AST 301
Introduction to Astronomy

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Topics for this week

How do the life stages of a high-mass star differ, and why?

Describe the events that lead up to the two types of supernova.

What is a white dwarf?

- What is a typical white dwarf mass, radius, composition?
- How does pressure in a white dwarf differ from normal gas pressure?

What is a neutron star?

- How big is it, what is it made of?
- How could one form?

What is a black hole?

Office hours

I will be at a meeting during my normal office hours this week.

I will answer questions after class.

I will have office hours this afternoon 2-3:00.

I will not have office hours tomorrow.

How were the atoms in your body made?

The hydrogen atoms (or the protons and electrons they are made of) were made in the big bang.

Many of the helium atoms in the Universe were also made in the big bang.

The other atoms were made inside of stars or during explosions of stars.

When the Sun becomes a red giant, carbon and maybe oxygen will be made in its core.

But the core will be the left-over white dwarf.

The gas put back out into space will come from the red giant’s envelope, which hasn’t been hot enough for fusion to make new elements.

Most of the elements in space were put there by supernova explosions.

After the planetary nebula

A planetary nebula can be seen for about 10,000 years.

After that, it expands and becomes faint.

And the central star (the core of the red giant) cools off and no longer lights it up.

The central star is then called a white dwarf.

Why does the white dwarf cool off?

It has lost its envelope, which served as a blanket to keep its heat in.

But that means it can lose heat faster. Shouldn't it then contract and heat up?

It turns out it doesn't contract because it is no longer a normal gas.

Normal gas and degenerate gas

Pressure is the force a gas exerts on its surroundings.

It is caused by the motion of the atoms.

Or in a star, it is mostly the free electrons that cause pressure, since it is too hot for atoms to hold onto their electrons.

In a normal gas, the electrons' motion is caused by heat.

But at very high densities, the wave properties of the electrons become important, and the electrons must move fast even if the temperature is low.

The result is that when a white dwarf loses energy, its electrons don't slow down, so its pressure doesn't decrease, so it doesn't contract.

So it cools off instead of heating up.

White Dwarfs

Because the pressure of degenerate electrons doesn’t decrease when they lose energy, the core of the red giant doesn’t contract, and so it doesn’t heat up.

It simply cools off.

Fusion stops and never starts up again.

It is then a white dwarf.

White dwarfs have masses ½ - 1 times that of the Sun.

They start out very hot, about 100,000 K, but cool off.

Their sizes are about like that of the Earth.

Density of matter in a white dwarf

Density = mass / volume

The density of the Sun is about equal to the density of water, and the mass of a white dwarf is about equal to the mass of the Sun.

The radius of a white dwarf is about 100 times smaller than the radius of the Sun.

How does the volume of a white dwarf compare to the volume of the Sun?

A. 100 times smaller
B. 1,000 times smaller
C. 10,000 times smaller
D. 1,000,000 times smaller

Density of matter in a white dwarf

Density = mass / volume

The density of the Sun is about equal to the density of water, and the mass of a white dwarf is about equal to the mass of the Sun.

The volume of a white dwarf is about 1,000,000 times smaller than the volume of the Sun.

How does the density of a white dwarf compare to the density of the Sun?

Density of matter in a white dwarf

Density = mass / volume

The density of a white dwarf is about 1,000,000 times the density of the Sun.

The density of a white dwarf is about 10^6 grams/cubic cm, or 1 ton/cm^3, or 16 tons/cubic inch.

