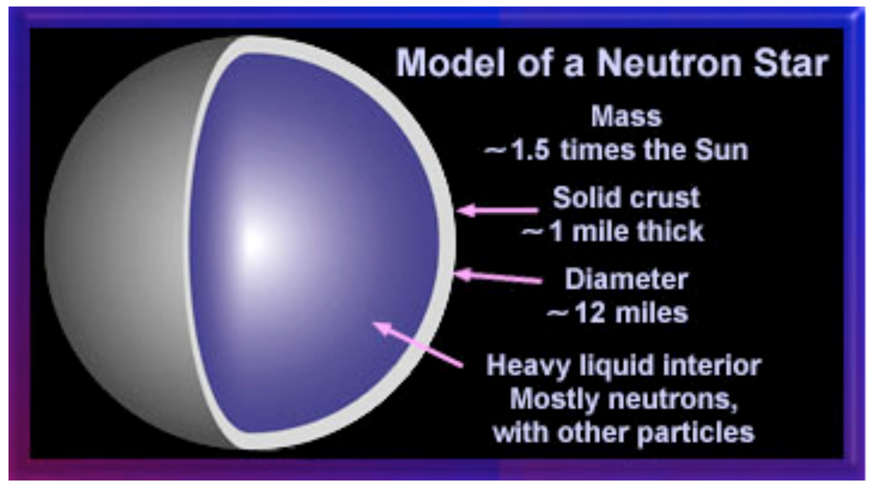
Neutron Stars and Black Holes

We have seen that stars of various masses end their lives in different ways. The lowest masses continue to quietly burn H until they fade into black dwarfs, sun-like stars end up as white dwarfs and massive stars go supernova. But what is left after the SN explosion that rips all the gas away?

The core of a star undergoing a supernova gets compressed by the implosion that occurs when nuclear reactions fail. So the remains of a SN are predictably very dense.

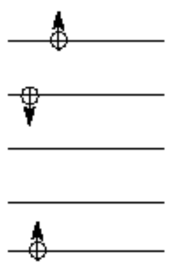
Stars with masses of about 10-30 solar masses (the exact mass range is still debated) that go supernova end up as neutron stars. In the SN explosion the star will lose most of its material and only retain about 1 solar mass of material. However, this material is VERY dense and is packed in a sphere a few tens of km across.



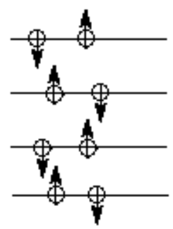
A neutron star is made of, well, neutrons. We have seen that WDs mark the end of the road for sun-like stars because the electrons become degenerate, so how do neutron stars manage to become even denser?

Forming a Neutron Star

Although neutrons are not charged, they do have spin, so they can become degenerate in the same way as electrons. However, neutrons become degenerate at much higher densities than electrons. The limit for degenerate electrons is 1.4 solar masses (the Chandrasekhar limit).



Regular gas: many unfilled energy levels. Particles free to move about and change energy levels.



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

Gamma rays in the core of a SN break atomic bonds in the nucleus releasing protons. Almost instantly the great pressure forces these free protons to bind with free electrons to form neutrons:

e + p = n + neutrino

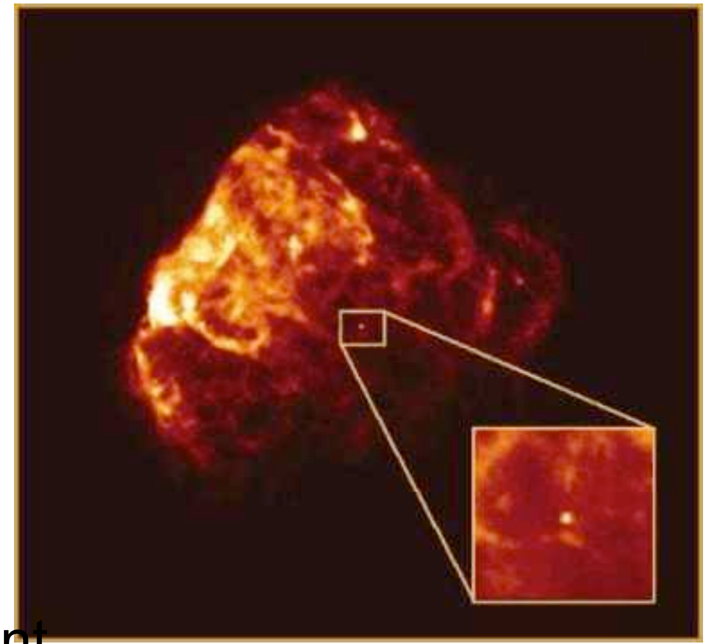
The density of a neutron star is about 10^{14} g/cubic cm, compared with 10^{6} g/cubic cm for WDs. Calculations indicate that the maximum mass of a neutron star is about 2-3 solar masses. This is the limit of mass that degenerate neutrons can support. Beyond this, even neutrons can't hold up and more massive objects collapse to black holes.

Properties of Neutron Stars

Neutron stars should be very hot because of the violent collapse they have undergone. Neutron stars can therefore be X-ray emitters. However, they will cool slowly because of their small surface area. Neutron stars should also spin very rapidly since the angular momentum (spin) of the original stellar core is now in a much smaller volume.

If the sun became a NS its period would go from 25 days to 0.001 second!!

Finally, because stars have magnetic fields, so should a NS because the field is "frozen" onto the core during collapse, and intensifies for the more compact object.



X-ray image of Puppus SN remnant

Example: A given neutron star has a period of 0.01 seconds. Assuming that the radius of this neutron star is 5 km, how fast is the rotational velocity at the surface?

To answer this question, consider a spot on the surface of the star and how it rotates. If the radius of the star is 5km, then the circumference is $2\pi r = 2 \times 5 \times 3.142 = 31$ km.

Given that the rotation period is 0.01 seconds, this means that a given spot on the surface of the star travels 31 km in 0.01 seconds. So, the velocity is distance/time = 31/0.01 = 3100 km/s.

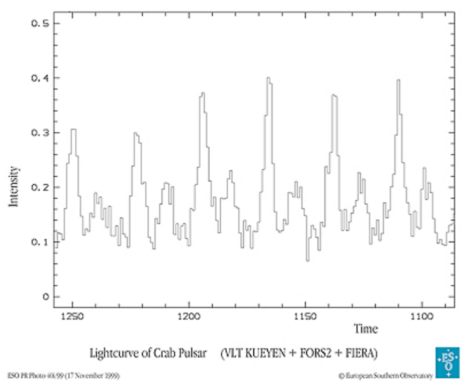
Since light speed is 300,000 km/s, the rotation speed as a fraction of the speed of light is 3100/300000 = 0.01, or 1%.

Observing a Neutron Star

Although the theory of neutron stars was worked out in the 1930s and 40s, they were not observed until 1967. This is because the high temperature of a NS means we expect most of the energy to be emitted in the X-rays, and X-ray telescopes (which need to be put in space) are a relatively new invention.

However, the discovery of neutron stars was actually made using a radio telescope, by a young British graduate student....

Jocelyn Bell was working with her advisor, Anthony Hewish with the Cambridge radio telescope, to study quasars. Bell discovered periodic radio blips separated by only a few seconds. Having ruled out instrumental problems and man made signals they even toyed with the idea of alien signals!



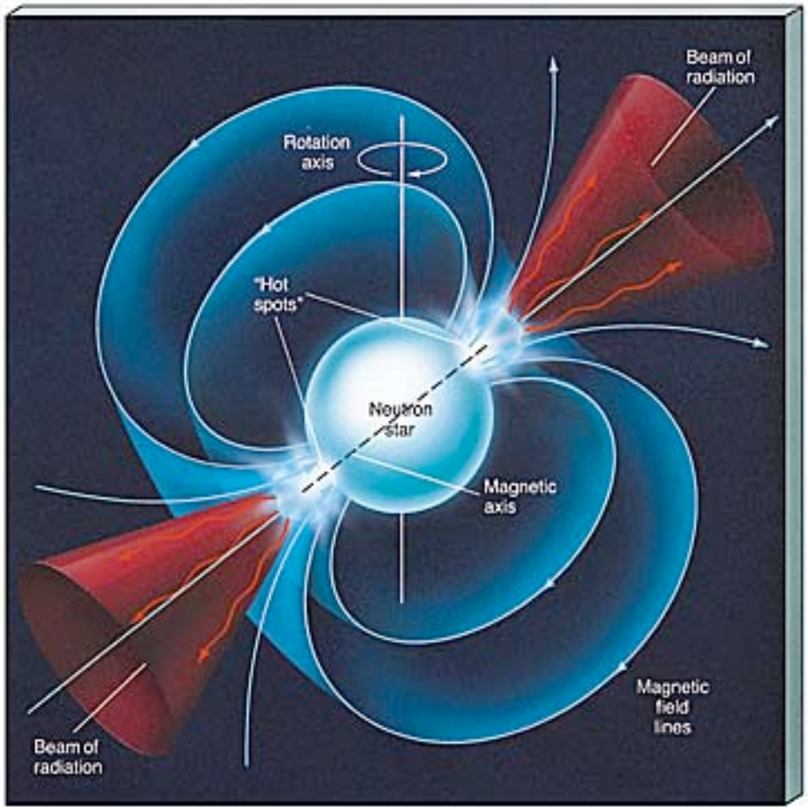
This is an *optical* light curve of a pulsar, analogous to what Jocelyn Bell observed with her radio telescope.

Pulsars

An object can not change its brightness in an interval shorter than the light crossing time of the diameter, or the pulse will be smeared, so a short pulse means a small object.

Pulsars have periods from about 0.001 seconds up to a few seconds. Considering the shortest period, we expect pulsars to have sizes that are at most the a light crossing time of 0.001 seconds i.e. 0.001 x 300,000 = 300 km.

