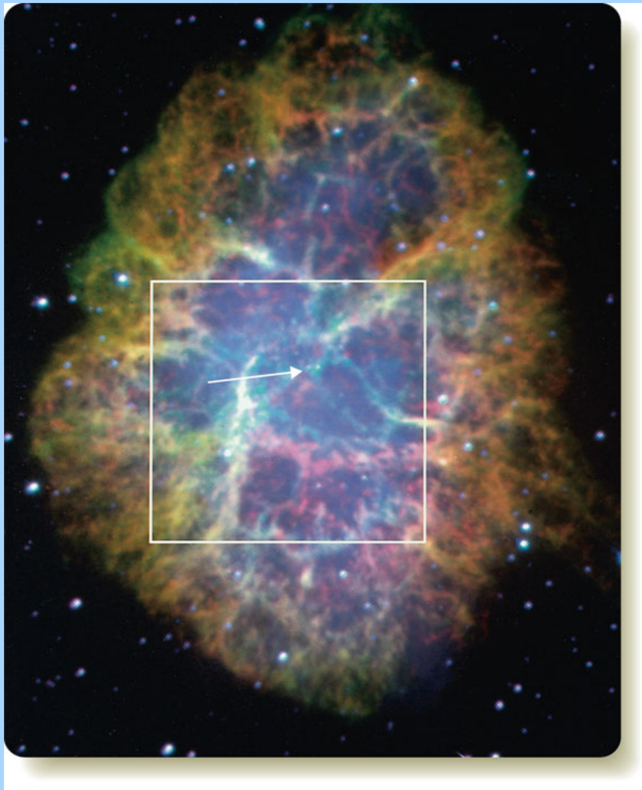
Neutron Stars and Black Holes



In the center of the Crab Nebula there is a neutron star that pulses every 33 millisec.

If the Sun should suddenly collapse to become a black hole, what would happen to the orbit of the Earth?

a. the Earth would get sucked into the black hole
b. the shape of the Earth's orbit would suddenly become much more eccentric
c. the Earth's orbit would become perfectly circular
d. the Earth would happily keep orbiting the Sun, just as it does now.

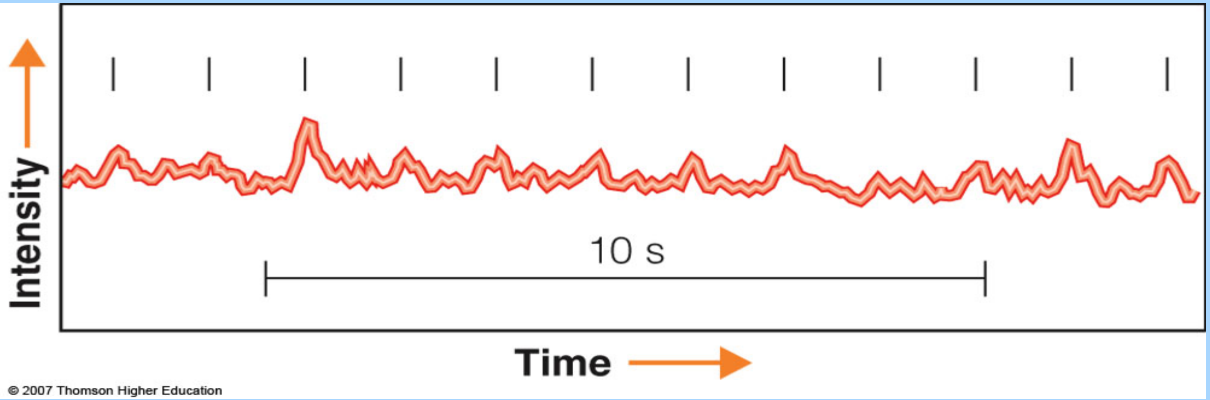
Say a 10 solar mass star blows up at the end of its supergiant phase. It leaves behind a dense remnant having a mass of 2.0 solar masses. This remnant is

a. a black hole
b. a neutron star
c. a white dwarf star

J. Bell Burnell

A. Hewish

Pulsars were discovered serendipitously in 1967 when Jocelyn Bell found unexplained "noise" in radio signals from a particular place in the sky. Her thesis advisor eventually won a Nobel Prize for the explanation.



But first, let us consider how small a compact object might be. In chapter 4 we find an expression for the escape speed (V_{esc}) from an object of mass M:

$$(V_{esc})^2 = 2\,G\,M\,/\,r$$

A very small object can have a very large escape speed. The maximum possible value of the escape speed would be the fastest speed anything can travel, namely the speed of light. In other words, what if

$$c^2 = 2\,G\,M\,/\,r \qquad ?$$

Rearranging the previous equation, we have

$$r = 2\,G\,M\,/\,c^2$$

With $G = 6.67 \times 10^{-11}$ in MKS units,
$M_{sun} = 2.0 \times 10^{30}$ kg, and
$c = 3.0 \times 10^{8}$ m/sec, it follows that
$r = 3.0$ km.

This would be the radius of a black hole of one solar mass. If the Earth were squeezed to a radius of 0.9 cm, it would have an escape speed equal to the speed of light and would be a black hole.

The radius of a black hole scales linearly with the mass.

Since a 1 solar mass black hole has a radius of 3 km

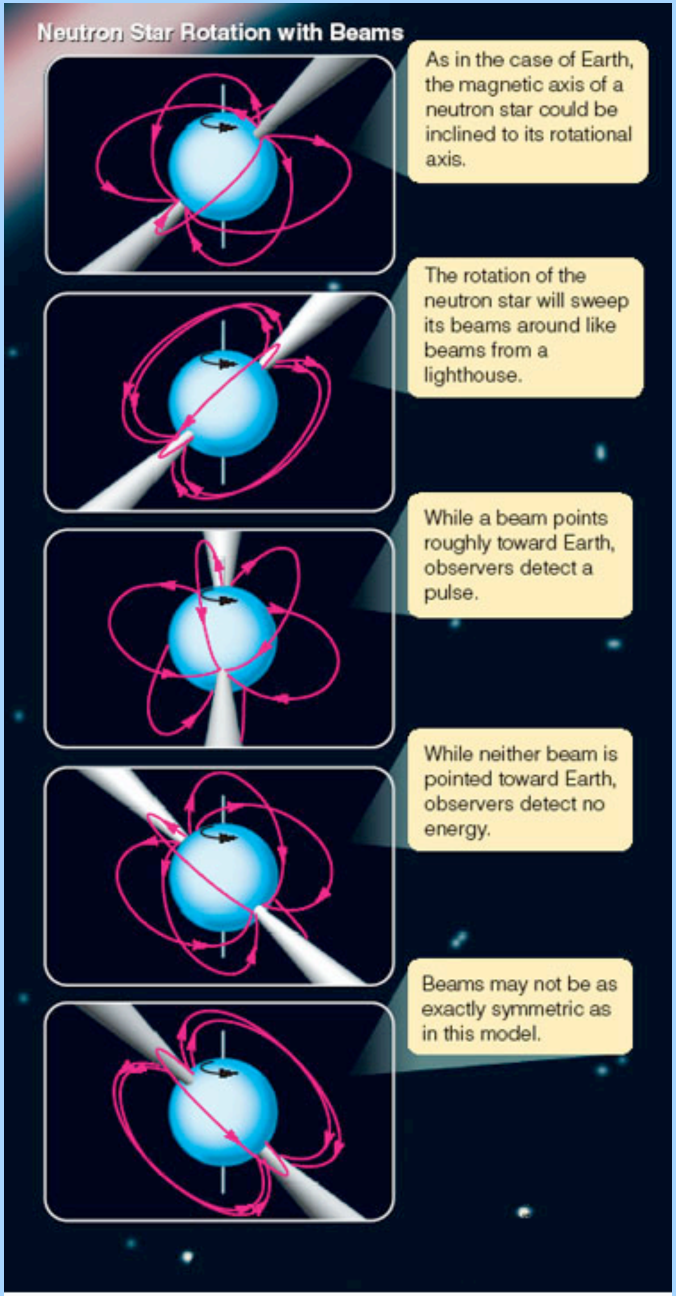
a 2 solar mass black hole has a radius of 2 X 3 = 6 km

a 10 solar mass black hole has a radius of 10 X 3 = 30 km

a 3 million solar mass black hole has a radius of 3 million X 3 = 9 million km, or about 13 times the size of our Sun. (There is strong evidence that the center of our Galaxy contains a 3 million solar mass black hole.)

