# XV. STELLAR DEATH:

A. The collapsed core in a Type II supernova is a very compact object, generally a neutron star.

1. A neutron star is held up by neutron degeneracy pressure, which is analogous to the electron degeneracy pressure that supports a white dwarf.
    a. Theoretically, up to 2 or 3 solar masses of material is compressed into a sphere of radius only 10 to 15 km.
    b. With a few possible exceptions, all reliably measured masses of neutron stars are about 1.4 solar masses, the value at which an iron core becomes unstable and collapses.
    c. The density of a neutron star is therefore comparable to that of an atomic nucleus.
2. Neutron stars were predicted in the 1930s, but first observed in 1967 as pulsars.
    a. Jocelyn Bell, a graduate student working in Cambridge, England, noticed that extremely rapid and regular (P = 1.3373011 sec) bursts of radio wave came from a certain location in the sky.
    b. For a short time, the possibility that these are signals from intelligent extraterrestrials was considered, and the discovery was kept secret.
        i) Sometimes the object was half-jokingly called LGM, for "little green men."
        ii) The subsequent discovery of many pulsars, in different directions of the sky and with different periods, cast doubt on this hypothesis.
        iii) The absence of periodic shifts in the pulse arrival times suggested that the signals were not coming from a planet orbiting a star.
    c. There are how hundreds of known pulsars, generally with periods in the range 0.1-10 seconds. A majority of them are concentrated in the flat plane of our Galaxy.

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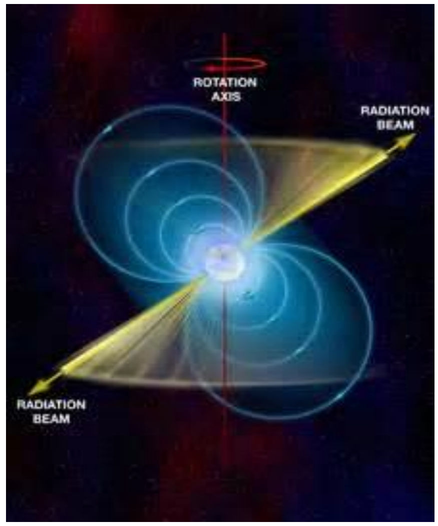
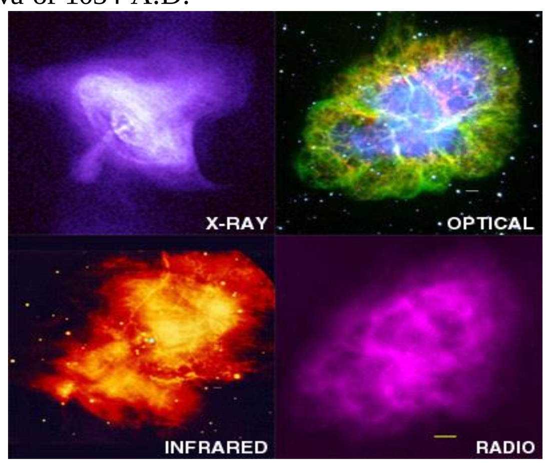
3. What produces the clock-like regularity of pulsars? By the process of elimination, the most plausible explanation is the rotation of a neutron star.
    a. The oscillation (in size) of a normal star is much too slow.
    b. The oscillation of a white dwarf is too slow (P = 10 sec) for the rapid pulsars.
    c. The oscillation of a neutron star is too fast (P = 0.001 sec) for most pulsars.
    d. Two normal stars or white dwarfs cannot orbit each other so quickly.
    e. Two neutron stars (or a white dwarf plus neutron star pair) can have such a tight orbit, but they would rapidly lose energy, and the orbital period would decrease—yet pulsar periods were observed to be very stable.
    f. The surface of such a rapidly rotating normal star would exceed the speed of light.
    g. A white dwarf is disrupted if it's rotation period is less than about 0.3 seconds, too slow for the rapid pulsars.
    h. The hypothesis of a rapidly rotation neutron star has no obviously fatal flaws.
4. If the neutron star is highly magnetized (as could be the case due to compression of existing magnetic fields during core collapse), it may emit two oppositely directed beams of radiation along the magnetic poles.
    a. If the rotation axis differs from the magnetic axis, a beam might sweep across the Earth once (or twice in some cases) per rotation period if the orientation is favorable.
    b. This is similar to what happens in a lighthouse: it is "on" all the time, but we

see it only when it points toward us.

c. The production mechanism of the beam itself is complicated and not well understood, but it has to do with the rapid rotation of the very strong magnetic field.