Eventually it was figured out that these signals were coming from a rotating neutron star, called a pulsar. Hewish (not Bell) was awarded the Nobel prize for this work and you can read more of the whole story in Bell's own words here:http://www.bigear.org/vol1no1/burnell.htm

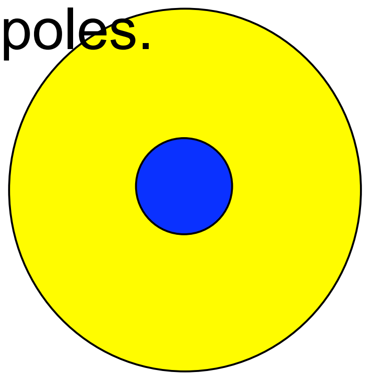


The blips that Bell detected were caused by the magnetic field around a neutron that strongly beams energy near the magnetic poles. As the neutron star spins, these beams of radiation sweep across the sky like a lighthouse.

Why the period of a pulsar tells us it must be small.

Imagine that the sun were to turn blue. We would not notice any difference for the first 8 minutes because that is how long it takes for light to get from the sun to the Earth.

After 8 minutes, we'd receive the first blue photons. These would be coming from near the equator of the sun, because the distance light has to travel to us on Earth is slightly smaller than from the poles.



Then, we would see a blue spot growing from the centre of the sun, until eventually all the sun looked blue. So there is a finite time associated with receiving the complete signal that the sun has turned blue and send its complete blue 'pulse'

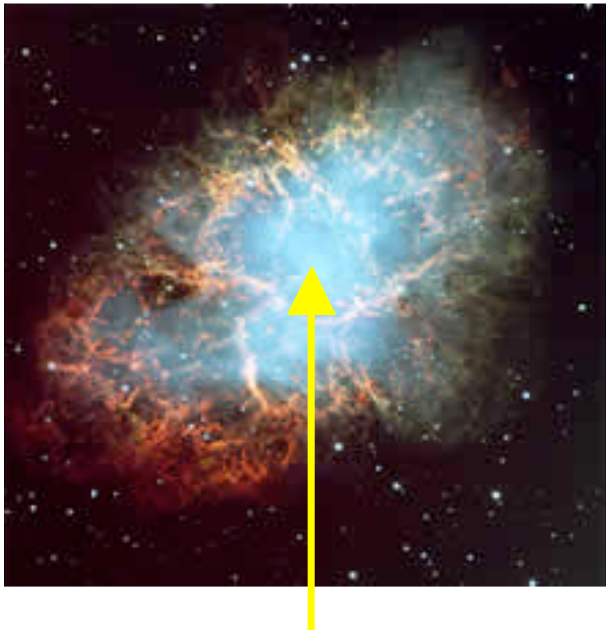
Therefore, in order to receive a pulse from a varying object, the time between pulses has to be larger than the time it takes for the entire object to send us the information about this fluctuation, i.e. the light crossing time.

For example, in 1 second light travels 300,000 km. So if an object has a pulse every second, it must have a radius SMALLER than 300,000 km Otherwise, we would not see a sharp pulse.

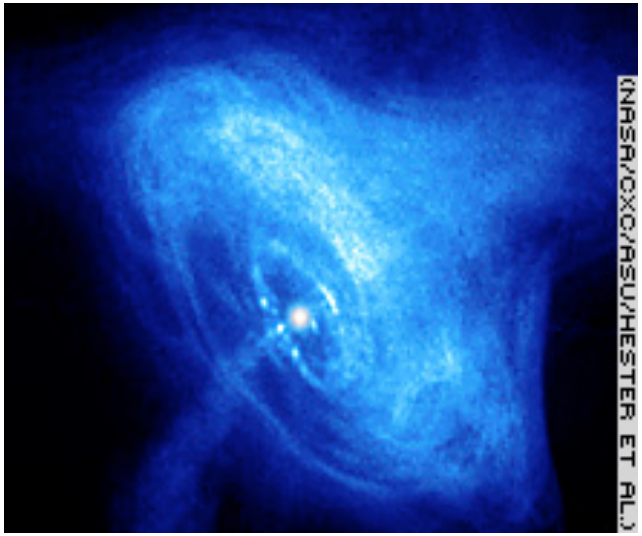
Energy in a Pulsar

So what is the radiation that we see as the lighthouse beam of a pulsar sweeps across our field of view? We saw in the the lectures on supernova remnants that synchrotron radiation is often detected as electrons spiral around magnetic fields.

This is exactly what happens in a pulsar. The only reason that the Crab nebula continues to glow 900 years after the actual SN is because it is powered by the pulsar that has been left behind.



With the advent of X-ray telescopes in space, such as Chandra (named after Chandrasekhar) astronomers have been able to directly image the high energy radiation and jets associated with pulsars. The outflowing gas in this image is moving at half the speed of light.



The Periodicity and Aging of Pulsars

The first pulsars found by Jocelyn Bell had periods of a few seconds, but many that have periods of less than a second. However, studying individual pulsars shows that the periods get longer over the years – an indication that they are slowing down.

This is a sign that the rotational energy is being transferred into other types of energy, for example, in the Crab nebula it explains why the gas is still glowing so long after the SN explosion.

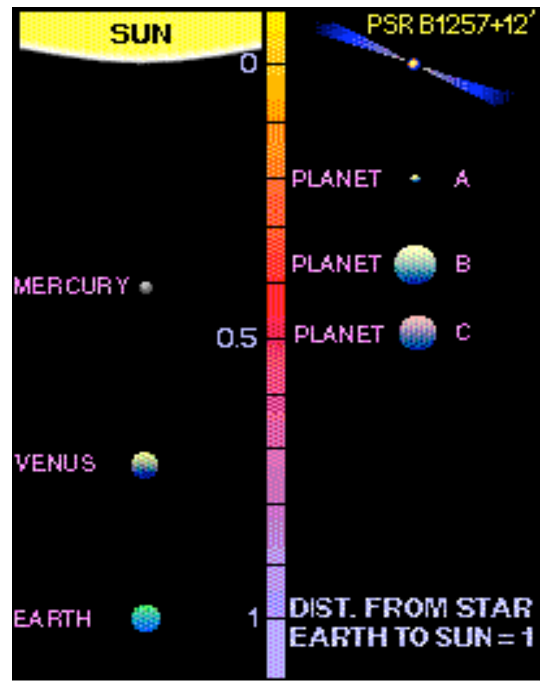
Our theory about pulsar periodicity tells us that, in general, older pulsars with have longer periods (but this is influenced by many other factors as well). Also, pulsars are more energetic when they are younger, so we see higher energy radiation in young remnants (even visible in the optical, as well as the radio) than older ones.

Occasional glitches in the periodicity are seen, and some suggest that this is due to a starquake (but this is largely theoretical). Since it is proposed that neutron stars have “crusts” of crystalised iron lattice, and liquid neutron cores, occasionally the spinning of the star (which flattens the the star) causes the crust to break, analogously to earthquakes.

Planets Around Pulsars

Just as Taylor and Hulse found relatively large Doppler shifts in their binary pulsars, so did Alex Wolszczan find a much smaller shift around the pulsar PSR1257+12.

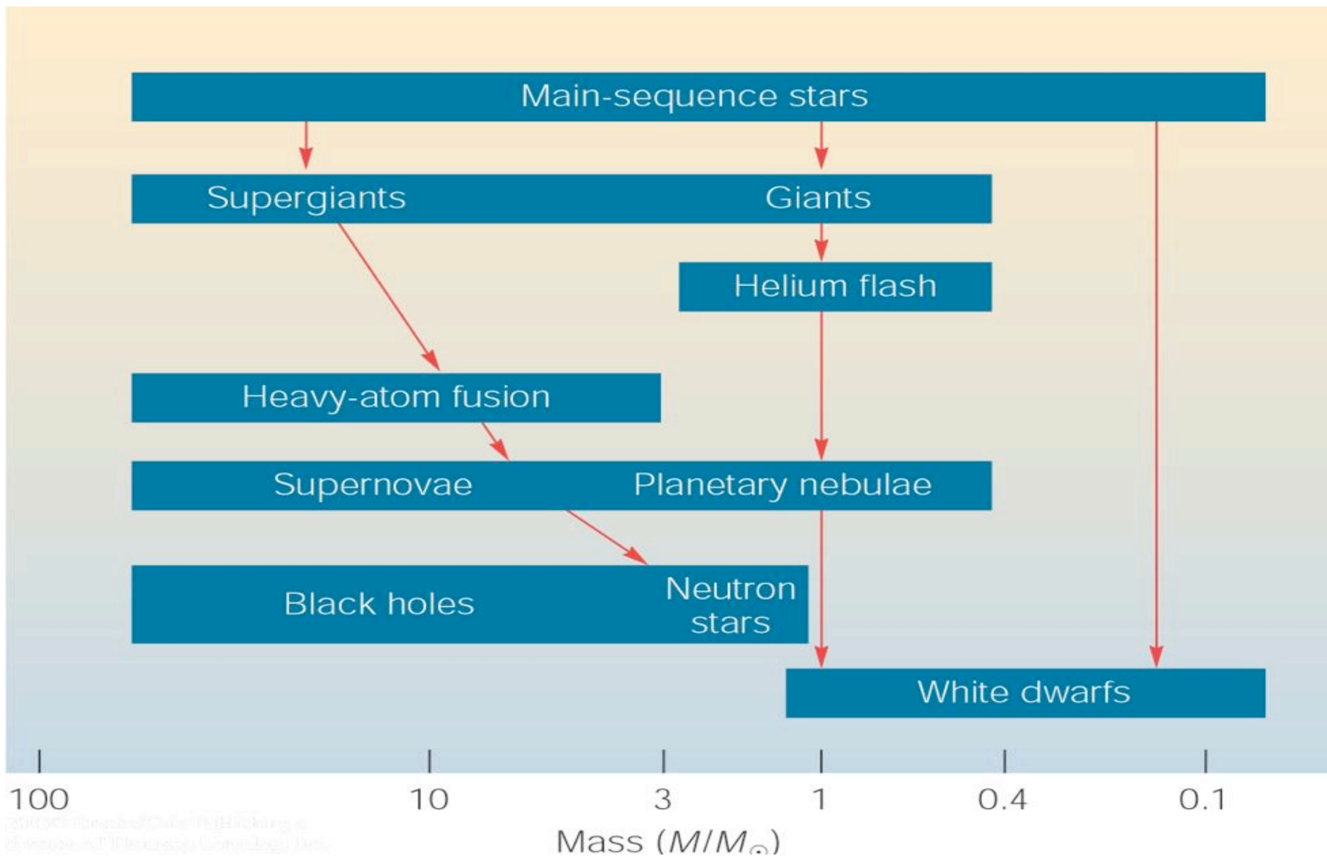
This "Doppler wobble" was far too small to be due to a pulsar, or even a normal star. In fact, the shift is big enough to only be caused by an object with a few Earth masses. Upon closer inspection of the data, Wolszczan found that there are actually 3 wobbles, so he inferred the presence of 3 small planets around the pulsar!



