter of about 10^{-15} m.
- The nucleus consists out of protons and neutrons.
- The protons and electrons carry an electrical charge equal in magnitude, but opposite in sign.



The atom.

- The number of protons in the nucleus is equal to the number of electrons in the atom.
- The neutrons do not carry an electric charge.
- The protons and neutrons are very similar in mass, and are about 1800 times heavier than an electron.
- The wave length associated with matter waves is equal to $h/(mv)$, and electrons will have a wavelength that is 1800 times larger compared to protons moving with the same velocity.



Degeneracy pressure.

- When the atoms in a star are compressed, the Pauli exclusion principle will start to influence the distribution of the electrons long before it will start to influence the distribution of the nucleons.
- The degeneracy pressure is much stronger than the electric repulsion between electrons, but it has an upper limit. When the gravitational force exceeds a certain limit, the degeneracy pressure can no longer balance the gravitational force, and prevent a further collapse.
- When a proton and an electron are confined to a small enough volume, the proton can be converted into a neutron.
- The degeneracy pressure of neutrons is much stronger than the degeneracy pressure of electrons, and it may or may not be able to stop the collapse of the star.

Degeneracy pressure and stellar collapse.

- The time required for the stellar collapse depends on the speed of the atoms in the interior of the star and the on its size.
- The limiting factor will be the fact that the speed of the atoms can not exceed the speed of light, independent of the forces exerted on them.

The maximum mass and the speed-of-light limit.

- One of Einstein's original assumptions that lead to the theory of special relativity was that the speed of light is constant, independent of the reference frame in which it is observed.
- One of the consequences of the theory of relativity is that no body can move faster than the speed of light, but it is important to recognize that this was not one of the original assumptions made by Einstein.
- The theory of relativity predicts that the mass of an object will increase when its speed increases (**note**: the mass in the rest frame of the object does not change).

The maximum mass and the speed-of-light limit.

- The mass of an object in its rest frame is often called its rest mass m_0.
- When we observe this object moving with the velocity V, its mass in our frame will be equal to

$$m = \frac{m_0}{\sqrt{1 - \frac{V^2}{c^2}}}$$

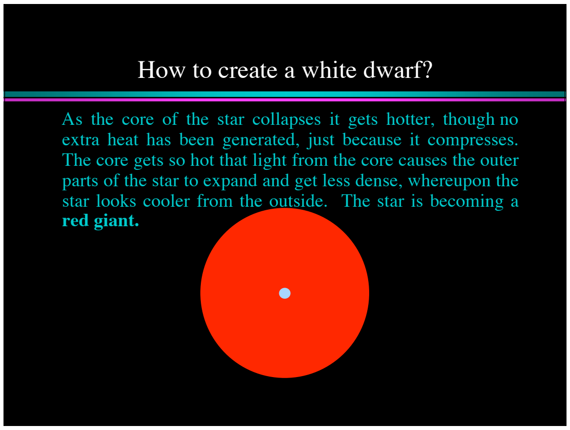
- As the mass of the object increases, the force acting on it will produce a decreasing acceleration.
- As a result, the velocity of the object will never be able to exceed the speed of light.

Let’s review stellar evolution.
How to create a white dwarf?

Start with a normal star like the Sun. Fusion of protons into helium in the star’s center generates heat and pressure that can support the weight of the star. The Sun was mostly made of hydrogen (=1 proton + 1 electron) when it was born, and started with enough hydrogen to last like this for about 10 - 15 billion years.

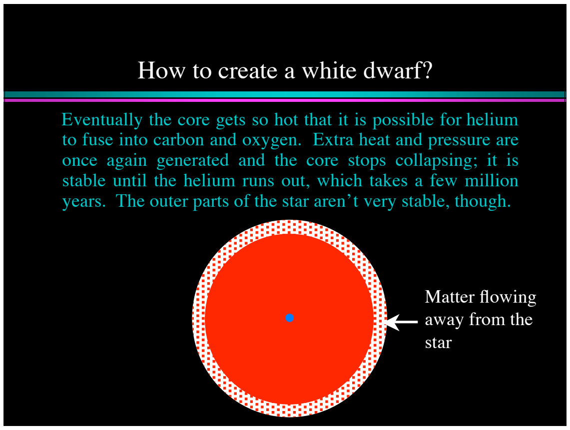
How to create a white dwarf?