5. One of the most famous pulsars is in the middle of the Crab nebula, the remnant of the supernova of 1054 A.D.



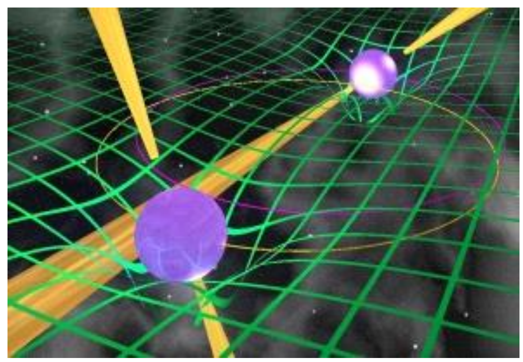

   a. It rotates 33 times per second.
   b. It's beam is visible at optical and X-ray energies, not just at radio wavelengths.

6. Every pulsar is believed to be a neutron star. However, not every neutron star is pulsar.
   a. The beam might not be on (if either the magnetic field is too weak, or the rotation is too slowly).
   b. The orientation might be unfavorable.
7. A few neutron stars have been detected in steady light, not as pulsars. However, they must be young and hot for this to be feasible.

B. Being so dense and massive, neutron stars provide excellent tests of Einstein's General theory of relativity, which postulates that matter and energy warp (curve) space and time ('space-time").
   1. The effects of general relativity are small in the Solar Sstem, but have been measured.
      a. Light traveling in the vicinity of the Sun follows a slightly curved path.
      b. The perihelion (closest point to the Sun) Mercury's orbit shifts slowly with time.

c. Light from the Sun is red-shifted a little; it loses energy while climbing out of the gravitational field.

2. The best existing evidence for the general theory of relativity comes from a "binary pulsar": a system of 2 neutron stars (one visible as a pulsar) orbiting each other.
   a. The orbital period of this particular system is slightly less than 8 hours – the stars are so close together that they would nearly fit inside our Sun.
   b. Careful analysis of the pulse arrival times during more than a decade has shown that the orbital period is decreasing; the two stars are gradually spiraling toward each other.
   c. The observed rate is exactly equal to that predicted by general relativity: the system is losing energy through the emission of "gravity waves", which are "ripples" in the curvature of space-time.
   d. The system also confirms several other predictions of relativity. For example, the pulsar's orbit precesses, like that of Mercury but much more obviously.



   e. J. Taylor and R. Hulse were awarded the 1993 Nobel Prize in physics for their discovery of this first binary pulsar.

C. Theoretical calculations suggest that a neutron star's mass cannot exceed 2-3 solar masses.
1. If it does, then further collapse ensues, and no known forces can halt the process.
   a. This might happen to a very massive star if it cannot successfully eject it's envelope after the iron core collapses.
   b. It might also occur if a neutron star accretes sufficient material from it's surroundings or a companion star, or if it merges with another star.
2. The resulting object is called a "black hole". According to the general theory of relativity, it's gravitational field is so strong that nothing, not even light, can escape.
3. A qualitative understanding of this can be obtained by considering Newton's law of universal gravitation applied to a ball at the surface of the Earth.
   a. The ball must be thrown with a certain minimum speed, the "escape velocity" (about 11 km/s, neglecting air resistance), to fly completely away from Earth.
   b. Now suppose the Earth is compressed while it's mass remains constant. Te escape velocity at Earth's surface would increase; the ball could escape only if thrown faster.
   c. Continuing to compress the Earth, eventually the escape velocity reaches and then exceeds the speed of light, so neither the ball nor anything else (including light) can escape.
   d. John Michell and Pierre Laplace independently reached this conclusion in

1783 and 1795 (respectively), but the Newtonian reasoning turns out to be incorrect when the gravitational field is very strong; general relativity must be used.