These were the first extrasolar planets to be discovered (1991), but remain the only ones known around pulsars. However, this method of Doppler shifts has been used to discover in excess of 100 planets around other stars.

It is hard, however, to understand how planets survived around a neutron star during the SN explosion. Several astronomers have suggested that these pulsar "planets" are actually the remains of a stellar companion.

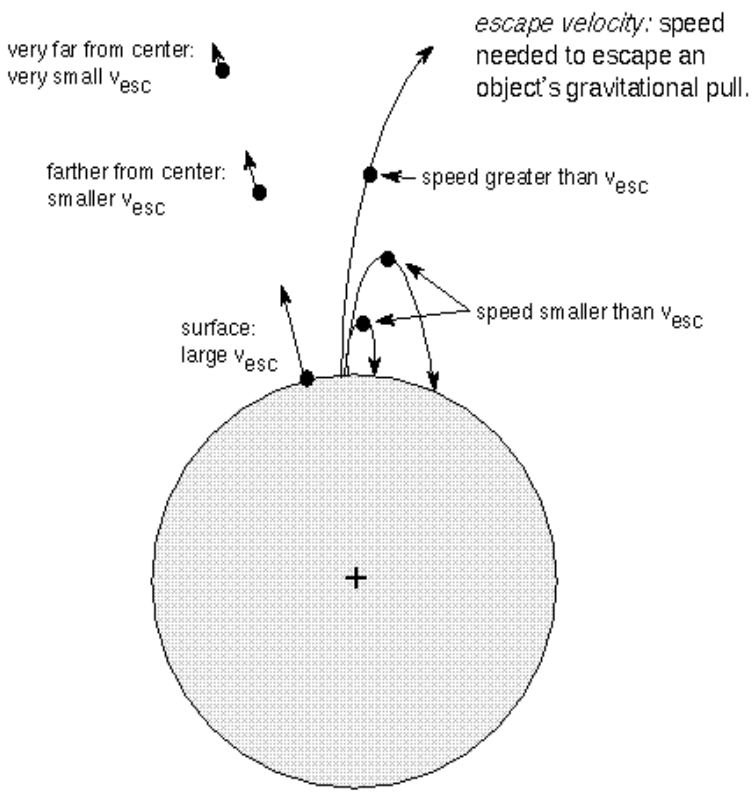
We have seen that white dwarfs can only form up to 1.4 solar masses, and pulsars/neutron stars have a maximum mass of about 3 solar masses. So what happens if a star has more than 3 solar masses at the end of its lifetime? It becomes a black hole.



But what makes a black hole black?

Escape Velocity

Imagine throwing a ball in the air, we know it will come back to Earth because of the pull of gravity. The faster you throw the ball, the higher it will go before it falls back. At some critical velocity, the ball could actually escape the gravity of the Earth and go into orbit.



The Earth's escape velocity is about 11km/s. All rockets need to obtain this speed in order to lift-off.

The escape velocity of a body (eg a planet) depends on its mass and the distance from the centre of mass:

$$V^2_{esc} = 2\,GM / R$$

Where G is the gravitational constant = $6.67 \times 10^{-11}\ m^3/s^2kg$

Let's calculate the escape velocity of a few examples.

$$V^2_{esc} = 2\,GM / R$$

in m/s   const.   in kg   in m

The Earth from the ground: $\text{sqrt}(2 \times 6.67 \times 10^{-11} \times 6 \times 10^{24} / 6378 \times 10^{3})$

$= 11202$ m/s $= 11$ km/s

The Earth from a space station in a 1000 km high orbit:
$\text{sqrt}(2 \times 6.67 \times 10^{-11} \times 6 \times 10^{24} / 7378 \times 10^{3}) = 10416$ m/s $= 10$ km/s

The moon: $\text{sqrt}(2 \times 6.67 \times 10^{-11} \times 7.4 \times 10^{22} / 1738 \times 10^{3}) = 2.4$ km/s

Jupiter: $\text{sqrt}(2 \times 6.67 \times 10^{-11} \times 2 \times 10^{27} / 71500 \times 10^{3}) = 61$ km/s

The sun: $\text{sqrt}(2 \times 6.67 \times 10^{-11} \times 2 \times 10^{30} / 7 \times 10^{8}) = 617$ km/s

For more massive stars, the escape velocity will continue to rise, and is even higher for objects like neutron stars where the mass is large AND the radius is very small. Eventually, the escape velocity becomes the same as the speed of light. If the escape velocity of a body is larger than the speed of light, then not even photons can escape its gravity.

This gives rise to a black hole.
A black hole is simply any mass that has collapsed so much that its escape velocity is larger than c.

Question: What would happen to a planet orbiting around a star that became a black hole? Would it get swallowed up?

Black holes are not like vacuum cleaners that suck things in – it's just a gravitational field!

We can define a radius to which any mass must contract in order to become a black hole. We call this the Schwarzschild radius.

Take the equation for escape velocity: $V^2_{esc} = 2\ GM / R$ and set the velocity to be the speed of light: $c^2 = 2\ GM / R$.

Now re-arrange this equation so that we can find R:

$R_s = 2\ GM / c^2$

So the Schwarzschild radius is proportional to the mass. So if the sun has a Schwarzschild radius of 3km, a 2 solar mass star has R_s= 6 km etc.

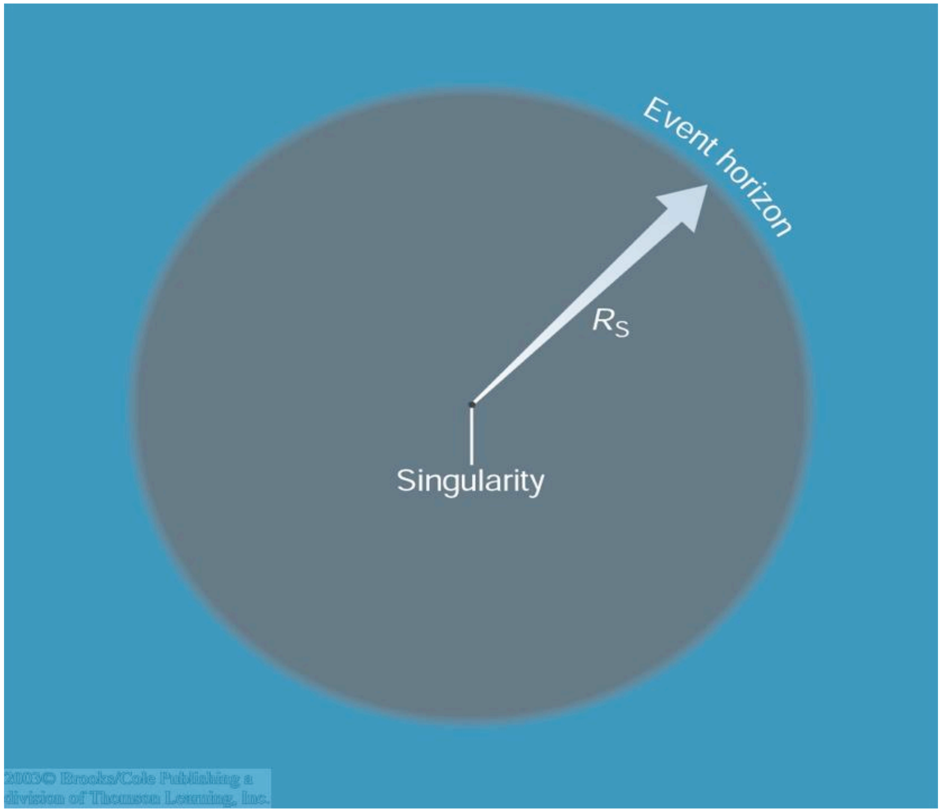
We can now work out the size that any object must shrink to in order to become a black hole.

Example: What size would the Earth have to shrink to in order to become a black hole?

$$2 \times 6.67 \times 10^{-11} \times 6 \times 10^{24} / (3 \times 10^8)^2 = 0.009 \text{ m} = 0.9 \text{ cm}$$

We have seen that if you compress *any* object enough, you could form a black hole. However, stars form black holes only when they are very massive and gravity forces them to contract at the end of the lifetimes when nuclear fuel is exhausted.

Whereas some massive stars collapse to white dwarfs or neutron stars, black hole formation is the result of much more catastrophic collapse where the mass is compressed into an infinitely small volume called a singularity.



