Black Holes
Guiding Questions

1. What are the two central ideas behind Einstein’s special theory of relativity?
2. How do astronomers search for black holes?
3. What are super massive black holes, and where are they found?
4. In what sense is a black hole “black”?
5. In what way are black holes actually simpler than any other objects in astronomy?
6. What happens to an object that falls into a black hole?
7. Why do some pulsars emit fantastic amounts of X rays?
8. Do black holes last forever?
Recall Life Cycle of Stars

- Main sequence stars
- Giants
- Helium flash
- AGB stars
- Planetary nebulae
- White dwarfs
- Neutron stars
- Supernovas
- Black holes

Main sequence mass (M☉) vs. Stellar corpse mass (M☉)

Time
The special theory of relativity and our conceptions of space and time

As seen by the outfielder, the ball is approaching her at \((30 \text{ m/s}) + (10 \text{ m/s}) = 40 \text{ m/s}\).

- This theory, published by Einstein in 1905, is based on the notion that there is no such thing as absolute space or time.
- Space and time are not wholly independent of each other, but are aspects of a single entity called spacetime.
The speed of light is the same to all observers, no matter how fast they are moving.

*Incorrect* Newtonian description:
As seen by the astronaut in spaceship, the light is approaching her at \((3 \times 10^8 \text{ m/s}) + (1 \times 10^8 \text{ m/s}) = 4 \times 10^8 \text{ m/s} \).

*Correct* Einsteinian description:
As seen by the astronaut in spaceship, the light is approaching her at \(3 \times 10^8 \text{ m/s} \).
An observer will note a slowing of clocks and a shortening of rulers that are moving with respect to the observer. This effect becomes significant only if the clock or ruler is moving at a substantial fraction of the speed of light.
Published by Einstein in 1915, this is a theory of gravity
A massive object causes space to curve and time to slow down
These effects manifest themselves as a gravitational force
These distortions of space and time are most noticeable in the vicinity of large masses or compact objects
This compartment is at rest in the Earth's gravitational field.

(a) The apple hits the floor of the compartment because the Earth's gravity accelerates the apple downward.

This compartment is moving in a gravity-free environment.

(b) The apple hits the floor of the compartment because the compartment accelerates upward.
The theory of relativity predicts a number of phenomena, including the bending of light by gravity and the gravitational redshift, whose existence has been confirmed by observation and experiment.
• The general theory of relativity also predicts the existence of gravitational waves, which are ripples in the overall geometry of space and time produced by moving masses.

• Gravitational waves have been detected indirectly, and specialized antennas are under construction to make direct measurement of the gravitational waves from cosmic cataclysms.
The general theory of relativity predicts black holes

1. A supergiant star has relatively weak gravity, so emitted photons travel in essentially straight lines.
2. As the star collapses into a neutron star, the surface gravity becomes stronger and photons follow curved paths.
3. Continued collapse intensifies the surface gravity, and so photons follow paths more sharply curved.
4. When the star shrinks past a critical size, it becomes a black hole: Photons follow paths that curve back into the black hole so no light escapes.
• If a stellar corpse has a mass greater than about 3 $M_\odot$, gravitational compression will overwhelm any and all forms of internal pressure.
• The stellar corpse will collapse to such a high density that its escape speed exceeds the speed of light.
• Could a black hole somehow be connected to another part of spacetime, or even some other universe?
• General relativity predicts that such connections, called wormholes, can exist for rotating black holes
Certain binary star systems probably contain black holes

- Black holes cannot be seen because they do not emit nor reflect light
- Black holes that are in binary systems may be detected using indirect methods
- In such a system, gases captured from the companion star by the black hole emit detectable X-rays
- As material races toward a black hole, it heats and emits X-rays
A schematic diagram of Cygnus X-1

1. Gases from the supergiant are captured into an accretion disk around the black hole.

2. As gases spiral toward the black hole, they are heated by friction: Just outside the black hole, they are hot enough to emit X rays.
An artist’s impression of Cygnus X-1
This black hole is surrounded by a disk of hot gas.

Torus (doughnut) of cooler gas and dust (shown cut away)

Fast-moving jets of subatomic particles are formed and ejected by electric and magnetic fields.

X rays from the hot disk excite iron atoms in the torus, making them glow.
Supermassive black holes exist at the centers of most galaxies. These are detected by observing the motions of material around the black hole.
A non-rotating black hole has only a “center” and a “surface”

- A black hole is surrounded by an event horizon which is the spherical region at which the escape velocity is exactly the speed of light.
- The distance between the black hole and its event horizon is the Schwarzschild radius ($R_{Sch} = \frac{2GM}{c^2}$).
- The center of the black hole is a point of infinite density and zero volume, called a singularity.
Escape speed and the **event horizon** (Schwarzschild radius)

1. Gravitational escape speed for any object with mass $M$, radius $R$ ($G$ is grav. constant):

   
   $$ V_{esc} = \sqrt{\frac{2GM}{R}} $$

2. Suppose escape speed $V_{esc} = c$ (speed of light)?

3. Set $V_{esc} = c$, solve for $R$:

   $$ R = \frac{2GM}{c^2} = 3km \cdot \left[ \frac{M}{M_{sun}} \right] $$

   This is known as the Schwarzschild radius, or the **event horizon**.
Structure of a Kerr (Rotating) Black Hole

- A black hole has only three physical properties: mass, electric charge, and angular momentum.
- A rotating black hole (one with angular momentum) has an ergoregion around the outside of the event horizon.
- In the ergoregion, space and time themselves are dragged along with the rotation of the black hole.

In the **Ergoregion**, nothing can remain at rest as spacetime here is being pulled around the black hole.
(a) Looking directly toward the black hole from a distance of 1000 Schwarzschild radii: Note positions of stars 1, 2, and 3.

(b) Looking directly toward the black hole from a distance of 10 Schwarzschild radii: Light bending causes multiple images.
Falling into a black hole is an infinite voyage as gravitational tidal forces pull spacetime in such a way that time becomes infinitely long (as viewed by distant observer). The falling observer sees ordinary free fall in a finite time.

Note: A black hole of Mass M has EXACTLY the same gravitational force outside the event horizon as an ordinary object of mass M.
Journeys to Black holes

1. A freely falling observer would pass right through the event horizon in a finite time, would be not ‘feel’ the event horizon

2. A distant observer watching the freely falling observer would never see her fall through the event horizon (takes an infinite time)

3. Signals sent from the freely falling observer a regular intervals (‘clock ticks’) would be
   1. Dilated (take a longer time interval as measured by distant receiver
   2. Signals are redshifted

4. Once inside the event horizon, no communication with ‘external’ world ever possible
   1. But ‘incoming’ signals from external world can enter

5. The tidal force near the event horizon

6. A black hole of mas M has exactly the same gravitational field as an ordinary mass M at large distances
Black holes evaporate

1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.

2. If a pair appears just outside a black hole’s event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.

3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.
Jargon

- black hole
- black hole evaporation
- equivalence principle
- ergoregion
- event horizon
- general theory of relativity
- gravitational radiation
- gravitational waves
- gravitational redshift
- Heisenberg uncertainty principle
- law of cosmic censorship
- length contraction
- Lorentz transformations
- mid-mass black hole
- no-hair theorem
- primordial black hole
- proper length (proper distance)
- proper time
- Schwarzschild radius (RSch)
- singularity
- spacetime
- special theory of relativity
- stellar-mass black hole
- supermassive black hole
- time dilation
- virtual pairs
- wormhole