NEUTRON STARS, GAMMA RAY BURSTS, and BLACK HOLES

(chap. 22 in textbook)

Neutron Stars

For carbon detonation SN ⇒ probably no remnant
For core-collapse SN ⇒ remnant is a neutron-degenerate core
⇒ neutron star
Densities ~ 10^{14} to 10^{15} g/cm^3 ~ billion times denser than water

Cubic centimeter contains ~ 100 million tons! Like a single enormous nucleus, all neutrons nearly touching.

Gravity at surface is huge. e.g. a human would weigh ~ million tons

Rotation period ~ fraction of a second when first formed (conservation of angular momentum)

Magnetic field is huge, amplified by the collapse (~10^{12} x Earth's field strength). Most extreme of these are called "magnetars"—100s now known.

Observed as pulsars (discovered 1967). Each pulsar has different pulse period (0.03 to 0.3 sec for most) but most are *very* stable. (Fig. 22.2)

A few pulsars are seen within supernova remnants (e.g. Crab Nebula, Fig. 22.4, 22.5), but not all remnants have a detectable pulsar.

Interpretation: rotating "lighthouse model." (Fig. 22.3) Rotation slows down with time, on a timescale of about a million years.

Understand why, in this model, not all neutron stars can be observed as pulsars.

"Glitches" (not in text) –sudden change in period probably due to "starquakes".

Neutron stars in binaries

1. x-ray bursters—neutron star accretes matter from main sequence or giant companion. Get accretion disk, heating at surface ⇒ fusion of H ⇒ outburst of x-rays lasting only a few seconds (analogous to novae, but much more violent).

Where did the binary companion go? See Fig.22.10 on p.575 for strange process that could explain it.

SS443—Some material being shot out in jets at 25% the speed of light! See Fig. 22.9.

2. Millisecond pulsars—Periods ~ few x 0.001 sec. Spinning 100s of times per second! Found in globular clusters! (Fig. 22.11. Unexpected because pulsars should slow down and fade in millions of years, while all globular clusters are more than 10 billion years old!) So very old. Interpretation: Neutron star spun up by accretion from binary companion (closely related to x-ray bursters, which may be on their way to becoming millisecond pulsars). See Fig. 22.10.

Pulsar planets—1992: Pulse period of a millisecond pulsar found to vary periodically ⇒ planet in orbit around pulsar. Pulses arise earlier and later, depending on what part of the orbit the pulsar is in. Now evidence for *three* planets orbiting this pulsar, with masses like that of the Earth! But almost certainly not primordial (because planet would be destroyed by the supernova explosion that gave rise to the neutron star).

Gamma Ray Bursts

Known since 1970s—brief (~10 sec) highly irregular (see Fig.22.13) flashes of gamma ray light. Until about 1995, no one knew what they could be or where located—solar system? Nearby stellar event flare? Need distance to get brightness (luminosity).

First indication: they are distributed *isotropically* in the sky (no preferred direction, like the plane of the Milky Way if they were in our Galactic disk). But they could be in the Oort comet cloud surrounding our solar system, or in the halo of our Galaxy, or…

Then in 1997 it was possible (from the Italian-Dutch BeppoSAX satellite) to see the x-ray "afterglow" from a gamma ray burst to locate its position in the sky more accurately, and then see spectral lines in its optical "afterglow." The resulting Doppler shift was a redshift and it was enormous. As we'll see later, because the universe is expanding, redshift can be used to get distance. Resulting distance for this gamma ray burst was 2 billion parsecs!

By now we have seen ~10 afterglows from gamma ray bursts (and their parent galaxies) and they are all extremely distant ⇒ *extremely* luminous. In fact more energy produced than a supernova, and all in a matter of seconds! Probably most powerful objects in the universe.

What are they?? A hint is that they flicker on timescales of a hundredth or thousandth of a second, which means they can't be larger than a few hundred kilometers across. (See p. 578 for the explanation.)

Much evidence that these are relativistic (i.e. moving near the speed of light) expending fireball jets. But what causes them? Leading theories:

1. Coalescing neutron star binary.
2. Hypernova—some evidence for this because of probable association of 1998 supernova with a gamma ray burst. Actually these may just be supernovae in a particular mass range, since the rate of supernova explosions far exceeds that of gamma-ray bursts.