4. A non-rotating object of mass M must be compressed to a radius $R_s = GM/c^2$ for it to form a black hole.

    a. This is known as the Schwarzschild radius, after Karl Schwarzschild who was the first to derive it rigorously (1916).

$$R_{Sch} = \frac{2GM}{c^2}$$

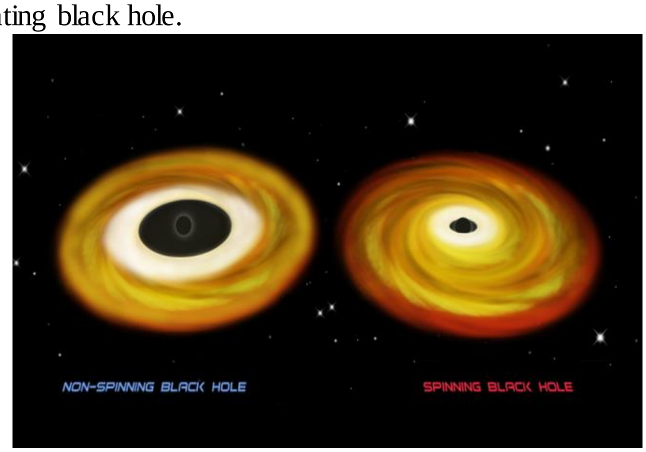
$$R_{Sch} = Schwarzchild\ radius$$
$$G = Gravity\ Constant$$
$$M = mass\ of\ black\ hole$$
$$c = speed\ of\ light$$

        i) The Sun's radius would have to be less than or equal to 3 km for it to become a black hole.
        ii) The Earth's radius would have to be less than or equal to 0.89 cm for it to become a black hole.

    b. Actually, since space is so highly warped in a black hole, the "radius" is not really $2\ GM/c^2$ and in any case is not a measurable quantity. However, this is the radius obtained by dividing the black hole's circumference (a measurable quantity).

5. The imaginary spherical surface surrounding the region from which nothing can escape is called the "event horizon" of the black hole.

    a. This boundary has a radius equal to the Schwarzschild radius if the black hole is not rotating, but the radius can be as much as a factor of 2 smaller for a rotating black hole.




    b. According to classical general relativity, the matter inside the event horizon continues collapsing to a mathematical point of infinite density called a "singularity."

        i) The quantum world, on the other hand, appears to avoid singular points and their associated infinite quantities; the structure of matter is described by a probability distribution of nonzero spatial extent.

ii) The singularity is nevertheless very small and dense, so we will retain this terminology.

c. If you were to cross the event horizon, nothing can save you from the singularity: you will hit it in a finite amount of time (according to your own clock).

6. There is a famous theorem stating that "black holes have no hair".

a. The gist is that black holes are simple objects, completely described from the perspective of an outside observer by only three quantities: mass, electric charge, and angular momentum (the amount of "spin" of the black hole).

b. External observations of a black hole cannot reveal the identity of objects that might have been thrown into it.

D. Misconceptions about black holes

1. Black holes do not such up everything in sight, like a giant cosmic vacuum cleaner.

a. Only objects very near a black hole will be strongly pulled toward it, and even then it is often possible to achieve stable (or nearly stable) orbits.

b. If the Sun were turned into a black hole, Earth's orbit would not be altered; the masses of the Sun and Earth would remain constant, as would the distance between them, so the force of gravity would be unchanged. Only at smaller distances would the force of gravity be stronger.

2. Black holes do not form in random places for no apparent reason.

a. They might be produced....

i) by the collapse of very massive stars;

ii) by neutron stars accreting mass from gravitationally bound companions;

iii) in the centers of galaxies; and

iv) perhaps by inhomogeneities in the density of matter shortly after the Big Bang.

b. In other situations they are very difficult to make. Our Sun, for example, definitely will not turn into a black hole.

c. It is possible that the neutron star formed by SN 1987A subsequently collapsed to a black hole, but this is still controversial.

3. Black holes probably cannot be used for travel to other universes.

E. What would happen, according to general relativity, to light emitted from the surface of a star that is collapsing to form a black hole.

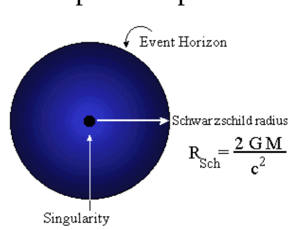
1. When the star is large, light sent in any direction is able to escape.

a. It is bent a little (unless directed radially outward), and gravitationally redshifted.

b. As the star contracts, these two effects become more pronounced.