OK, back to pulsars. A pulsar is a remnant of the explosion of a star more massive than 8 solar masses. Recall that a Type II supernova is the explosion of a single, massive star. Type Ib and Ic supernovae are also explosions of single, massive stars, but stars which have lost their outer envelopes of hydrogen or hydrogen and helium.

A pulsar does not pulse like a Cepheid variable star. Rather, it beams out its energy in two opposite directions, and if one of these beams intersects the Earth, we see a pulse of radiation.



Neutron Star Rotation with Beams

As in the case of Earth, the magnetic axis of a neutron star could be inclined to its rotational axis.

The rotation of the neutron star will sweep its beams around like beams from a lighthouse.

While a beam points roughly toward Earth, observers detect a pulse.

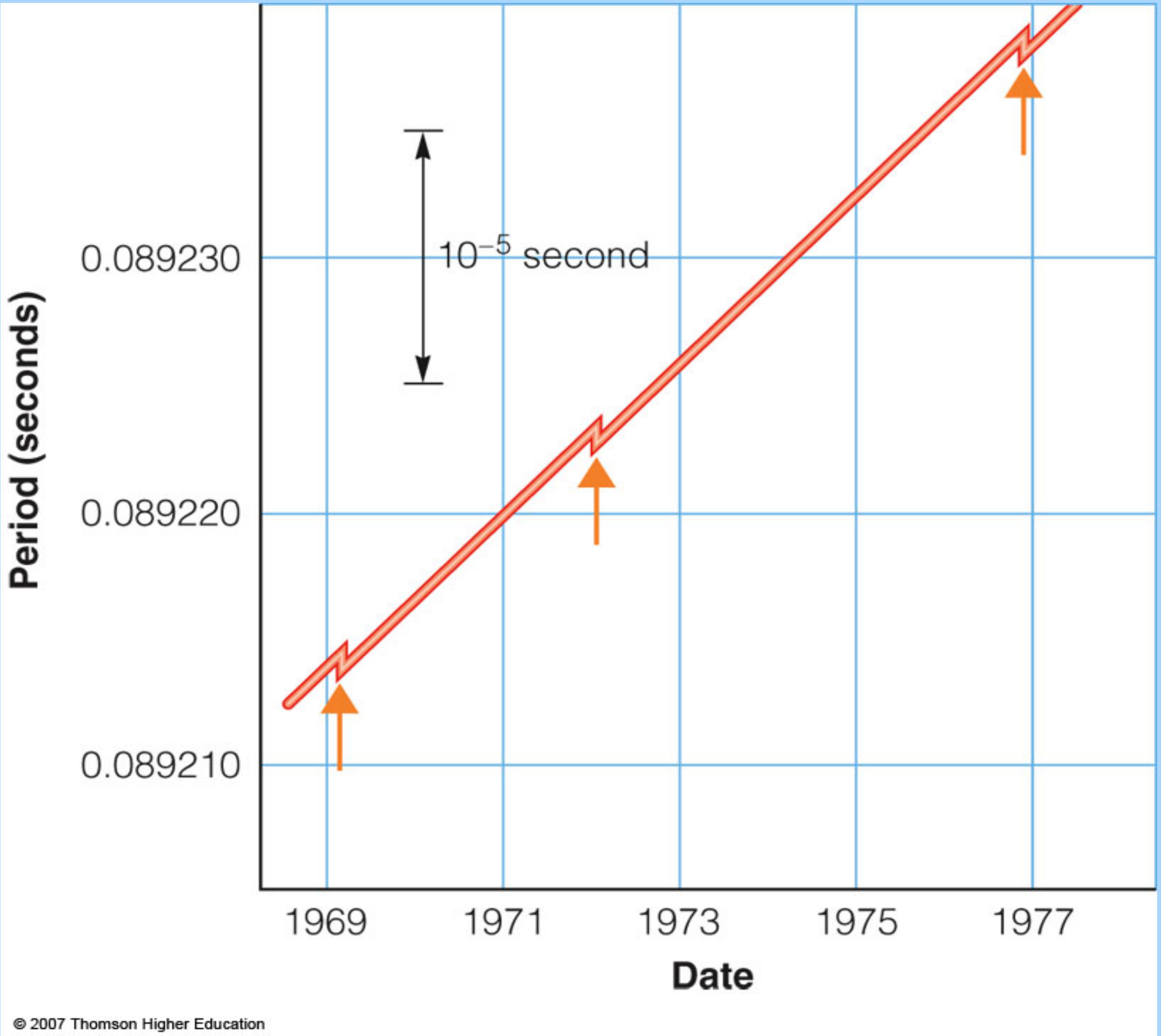
While neither beam is pointed toward Earth, observers detect no energy.

Beams may not be as exactly symmetric as in this model.

If the beam of radiation does NOT intersect the Earth, then we would see almost nothing. Though neutron stars are very hot, so give off a lot of radiation per square meter, they are very small, so have very little surface area, and hence not much luminosity. The jets are actually brighter.

The time in between pulses of a pulsar can be determined with incredible accuracy. They slow down as time goes on, but occasionally they experience a glitch and speed up every so slightly before resuming the process of slowing down.

There are two theories that attempt to explain these glitches: 1) “starquakes” on the surface of the neutron star; and 2) vortices in the frictionless interior of the neutron star transferring angular momentum to the crust. Both of these theories might be right.



Glitches in the spin down of the Vela pulsar.

A typical pulsar

radius ~ 10 km

mass ~ 1.4 to 3.0 solar masses

temperature ~ 1 million degrees K
(so it gives off X-rays, with
λ_{max} ~ 3 nm)

Let's compare the *total* luminosity of a neutron star with that of the Sun.