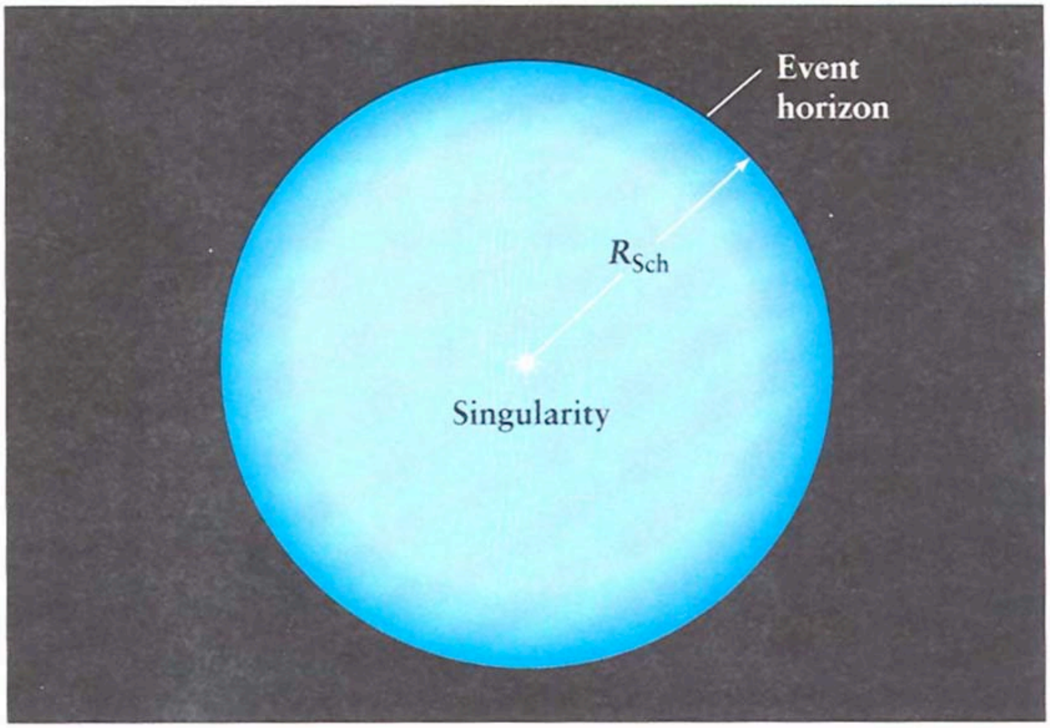
See discussion and sketches of these models on pp. 578-579. We will discuss briefly in class.

But really, no one knows, and it is one of the biggest challenges for theoretical modelers. Recent evidence supports the idea that the *short*-duration bursts (~ few seconds) are best explained as coalescing neutron stars, while the *longer*-duration bursts are probably exploding stars.

Black Holes (sec. 22.5-22.8)

For stars: if mass of core greater than about 3Mo, neutron degeneracy cannot prevent collapse ⇒ "black hole" *singularity*.

Event horizon = distance from BH within which even light cannot escape (also known as "Schwarzschild radius"). This is *not* size of black hole itself (in principle infinitesimal radius, infinite density).

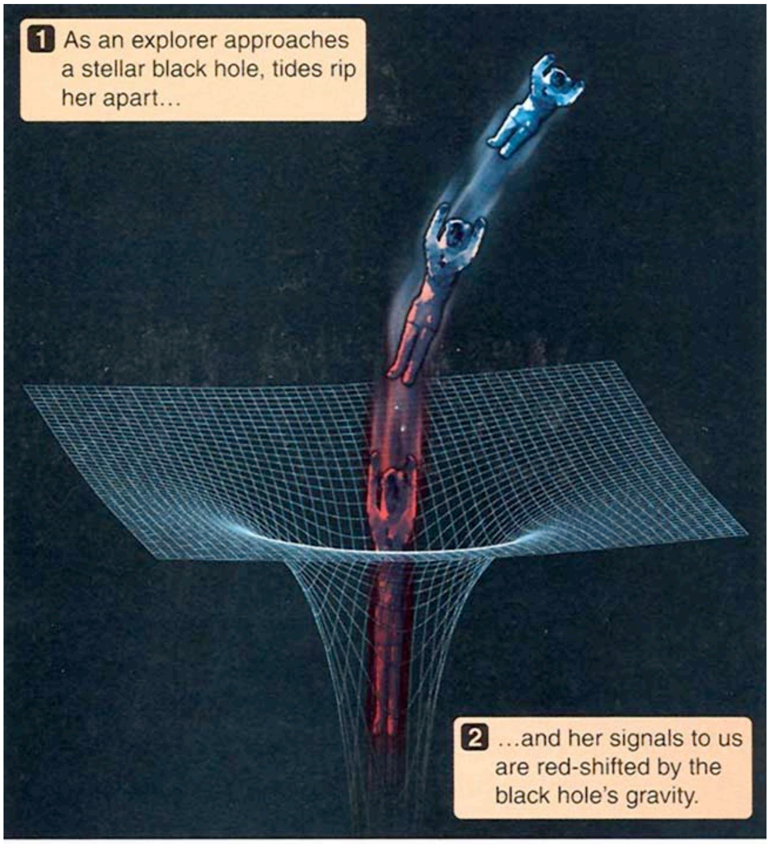


Object falling into BH:

1. Matter falling toward BH is stretched and squeezed by huge tidal forces ⇒ heating to x-ray temperatures (**will be one way to indirectly detect BHs**).