2. When the star reaches a radius of 1.5X the Schwarzschild radius (i.e., $R = 2\,G\,M/c^2$), light directed along it's surface goes into a circular orbit at that radius.

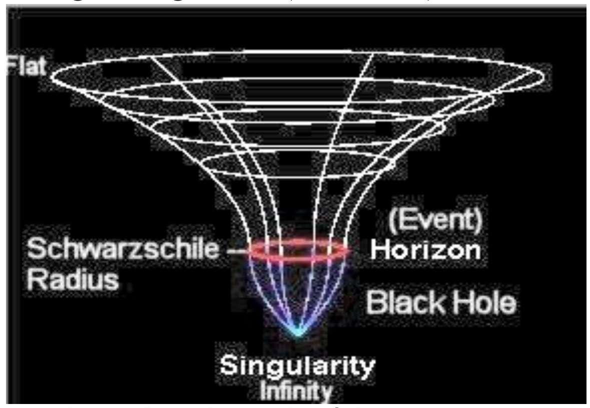
a. This is called the "photon sphere."



b. Light directed even slightly up from the surface is able to escape, but it gets strongly bent (if not radial) and red-shifted.

3. As the star shrinks still further, light must be aimed progressively more closely toward the zenith to escape; otherwise it falls back onto the star.

   a. This angle defines an "exit cone" within which light can escape. However, light still gets bent (if not radial) and red-shifted.




   b. Light aimed exactly at the angle of the exit cone goes into the photon sphere. Incidentally, an observer at the radius of the photon sphere could see the back of his head, if it emits or reflects light.

4. As the star continues to contract, the exit cone becomes progressively narrower.

   a. That is, light has to be aimed closer to the zenith for it to escape.

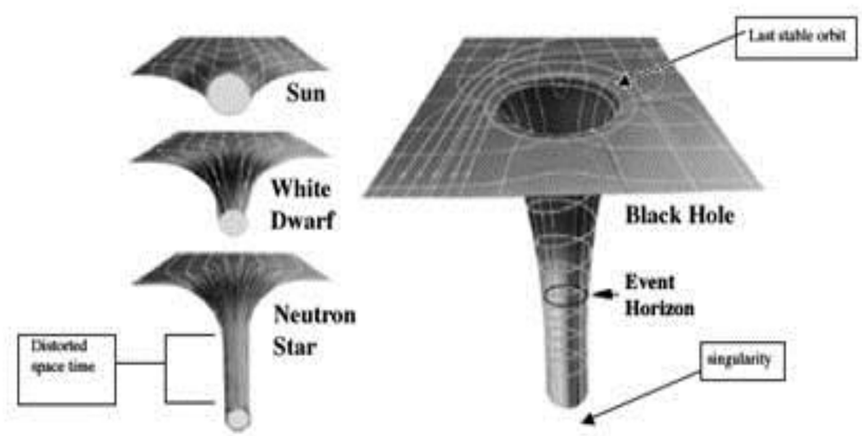
   b. Light directed outside the exit cone curves back and hits the star.

   c. To an outside viewer, the star dims very rapidly; fewer photons are escaping because the size of the exit cone is shrinking, and the detected photons are gravitationally red-shifted to lower energy.

5. When the star's radius reaches the Schwarzschild radius, $2\ GM/c^2$, the exit cone shrinks to zero, and no light can escape.

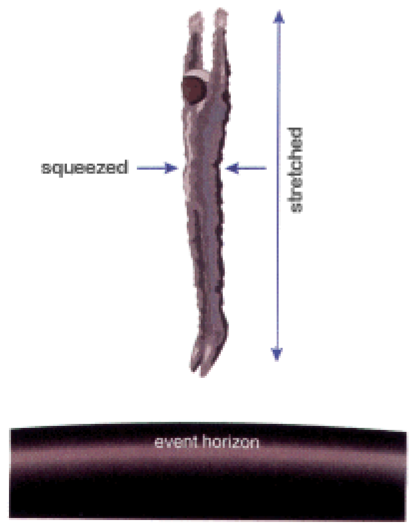
   a. At this stage, the collapsing star becomes a black hole.

   b. Light is effectively trapped by the severe curvature of space-time.



