VII. On the Means of discovering the Distance, Magnitude, &c. of the Fixed Stars, in consequence of the Diminution of the Velocity of their Light, in case such a Diminution should be found to take place in any of them, and such other Data should be procured from Observations, as would be farther necessary for that Purpose. By the Rev. John Michell, B. D. F. R. S. In a Letter to Henry Cavendish, Esq. F. R. S. and A. S.

Read November 27, 1783.
The fate of a star depends on its mass (size not to scale).

- Low to Average Mass Star: White Dwarf
- Large Mass Star: Neutron Star
- Very Large Mass Star: Black Hole
Black Holes

The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.

Eventually, the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.
Neutron Star
M = 1.5 $M_{\text{sun}}$
$R_{S} \approx 10$ km

Black Hole
M = 1.5 $M_{\text{sun}}$
$R_{S} = 4.5$ km

Manhattan
(spaceimaging.com)
Event Horizon

Schwarzschild radius

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

Singularity
The gravitational effects of a black hole are unnoticeable outside of a few Schwarzschild radii—black holes do not “suck in” material any more than an extended mass would.

“FALSE. AN OBJECT WOULD HAVE TO BE AS CLOSE AS ABOUT 10 KM TO THE BLACK HOLE’S CENTER BEFORE THEY BEGAN SPIRALING IN.”
Matter encountering a black hole will experience enormous tidal forces that will both heat it enough to radiate, and tear it apart...

“Spaghettification”!
Types of Black Holes--

1- Supermassive Black holes.

2- Stellar- mass black holes.

3- Intermediate mass black holes.

+ (Perhaps) “Primordial” Mini- or Micro-Black Holes!
XTE J1650-500

One of the smallest, but already a destroyer of worlds.

Link to Video, “Black Hole Comparison”:
https://www.youtube.com/watch?v=QgNDao7m41M
29. If there should really exist in nature any bodies, whose density is not less than that of the sun, and whose diameters are more than 500 times the diameter of the sun, since their light could not arrive at us; or if there should exist any other bodies of a somewhat smaller size, which are not naturally luminous; of the existence of bodies under either of these circumstances, we could have no information from sight; yet, if any other luminous bodies should happen to revolve about them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones with some degree of probability, as this might afford a clue to some of the apparent irregularities of the revolving bodies, which would not be easily explicable on any other hypothesis; but as the consequences of such a supposition are very obvious, and the consideration of them somewhat beside my present purpose, I shall not prosecute them any farther.
Observational Evidence for Black Holes: “Gravitational Lensing” (from the Gravitational Deflection of Light)
Gravitational Lensing (cont’d.)
This bright star has an unseen companion that is a strong X-ray emitter called Cygnus X-1, which is thought to be a black hole!

Cygnus X-1 is a very strong black-hole candidate:

- Its visible partner is about 25 solar masses.
- The system’s total mass is about 35 solar masses, so the X-ray source must be about 10 solar masses.
- Hot gas appears to be flowing from the visible star to an unseen companion.
- Short time-scale variations indicate that the source must be very small.
The existence of black-hole binary partners for ordinary stars can be inferred by the effect the holes have on the star’s orbit, or by radiation from infalling matter.
There are several other black-hole candidates as well, with characteristics similar to those of Cygnus X-1.

The centers of many galaxies contain supermassive black hole—about 1 million solar masses.

Observational Evidence for Black Holes
Recently, evidence for intermediate-mass black holes has been found; these are about 100 to 1000 solar masses. Their origin is not well understood.
The heart of the Milky Way... 26,000 light years away

- Arched Filaments
- X-ray Binary Star
- Quintuplet Cluster
- Pistol Star
- Sickle
- Sagittarius A

50 Light Years Scale
Kerr (Rotating) Black Hole

- The singularity of a Kerr black hole is located in an infinitely thin ring around the center of the hole.
- The event horizon is a spherical surface.
- The doughnut-shaped region is called the ergoregion.
- Space in the ergoregion is being curved or pulled around by the rotating black hole.
Kerr Black Hole

- Outer Event Horizon
- Singularity
- Inner Event Horizon
- High-Speed Jets
- Accretion Disk
- Ergosphere

axis of rotation

outer horizon
inner horizon
singularity
static limit
ergosphere

Probing the edge of a Black Hole

- High speed jets ejected by Black Hole.
- Disk of material spiraling into Black Hole.

Detail of Black Hole region.
Size found by new observations
Nature of Black Hole

General Relativity - once a black hole is created, it will last forever since nothing can escape it.

Quantum Mechanics - all black holes will eventually evaporate as they slowly leak Hawking radiation.

Hawking Radiation Detailed...

Cosmic refugees. Virtual particles that escape destruction near a black hole (case 3) create detectable radiation but can’t carry information.

Typical Time of Evaporation

<table>
<thead>
<tr>
<th>Black hole with mass about</th>
<th>Time for evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A man</td>
<td>$10^{-12}$ seconds</td>
</tr>
<tr>
<td>A building</td>
<td>4 seconds</td>
</tr>
<tr>
<td>The Earth</td>
<td>$10^{49}$ years</td>
</tr>
<tr>
<td>The Sun</td>
<td>$10^{66}$ years</td>
</tr>
<tr>
<td>A galaxy</td>
<td>$10^{99}$ years</td>
</tr>
</tbody>
</table>

For reference, the age of the universe is about $10^{10}$ years.
A probe nearing the event horizon of a black hole will be seen by observers as experiencing a dramatic redshift as it gets closer, so that time appears to be going more and more slowly as it approaches the event horizon.

This is called a gravitational redshift—it is not due to motion, but to the large gravitational fields present.

The probe, however, does not experience any such shifts; time would appear normal to anyone inside.

Similarly, a photon escaping from the vicinity of a black hole will use up a lot of energy doing so; it cannot slow down, but its wavelength gets longer and longer...
Time Dilation near the “Event Horizon” of a Black Hole:

\[ r_S = \frac{2Gm}{c^2} \]

\[ \frac{t'}{t} = \sqrt{1 - \frac{r_S}{r}} \]

- \( t' \) is the elapsed time for Observer A
- \( t \) is the elapsed time for Observer B
- \( G \) is the gravitational constant
- \( c \) is the speed of light