2. Gets redder due to gravitational redshift. This is *not* Doppler shift; it occurs because time slows down (see below), and a light wave is like a clock. Or can interpret this redshift as energy used by photon trying to get out of the increased gravitational "well." (See illustration later. But remember, the photons still travel at the speed of light.)

3. Appears to slow down, then freezes at event horizon due to "time dilation." (We'll return to this below.)

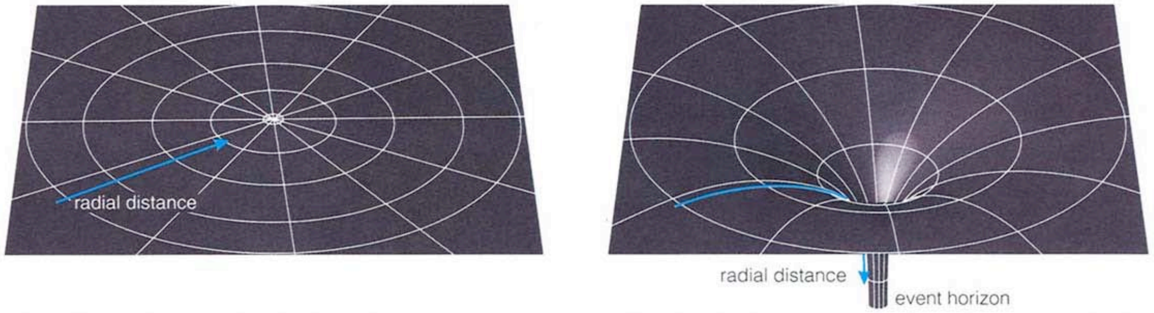


A trip into a black hole.

Most of the strange effects near a black hole are just phenomena predicted by Einstein's theory of relativity, but at extremely strong gravitational fields. The main effects:

Curved paths of light ⇒ gravity distorts space so shortest paths are not straight lines. Well-verified experimentally (e.g. deflection of starlight passing near sun).

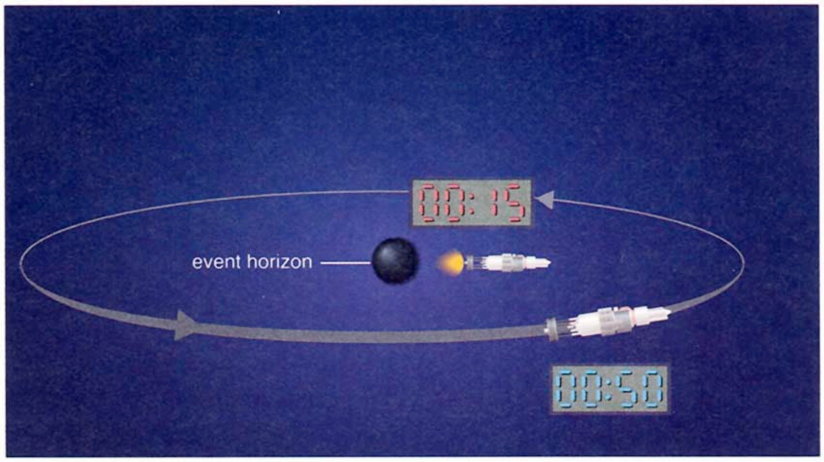
Spacetime is strongly curved near a black hole.



a A two-dimensional representation of "flat" spacetime. The circumference of each circle is 2π times its radius.

b A two-dimensional representation of the "curved" spacetime around a black hole. The black hole's mass distorts spacetime, making the radial distance between two circles larger than it would be in "flat" spacetime.

Time slows down in gravitational field. Tested in 1959 (using physics building at Harvard), and then from aircraft, space flights. For sun's effect, Viking spacecraft (1976) sent pulses of radio waves toward Earth that passed near the sun.



Time runs slower on the clock nearer to the black hole, and gravitational redshift makes its glowing blue numerals appear red from your spaceship.

Detection of Black Holes

In binary systems: For stellar-mass black holes, strong evidence for existence of BHs comes from spectroscopic binary star systems with an invisible companion of mass greater than about 3Mo.

Best candidate: Cygnus X-1. Three main lines of evidence;

1. Visible companion has mass around 25Mo. Using the known period and the primary star's orbital speed from the radial velocity, get sum of masses, and hence mass of invisible companion: about 10Mo ⇒ must be black hole (assuming theoretical calculation of neutron star/black hole mass limit is ok).