When the star begins to run out of hydrogen in its center, not enough heat and pressure are generated to balance the star’s weight, and the core of the star gradually begins to collapse.



How to create a white dwarf?

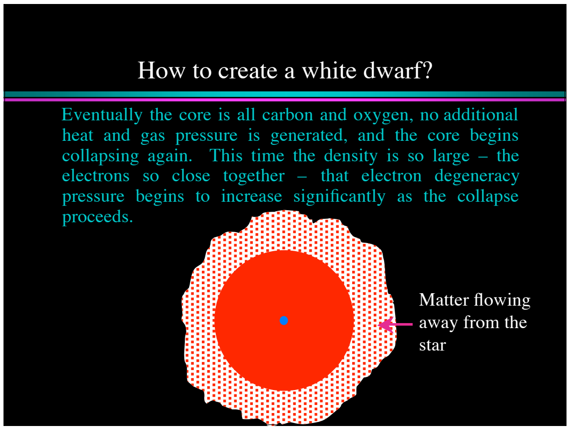
As the core of the star collapses it gets hotter, though no extra heat has been generated, just because it compresses. The core gets so hot that light from the core causes the outer parts of the star to expand and get less dense, whereupon the star looks cooler from the outside. The star is becoming a **red giant.**



How to create a white dwarf?

Eventually the core gets so hot that it is possible for helium to fuse into carbon and oxygen. Extra heat and pressure are once again generated and the core stops collapsing; it is stable until the helium runs out, which takes a few million years. The outer parts of the star aren't very stable, though.

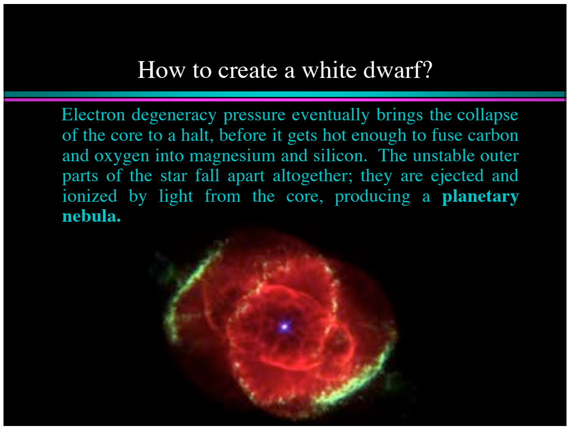
Matter flowing away from the star



How to create a white dwarf?

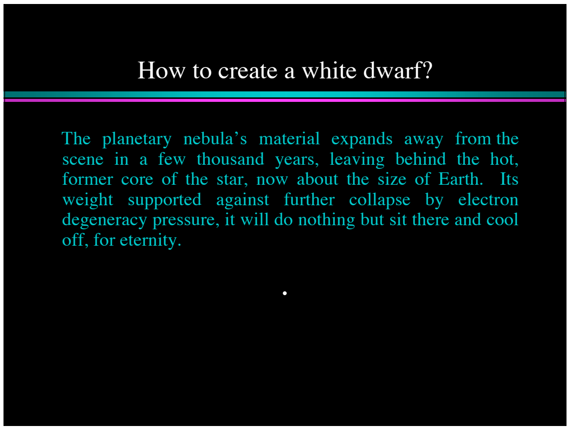
Eventually the core is all carbon and oxygen, no additional heat and gas pressure is generated, and the core begins collapsing again. This time the density is so large – the electrons so close together – that electron degeneracy pressure begins to increase significantly as the collapse proceeds.

