The Color-Magnitude or HR Diagram
Low-Mass stars (like the Sun) evolve into Red Giants, then White Dwarfs. High-Mass stars explode, leaving a neutron star or a black hole.
Evolution onto the Main Sequence
Evolution off of the Main Sequence

- **SUPERGIANTS (I)**
- **AGB**
- **Helium flash**
- **GIANTS (II,III)**
- **RGB**
- **WHITE DWARFS (wd)**

**Key Terms:**
- RGB - Red Giant Branch
- HB - Horizontal Branch
- AGB - Asymptotic Giant Branch
Evolution of a Sun-Like Star

Sunlike star evolution into a white dwarf and planetary nebula
Planetary Nebulae

Cat’s Eye Nebula • NGC 6543

Helix Nebula • NGC 7293
Hubble Space Telescope • Advanced Camera for Surveys
NOAO 0.9m • Mosaic I Camera
MESA Movie of the Solar Evolution

This is from the MESA stellar evolution code.
Globular Cluster stars are all about the same age. We can tell the age by where the main sequence ends.
Evolution of a Massive Star
Basics of Nuclear Energy

We can gain energy by either splitting heavy nuclei (nuclear fission, which powers nuclear reactors), or by putting together light nuclei (nuclear fusion, which powers the stars). Iron is the most stable nucleus.
Massive stars have an “onion-like” structure, with each layer being successively hotter and fusing more massive elements. Iron is the end-point of nuclear fusion - no more energy can be produced by fusing iron.
Supernovae - Massive Stellar Explosions

- After a massive star has exhausted its nuclear fuel, the core collapses and the star explodes in an enormous explosion.
- There is about 1 supernova per galaxy per century.
Supernova Remnants

The Crab Nebula - M1. This supernova exploded in 1054.

This supernova exploded in 1006.
Endpoints of Stellar Evolution - Compact Objects

1. **White dwarfs - end point of sun-like stars.**
   - White dwarfs have about the mass of the sun, but are about the size of the Earth.
   - A teaspoonful of white dwarf material would weigh approximately 1 ton.

2. **Neutron stars - end point of massive stars.**
   - Neutron stars have about the mass of the sun, but are about the size of Manhattan.
   - A teaspoonful of neutron star material would weigh approximately 100 million tons.

3. **Black holes - end point of massive stars.**
   - A black hole curves space so strongly that nothing, not even light, can escape.
   - A black hole the mass of the sun has a radius of 3 km.
Sources of Pressure to Resist Gravitational Collapse

**Mass < 1.4 solar masses**

**White Dwarf**

*Electrons* run out of room to move around. *Electrons* prevent further collapse. *Protons* & *neutrons* still free to move around.

Stronger gravity => more compact.

**Mass > 1.4 solar masses but mass < 3 solar masses**

**Neutron Star**

*Electrons* + *protons* combine to form *neutrons*. *Neutrons* run out of room to move around. *Neutrons* prevent further collapse. Much smaller!

**Mass > 3 solar masses**

**Black Hole**

Gravity wins! Nothing prevents collapse.
White Dwarfs

Sirius has a white dwarf companion called Sirius B.
White Dwarf stars are quite common, as you can see from this HST image.
Neutron Stars

1. Neutron stars are extremely dense objects.
   - Basically the same density as an atomic nucleus.

2. Neutron stars were first discovered as pulsars.
   - Pulsars are pulsating radio sources.
   - They pulse from every few seconds to about 1000 times per second.
   - The pulses are caused by the rotation of a magnetized neutron star.
   - The magnetic fields are huge - billions to trillions of times larger than a typical magnet.
   - We have discovered tens of thousands of these objects.
Pulsars - Rotating Magnetized Neutron Stars

X-ray image of the Crab pulsar.

Model of pulsar structure.
Pulsar P - Pdot Diagram

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer
Pulsars cluster in the plane of the galaxy because that is where the massive stars are formed.
Einstein’s theory of gravity (General Relativity) predicts the existence of black holes.

- Black holes are collapsed objects where gravity overwhelms all other forces.

- Black holes have an *Event Horizon*. Once inside the event horizon, nothing, not even light, can escape.

- The region inside the event horizon is “causally disconnected” from the rest of the universe, meaning it can no longer interact with the region outside the event horizon.

- We can approximate the size of the event horizon by the assumption that the escape velocity is equal to the speed of light (next page):
We can approximate the size of the event horizon by the assumption that the escape velocity is equal to the speed of light:

\[ V_{\text{Escape}} = \sqrt{\frac{2GM}{R}} \]

Use speed of light (c) for escape velocity:

\[ R_{\text{Event Horizon}} = \frac{2GM}{c^2} \]

For the mass of the sun:

\[ R_{EH} = \frac{2GM_{\text{Sun}}}{c^2} = \frac{2 \times 6.7 \times 10^{-11} \frac{m^3}{kg \ s^2} \times 2 \times 10^{30} \ kg}{(3.0 \times 10^8 \frac{m}{s})^2} = 3.0 \ km \]
We’re almost sure that black holes exist, but none has been seen directly:

- We see hot, X-ray emitting objects which appear to be hot gas falling into black holes.

- At the center of our galaxy, we see stars orbiting an invisible object with a mass of 4 million times the mass of the sun.

- We think all galaxies have a Super-Massive Black Hole (SMBH) at their centers.

- We see these objects emitting radiation due to the hot gas spiraling into them.

There are plans to image the black hole at the center of our galaxy directly within the next decade with arrays of radio telescopes.
Binary star system

Visible star

Black hole

Accretion disk

Gas temperature increases closer to black hole. Gas closest to black hole emits X-rays!

X-ray brightness fluctuates very rapidly => very small size

Visible star and black hole orbit the **center of mass**. See visible star “wobble”.
Cygnus-X1 - A Stellar-Mass Black Hole

Artist’s conception of Cygnus-X1.

This is believed to be a black hole “feeding” off its companion star.
M87 - An active Super-Massive Black Hole (SMBH)

Composite photograph of M87 galaxy in Virgo.

This black hole is believed to mass more than 10 billion times the Sun.
Gamma Ray Bursts - The Birth of Black Holes?

Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.

Jet
Torus
Gamma rays

Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.

*Possibly neutron stars.
Gamma Ray Bursts come from outside our galaxy

The uniform distribution implies an extragalactic origin. We see about one GRB each day.
We have models of the production of the chemical elements which largely agree with what we measure.

The Big Bang produced mainly hydrogen ($\approx 75\%$) and helium ($\approx 25\%$).

All heavier elements were produced by nuclear fusion inside stars.

Stars like the sun only produce elements up to carbon or oxygen.

Heavier elements than this were produced in massive stars and then scattered through the galaxy by supernova explosions.

As the song goes “We are stardust.”
Abundance of the Chemical Elements

The graph shows the abundance of various chemical elements plotted against their atomic numbers (Z). The abundance is given in logarithmic scale (Log_{10}(Abundance)). The abundance of Si is normalized to 10^6. The elements are labeled along the graph, with a general decreasing trend in abundance as you move from left to right along the graph.
Stars evolve onto the Main Sequence, then reside there until their hydrogen fuel is exhausted.

Stars like the sun expand into red giants, shed their outer layers, and then become white dwarfs.

White dwarf stars have about the mass of the sun, but are about the size of the Earth.

More massive stars expand into supergiants, then explode in massive explosions called supernovae.

They then collapse into neutron stars or black holes.

Neutron stars have about the mass of the sun, but are about the size of Manhattan.

Black holes are collapsed objects from which nothing can escape.

The chemical elements heavier than helium were forged in the interiors of stars.