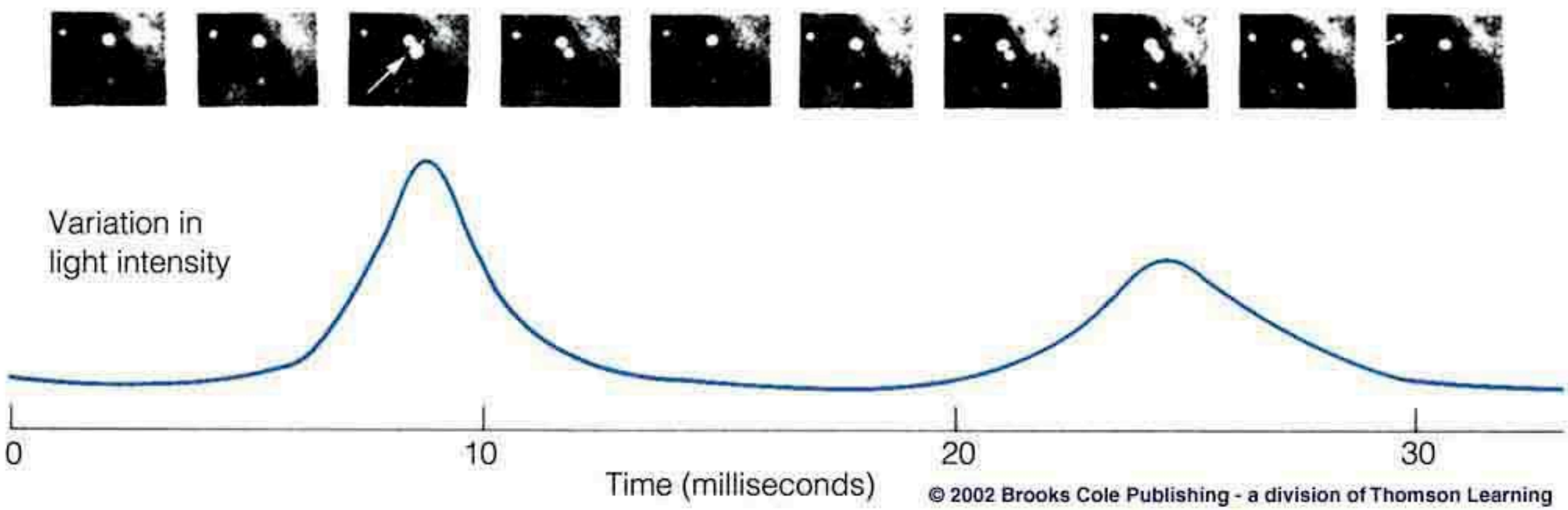
The discovery of pulsars

Jocelyn Bell, a student in England, was observing ‘radio stars’ with a radio telescope in 1967.

She noticed that one of the stars seemed to flicker regularly.

Perhaps jokingly, they at first thought it was a signal from an extraterrestrial civilization, but soon other stars like it were found, and they concluded that it was a natural phenomenon.

(The professor she was working for got the Nobel Prize for the discovery.)


Variation in
light intensity
0
10
20
30
Time (milliseconds)

How can a star flash 30 times a second?

Even if the Sun could turn on and off in 1/30 second, its radius is about 2 light-seconds, so it wouldn't appear to us to all turn on and off together.

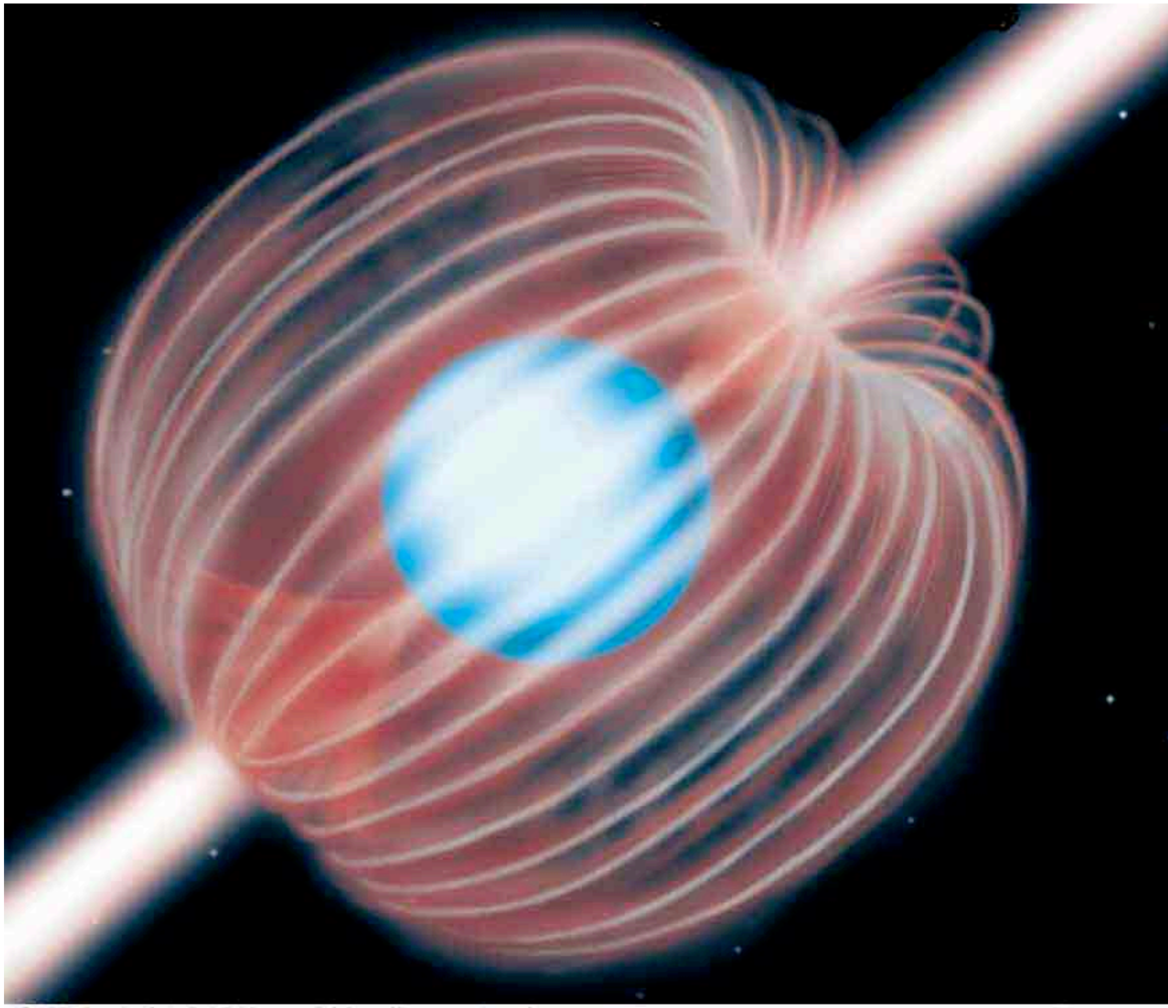
White dwarfs are small enough to avoid this problem, but what could make them flash?