Matter flowing away from the star



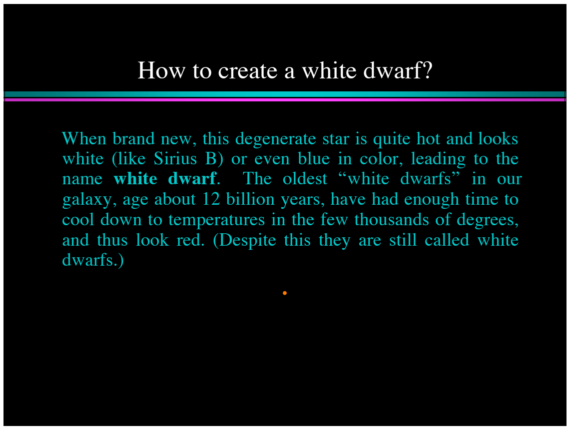
How to create a white dwarf?

Electron degeneracy pressure eventually brings the collapse of the core to a halt, before it gets hot enough to fuse carbon and oxygen into magnesium and silicon. The unstable outer parts of the star fall apart altogether; they are ejected and ionized by light from the core, producing a **planetary nebula.**



How to create a white dwarf?

The planetary nebula's material expands away from the scene in a few thousand years, leaving behind the hot, former core of the star, now about the size of Earth. Its weight supported against further collapse by electron degeneracy pressure, it will do nothing but sit there and cool off, for eternity.



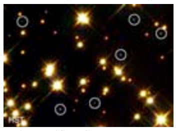
How to create a white dwarf?

When brand new, this degenerate star is quite hot and looks white (like Sirius B) or even blue in color, leading to the name **white dwarf**. The oldest "white dwarfs" in our galaxy, age about 12 billion years, have had enough time to cool down to temperatures in the few thousands of degrees, and thus look red. (Despite this they are still called white dwarfs.)

What will it be?
A white dwarf or something else?

- Electron degeneracy pressure can hold up a star of mass $1.4M_{sun}$ or less against its weight, and do so indefinitely. Stellar cores in this mass range at death become white dwarfs.
- For heavier stars: gravity overwhelms electron degeneracy pressure, and the collapse doesn't stop with the star at planet size.

NGC 2440: Cocoon of a New White Dwarf
Credit: H. Bond (STScI), R. Ciardullo (PSU), WFPC2, HST, NASA



White Dwarf Stars Cool
Credit: H. Richer (UBC) et al., WFPC2, HST, NASA

The formation of a neutron star.

- As the star is crushed past a circumference of 10^4 km, all the electrons and protons in the star are squeezed together so closely that they rapidly combine to form neutrons.
- Eventually, the collapse might be stopped by the onset of neutron degeneracy pressure.
- A star whose weight is held up by neutron degeneracy pressure is called a **neutron star**.

Mid-lecture break.

- Exam # 1 will be discussed in recitation next week.
- Please make sure you check the grading (answers are now available on our home page).
- Homework set # 4 is now available and is due on Friday October 21 at 8.30 am.
- Please take a few minutes to provide feedback to me about your recitation instructor. If you forgot who your recitation instructor is, do not worry.

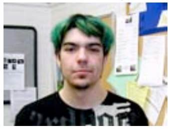
Peculiar Arp 295. Credit: Arne Henden (US Naval Observatory, Flagstaff)

Who is Who in Astronomy 102?

Brian Anderson

Amanda LaPage

Grant Tremblay



Joseph Yesselman

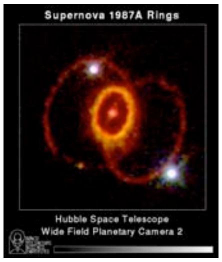
Neutron stars.

- Neutron stars were first proposed to exist by Zwicky and Baade (1934).
- Baade studied nova, which are a class of stars that suddenly flare up and shine 10,000 times more brightly than before, but return to “normal” after about a month.
- Baade focused on the much rarer super nova and discovered that during their flare-up, these nova are about 10^8 times more luminous than our sun (later this number was increased to about 10^{10} times).