F. The strong warping of space-time in the vicinity of a black hole manifests itself in many ways.

1. For example, if you were to fall feet-first toward a black hole, you would be stretched along the length of your body and squeezed along the width by the hole's tidal forces.
   a. The stretching occurs because the gravitational pull on your feet (which are closest to the black hole) significantly exceeds that on your head.



Tidal forces are lethal near the event horizon.

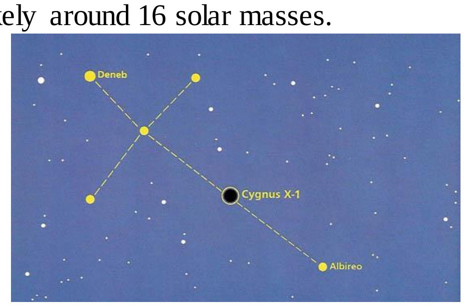
   b. Similarly, the squeezing is produced by the fact that all points are pulled toward the center of the black hole along radial lines. Your two shoulders therefore get progressively closer together.
   c. The strength of the tidal forces is a function of the mass of the black hole.
      i) Black holes formed from individual stars have enormous tidal forces even outside the event horizon; you would turn into something like human spaghetti.
      ii) Billion-solar-mass black holes such as those at the centers of some galaxies seem so benign that you would not feel anything unusual outside the event horizon. However, you would not be able to escape, after crossing the event horizon.
2. If you were far from a black hole and watching a friend fall in, your friend's clock would appear to run progressively slower as he approached the event horizon ("time dilation").
   a. From your perspective, time would be slowing down for your friend.
   b. Indeed, it would take an infinite amount of time for him to cross the event horizon, from your perspective.
   c. From your friend's perspective, in contrast, it takes a finite amount of time to cross the event horizon, and shortly thereafter he reaches the singularity.
3. On the other hand, if your friend were to approach the event horizon and subsequently escape from the vicinity of the black hole, he would have aged less than you did.
   a. This is a method for jumping into the future while aging very little..

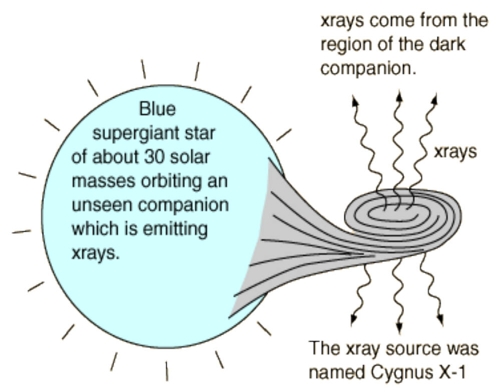
b. But this doesn't increase longevity ---your friend's life would not be extended.

4. Radiation emitted just outside the event horizon gets highly red-shifted as it escapes.
   a. Photons lose energy as they climb out of the highly warped space-time.
   b. A photon form the event horizon itself is red-shifted to infinite wavelength (zero energy) and cannot be detected.

G. Before we consider other weird properties of black holes, let's see whether there is any real observational evidence for the existence of them.