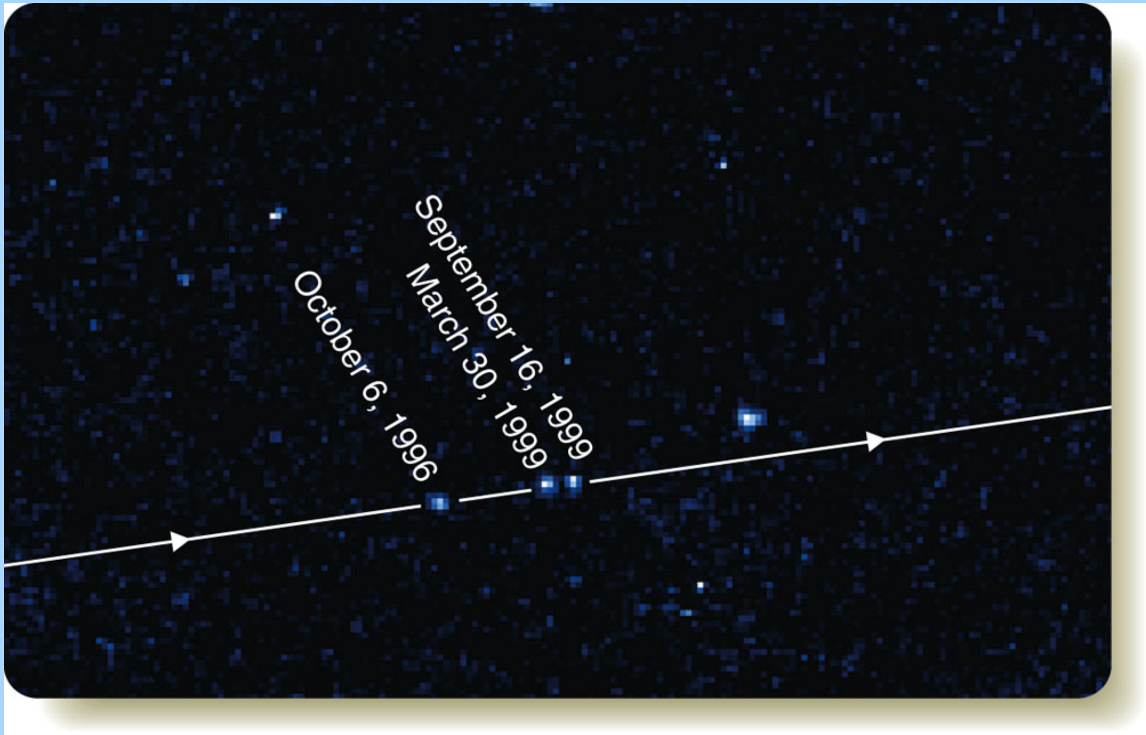
$$L_{NS} = 4\,\pi\,(R_{NS})^2\,\sigma\,(T_{NS})^4$$

$$L_{sun} = 4\,\pi\,(R_{sun})^2\,\sigma\,(T_{sun})^4$$

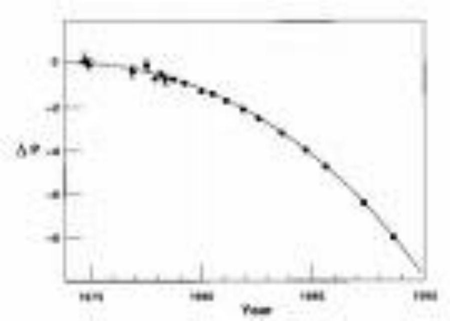
So $(L_{NS} / L_{sun}) = (R_{NS} / R_{sun})^2\,(T_{NS} / T_{sun})^4$

With R_{NS} = 10 km, R_{sun} = 6.96 X 10^5 km, T_{NS} = one million degrees K, and T_{sun} = 5800 K, the total luminosity of the neutron star is 18 percent that of the Sun. But most of that light is X-ray light. In the optical, neutron stars might be 21st magnitude or fainter.

The energy of the supernova explosion that gives rise to a neutron star/pulsar might be slightly asymmetric. As a result it can impart a velocity of a couple hundred km/sec to the neutron star.

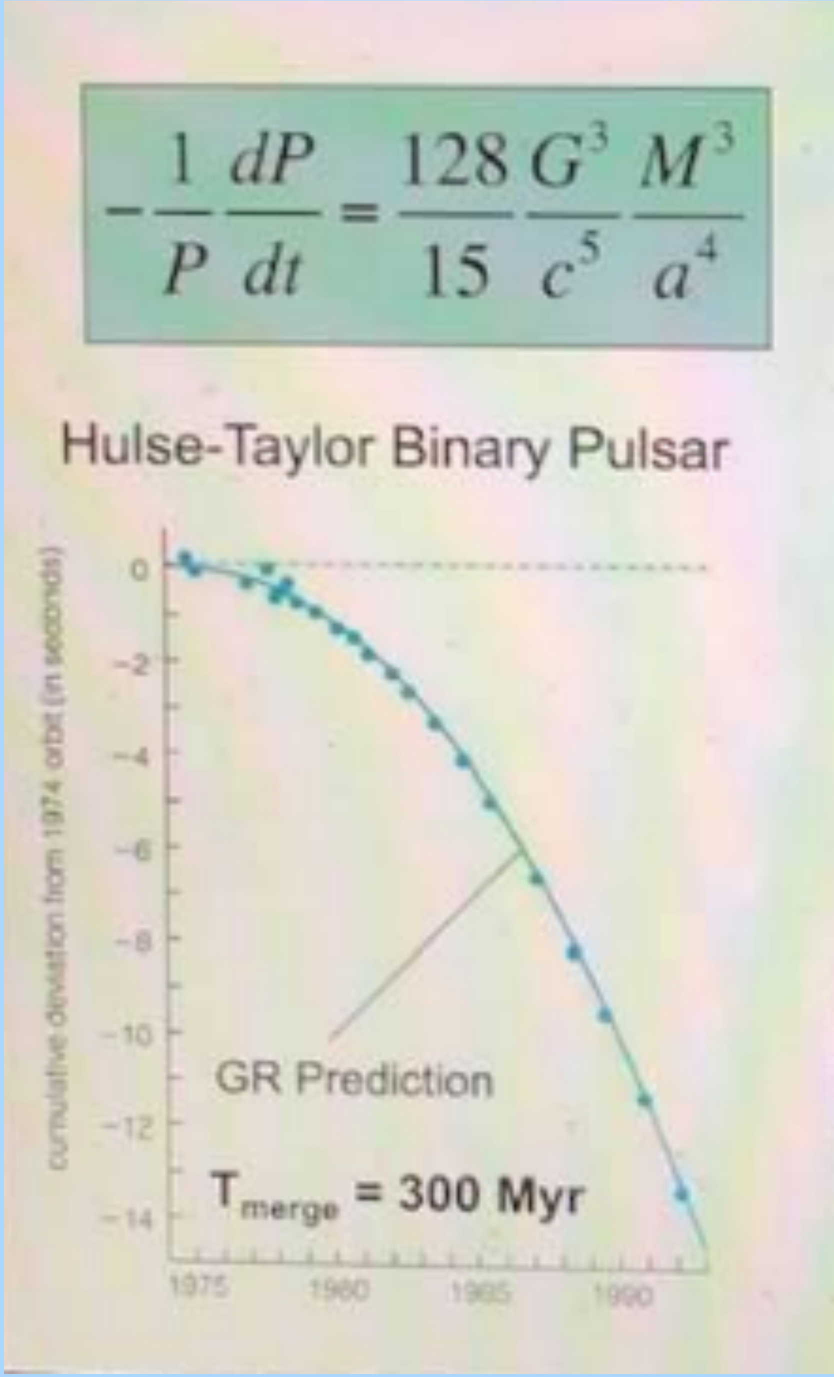


PSR 1913+16 is a pair of pulsars that orbit each other with a period of 7.75 hours. Joseph Taylor and Russell Hulse were able to show that the orbital period of this binary pair was getting shorter. This is because the system is radiating **gravitational waves**. For this work Hulse and Taylor were awarded the 1993 Nobel Prize in physics.