The boundary of a black hole is called the event horizon. This is the limit at which light can escape from the clutches of the black hole and its singularity.

Properties of Black Holes

Black holes are characterised by only 3 properties: mass, angular momentum and charge. Once you know these 3 things, you know all there is to know about a black hole .... "Black holes have no hair."

Schwarzschild black hole: This is your basic vanilla black hole with no charge and not rotating.

Kerr black hole: A rotating, neutral black hole.

In fact, theorists believe that charged black holes don't exist, because any star with a strong charge is likely to get neutralised (e.g. by capturing extra electrons) way before it becomes a black hole.

In order to really understand black holes, we need to know a little bit about Einstein's theories of relativity.

Our understanding of physics on Earth is based upon the principles laid out by Newton. Newton devised the laws of motion which tell us about how things move, and the law of gravity.

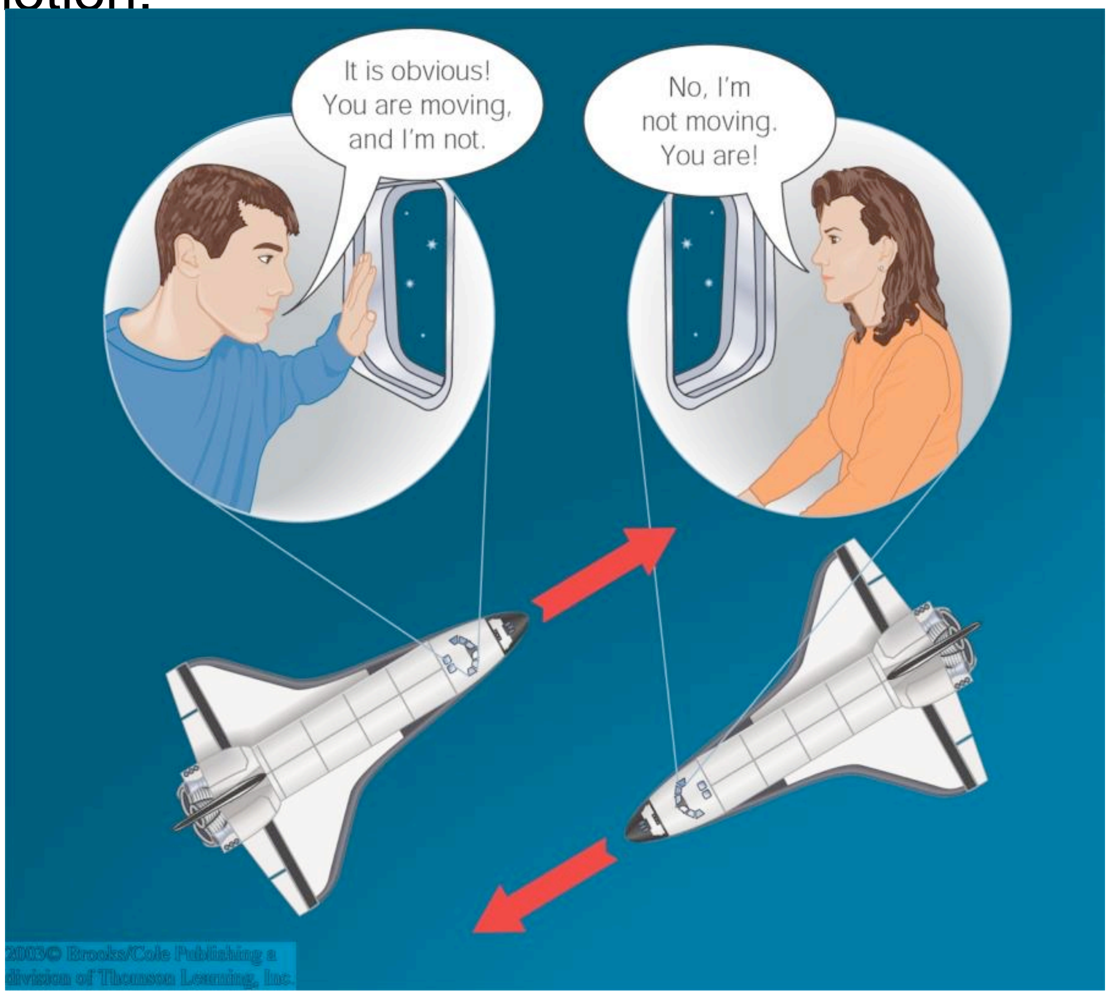
Einstein revised these laws of motion and gravity, to take into account the most extreme cases of speed and and gravity.

Einstein's theory of special relativity: tells us about motion at near light speed

Einstein's theory of general relativity: tells us about gravity near large masses

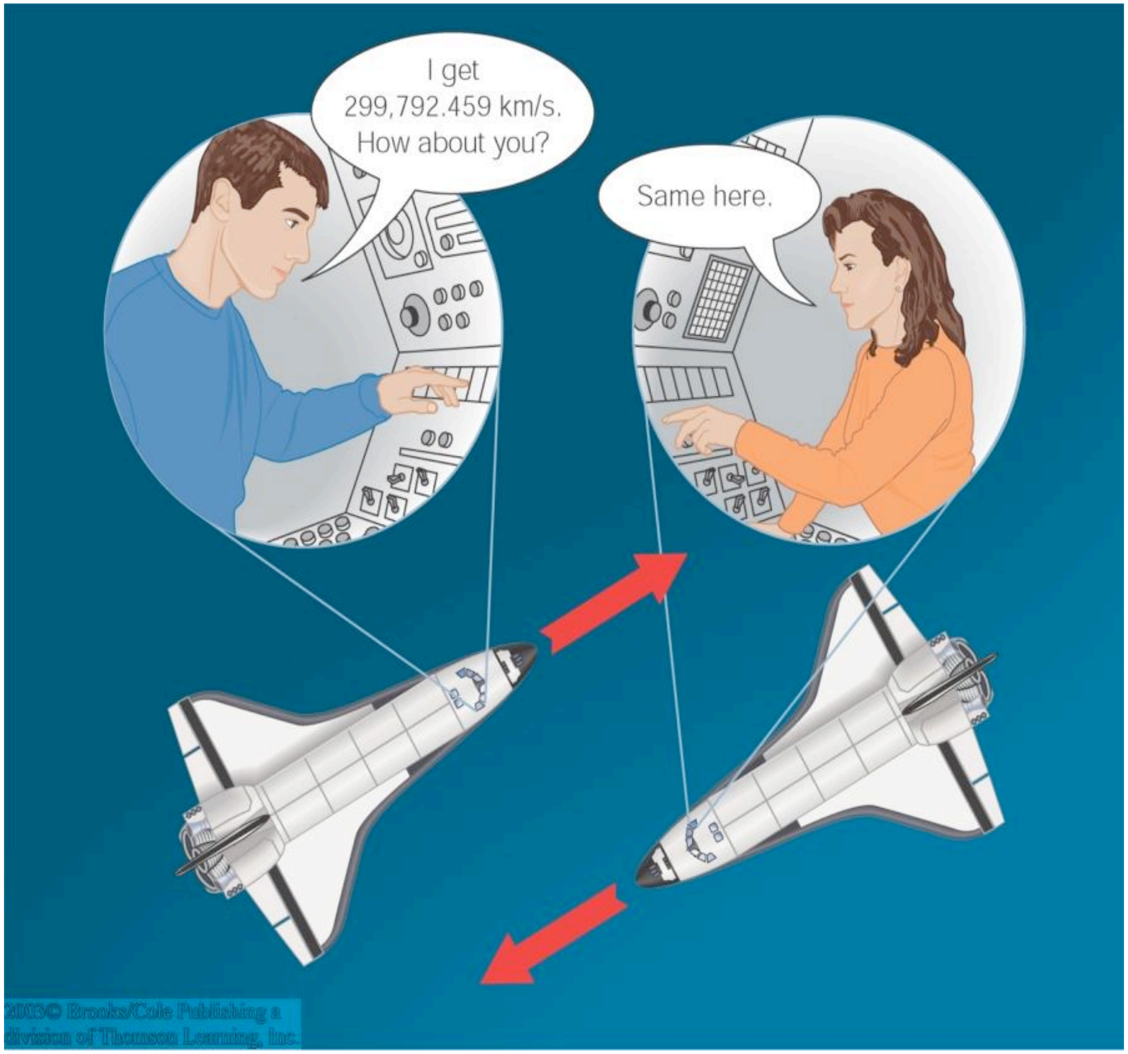
Special Theory of Relativity

The theory of "relativity" is based on the basic principle that observers can only detect relative motion within a given rest frame, not absolute motion.



1st postulate: The laws of physics are the same for all observers as long as they are not accelerating.

Put another way, it is impossible to do an experiment to determine if you are moving at a constant velocity. However, as soon as an observer starts to accelerate, they feel a force which tells them that they must be moving.



2nd postulate: the velocity of light is constant and remains constant independent of the motion of the light source.

This is not what we experience for everyday objects. For example, if we fire a missile from an airplane with a certain ejection speed, it will have a total speed that is the ejection speed plus airplane speed.

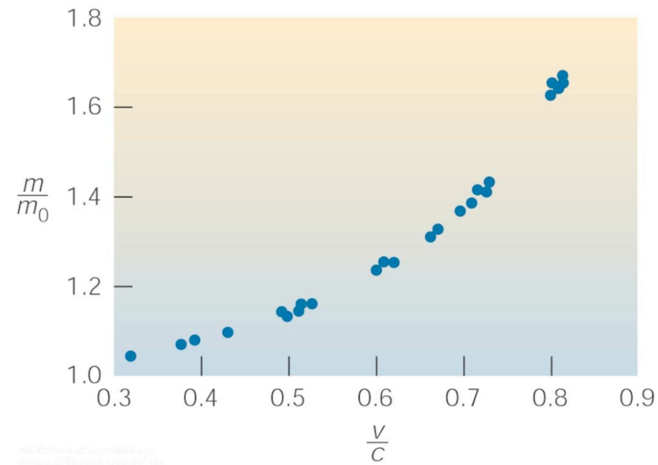
Similarly, if that missile hits another plane, the impact velocity is the sum of the velocity of the moving target and the missile.

