# Observational Astronomy - Lecture 9
# Stars II - Structure and Evolution

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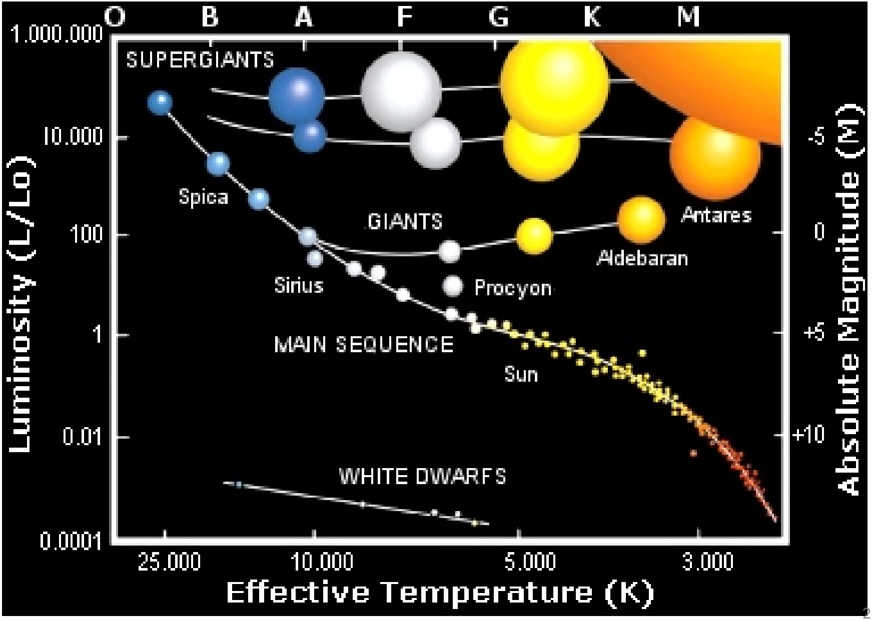
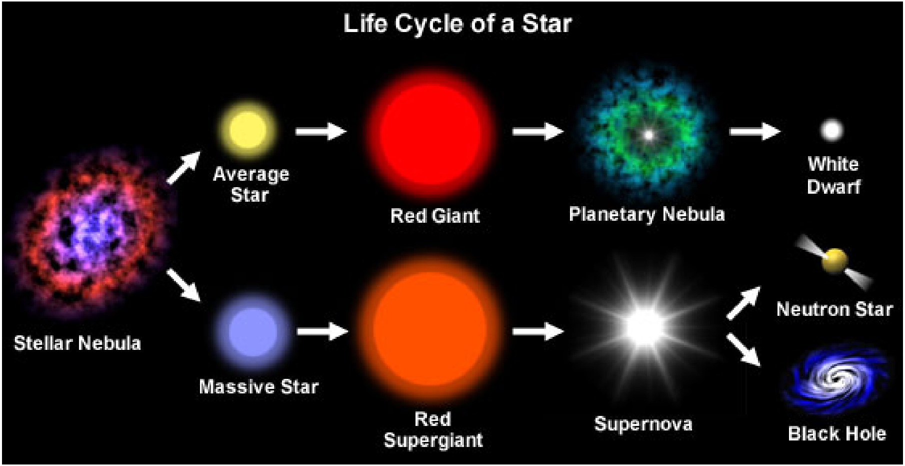
April 12, 2014