Taylor


Hulse



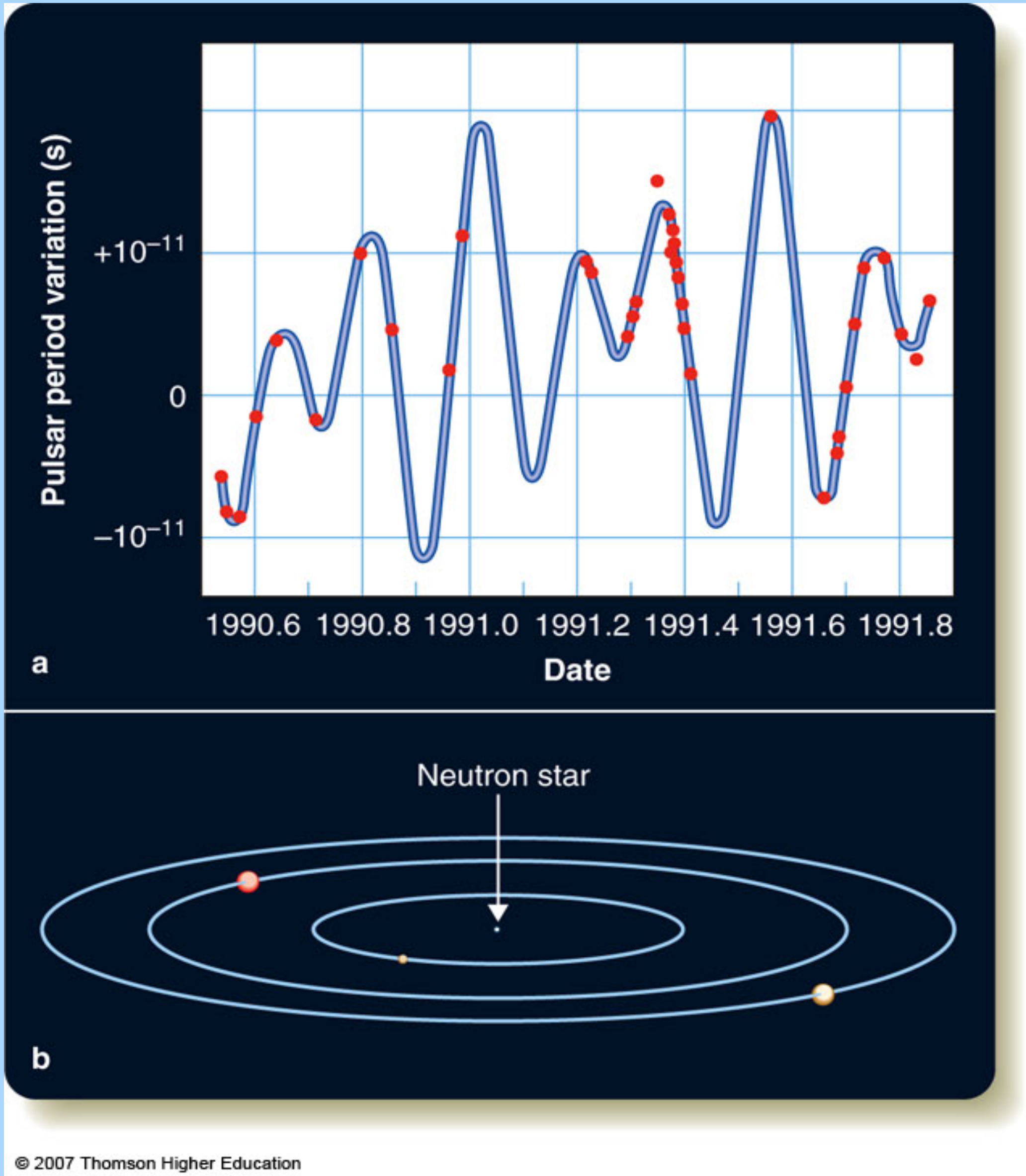
$$-\frac{1}{P}\frac{dP}{dt}=\frac{128}{15}\frac{G^3}{c^5}\frac{M^3}{a^4}$$

Hulse-Taylor Binary Pulsar

Y-axis label = cumulative deviation from 1974 orbit (in seconds)

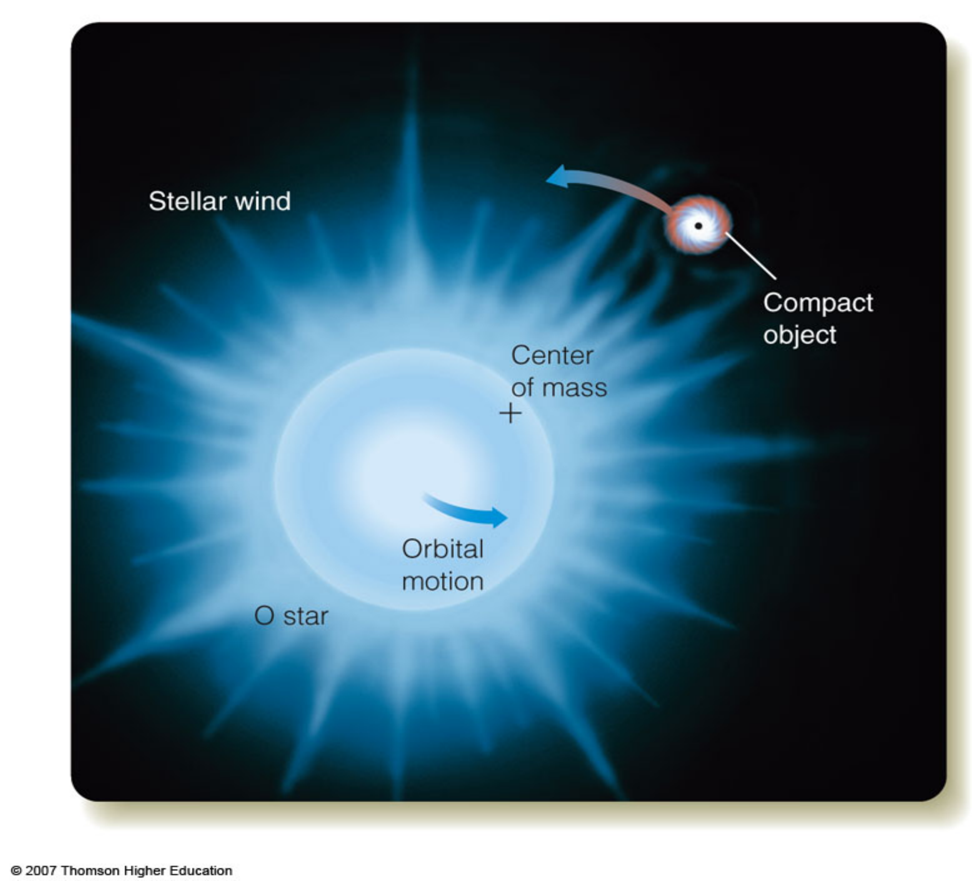
X-axis label = year, from 1974 to 1993

When the two neutron stars eventually come together, they can cause another supernova explosion!



The pulsar PSR 1257+12 is known to have three planets. Two of the planets have masses of 4.3 and 3.9 Earth masses. They were discovered from variations in the pulsar's period. These planets did not survive the SN explosion. They are remains of a stellar companion destroyed by the SN.

Black Holes



Cygnus X-1 is a binary consisting of a supergiant B0 star and a compact object. Wind from the B0 star flows into the hot accretion disk of the compact object, giving rise to X-rays.