Not so for photons! Their speed is ALWAYS 300,000 km/s.

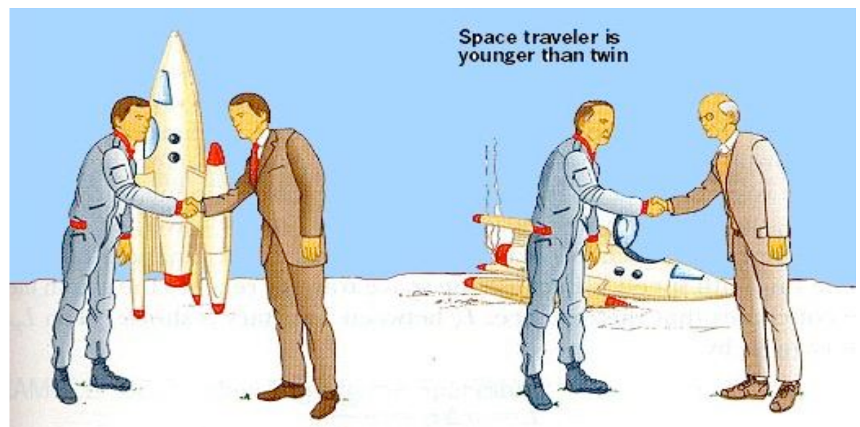
Some Weird Predictions of Special Relativity

The faster an object moves....

1) The heavier it becomes



2) The slower time travels



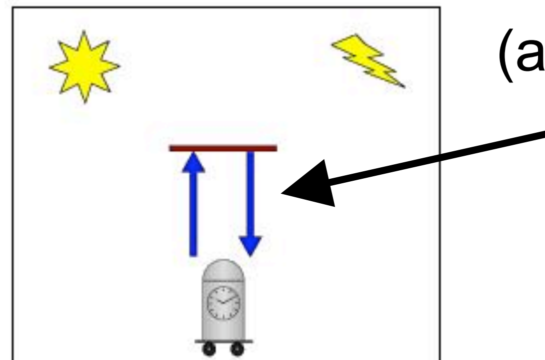
3) The shorter things become

This is beyond the scope of this course, but those who want to dig a little deeper into relativity will find many resources on the web. Try for example http://sol.sci.uop.edu/~jfalward/relativity/relativity.html . There are also some excellent books around, try the Mr Tompkins books by Gamow.

An example as to why time travels more slowly when we travel fast. In the cartoon below (a), we use a light clock to measure one second, i.e. the time it takes for the light to go from the clock to the mirror and back again.

Now imagine that the clock is moving to the right (b) and we take 3 snapshots of it. It looks like the light beam had to travel further in (b) than (a) and indeed it did!

(a)



1 sec.

Fig 4

(b)

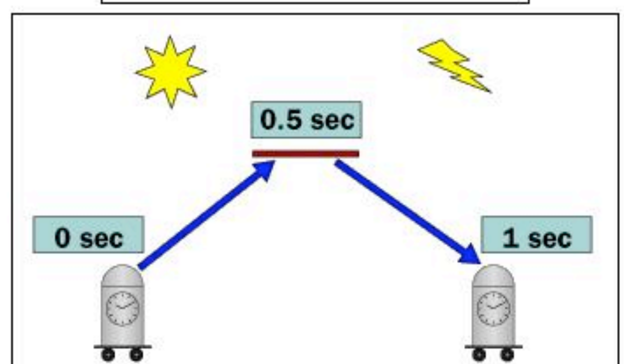


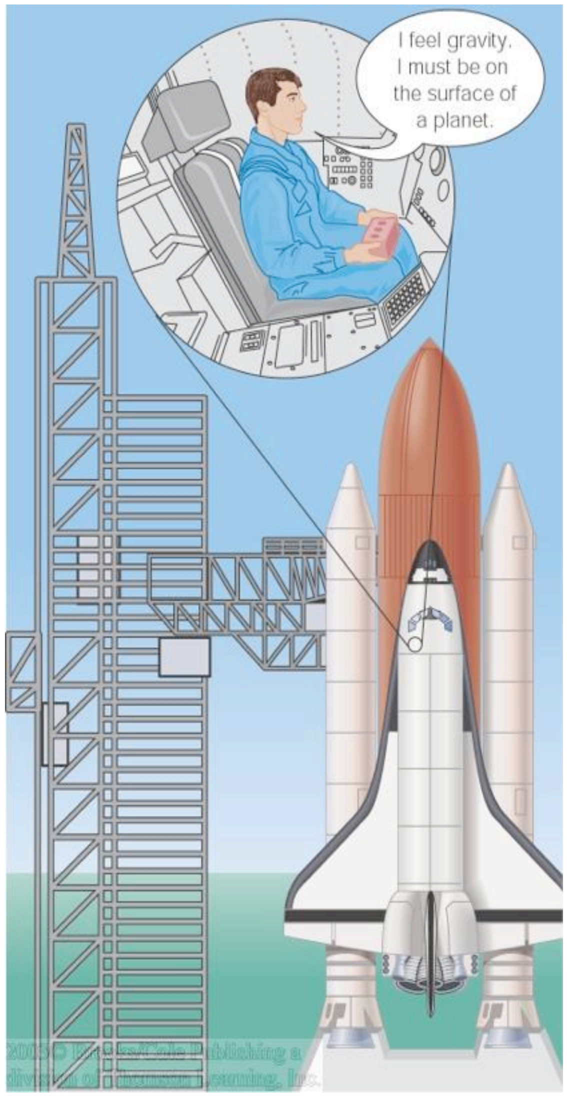
Fig 5

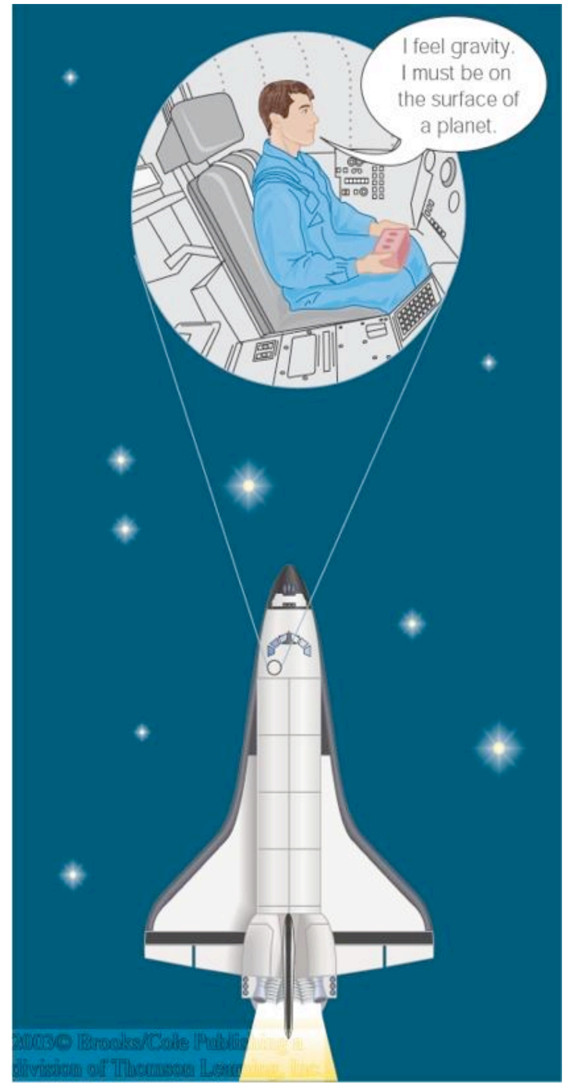
Since the speed of light is fixed but the distance is longer, it must take longer to receive the signal. Therefore, for an observer of this moving clock, time seems to travel more slowly. However, if you're moving *with* the clock (like in (a)) you won't notice any difference in the rate at which time passes.

The General Theory of Relativity

We saw that the special theory only works when there is no acceleration involved. The general theory incorporates accelerations, such as gravity.

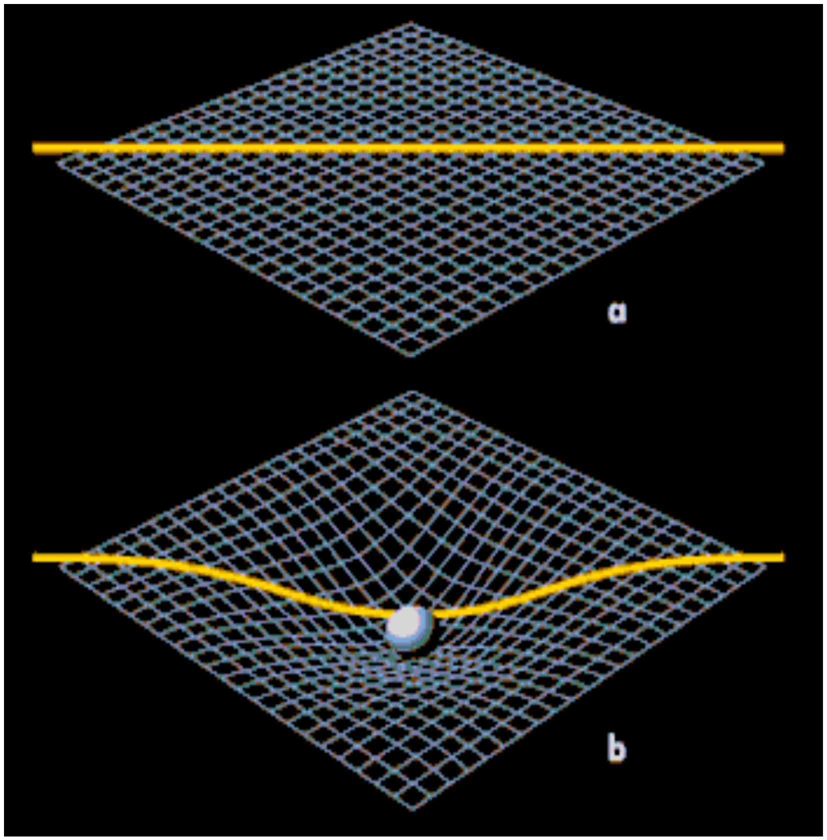
Einstein in fact showed that it is impossible to tell the difference between acceleration and the force of gravity. He called this the Equivalence principle.