# The Color-Magnitude or HR Diagram

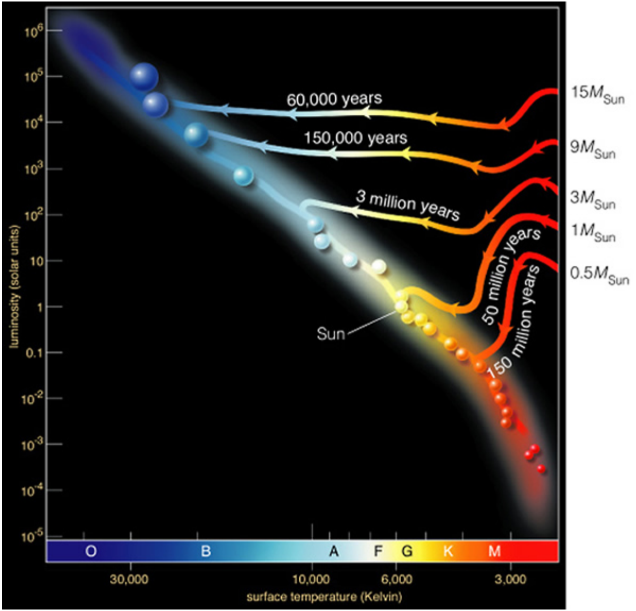


# Basic Chart of Stellar Evolution

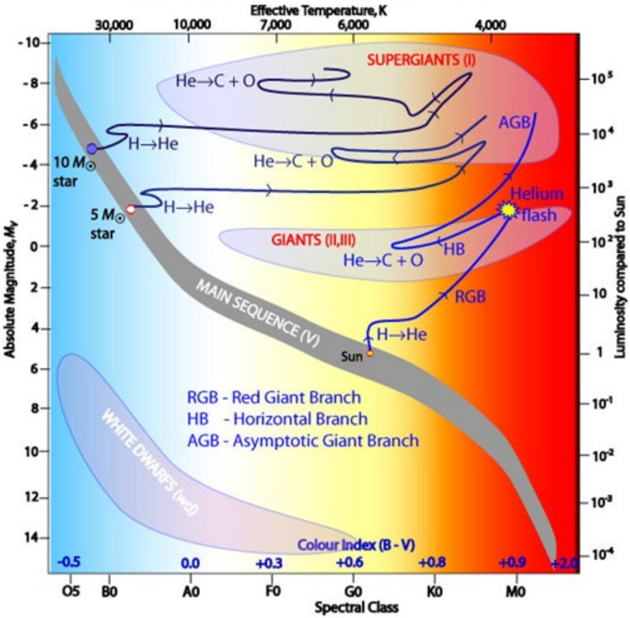



Low-Mass stars (like the Sun) evolve into Red Giants, then White Dwarfs.
High-Mass stars explode, leaving a neutron star or a black hole.