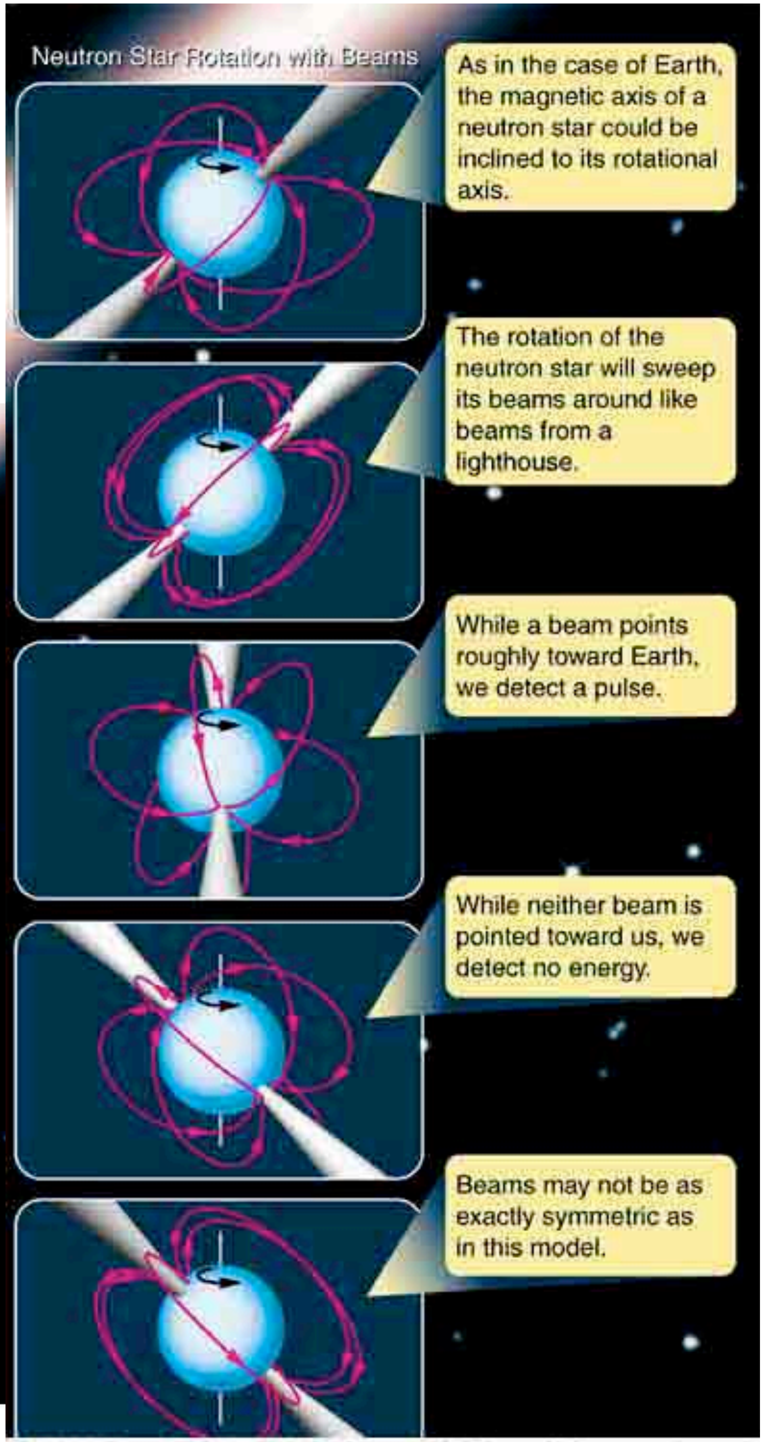
We know of pulsating stars that vary in brightness by varying in size, but they take minutes to years to vary.