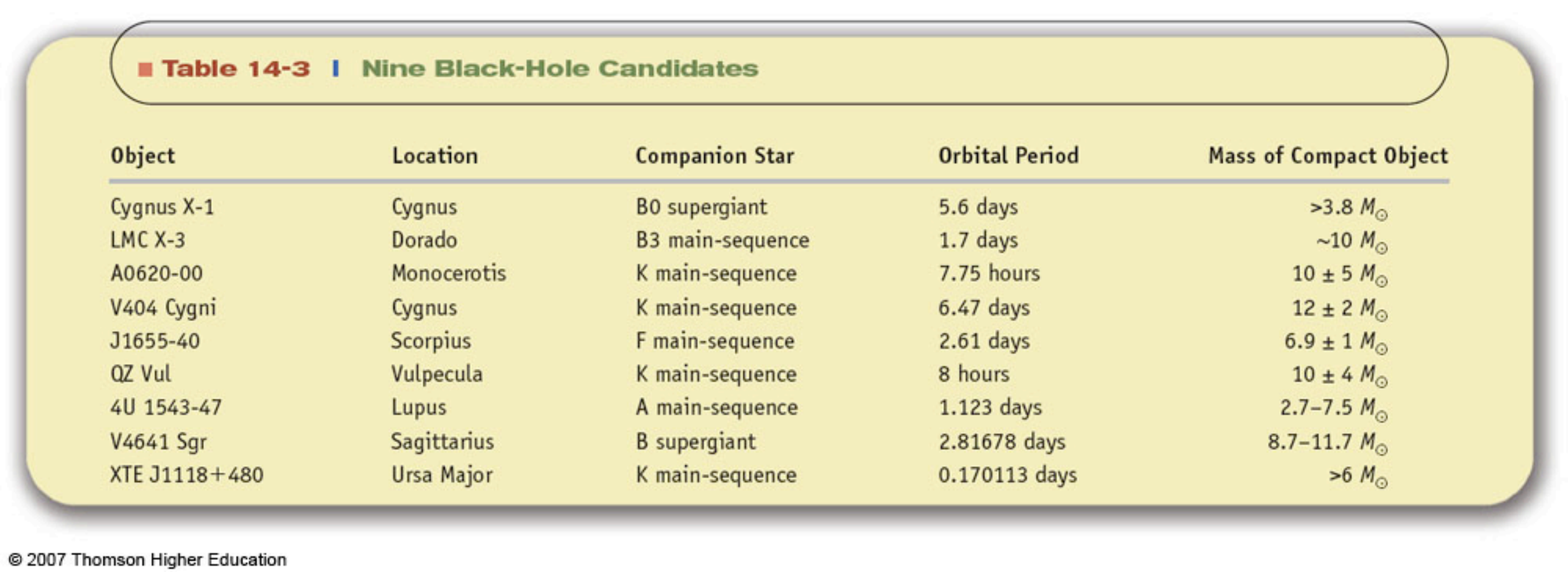
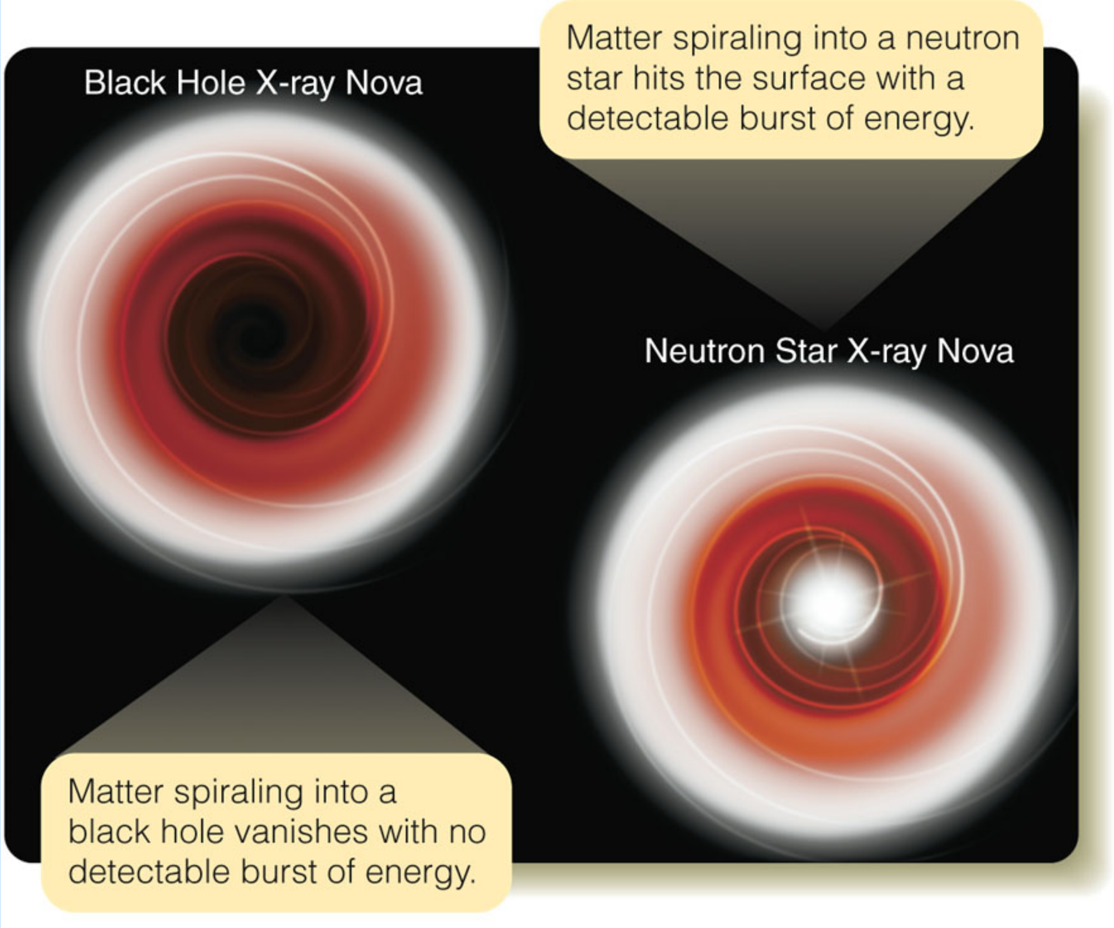


Table 14-3 | Nine Black-Hole Candidates

Object	Location	Companion Star	Orbital Period	Mass of Compact Object
Cygnus X-1	Cygnus	B0 supergiant	5.6 days	$>3.8\ M_\odot$
LMC X-3	Dorado	B3 main-sequence	1.7 days	$\sim 10\ M_\odot$
A0620-00	Monocerotis	K main-sequence	7.75 hours	$10 \pm 5\ M_\odot$
V404 Cygni	Cygnus	K main-sequence	6.47 days	$12 \pm 2\ M_\odot$
J1655-40	Scorpius	F main-sequence	2.61 days	$6.9 \pm 1\ M_\odot$
QZ Vul	Vulpecula	K main-sequence	8 hours	$10 \pm 4\ M_\odot$
4U 1543-47	Lupus	A main-sequence	1.123 days	$2.7–7.5\ M_\odot$
V4641 Sgr	Sagittarius	B supergiant	2.81678 days	$8.7–11.7\ M_\odot$
XTE J1118+480	Ursa Major	K main-sequence	0.170113 days	$>6\ M_\odot$

If the remnant of a Type II, Ib, or Ic supernova has a mass greater than 3 solar masses, it is a black hole, not a neutron star.