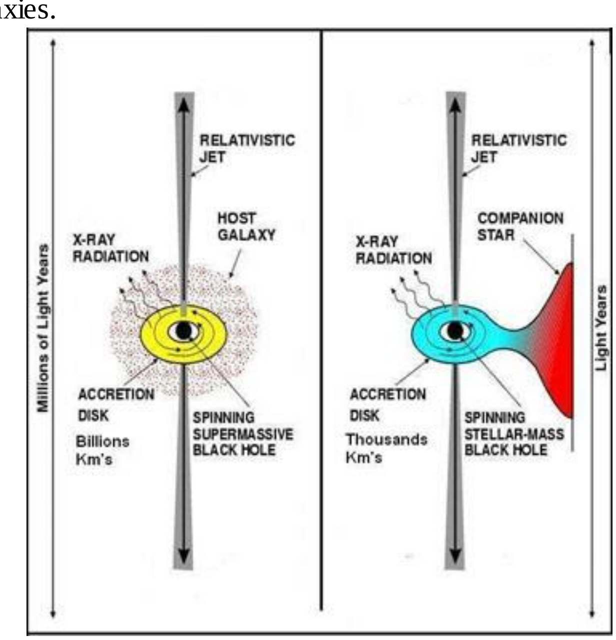
1. Black holes do not emit any electromagnetic radiation, so they must be detected more indirectly.
   a. The easiest way is to measure the period and orbital speed of a normal star gravitationally bound to a black hole.
   b. But of all the stars in the sky, which ones might be in orbit around a black hole?
2. Stars that emit sudden bursts of X-rays are good candidates.
   a. Matter torn away from a normal star can become part of an accretion disk around a companion black hole or neutron star, and it gets heated to high temperatures.
   b. X-rays are emitted, especially if a clump of material falls onto (or is formed in) the disk.
   c. The X-rays are a signature of a very strong gravitational field. Matter doesn't gain enough kinetic energy in a weak field, and hence it emits longer wavelengths of light.
3. Repeated spectroscopic measurements of the visible star yield it's radial velocity as a function of time.
   a. In some cases, a clear sinusoidal variation is found. The period and amplitude of the radial velocity variations can be measured, as in a normal spectroscopic binary star.
   b. Kepler's third law can be used to determine the sum of the masses of the two objects in the binary system. (Actually, this is a lower limit to the sum of the masses, since the radial velocity is only a lower limit to the total velocity).
   c. If the properties of the visible star are known, the mass of the invisible companion can sometimes be determined.
   d. If the mass of the invisible companion is at least 3 solar masses, it is a good candidate for a black hole by the process of elimination: It cannot be a white dwarf or a neutron star (too massive), and a normal star of that mass would be very bright.
   e. The first convincing black hole candidate found in this way was Cygnus X-1. The invisible object has a mass of at least 7 solar masses, and most likely around 16 solar masses.





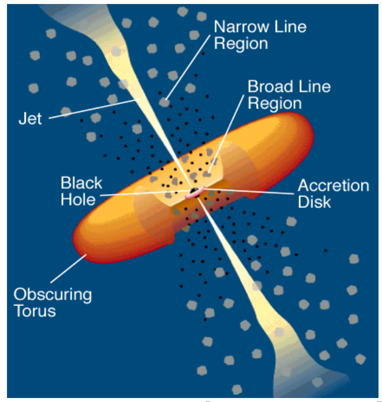

f. However, in this case the conclusions depend on the assumptions made about the visible star, which is a supergiant about 33X as massive as the Sun.

4. Rather unambiguous evidence for black holes comes from binary systems in which the visible star has very small mass (e.g., a K or M-type main sequence star).
   a. About a dozen reasonably good black hole candidates have been identified. In most cases, the minimum mass of the invisible object is about 3 solar masses.
5. Extremely convincing black holes have also been found in the centers of some galaxies.



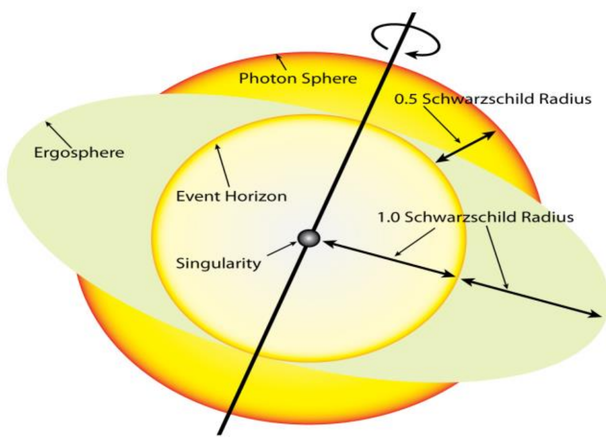

H. Black holes are likely to be rotating.

1. They form from collapsing stars, or merging binary stars, or matter spiraling into the center of a galaxy ---system with some intrinsic rotation.
2. Rotating black holes have many fascinating properties.
3. There are actually 2 spherical event horizons: an inner one and an outer one.
   a. If the rotation rate is low, the outer event horizon is slightly smaller than the Schwarzschild radius, and the inner one is very small.



