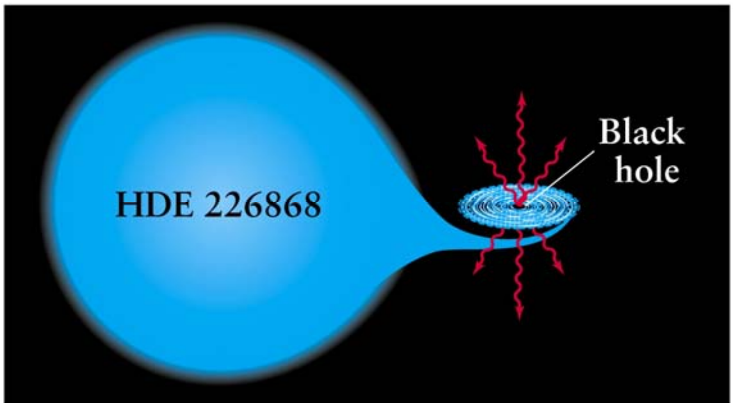
Black Holes



Theories of Relativity

Einstein's Special Theory of Relativity was a comprehensive description of the behavior of **light** and, by extension, of electricity and magnetism. It is called "Special" because it deals with the special case of constant velocity (no acceleration).

Einstein's next goal was to develop an even more comprehensive theory that also explained **gravity** (and acceleration). This is the General Theory of Relativity (1915).

Principle of Equivalence (Relativity)

The fundamental insight that led to the formation of general relativity is deceptively simple. Galileo observed that all bodies, despite their different masses, if dropped together, fall to the ground at the same rate.

According to Newton's Law of Gravitation, the Earth pulls on a more massive object with a greater force than it does on a less massive one.

The two objects fall together, however, because according to Newton's second law, a proportionately greater force is required to impart the same acceleration to the heavier object.

Principle of Equivalence (Relativity)

Therefore, any two freely falling bodies, independent of their internal structure and composition, will follow identical paths.

This similarity of behavior of all types of objects is called an **Equivalence Principle**.

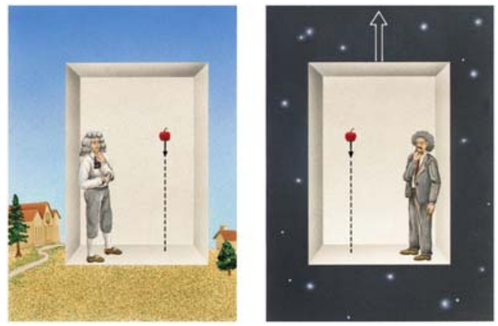
Principle of Equivalence (Relativity)

The Equivalence Principle (i.e., Relativity) asserts that you cannot tell the difference between

(a) being at rest in a gravitational field and

(b) being accelerated upward in a gravity-free environment.

This idea was an important step in Einstein's quest to develop the General Theory of Relativity.



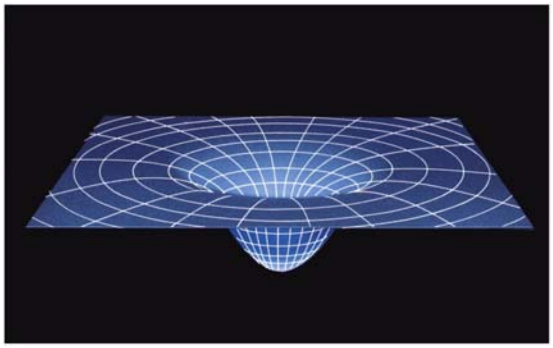
General Relativity

No Place is Special

Light Can be Bent (by gravity)

Space-Time

Mass-Energy tells Space-Time how to curve;
Curved Space-Time tells Mass-Energy how to move.

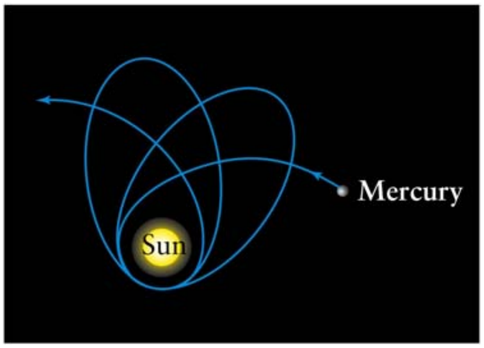


Tests of General Relativity

1. Perihelion Advance of Mercury

The Perihelion distance (i.e., closest approach) is 2/3 of the Aphelion distance.

Astronomers observed 574 arcsec per century advance but only 531 arcsecs were accounted for by Newtonian mechanics (due to the planets in the Solar System). The other 43 arcsecs are supplied by General Relativity.

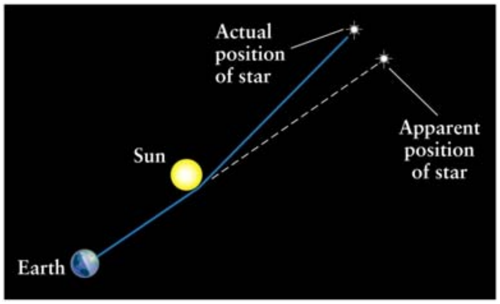


Tests of General Relativity

2. Deflection of Starlight

An eclipse expedition (1919) obtained 1.75 arcsec deflection.

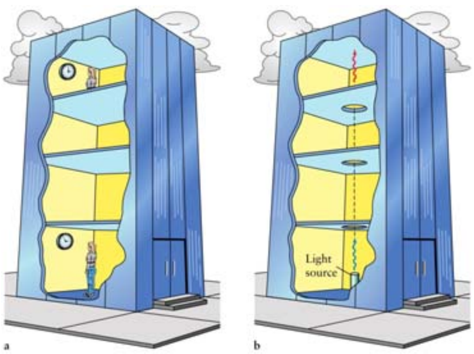
Newton's Laws do not predict that light can be bent.