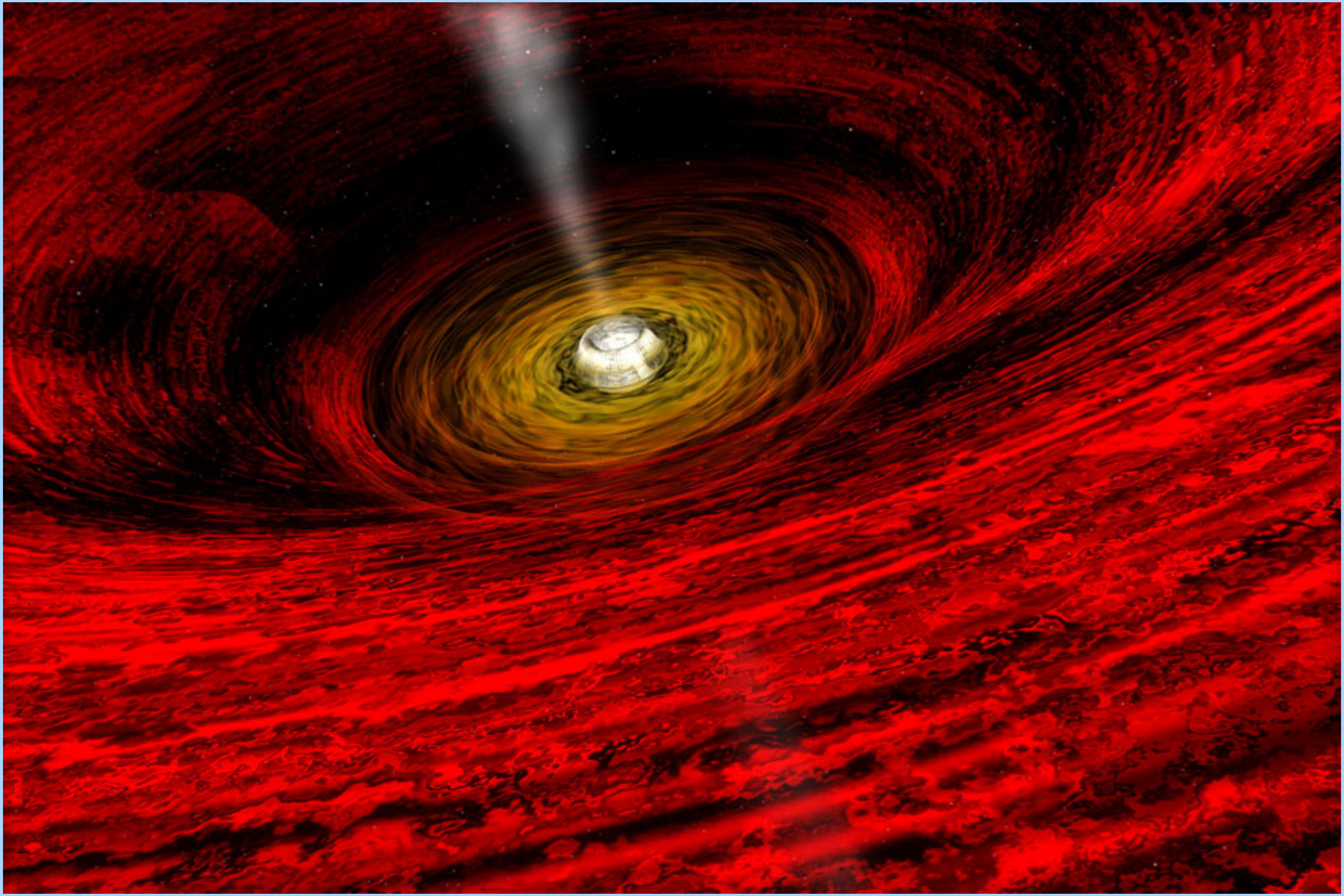
Black Hole X-ray Nova

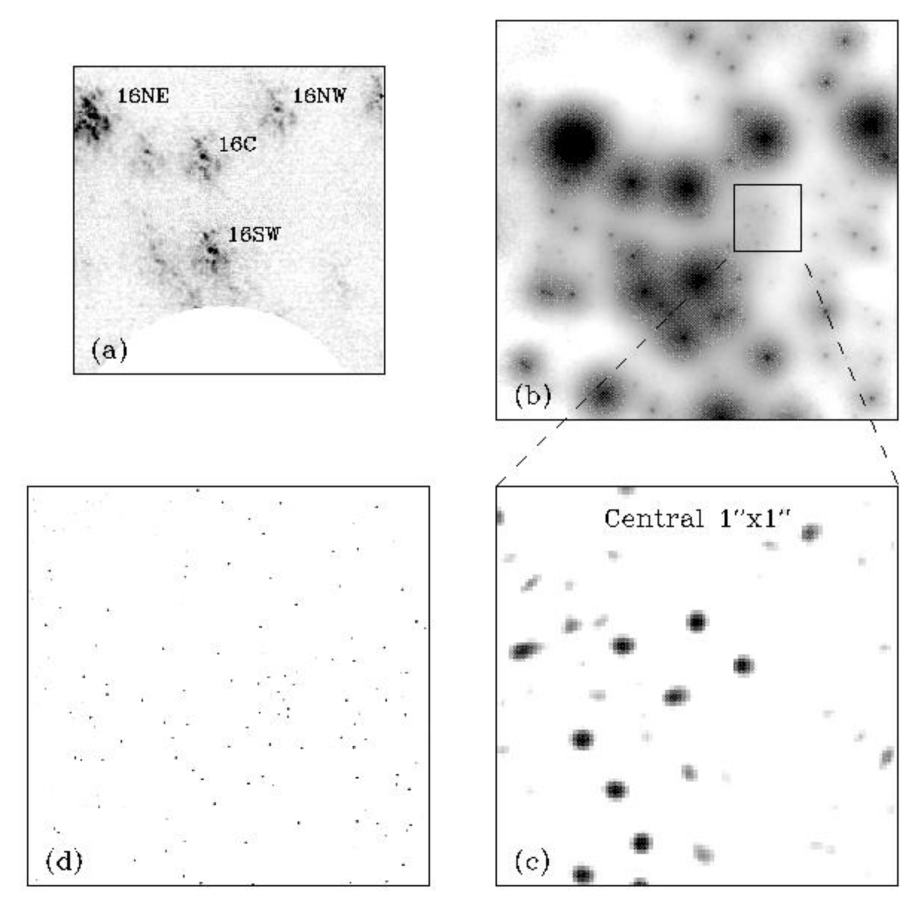
Matter spiraling into a black hole vanishes with no detectable burst of energy.

Neutron Star X-ray Nova

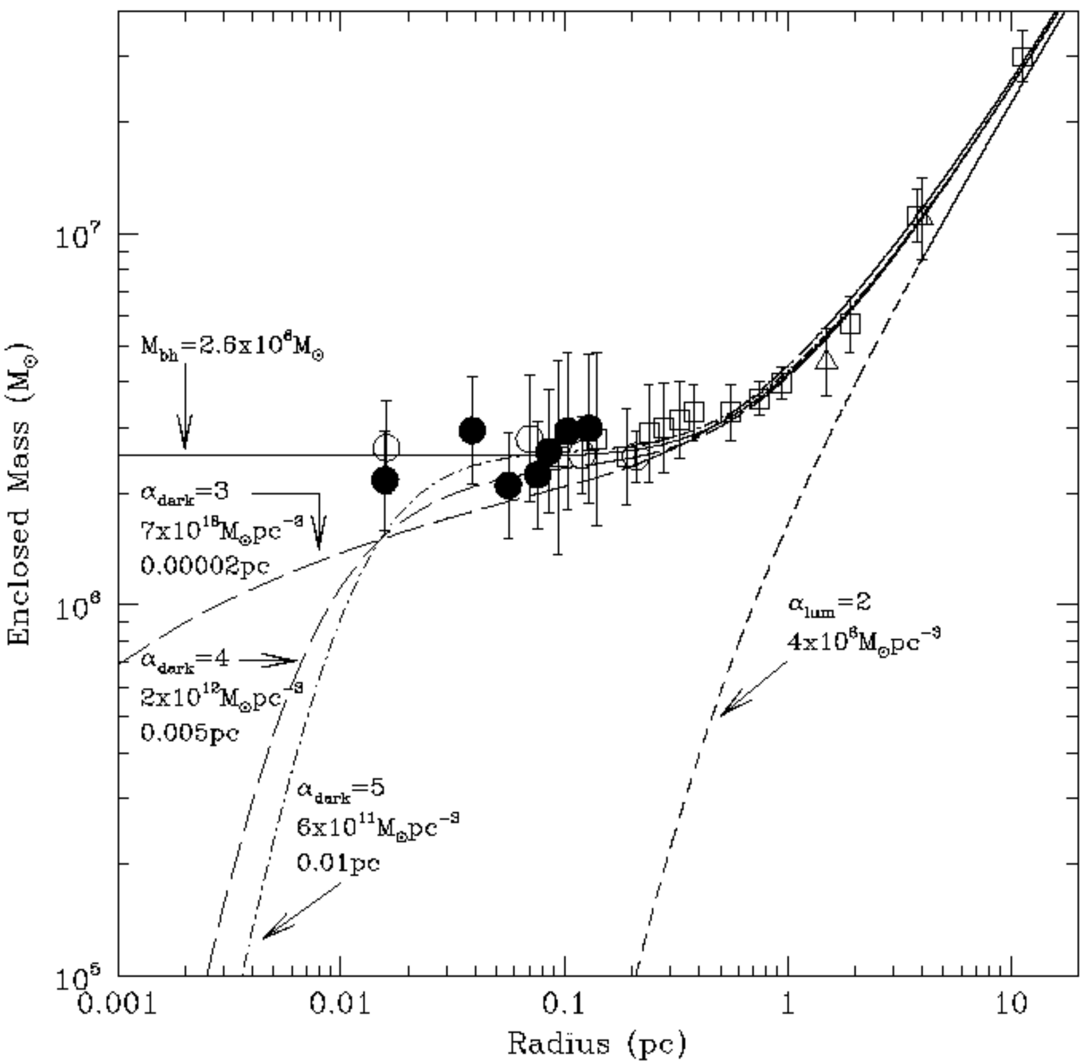
Matter spiraling into a neutron star hits the surface with a detectable burst of energy.