Fritz Zwicky looking through eyepiece of a Telescope. Caltech.

Supernova Explosions.
What is left after the explosion in 1054 AD?

Supernova Explosions.
1987A.

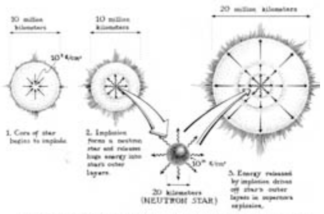


Neutron stars.

- Zwicky and Baade proposed that the enormous amount of energy released during a super nova explosion was created during the formation of a neutron star.
- The calculations of the properties of neutron stars are much more difficult than those for white dwarfs, due to the role of the strong nuclear force (which keeps the nucleus together) and the fact that general relativity must be taken into account.

Walter Baade. Caltech.

Neutron stars.



5.1 Fritz Zwicky's hypothesis for triggering supernova explosions: The supernova's explosive energy comes from the implosion of a star's normal-density core to form a neutron star.

Figure from Thorne, *Black holes and time warps*

Neutron stars. Can they prevent the formation of black holes?

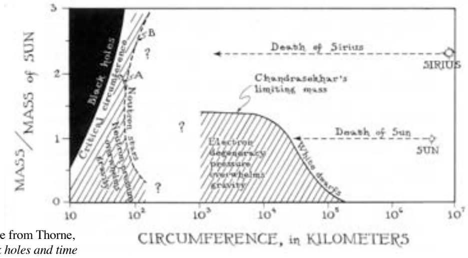


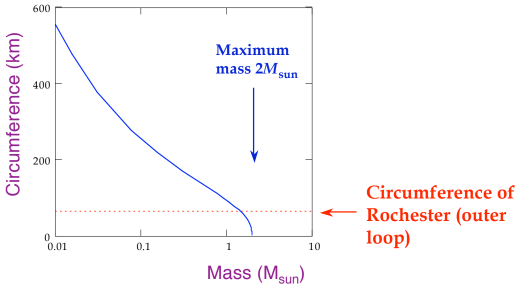
Figure from Thorne, *Black holes and time warps*

Neutron stars.

- If neutron stars are similar to white dwarfs, one can expect that they might also have a maximum mass for which the degeneracy pressure can balance the gravitational force.
- The first calculation of the maximum mass was carried out by Oppenheimer and Volkoff in 1939. They determined that $M_{max} = 0.7M_{sun}$.
- More recent calculations, with improvements in the expression of the nuclear forces, give 1.5 - 3 M_{sun}.

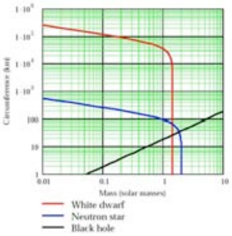
Einstein and Oppenheimer discussing neutron stars at Caltech (1939).

Neutron stars.
Calculated circumference.



Stellar collapse. What will be left?

- The final result of the collapse of a star depends on its mass.
- If its mass is less than 1.4 M_{sun}, a white dwarf will be formed.
- If its mass is more than 1.4 M_{sun}, the electron degeneracy pressure can not balance the gravitational force, and the star will continue to collapse until the neutron degeneracy pressure balances the gravitational force. This will happen as long as the mass of the star is less than 2 M_{sun}.
- Heavier stars will continue to collapse and form black holes.



Astronomy 102.
Let us practice ………

- Let us practice what we have learned so far.
- This test allows me to assess your understanding of the material, but will not be effect your Astronomy 102 grade.
- Your PRS will be used to enter your answers.

Equation of State of Matter

- The resistance of matter to compression was studied in detail by Harrison and Wheeler over wide range of densities.
- The results of their calculations for iron are shown in the figure on this page.
- The resistance shown in this figure is defined as the increase in pressure (in %) for each 1% increase in density.
- Harrison and Wheeler predicted a dramatic change in the resistance when electrons and neutrons are combined.