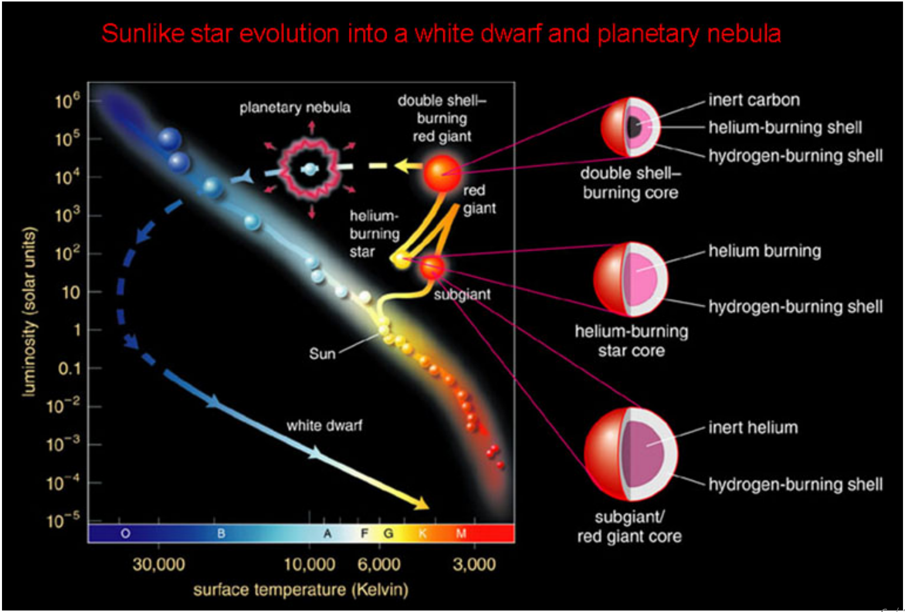
# Evolution onto the Main Sequence



# Evolution off of the Main Sequence

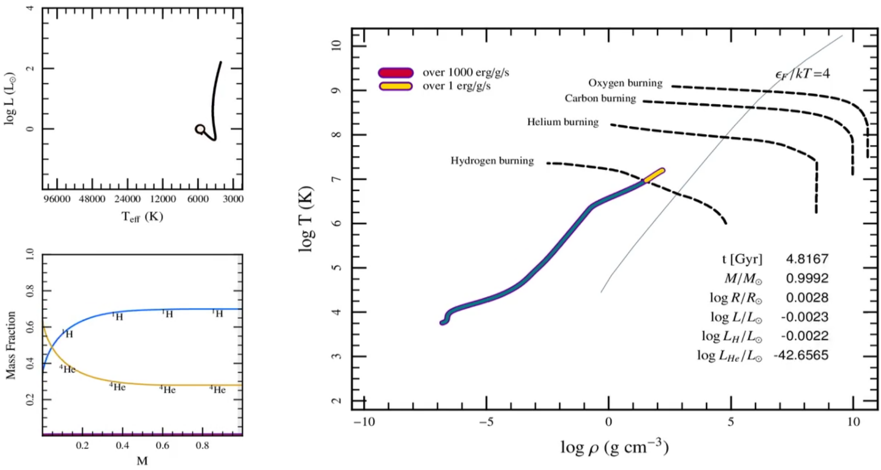


# Evolution of a Sun-Like Star



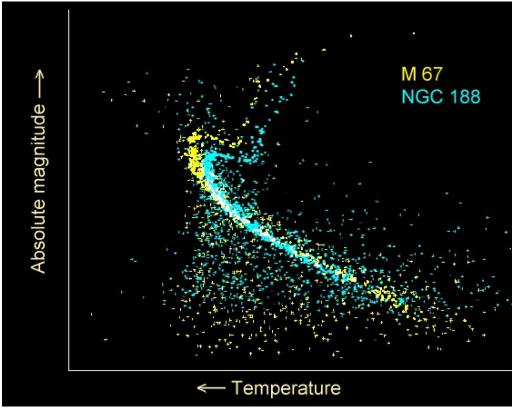
# Planetary Nebulae


# MESA Movie of the Solar Evolution



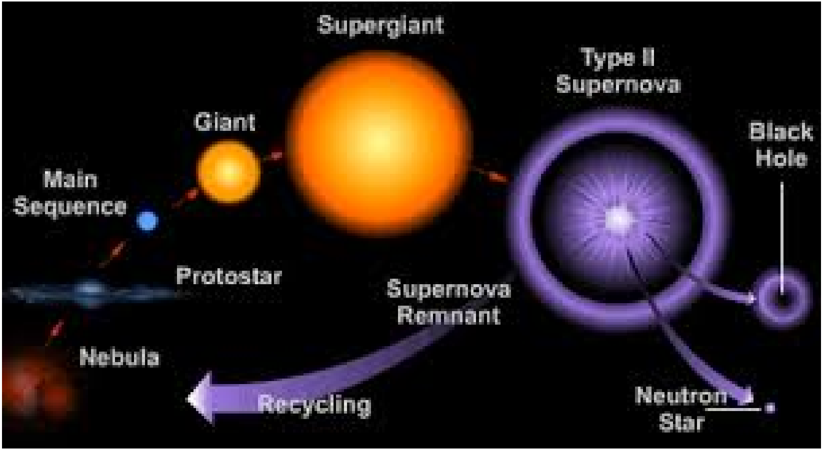

This is from the MESA stellar evolution code.