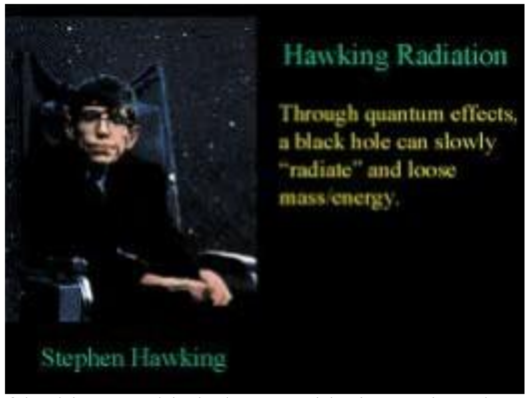

b. With increasing rotation rate, the outer event horizon shrinks and the inner one grows.
c. At a particular rotation rate, the two event horizons merge to form a single horizon with a radius equal to half the Schwarzschild radius.
d. It is believed that the rotation rate cannot exceed this value; otherwise, the event horizon would disappear, leaving a "naked singularity."
e. Charged black holes also have two event horizons. These would merge and disappear if the charge reached and exceeded a certain value. However, we do not expect significantly charged black holes to exist, since they would rapidly pull opposite charge toward them.

4. Around the outer event horizon of a rotating black hole is a region called the "ergosphere."
   a. Nothing can remain stationary within the ergosphere; space-time is dragged around the black hole at a very high rate.

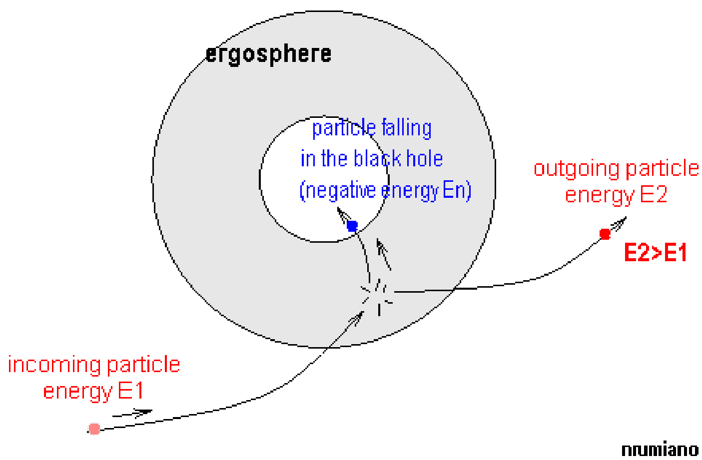



   b. It's equatorial radius is equal to the Schwarzschild radius, and it approaches the event horizon at the poles.
   c. Energy can be extracted by sending an object into this region (along the direction of rotation), and letting part of the object break of and fall through the event horizon. The other part will emerge with more kinetic energy than it had on the way in.
   d. The energy extracted in this manner is rotational energy of the black hole.

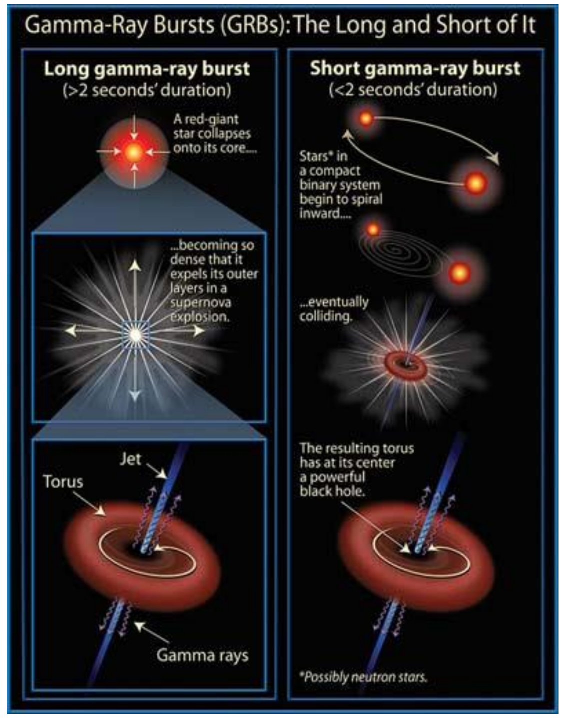
I. An interesting prediction made by Stephen Hawking is that black holes can evaporate (lose mass) due to a "quantum tunneling" process.
   1. Particles within the event horizon can suddenly find themselves outside the horizon, and they subsequently escape.