Figure from Thorne, *Black holes and time warps*.

Sorry Einstein, neutron stars do not prevent the formation of black holes for heavy stars.

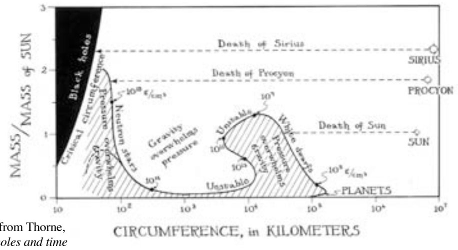
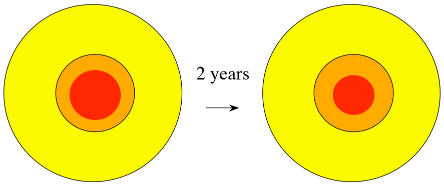


Figure from Thorne, *Black holes and time warps*

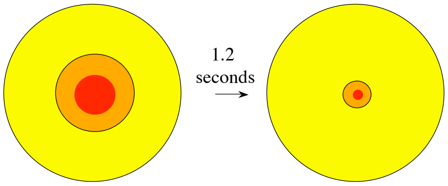
Supernova explosions. A time table!



Star: 6 M_{sun}, 10^7 km circumference.
Core: 1.4 M_{sun}, 10^5 km circumference.

Core: 10^4 km circumference. Electrons and protons begin combining to form neutrons.

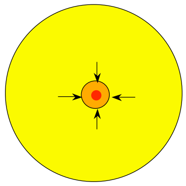
Supernova explosions. A time table!



Core: 10^4 km circumference. Electrons and protons begin combining to form neutrons.

Core: 70 km circumference, neutron degeneracy pressure sets in.

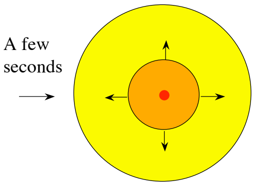
Supernova explosions.
A time table!



Core: 70 km circumference, neutron degeneracy pressure sets in. This makes the core very stiff.

Outside of core: still collapsing, moving inwards at about 10^{10} cm/s. (Near light speed!) Bounces off stiff core.

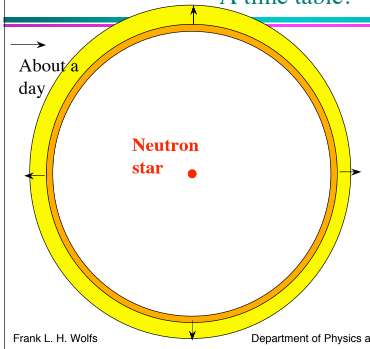
Supernova explosions.
A time table!



Core: still 70 km circumference; it is now stable.

Outside of core: the rebounding outer-star material explodes the rest of the star. Energy comes from bounce, and from gravitational energy of core.

Supernova explosions.
A time table!

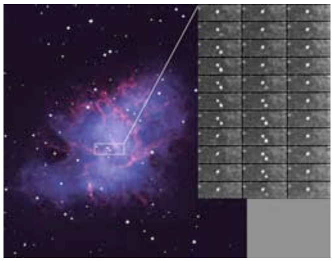


Expanding supernova shell. Very, very bright for about a month after explosion (can outshine rest of galaxy!).

Neutron stars.

- Many hundreds of neutron stars are known today.
- The neutron stars appear mostly as pulsars: pulsating, star-like sources of radio and visible light, discovered in 1967 by Jocelyn Bell.
- Astronomers have only been able to measure the masses of a handful of neutron stars; they all turn out to be around 1.4 - $1.5M_{sun}$, comfortably less than $2M_{sun}$.

Neutron stars.
Looking for pulsars.



NOAO image of the Crab pulsar. Each of the 33 images represents a time slice of about 1 millisecond in the pulsar period. The observed period that day was 33.36702 milliseconds.

We are done for today! Have a good fall break! See you on Tuesday!