Tests of General Relativity

3. Gravitational Redshift

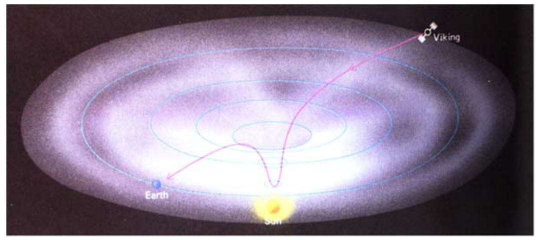
In the 1960's, an experiment using radioactive Cobalt measured a slight redshift of the upwardly emitted gamma ray. One has to have a gravitational redshift because the "top of the elevator" was moved ever so slightly toward the source in order for the desired reaction to occur.



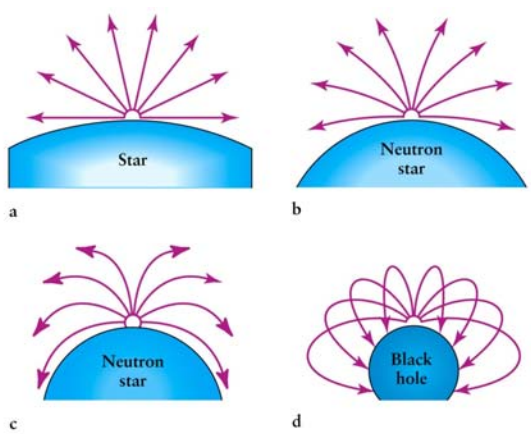
Tests of General Relativity

4. Time Delay of Light

Radar waves from the Earth to Viking on Mars and back, (when Mars is at conjunction), take 250 millionth of a second longer (about 75 km) than what the separation according to Kepler's Laws give.

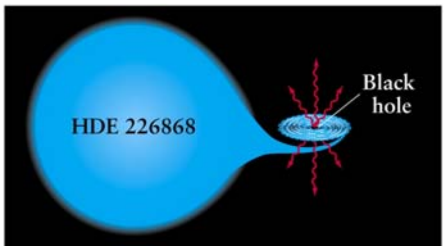


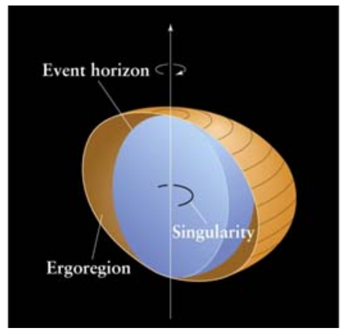
Light Deflection of a Black Hole



Only Measurable Characteristics

Mass, Electric Charge, and **Angular Momentum**





Finding Black Holes

Kepler's 3rd Law

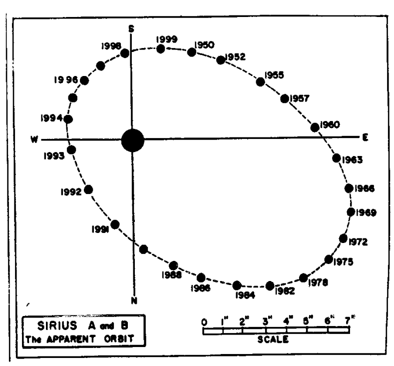
$(\mathcal{M}_1 + \mathcal{M}_2)\ P^2 = a^3$

$\mathcal{M}$ is in solar masses

P is in years, and

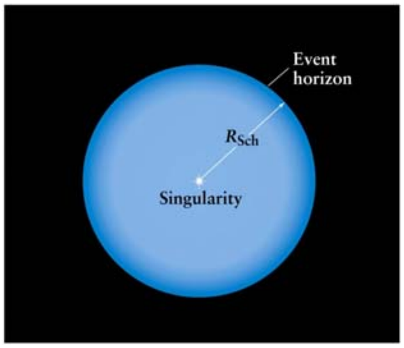
a is in Astronomical Units

(1 AU = mean Earth-Sun distance)



Kepler's Third Law Interactive

Black Holes



The **Event Horizon** is where nothing escapes. It is given by the equation:

$$\text{Radius}_{\text{Schwarzschild}} = 2\,G\,\mathcal{M} \;/\; c^2$$

One Earth-Mass Example

$$\text{Radius}_{\text{Schwarzschild}} = 2\,G\,\mathcal{M} \;/\; c^2$$

$$= 2 \times (6.668 \times 10^{-11}\ \text{N m}^2 / \text{kg}^2) \times (5.976 \times 10^{24}\ \text{kg}) \;/\; (3 \times 10^{8}\ \text{m/s})^2$$

$$= 0.0089\ \text{m} = 0.9\ \text{cm}$$

$$\approx 1\ \text{cm}$$

Mass Determines Death

$0.08 < \mathcal{M} < 0.25$	He white dwarf
$0.25 < \mathcal{M} < 8.0$	CO white dwarf
$8.0 < \mathcal{M} < 12.0$	O Ne white dwarf
$12.0 < \mathcal{M} < 40.0$	Neutron star (SN)
$40 < \mathcal{M}$	Black hole (SN)

Pressure vs Gravity – Who Wins?

Type Ia SN	Pressure	No Remnant Left
White Dwarf	Truce	Mediated by Electron Degeneracy
Neutron Star	Truce	Mediated by Neutron Degeneracy
Quark Star (?)	Truce	Mediated by Quarks
Black Hole	Gravity	No Escape for Matter