How can we tell the difference between a neutron star and a BH acquiring mass from a companion? The neutron star exhibits bursts of X-rays. Matter that falls into the BH from the accretion disk just disappears.





The central 2 pc of our Galaxy contains a rotating ring of material around a central engine. There is also a very concentrated star cluster. In the very center is a compact object which causes the stars moving nearby to acquire velocities as high as 1400 km/sec

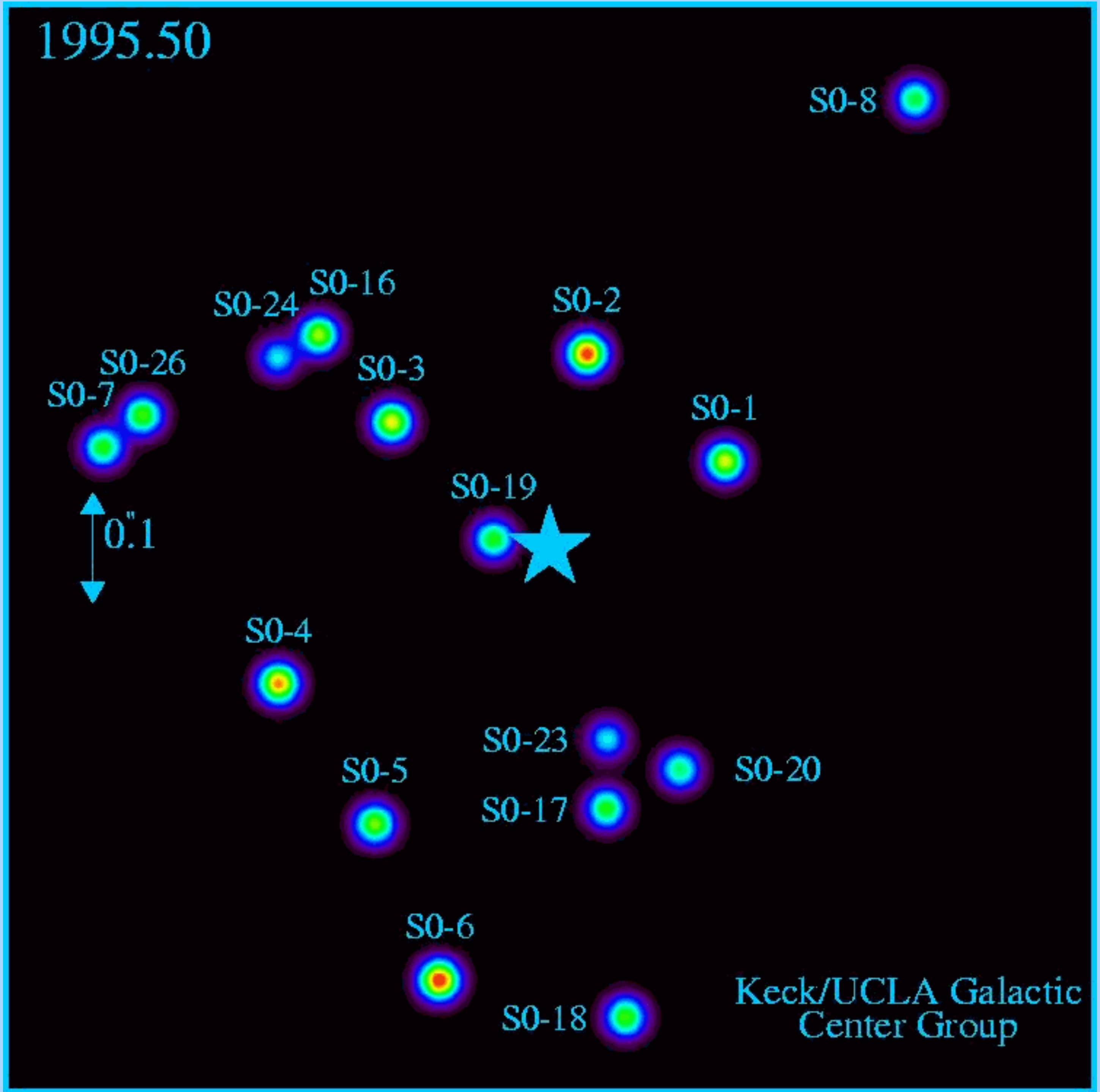


The mass of the
central black hole
is between 2.6 and
3.7 million solar
masses.

Some other galaxies
have black holes
of more than one
billion solar masses
in their cores!

The following little movie shows the paths and orbits of some stars near the black hole in the center of our Galaxy.

Courtesy Andrea Ghez, UCLA



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Keck/UCLA Galactic
Center Group

The density within black holes

The mass of the proton is 1.67 X 10^{-24} g, and its radius is about 0.877 X 10^{-13} cm (according to Wikipedia).
The volume of the proton is $4/3\ \pi\ r^3 = 2.82 \times 10^{-39}$ cm^3.
The density = mass/volume = 5.9 X 10^{14} g/cm^3.

The Sun's mass is 2 X 10^{30} kg = 2 X 10^{33} g. A one solar mass black hole has radius r ~ 3 km = 3 X 10^5 cm. The average density within the Schwarzschild radius is then 1.8 X 10^{16} g/cm^3. This is 31 times the density of the proton. So – stellar mass black holes are really dense!

Since the Schwarzschild radius of a black hole is $r_{Sch} = 2\ GM / c^2$, the radius of a black hole is proportional to its mass. A one billion solar mass black hole will have a radius of 3×10^9 km. Since one Astronomical Unit ~ 1.5×10^8 km, it follows that a one billion solar mass black hole has a radius of about 20 AU, or the size of the orbit of Uranus.

Since the radius of a black hole is proportional to its mass, and the volume of a sphere is proportional to the cube of the radius, it follows that the average density within the Schwarzschild radius is proportional to $1/\text{mass}^2$.

Thus, the mean density of a one billion solar mass black hole is $(1/10^9)^2$ lower than a one solar mass black hole, or $(1.8 \times 10^{16}) / 10^{18} \sim 0.018$ g/cm^3.

A one billion solar mass black hole has a density at least as small as 2 percent that of water!

So – supermassive black holes are NOT superdense!