They also don't turn off between flashes like pulsars do.

We think instead that pulsars work like lighthouses, with a light that doesn't turn on and off, but rotates around.

Lighthouse model of a pulsar





Can a star rotate 30 times per second?

A star can’t rotate faster than the time for a satellite would take to orbit near its surface.

Otherwise the gas near the surface of the star would go into orbit.

So the Earth can’t rotate in less than 90 minutes.

The Sun can’t rotate in less than 3 hours.

A white dwarf can’t rotate in less than about 10 seconds.

But neutron stars are so compact that they can rotate 1000 times a second without flying apart.

They also have strong magnetic fields to direct their beacons.

Density of matter in a neutron star

Density = mass / volume

The radius of a neutron star is about 10^5 times smaller than the radius of the Sun.

How does the volume of a neutron star compare to the volume of the Sun?

A. 10^5 times smaller

B. $3x10^5$ times smaller

C. 10^8 times smaller

D. 10^{15} times smaller

Density of matter in a neutron star

Density = mass / volume

The density of the Sun is about equal to the density of water, and the mass of a neutron star is somewhat more than the mass of the Sun.

The volume of a neutron star is about 10^{15} times smaller than the volume of the Sun.

How does the density of a neutron star compare to the density of the Sun?

Density of matter in a neutron star

The density of a neutron star is about 10^{15} times the density of the Sun (or about 10^{15} times the density of water).

The density of a neutron star is about 10^{15} grams / cubic cm, or 10^9 ton / cm^3, or 1 ton / cubic hair.

Why do neutron stars rotate so fast?

What happens when an ice skater goes into a spin and then pulls his hands in?

Or what happens to a planet orbiting the Sun if its orbit takes it from far from the Sun in closer to the Sun?

The Sun is rotating, with its surface moving at about 1 km/sec.

If the Sun suddenly collapsed to the size of a neutron star, about 10^5 times smaller than it is now, and gas on the surface of the Sun followed an elliptical path going 10^5 times closer to the center of the Sun, how fast would it go?

How fast could a collapsed star rotate?

If the Sun suddenly collapsed to the size of a neutron star its surface would be moving at 10^5 km/sec.

This is 1/3 the speed of light.

Neutron stars don’t actually rotate this fast because they lost some of their angular momentum when they were red giants.

(Although a few of them must have been spun-up after they formed, and do spin nearly this fast. They are called millisecond pulsars, because the time between their flashes is only a few milliseconds, so they rotate nearly 1000 times per second.)

Orbital speed around a neutron star

We can use Newton's version of Kepler's 3rd law to calculate the speed that an object would have when orbiting a neutron star. The formula is:

$$v_{orbit} = \sqrt{\frac{GM_{star}}{a}}$$

For a mass of 2 M_{sun} and an orbital radius of 10 km, the orbital speed is about 100,000 km/sec.

This is 1/3 the speed of light.

Escape speed

To leave Earth orbit and go to the Moon, the Apollo astronauts had to fire their rockets to increase their speed to about 1.4 times the orbital speed.

$$v_{escape} = \sqrt{\frac{2GM_{star}}{R}}$$

For a neutron star with M = $2M_{sun}$, $v_{escape} \sim 0.45$ c

If a neutron star had a mass of about 4 M_{sun}, its gravity would make it smaller than 10 km, and its escape speed would be greater than the speed of light.

Neutron stars with masses as big as 4 M_{Sun} can't exist.

Black Holes

If the collapsing core of a red giant has a mass greater than 4 M_{sun} the repulsion of tightly packed neutrons can't stop the collapse.

(It may not stop the collapse of 3 M_{sun} cores.)

Once the core contracts to less than about 5 km radius, the escape speed becomes greater than the speed of light.

Whatever happens after this, we can't watch it.

Any light emitted by the collapsing core can't get out.

The object is then a black hole.

The theory of General Relativity says that all of the mass collapses down to a point.

Type I supernovae

If two stars form together, orbiting each other, the more massive one will burn out faster.

It can turn into a red giant and then a white dwarf.

Later, the less massive star can become a red giant.

If the stars are close enough together, the red giant can pour mass onto the white dwarf.

If the white dwarf gains enough mass to exceed 1.44 M_{sun}, electron degeneracy pressure isn't large enough to support it against its gravity, and it will collapse.

This will cause fusion of carbon and oxygen to make neon and magnesium.

The energy released will blow the star apart.

Nothing will be left behind.