# HR Diagrams of Globular Clusters

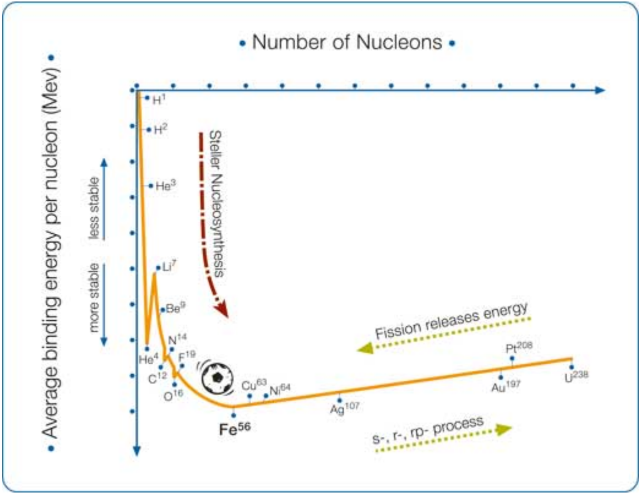



Globular Cluster stars are all about the same age.
We can tell the age by where the main sequence ends.

# Evolution of a Massive Star

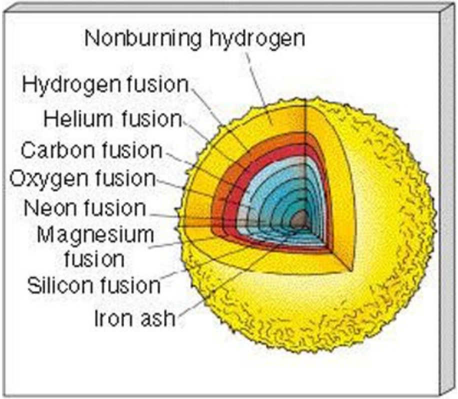


# Basics of Nuclear Energy




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.

# Structure of a Massive Star




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.

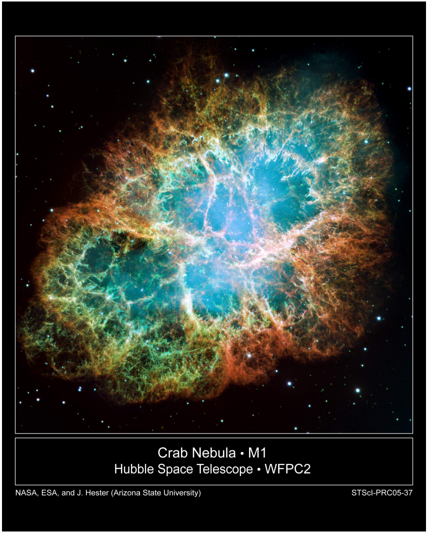
# Supernovae - Massive Stellar Explosions

SN1987A in the Large Magellanic Cloud.

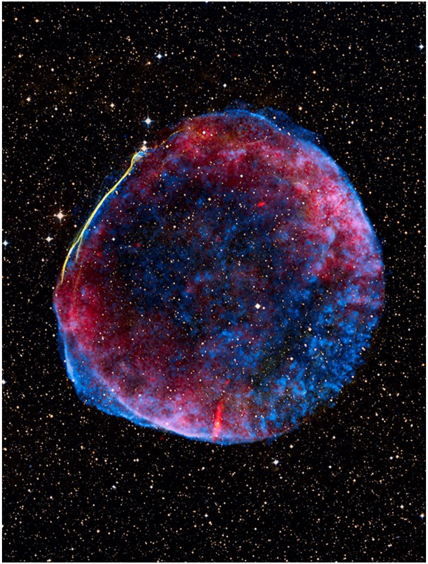

SN2011fe in M101.

- 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.