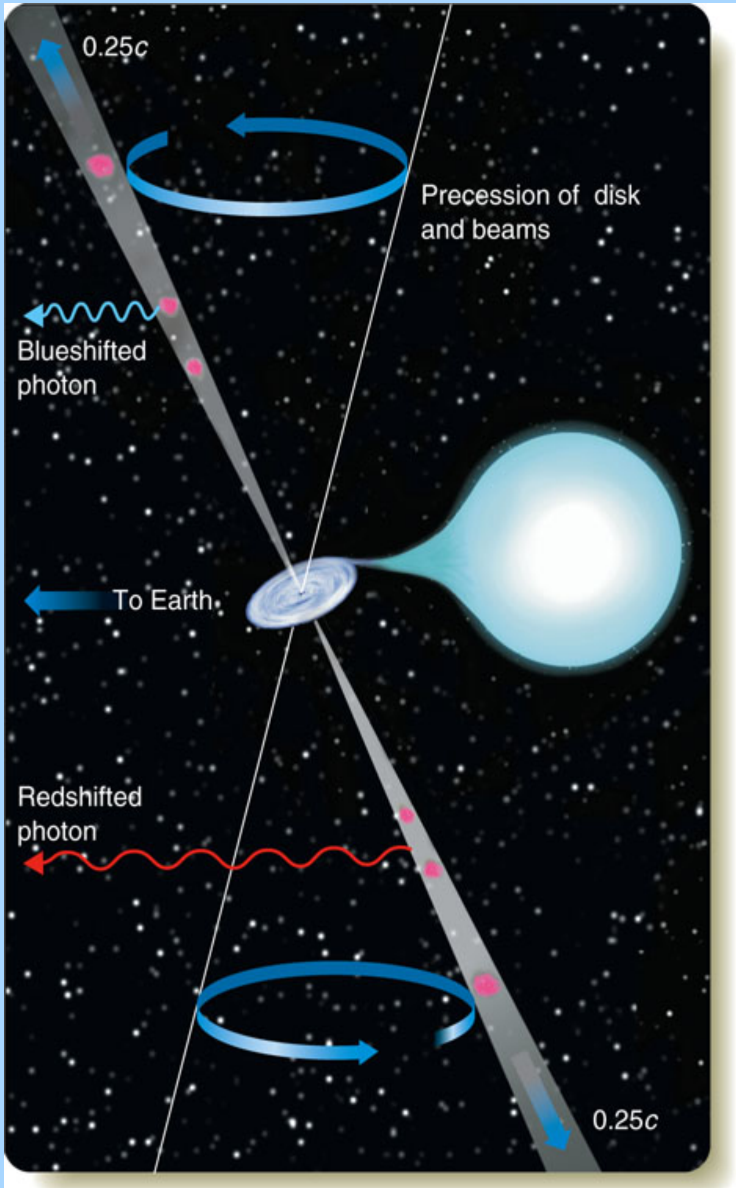
Even weirder…say the universe has a mean density of 6 hydrogen atoms per cubic *meter*. Neglecting any effect of "dark energy," in that case the universe would keep expanding, but more and more slowly, until it reached some maximum size. And if the mean density of the universe were ever so slightly greater than this, the universe would eventually start to contract, leading to the Big Crunch (the reverse of the Big Bang).

If we live in a critical density universe, then the sum of all the gravitational bending on a laser beam sent out by us in some direction would cause it eventually to come around from the other direction.

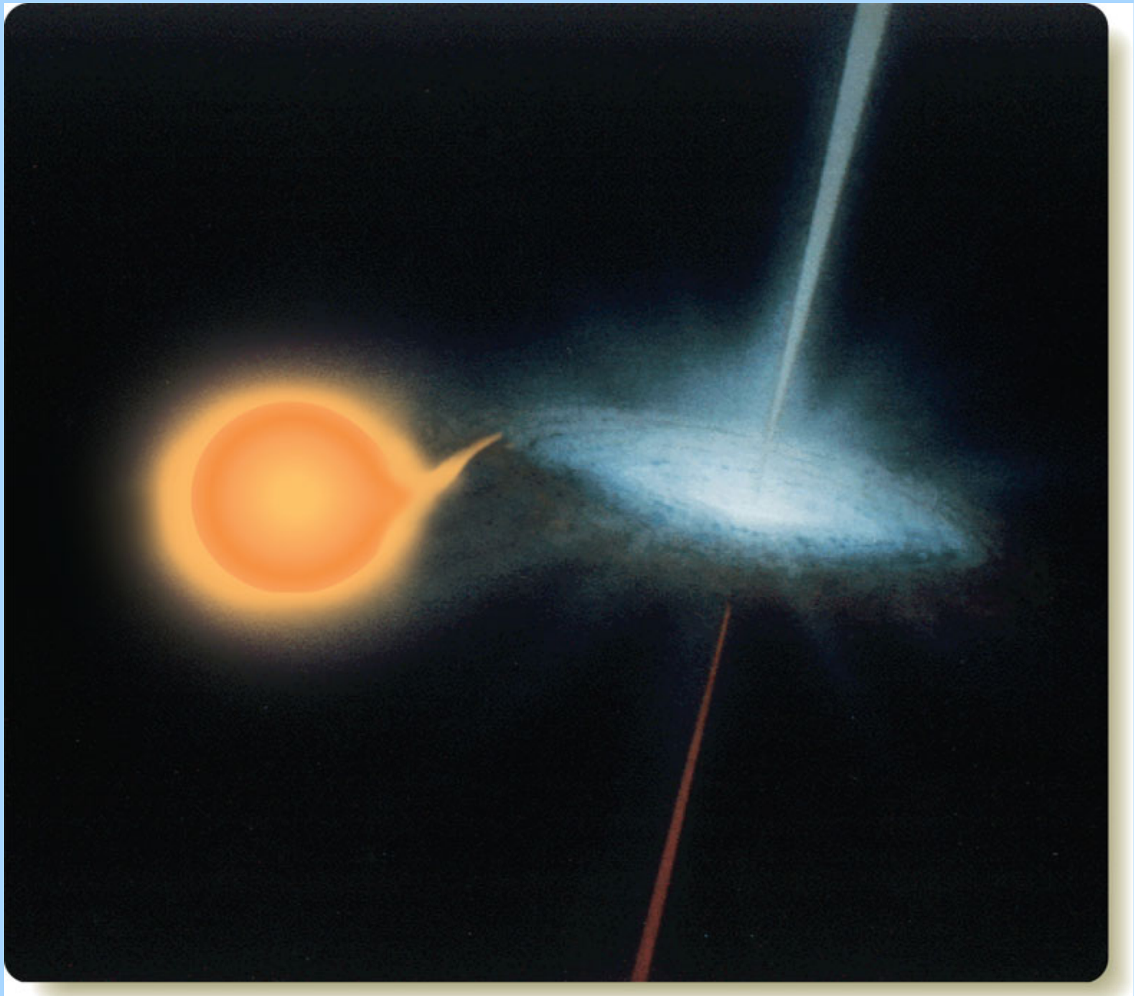
Another way of looking at that would be that a light beam is “bound” in a critical density universe. It can’t “get out”.

If even light can’t escape from some object, isn’t that the definition of a black hole?

If we live in a very low density, but critical-density, universe, another way of looking at that is: we live inside a black hole!



The unusual object SS 433 has two precessing jets which produce pairs of spectral lines like a spectroscopic binary but with velocities of ¼ of the speed of light!



Some interacting systems produce powerful bursts of gamma rays. Many of these objects are at distances of billions of light-years, so the light reaching us comes from explosions that occurred billions of years ago.

Approximately how many stars are there in the Milky Way Galaxy?

a. 200 thousand
b. 200 million
c. 200 billion
d. 200 trillion