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 supermassive 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?

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

- 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
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.

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 \((3 \times 10^8 \text{ m/s}) + (1 \times 10^9 \text{ m/s}) = 4 \times 10^9 \text{ m/s.}\)

Correct Einsteinian description:
As seen by the astronaut in spaceship, the light is approaching her at \(3 \times 10^8 \text{ m/s.}\)

The general theory of relativity is our most accurate description of gravitation:

- 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.
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 gravitational redshift
- 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.
If a stellar corpse has a mass greater than about 2 to 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.

Certain binary star systems probably contain black holes.

- Black holes have been detected using indirect methods.
- Some binary star systems contain a black hole.
- In such a system, gases captured from the companion star by the black hole emit detectable X rays.
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.

A schematic diagram of Cygnus X-1

An artist's impression of Cygnus X-1
Supermassive black holes exist at the centers of most galaxies.

These are detected by observing the motions of material around the black hole.

A nonrotating black hole has only a “center” and a “surface”:

- The entire mass of a black hole is concentrated in an infinitely dense singularity.
- The singularity is surrounded by a surface called the event horizon, where the escape speed equals the speed of light.
- Nothing—not even light—can escape from inside the event horizon.

Just three numbers completely describe the structure of a 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.
Falling into a black hole is an infinite voyage

- 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
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.

Key Words

- 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 (R_{Schi})
- singularity
- spacetime
- special theory of relativity
- stellar-mass black hole
- supermassive black hole
- time dilation
- virtual pairs
- wormhole