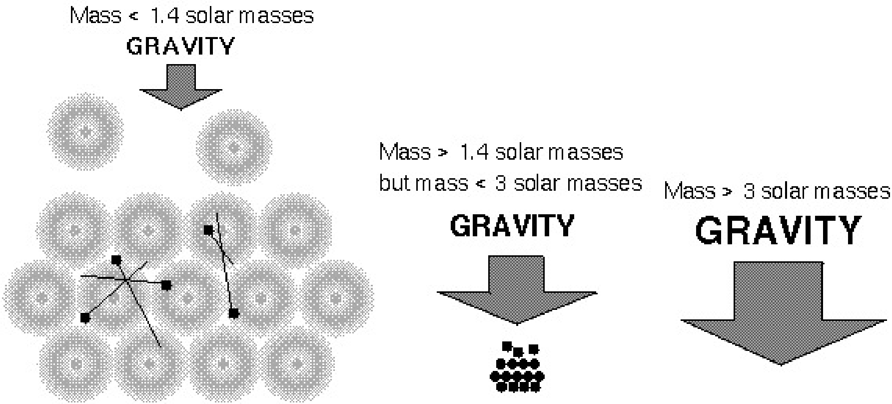


This supernova exploded in 1006.

# 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




**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.

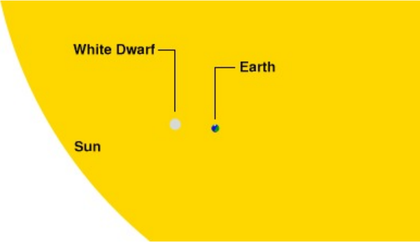
**Neutron Star**

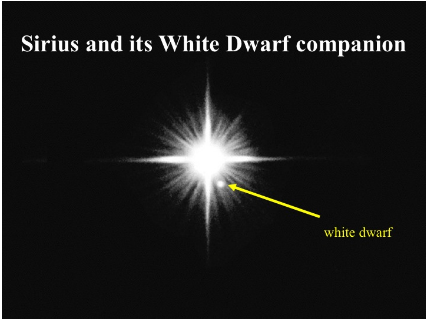
Electrons + protons combine to form neutrons. Neutrons run out of room to move around. Neutrons prevent further collapse. Much smaller!

**Black Hole**

Gravity wins! Nothing prevents collapse.

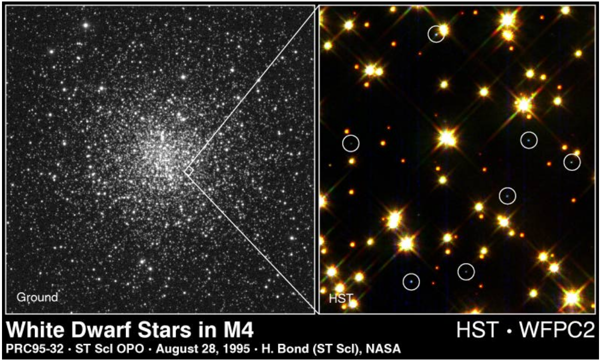
# White Dwarfs

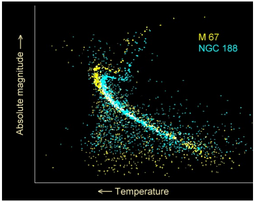



Sirius has a white dwarf companion called Sirius B.

# White Dwarfs in the Globular Cluster M4



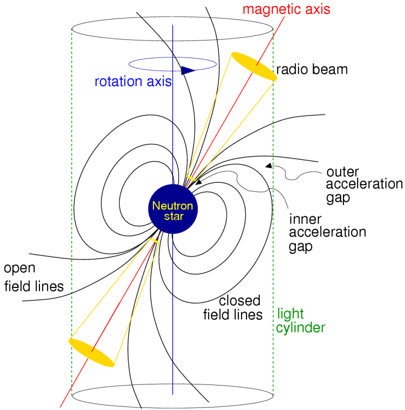

White Dwarf stars are quite common, as you can see from this HST image.

# 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.

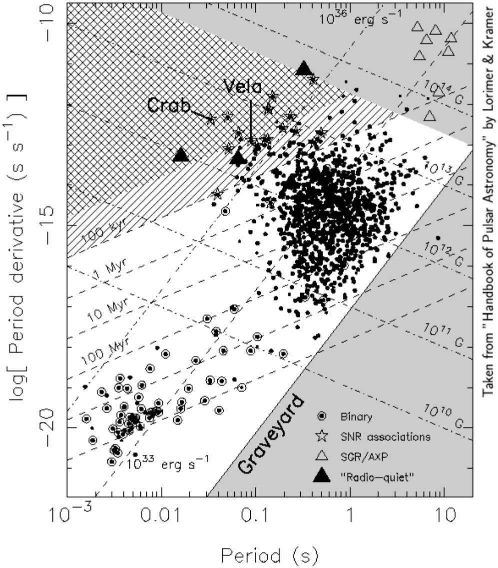
# Pulsars - Rotating Magnetized Neutron Stars

X-ray image of the Crab pulsar.