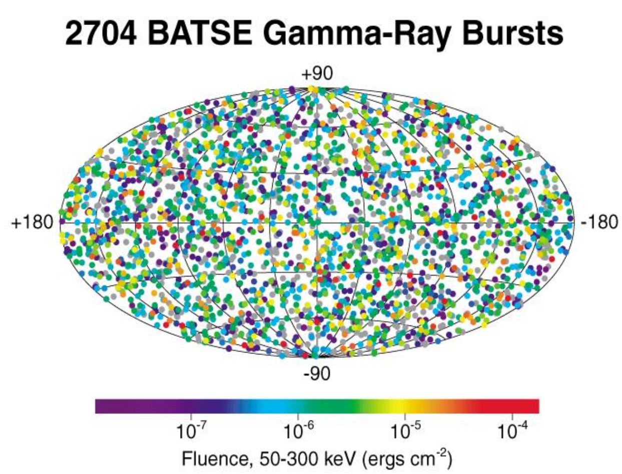

2. Another way of looking at this is by considering "virtual pairs" of particles and antiparticles produced slightly outside the event horizon of a black hole.
   a. Quantum physics tells us that such pairs often come into brief existence, even in empty space. This has been experimentally confirmed; the virtual particles affect the measured energy levels of atoms, for example.
   b. Near the event horizon of a black hole, a particle (or antiparticle) can sometimes escape, and the other one enters the black hole with negative energy (from the perspective of distant observers). This decreases the mass of the black hole.




3. After escaping, the particles and antiparticles annihilate each other and produce black-body radiation. Thus, black holes aren't completely black.
4. This "evaporation" process is most rapid for low-mass black holes.
   a. At the present time, it is negligible except for "mini black holes" (perhaps $10^{15}$g, about the mass of a large mountain).
   b. All stellar-mass or supermassive black holes accrete material far more quickly than they evaporate.
   c. If mini black holes were produced by fluctuations in the density of matter shortly after the Big Bang, then some of them should be evaporating now.
   d. The final stage of evaporation should produce an explosion of gamma rays.




5. There are, in fact, objects known as "gamma-ray bursts".
   a. These occur about once per day, with a random distribution throughout the sky.
   b. For several decades their distance and nature were unknown. However, it has long been recognized that they are not the bursts of gamma rays expected from exploding mini-black-holes: they don't have the right observational properties.
   c. Gamma-ray bursts have recently been shown to occur in galaxies billions of light years away (though some may be in nearby galaxies). They emit at least as much energy as a supernova, and probably have something to do with black holes, but not tiny ones.
      i) They might be 2 neutron stars merging to form a black hole.
      ii) Or, they might be a neutron star merging with a black hole.
      iii) Another, idea is the collapse of a massive star to form a black hole, with or without a successful supernova explosion.



K. Questions:

1. Discuss the significance of the discovery of pulsars.
2. Explain how astronomers concluded that pulsars are rotating neutron stars.
3. Discuss what is meant by warped spacetime.
4. Describe some observational tests of the general theory of relativity, especially that provided by a binary pulsar.
5. Summarize the Newtonian argument that the escape velocity form the surface of an object can exceed the speed of light.
6. Define a black hole, it's event horizon, and it's singularity.
7. Discuss the escape of light from the surface of a star that is collapsing to form a black hole.
8. Describe the tidal effects near a black hole, and their strength as a function of the hole's mass.
9. Discuss what happens to time indicated by clocks falling toward a black hole, as seen by a distant observer.

10. Explain how black hole candidates are detected in the Milky Way Galaxy.

11. Define the ergosphere of a rotating black hole.

12. Discuss the possibility of travel through a wormhole to another universe or a different part of our Universe.

13. Outline Hawking's argument that black holes can evaporate.

14. Describe the phenomena known as a "gamma-ray burst".

15. As measured by distant observers, nothing ever enters a black hole, since time slows down near the event horizon. Where does the material go?

16. If a visible star orbits an object at least 5X the mass of the Sun in a period of only 8 hours, can you think of anything the object could be besides a black hole? Explain.

17. What sorts of problems could be produced by the violation of causality---that is, if you could travel through a wormhole and return before your departure.