Einstein realised that gravity, motion, space and time were all interconne

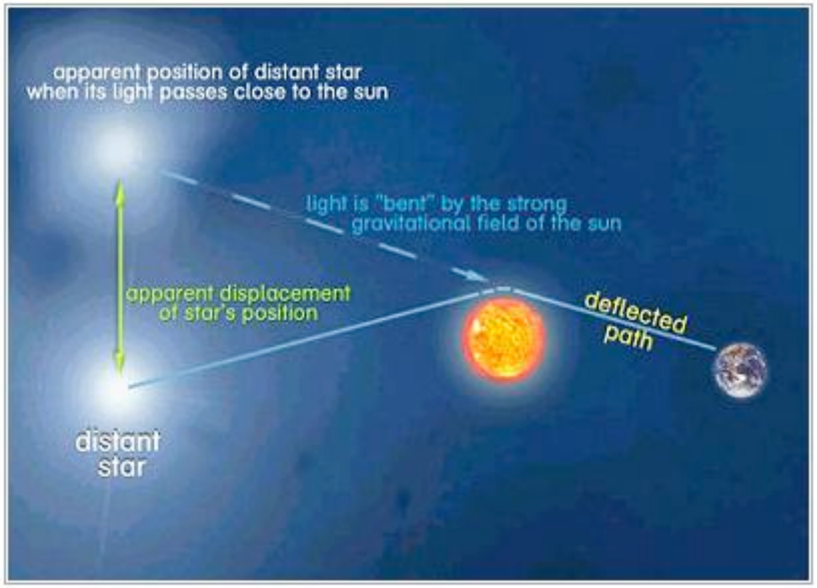
Mass tells space-time how to curve, and the curvature tells mass how to move and accelerate.



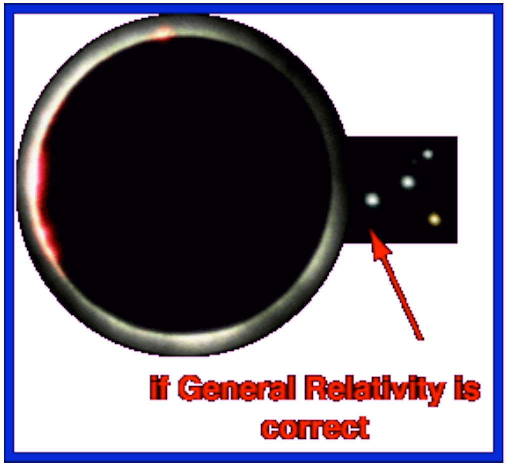
According to relativity, all masses cause curvature, larger masses having a larger effect than small masses. We feel the effect of gravity because we are in the space-time "dip" caused by the Earth's mass.

The 3 Tests of General Relativity

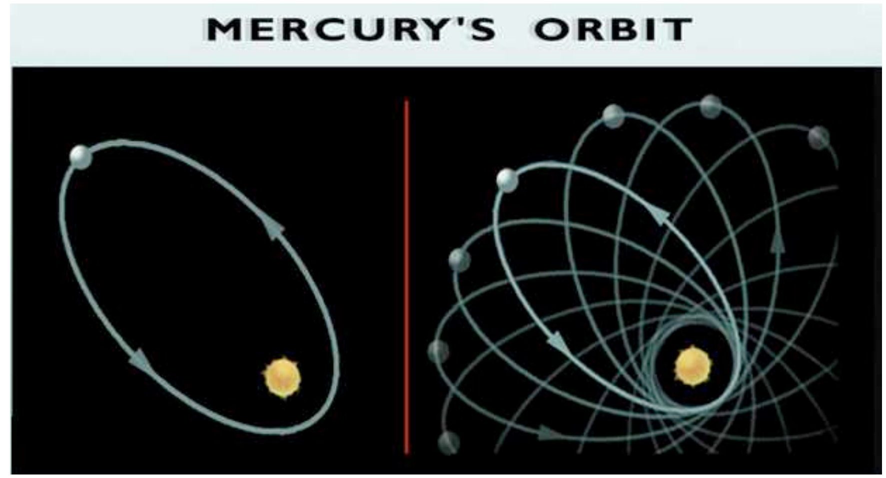
1) Bending of starlight. This was first tested in 1919 by a British expedition to Africa to see a solar eclipse. Einstein predicted that the position of background stars observed during the eclipse should shift. This is an example of gravitational lensing.



If the theory is correct, stars that actually lie behind the sun, will have their light paths bent and actually appear to the side of the sun.



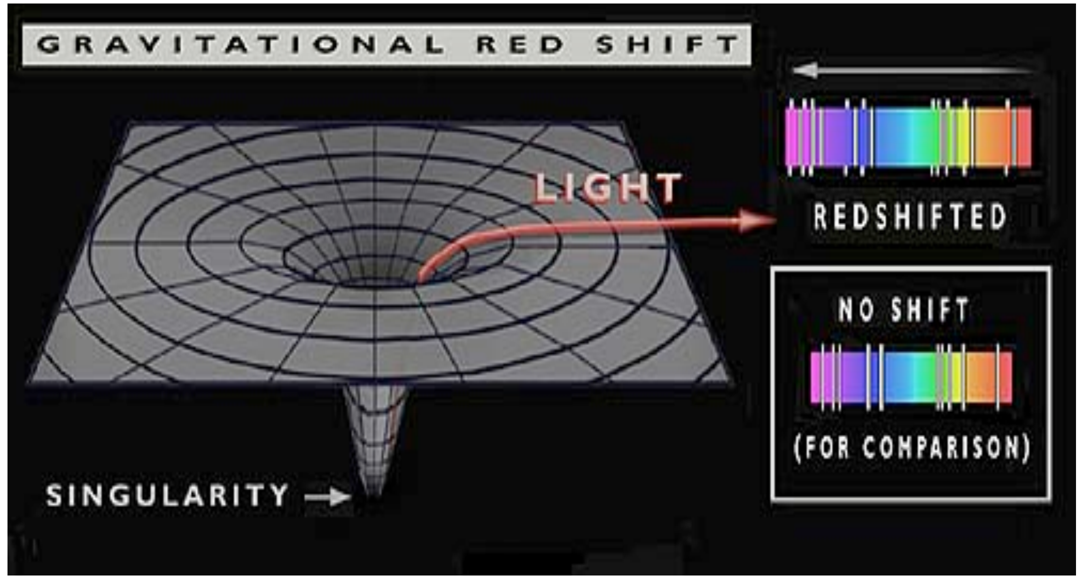
2) The precession of the perihelion of Mercury. That is, the drifting of Mercury's closest approach to the sun.



The observed drift is about 5600 seconds of arc per century. This precession is mostly due to the combined gravitational forces of the planets, but the predicted size of the drift is only 5557 seconds of arc.

Einstein showed that this discrepancy is because the sun curves space-time and that Mercury moves around in this dip, which also contributes towards its precession

3) Gravitational redshift. Do not confuse this with Doppler redshift!! Doppler shifts are associated with velocities causing red or blue shifts. Gravity can have the same effect. If a photon has to climb out of a dip in space-time caused by a large mass, it loses energy in doing so, and looks redder. This is often called "tired light". Similarly, light falling into a dip increases in energy and is blue shifted.



Such gravitational redshifts have been observed for the sun (where the effect is very small) and also for much more compact objects like white dwarfs and neutron stars.

Vacations near a Black Hole

The large gravitational fields associated with black holes mean that relativistic physics dominates over Newton's laws.

For example, if we were to cross the event horizon of a black hole and start to fall towards its centre, we would travel slowly at first and then speed up as the gravity got stronger towards the centre. Observers on Earth would see our approach slow down, due to time dilation. In fact, they would never see us reach the centre, things just appear in slower and slower motion. This is an effect of time dilation.

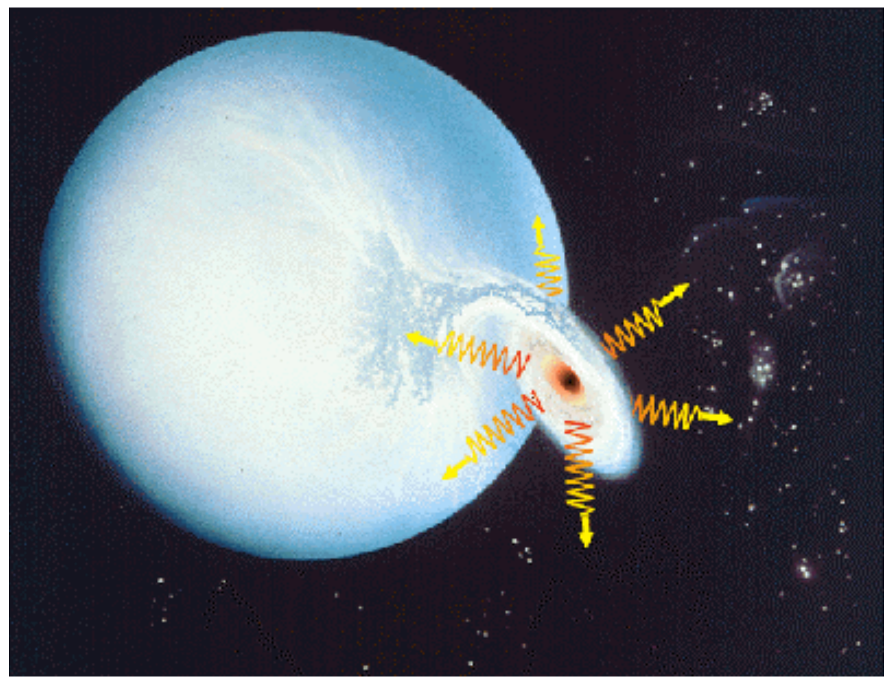
Anyone falling into a black hole would also get spaghettified, because the gravity pulling on their feet would be stronger than the force on their heads. This is a kind of tidal force. These forces would induce heating and raise our body temperatures to millions of degrees, causing us to emit X-rays.

Finding a Black Hole

If black holes don't emit any light, how can we detect them? Recall how we observe white dwarfs in binaries? These are very faint but contain very dense matter so they have strong effects on any orbiting companion. We can infer the presence of a black hole if a star seems to have a "dark companion".

If such a dark companion was calculated to have more than about 3 solar masses, it would probably be a black hole.

Also, although nothing can escape from within the event horizon, matter that gets heated and emits X-rays before this transition can be detected.

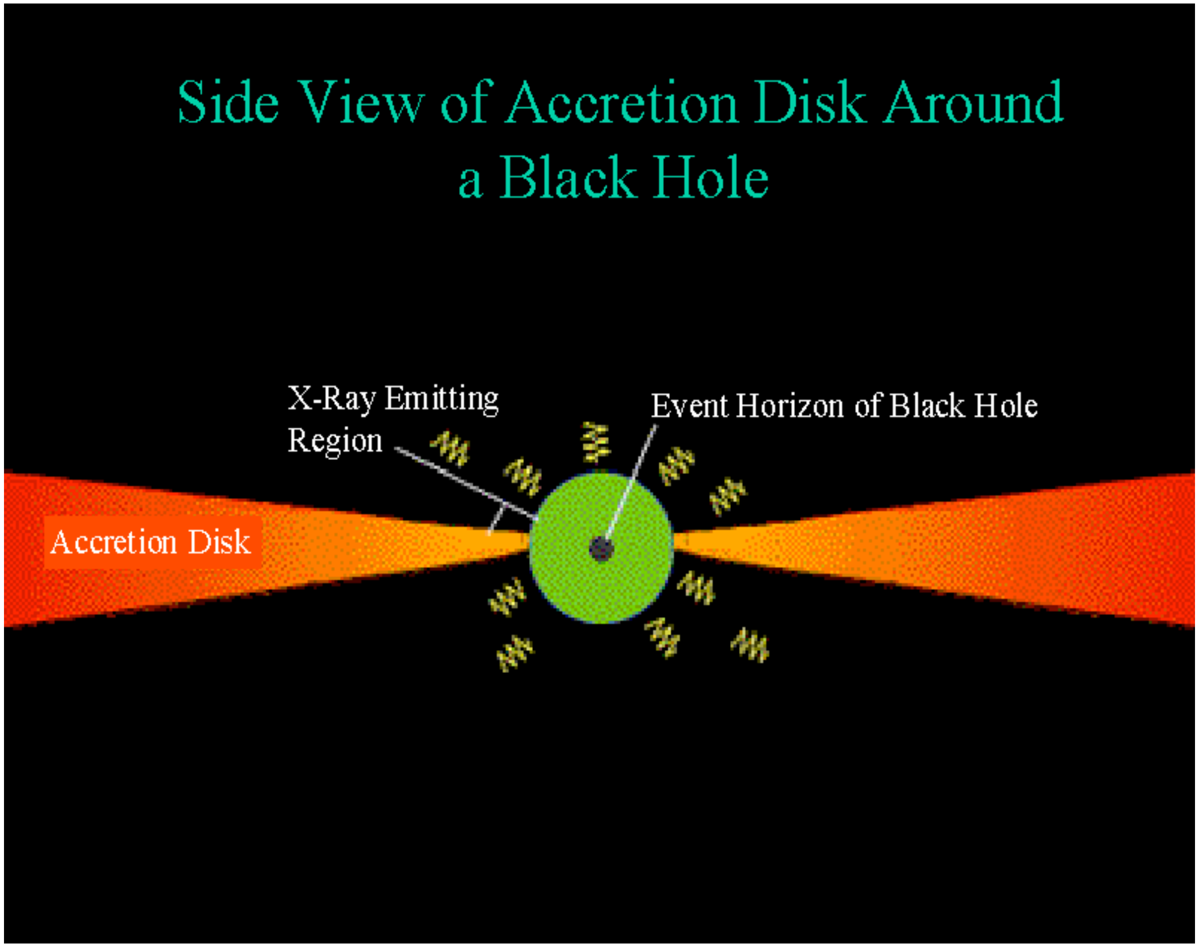


The most famous example is Cygnus X1, an Xray source with a mass of 10-15 solar masses orbiting an O star.

Xrays are only seen if there is material present to fall onto the black hole. So most Xray sources are in binary systems. The Xrays are not constant.

Material forms into a disk around the black hole, and it is as material falls onto to disk that Xrays are given off. If the infall stops, Xrays diminish.

The mass of the black hole can be determined either from the relative orbits of the BH and star, or from the gravitational redshift of starlight.

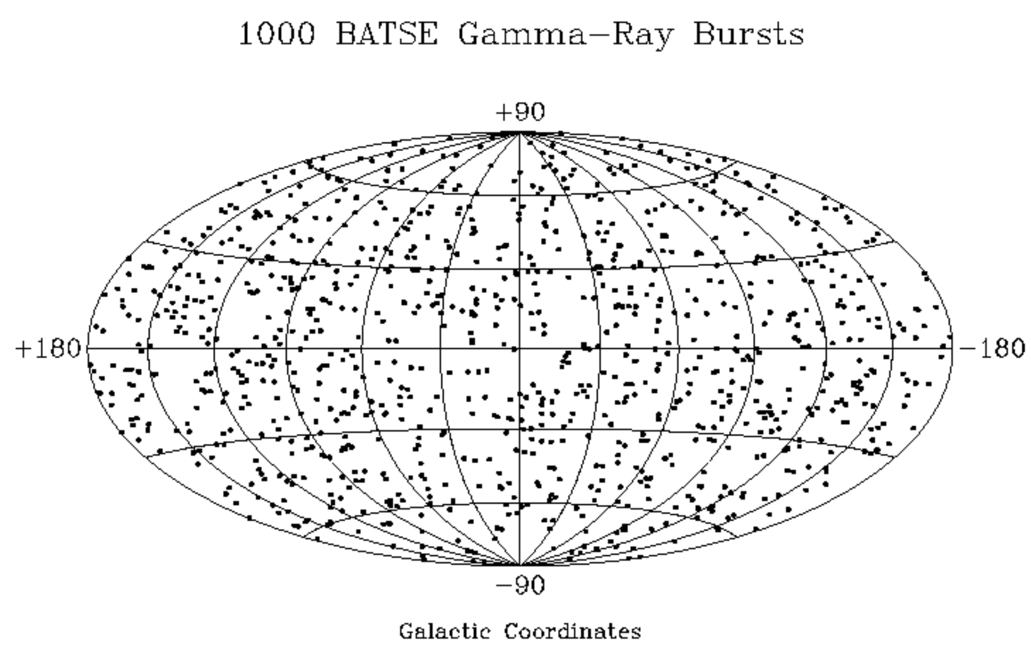


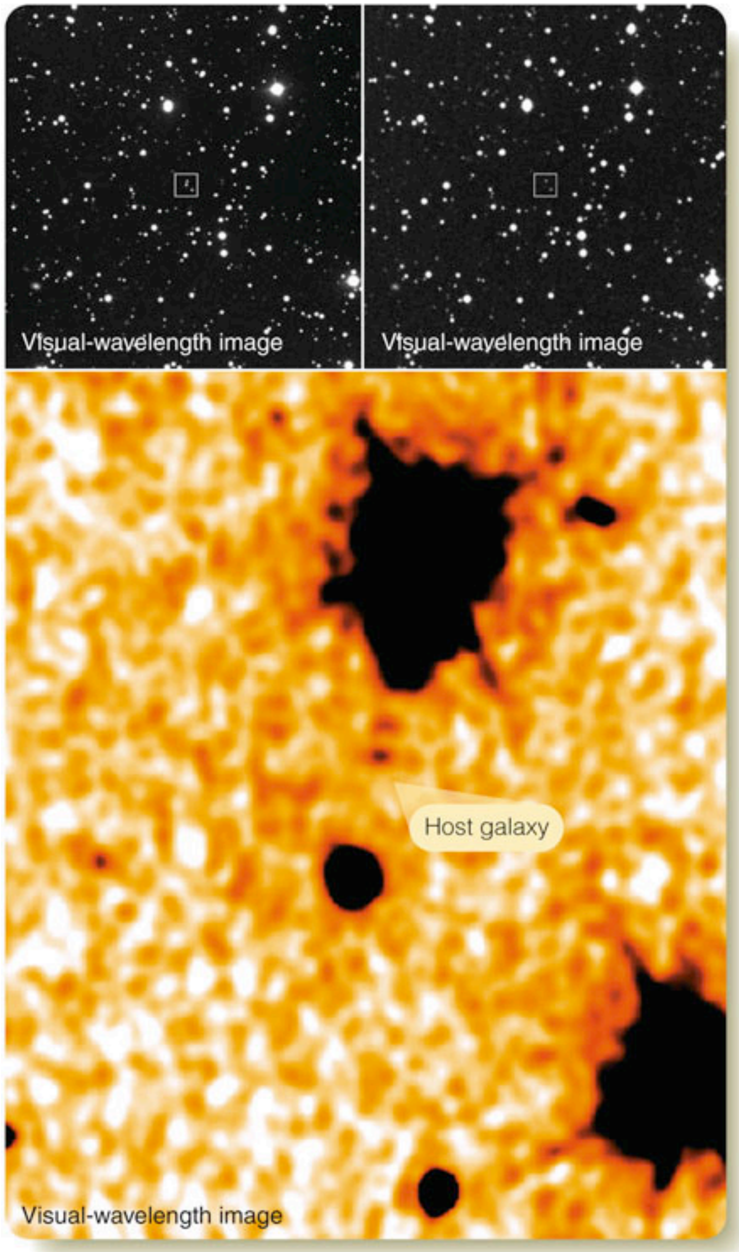
As material falls into the black hole, its mass increases, so the Schwarzschild radius will get larger.

Gamma Ray Bursts

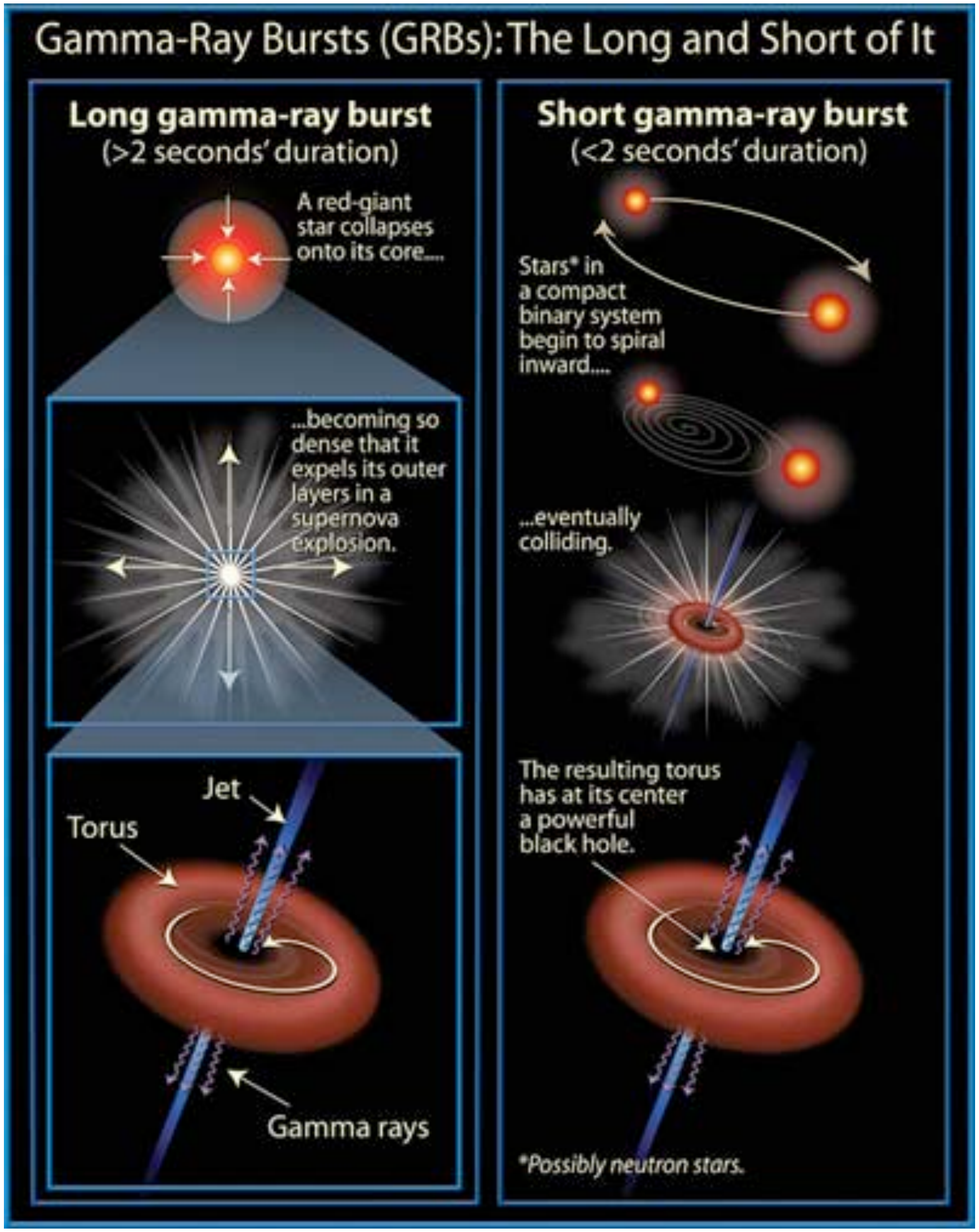
When the first military satellites went up into space in the 1960s to watch for nuclear testing. It was a big surprise when they found high energy gamma-ray bursts coming from outer space!

It was first thought that these bursts were coming from within the Milky Way, but as more were observed, it was found that they were evenly distributed across the sky, so probably extra-galactic.



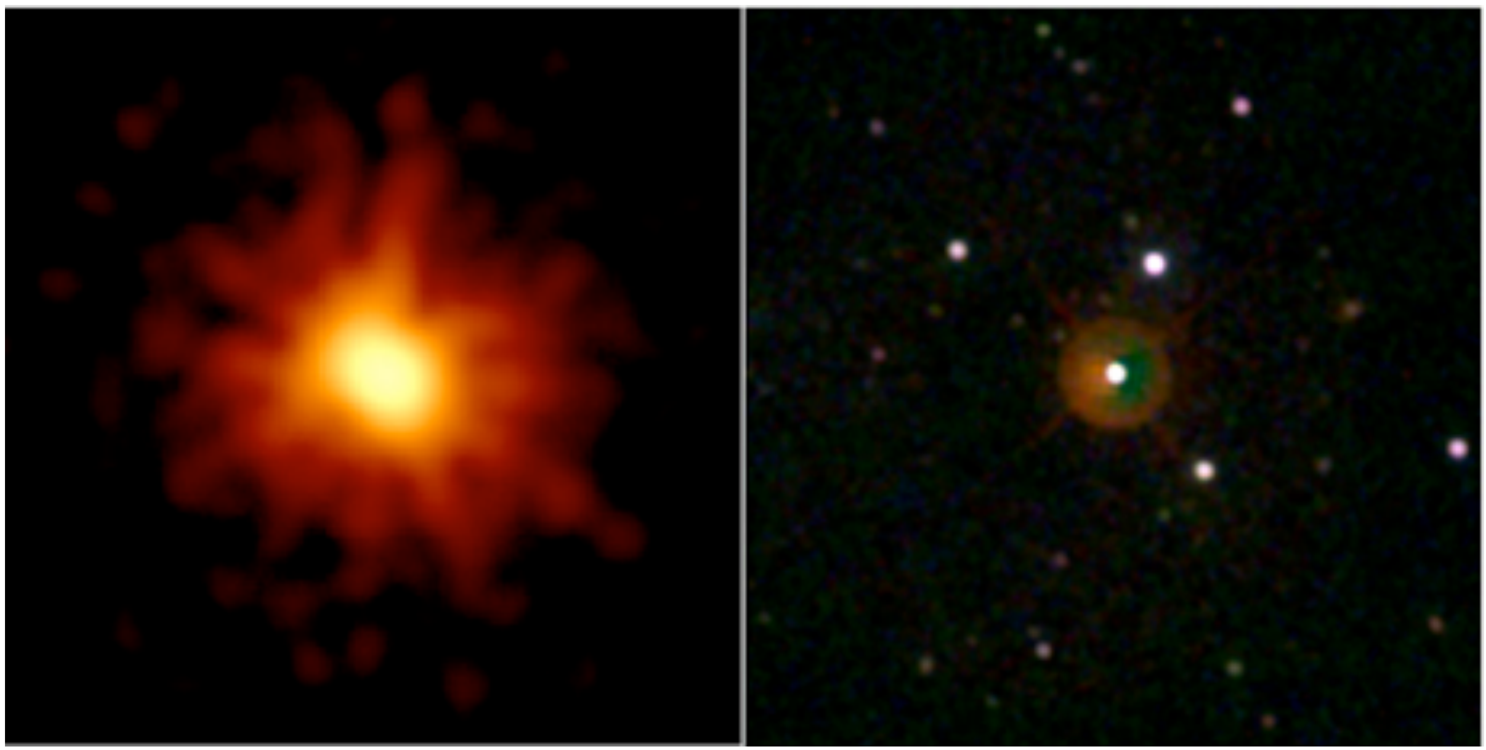


Gamma ray bursts (GRBs) are the most energetic phenomenon in the universe, supernovae are just firecrackers in comparison. These can be naked eye objects (but for less than a second) even though they are some of the most distant objects in the universe. The most powerful can be the equivalent to 10 million, billion suns, but they fade quickly.



The fact that GRBs fade so quickly makes them difficult to study, but astronomers have now figured out that they are probably associated with very massive supernovae, or hypernovae. However, the rare "short bursts" maybe due to merging neutron stars.

In 2008, astronomers discovered a GRB so bright it could be seen with the naked eye, even though it was 750 million light years away (half way across the universe!). The next most distant object we can see with the naked eye is the Andromeda galaxy, but that is 1000 times closer (and it's a whole galaxy!).



X-ray (left) and optical (right) image of the naked-eye GRB