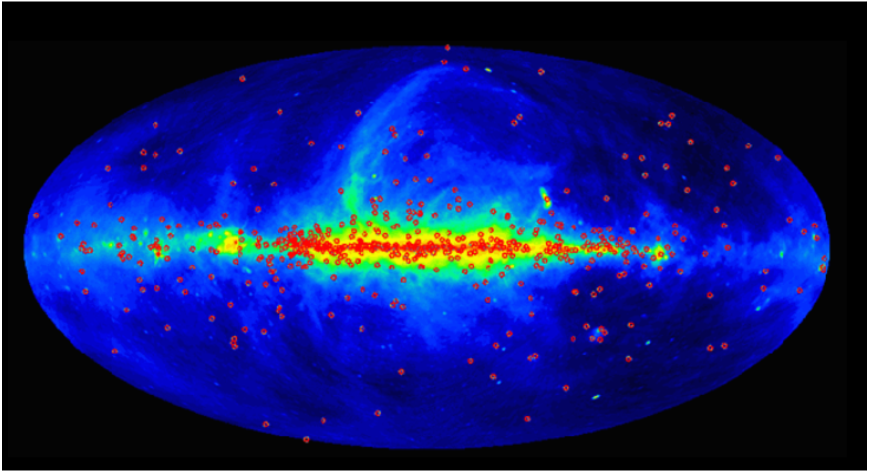



Model of pulsar structure.

# Pulsar P - Pdot Diagram



# Distribution of Galactic Pulsars



Pulsars cluster in the plane of the galaxy because that is where the massive stars are formed.

# Black Holes - 1

- 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):

# Black Holes - 2

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

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

- Use speed of light (c) for escape velocity:

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

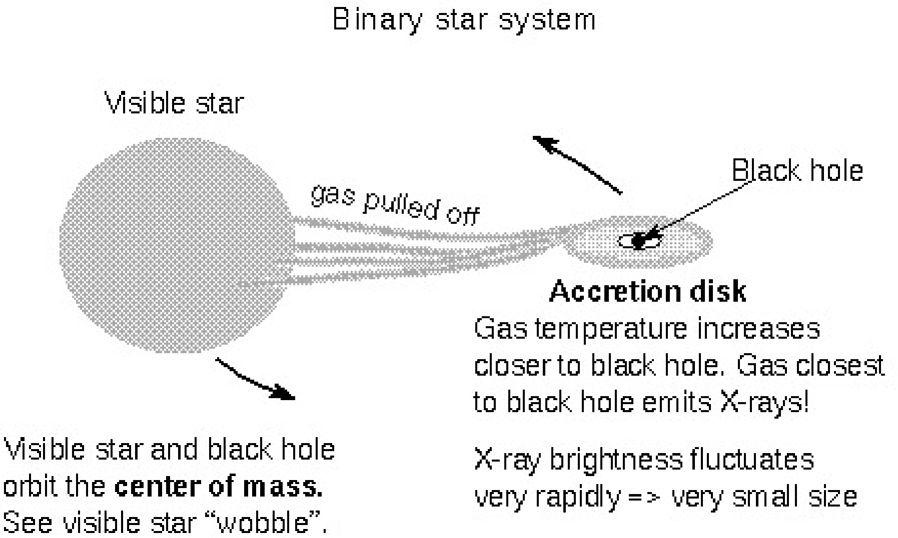
- For the mass of the sun:

$$R_{EH} = \frac{2GM_{Sun}}{c^2} = \frac{2 \times 6.7 \times 10^{-11} \frac{m^3}{kg\, s^2} \times 2 \times 10^{30}\, kg}{(3.0 \times 10^8 \frac{m}{s})^2} = 3.0\, km$$

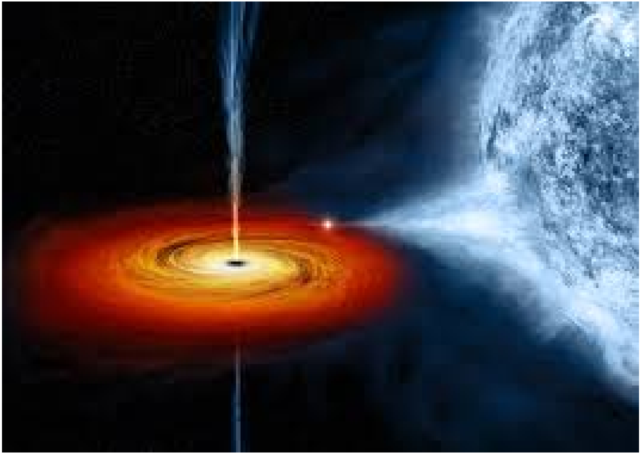
# Black Holes - 3

- 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.

# Black Hole Accretion Disk Schematic



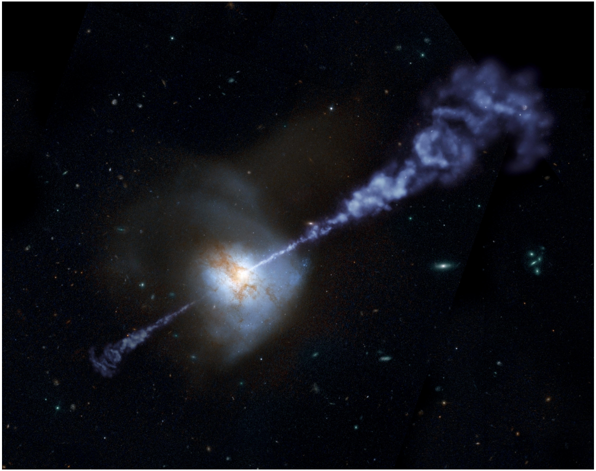
# Cygnus-X1 - A Stellar-Mass Black Hole



Artist's conception of Cygnus-X1.

This is believed to be a black hole "feeding" off its companion star.

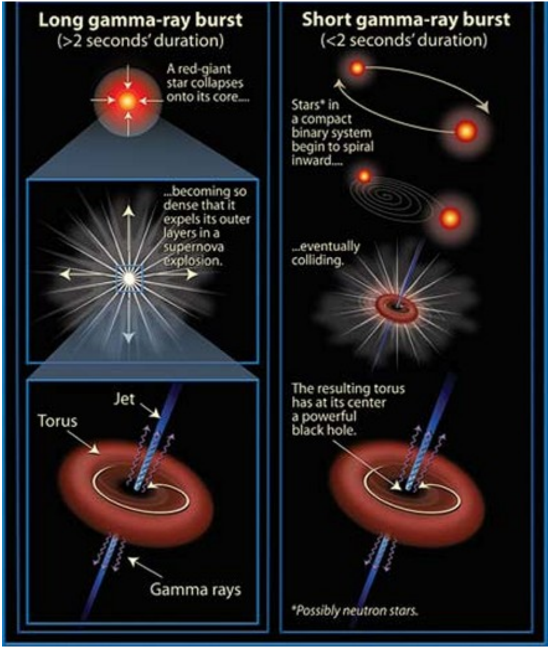
# M87 - An active Super-Massive Black Hole (SMBH)



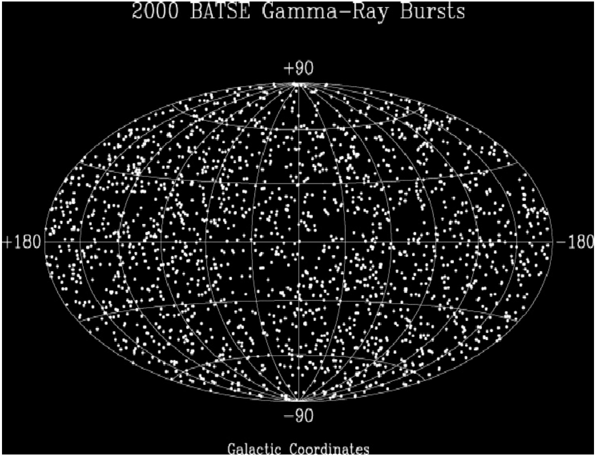
Composite photograph of M87 galaxy in Virgo.

This black hole is believed to mass more than 10 billion times the Sun.

# Gamma Ray Bursts - The Birth of Black Holes?



# Gamma Ray Bursts come from outside our galaxy

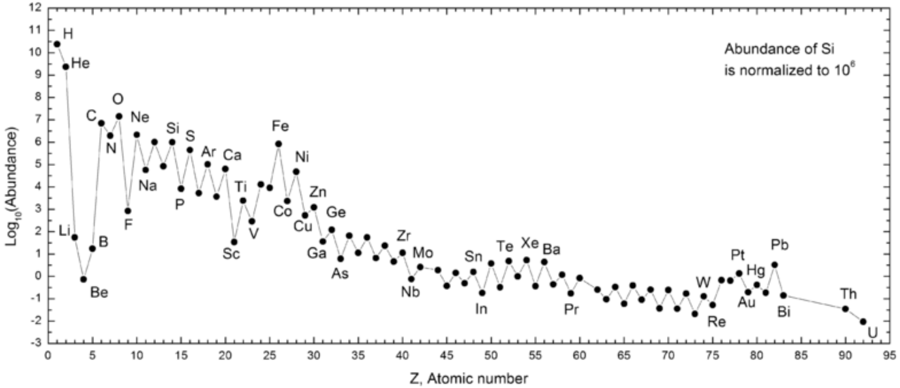



The uniform distribution implies an extragalactic origin.
We see about one GRB each day.

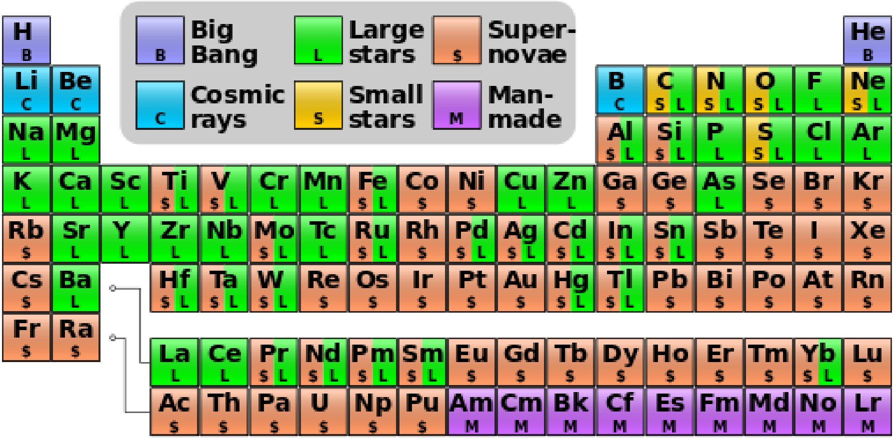
# Production of Elements

- 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



# Origin of the Chemical Elements



# Summary

1. Stars evolve onto the Main Sequence, then reside there until their hydrogen fuel is exhausted.
2. Stars like the sun expand into red giants, shed their outer layers, and then become white dwarfs.
3. White dwarf stars have about the mass of the sun, but are about the size of the Earth.
4. More massive stars expand into supergiants, then explode in massive explosions called supernovae.
5. They then collapse into neutron stars or black holes.
6. Neutron stars have about the mass of the sun, but are about the size of Manhattan.
7. Black holes are collapsed objects from which nothing can escape.
8. The chemical elements heavier than helium were forged in the interiors of stars.