2. Hot x-ray emitting gas is observed flowing toward the invisible companion. This is consistent with a black hole, but it would also be consistent with a neutron star.

3. Small duration of x-ray variations (about 1 millisecond) implies size less than about 300 km ⇒ could be neutron star or black hole.

So can see that only (1) above unambiguously identifies the invisible companion as a BH.

Two other good candidates: LMC X-3 (mass of invisible companion about 10 Mo) and A0620-00 (mass about 3.8 Mo).

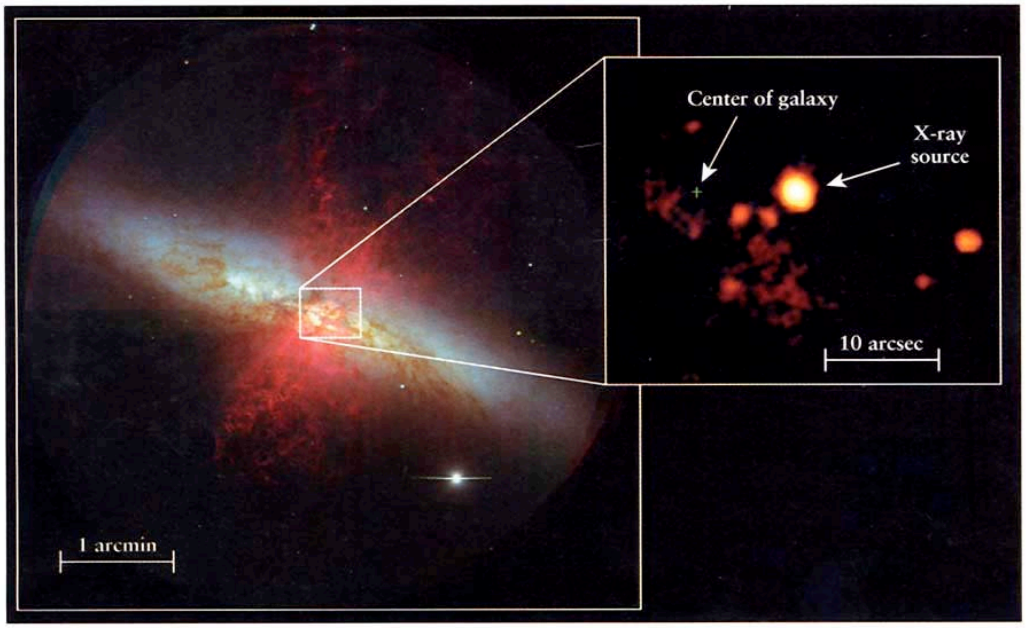
Note that BHs in binary systems may provide our best chance to detect gravity waves, a major prediction of Einstein's theory of general relativity that has been impossible to verify directly because it is an extremely small effect. Read Discovery 22-1 in your text on this subject; what is the result that most astronomers consider as an *indirect* confirmation of the existence of gravitational radiation?

Homework: search the web for current status of the LIGO experiment. Has there been a recent detection?

In globular clusters: Sept. 2002: UT astronomer Karl Gebhardt et al. discover intermediate mass BH in center of globular cluster.

At the centers of galaxies: Stars and gas very near the centers of galaxies (including our own) are moving very rapidly, orbiting some unseen object. Masses inferred from Newton's laws are millions to billions of solar masses! ⇒ <u>supermassive black holes</u>. This was uncertain until a few years ago, but in the past few years very accurate observations have confirmed the existence of these "monsters."

In young super star clusters in "starburst" galaxies like M82 (see pp. 595)—inferred BH masses thousands of Mo. These are inferred from presence of bright compact x-ray sources (i.e. consistent with accretion onto BH). These are "intermediate-mass" black holes, and they appear to have formed recently. No one knows how, but collisions and coalescence between massive stars in these dense clusters is one possibility.



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A "Mid-Mass" Black Hole? M82 is an unusual galaxy in the constellation Ursa Major. The inset shows an image of the central region of M82 from the orbiting Chandra X-ray Observatory (see Section 6-7). The bright, compact X-ray source shown by the arrow varies in its light output over a period of months. The properties of this source suggest that it may be a black hole of roughly 500 solar masses or more. (Subaru Telescope, National Astronomical Observatory of Japan; inset: NASA/SAO/CXC)

So we see evidence for BHs all the way from stellar masses to billions of solar masses.

Detection of an event horizon? See "decaying pulses from blob" discussed on p. 593.

[Additional topics below will NOT be covered on exam.]

<u>Rotating black holes</u>: singularity is a ring! BH drags space-time around with it. Could accelerate a star ship by whipping through the "ergoregion" outside the event horizon.
<u>Wormholes</u>: time travel, baby universes ("multiverse") possible.

Visual review of all of stellar evolution and how it depends on the initial mass of a star: