Life Cycle of the Stars

Life and Death of Stars

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Questions from last session


Large and Small Magellanic Clouds

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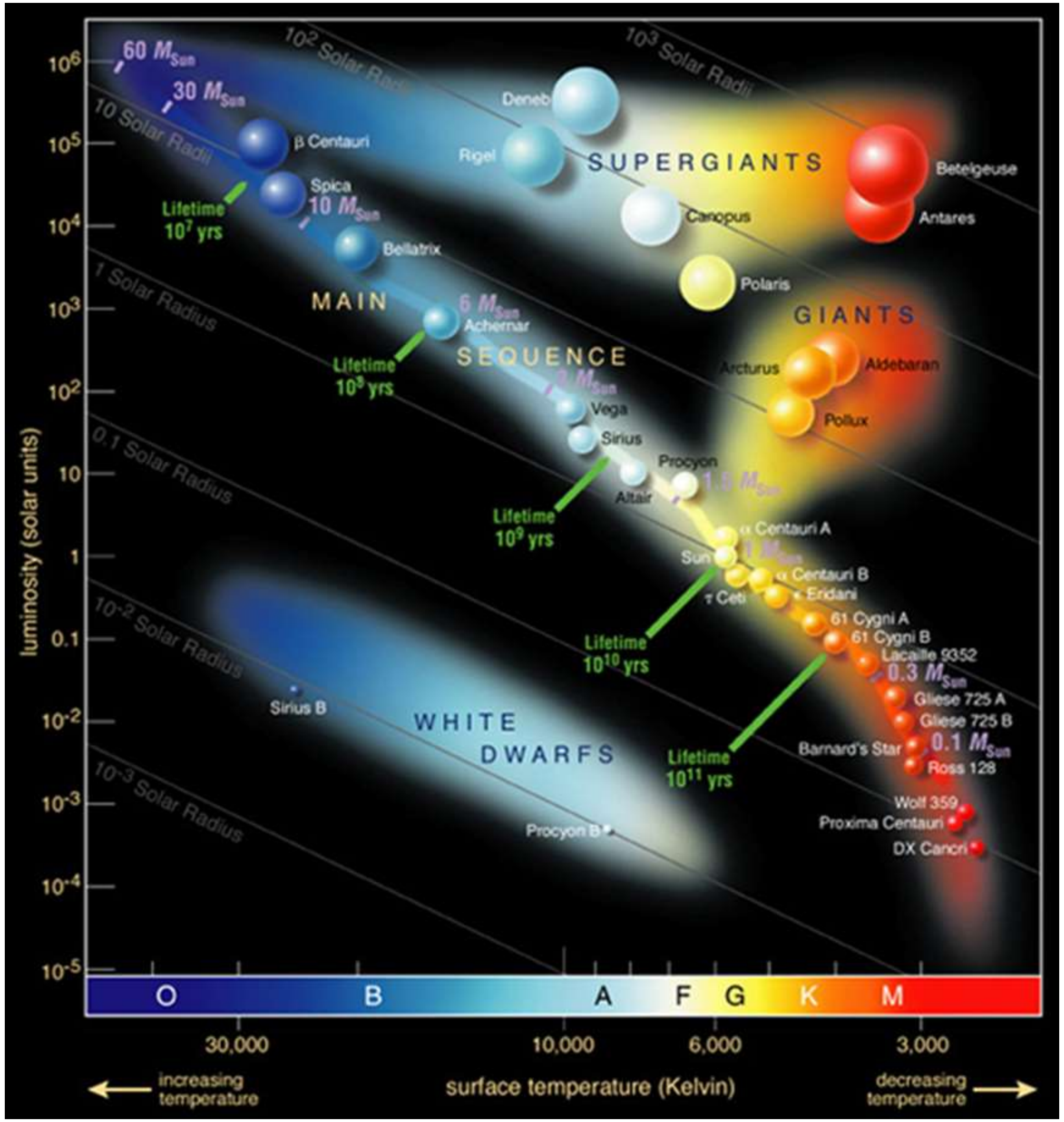
- **Large** and **Small Magellanic Clouds** Large and Small Magellanic Clouds are two irregular **galaxies** about 200,000 light years away
- They orbit the **Milky Way** once every 1,500 million years
- They orbit each other once every 900 million years
- They are now forming new stars at a rapid rate
- **Henrietta Leavitt** discovered (1908) the period-luminosity relation for **Cepheids** while studying variable stars in the SMC

- The earliest point in time we can ever look back and "**see**" is about 380,000 years after the Big Bang –prior to then the universe was opaque

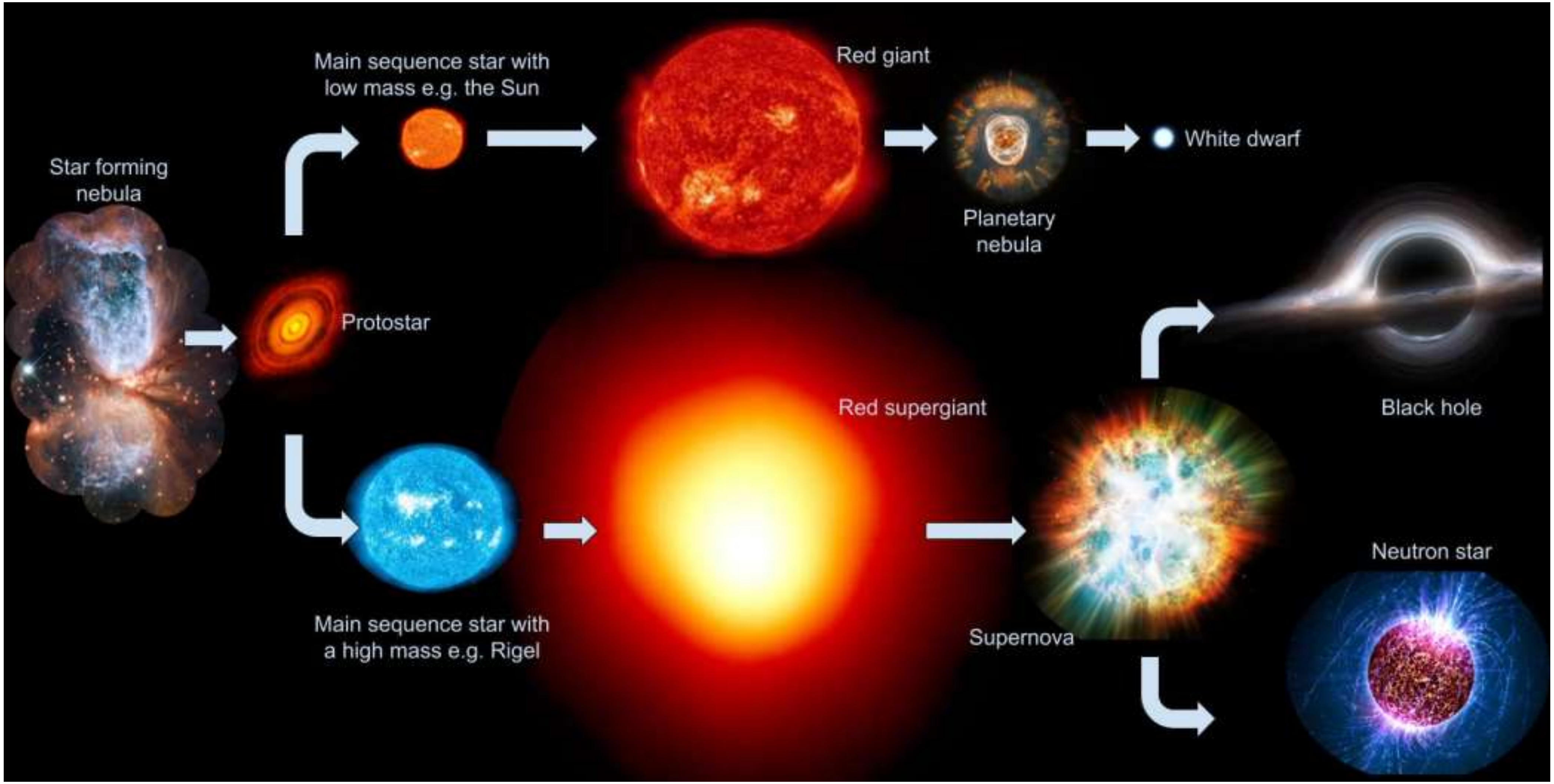
- Second generation stars are visible in the Milky Way
- They contain very little heavier elements since they were formed from first generation stars that were nearly totally hydrogen and helium

Main Sequence Stars-H-R Diagram

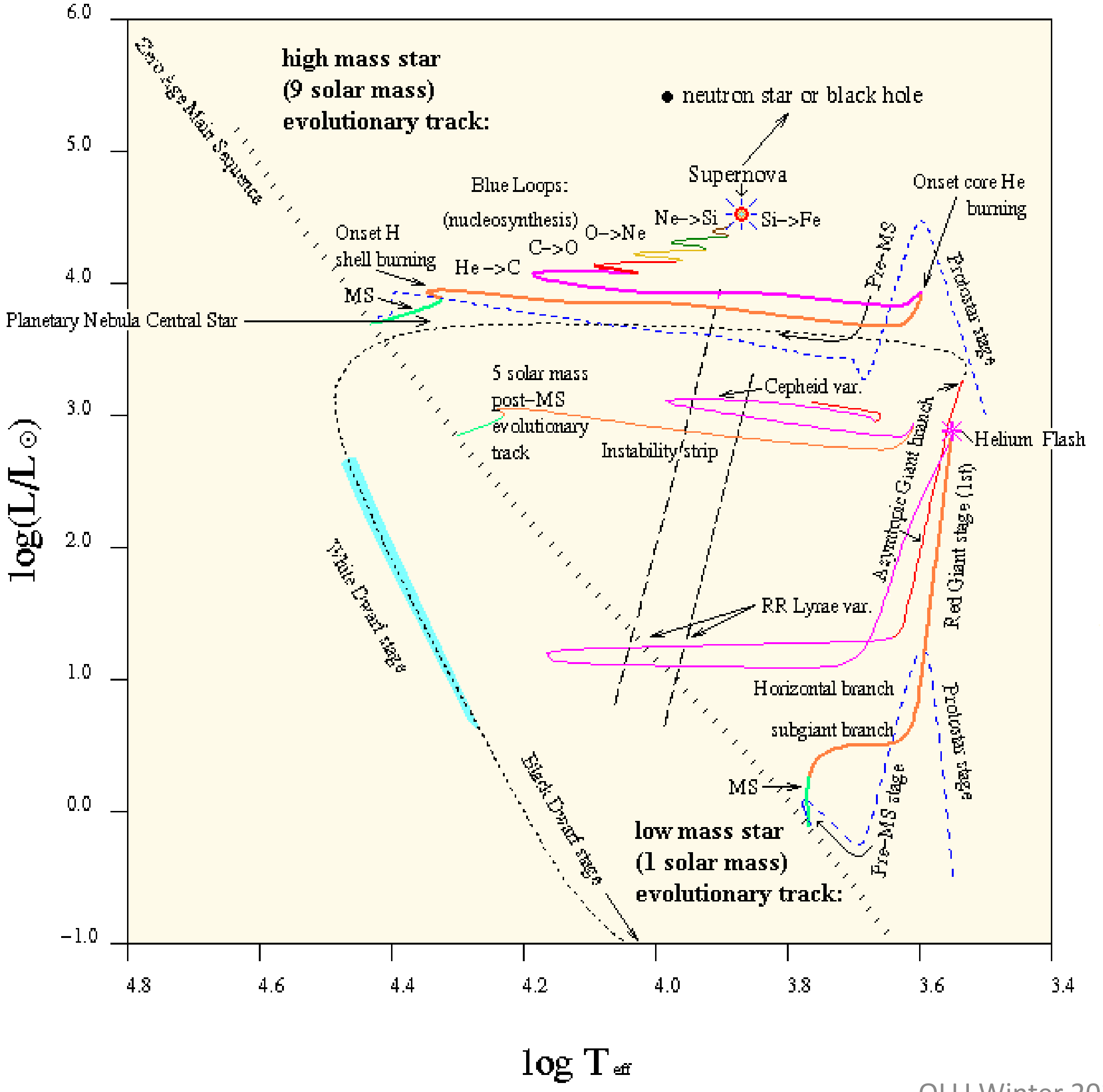


- **Main sequence** stars fuse hydrogen nuclei to form helium nuclei in their cores
- About 90 percent of the stars in the universe are main sequence stars
- They can range from about a tenth of the mass of the Sun to up to 200 times as massive
- Stars start their lives as clouds of dust and gas
- Gravity draws these clouds together
- A **protostar** forms, powered by the collapsing material
- If the proto star has sufficient mass, the collapsing gas and dust gets hotter, eventually reaching temperatures sufficient to fuse hydrogen nuclei into helium nuclei, releasing energy
- The star turns on and becomes a main sequence star, powered by hydrogen fusion

Evolution of Main Sequence Stars



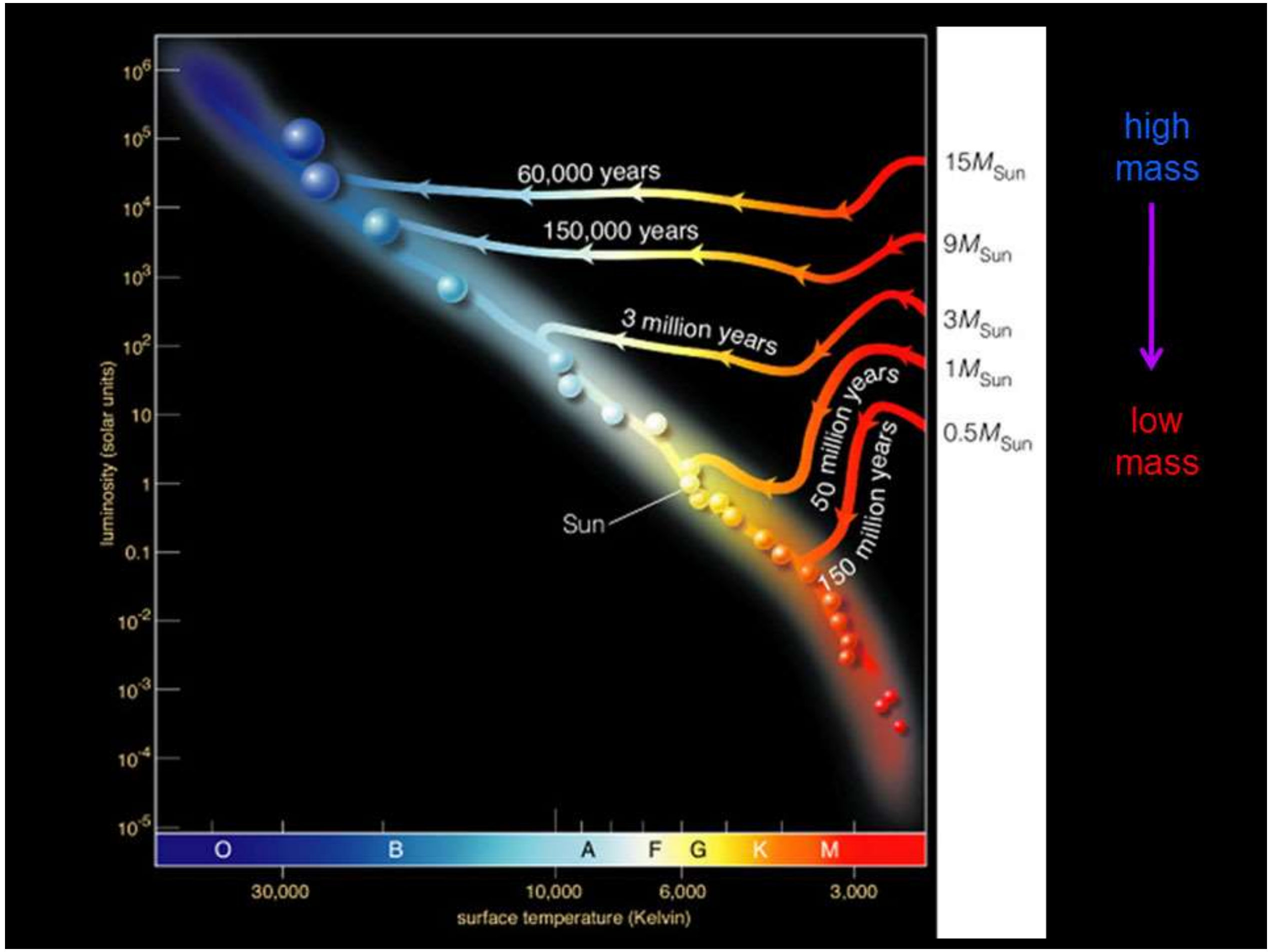
Low & High Mass Star Evolutionary Tracks



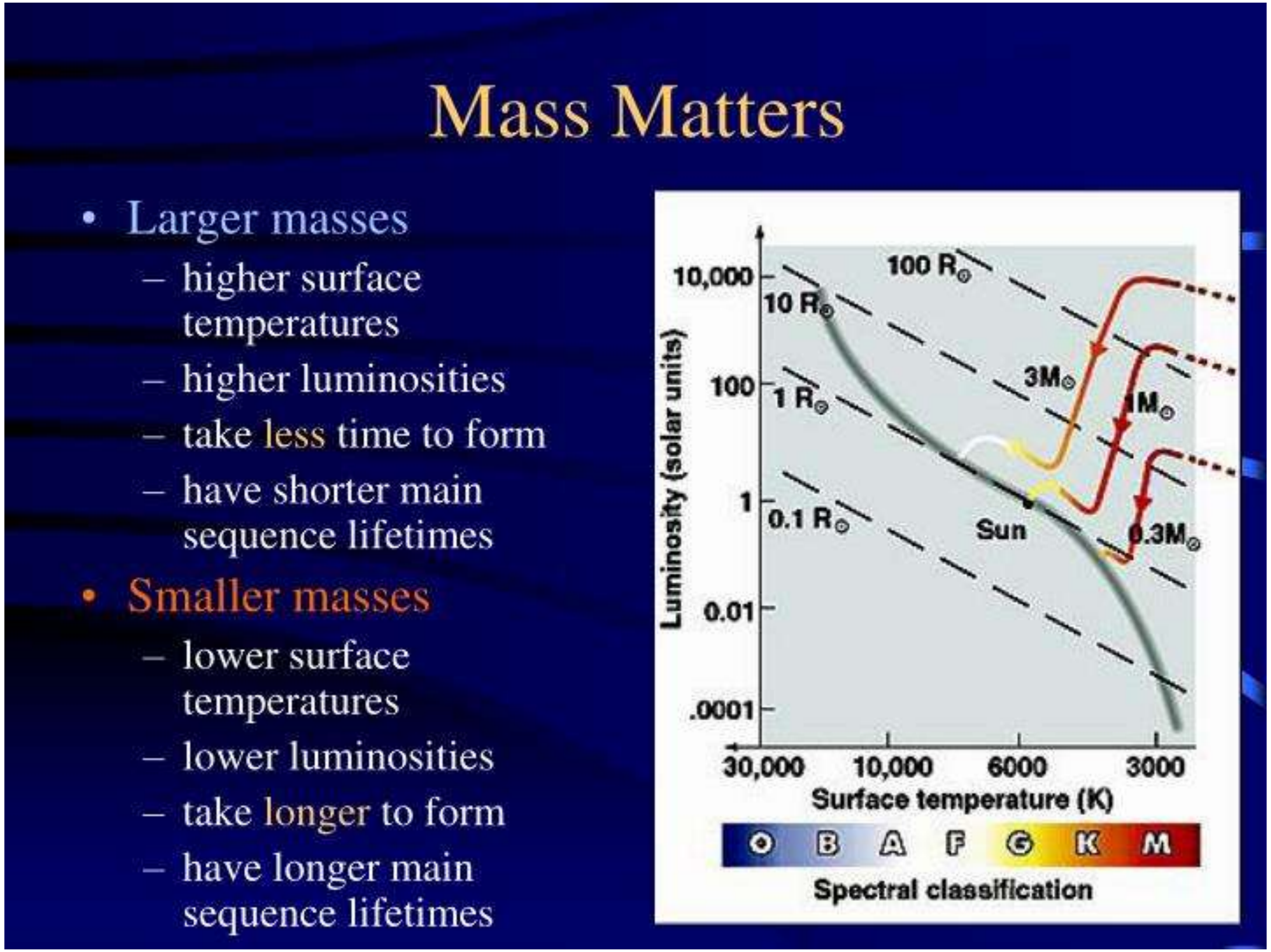
- Main Sequence Stars
- Red Giants
- White Dwarfs
- Neutron Stars
- Supernovae
- Planetary Nebula
- Pulsars
- Quasars-not stars
- Black Holes

Joining the Main Sequence

- Time to join the main sequence is a function of mass
- Massive stars join quickly ~60,000 years
- Lower mass stars join slowly ~50 million + years



Joining the Main Sequence



Mass Matters

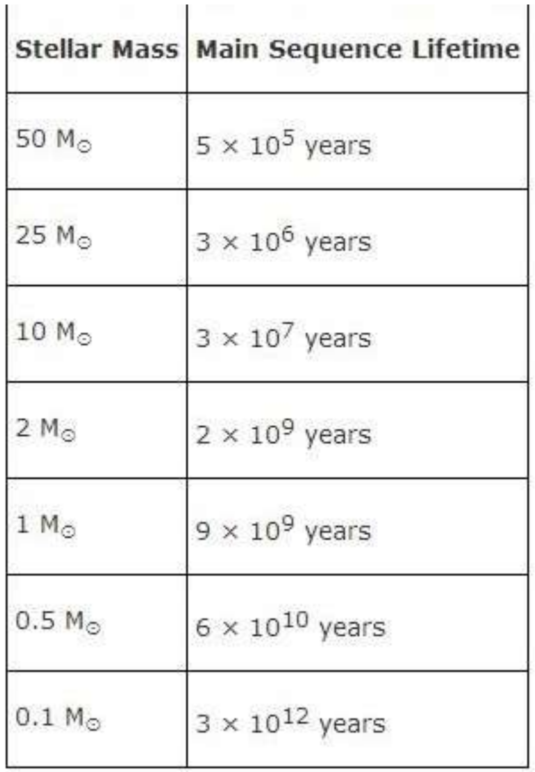
- Larger masses
  - higher surface temperatures
  - higher luminosities
  - take less time to form
  - have shorter main sequence lifetimes
- Smaller masses
  - lower surface temperatures
  - lower luminosities
  - take longer to form
  - have longer main sequence lifetimes

Main Sequence Stars

- Stars spend abut 90% of their lives as Main Sequence Stars
- The length of a star's main sequence life depends on the amount of hydrogen in the star's core and the rate at which it is consumed
- The more massive the star, the shorter its main sequence lifetime
- The **Sun** has been a main sequence life for almost 4.56 billion years and should remain one for about another 7 billion years
- During a star's main sequence lifetime, a star will expand some what and its luminosity will increase modestly
- The lifetime of a main sequence star can be estimated in terms of its number of solar masses:

$$\tau \approx 10^{10}\left(\frac{M_\odot}{M}\right)^{2.5} yrs$$

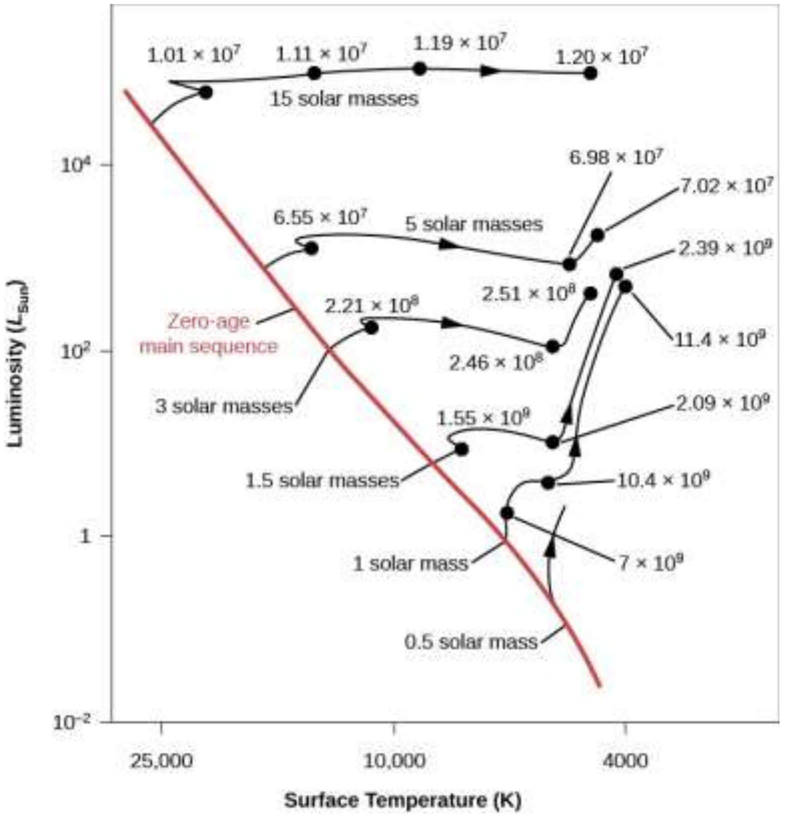
- Approximate Main sequence Lifetimes



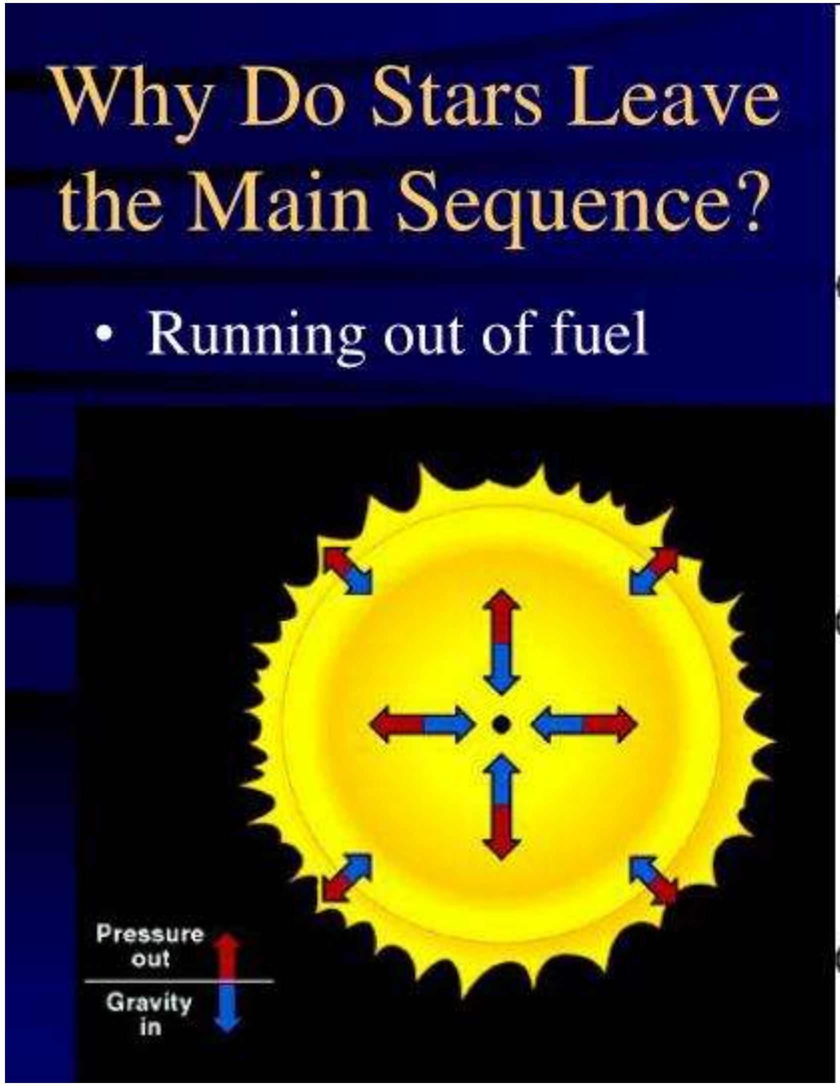
Stellar Mass	Main Sequence Lifetime
50 $M_\odot$	5×10^5 years
25 $M_\odot$	3×10^6 years
10 $M_\odot$	3×10^7 years
2 $M_\odot$	2×10^9 years
1 $M_\odot$	9×10^9 years
0.5 $M_\odot$	6×10^{10} years
0.1 $M_\odot$	3×10^{12} years

Leaving the Main Sequence

- Where and how fast a star evolves is determined by its **main sequence mass**
- Hot, massive **O** stars age quickly and become **red super giants**
- Cooler, less massive **G** stars like the **Sun** live for ~ 10 billion years, then evolve into **red giants**
- Notice also that we do not see evolutionary tracks for stars less than 0.8 solar masses
- This is because the time for those types of stars to evolve into red giants is longer than the current age of the Universe (about 15 billion years)
- So even if a star was born right at the big bang, there has not been enough time for a star with that low a mass to use up all its hydrogen fuel

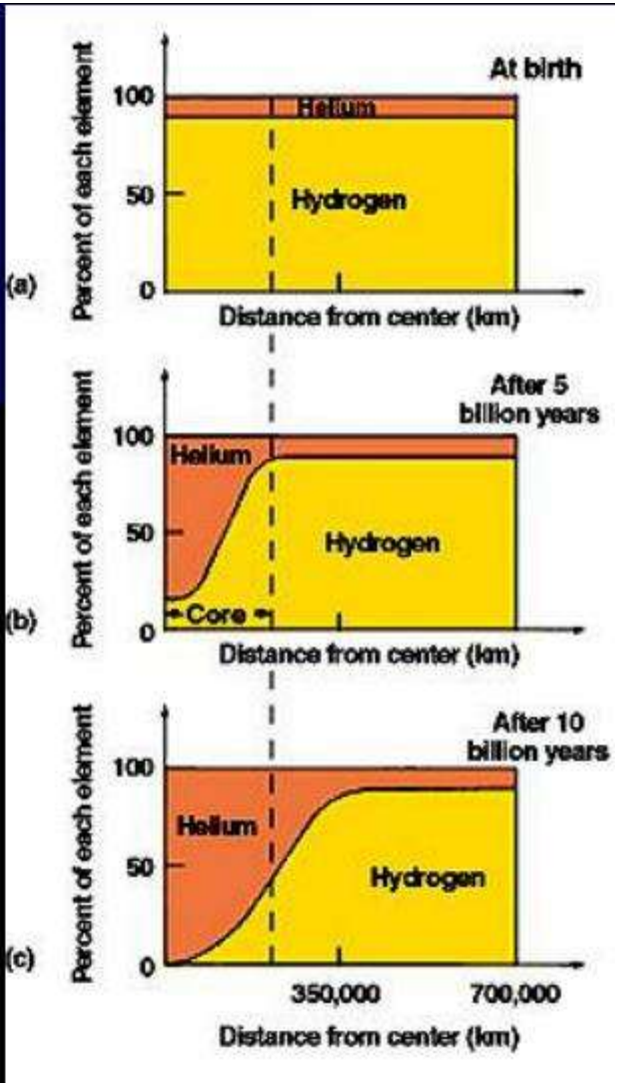


Leaving the Main Sequence



Why Do Stars Leave the Main Sequence?

- Running out of fuel

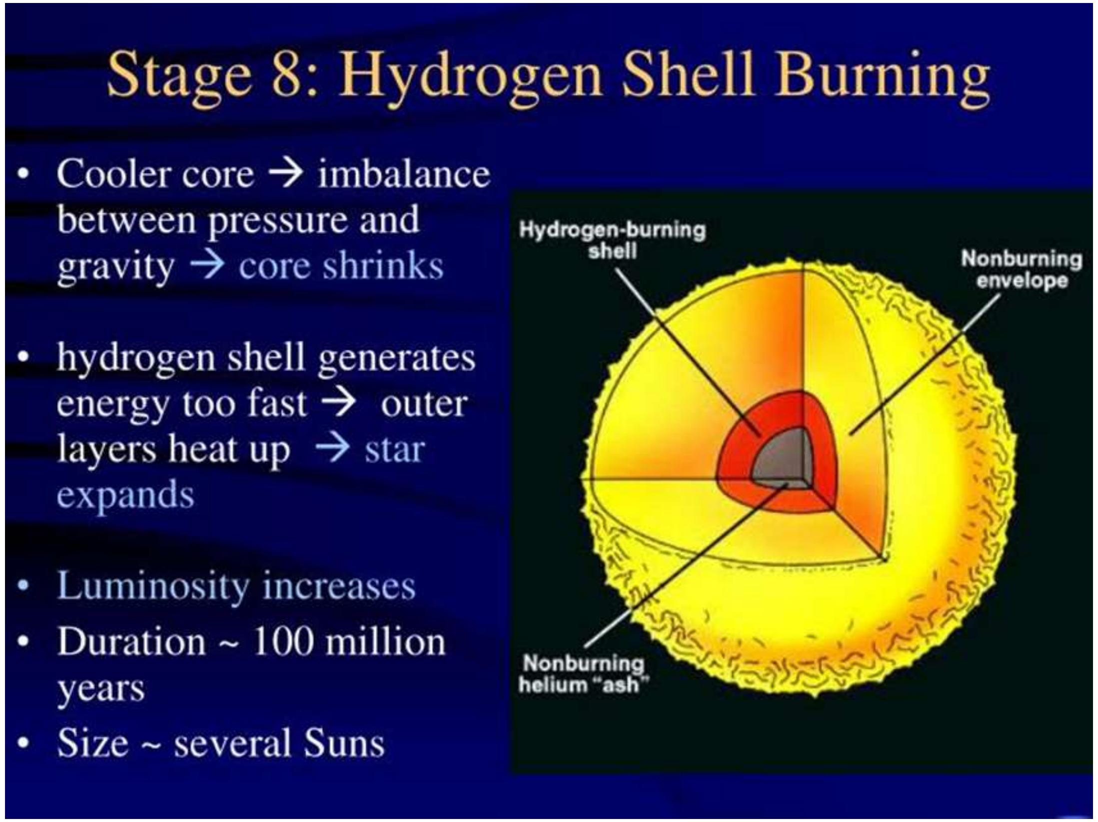


Leaving the Main Sequence

- As the supply of hydrogen in the core begins to decreases (having been fused into **helium**), the fusion rate goes down, and the amount of energy generated drops
- The temperature will then begin to drop and then the pressure will also decrease in the fusion core

$$PV = nRT$$

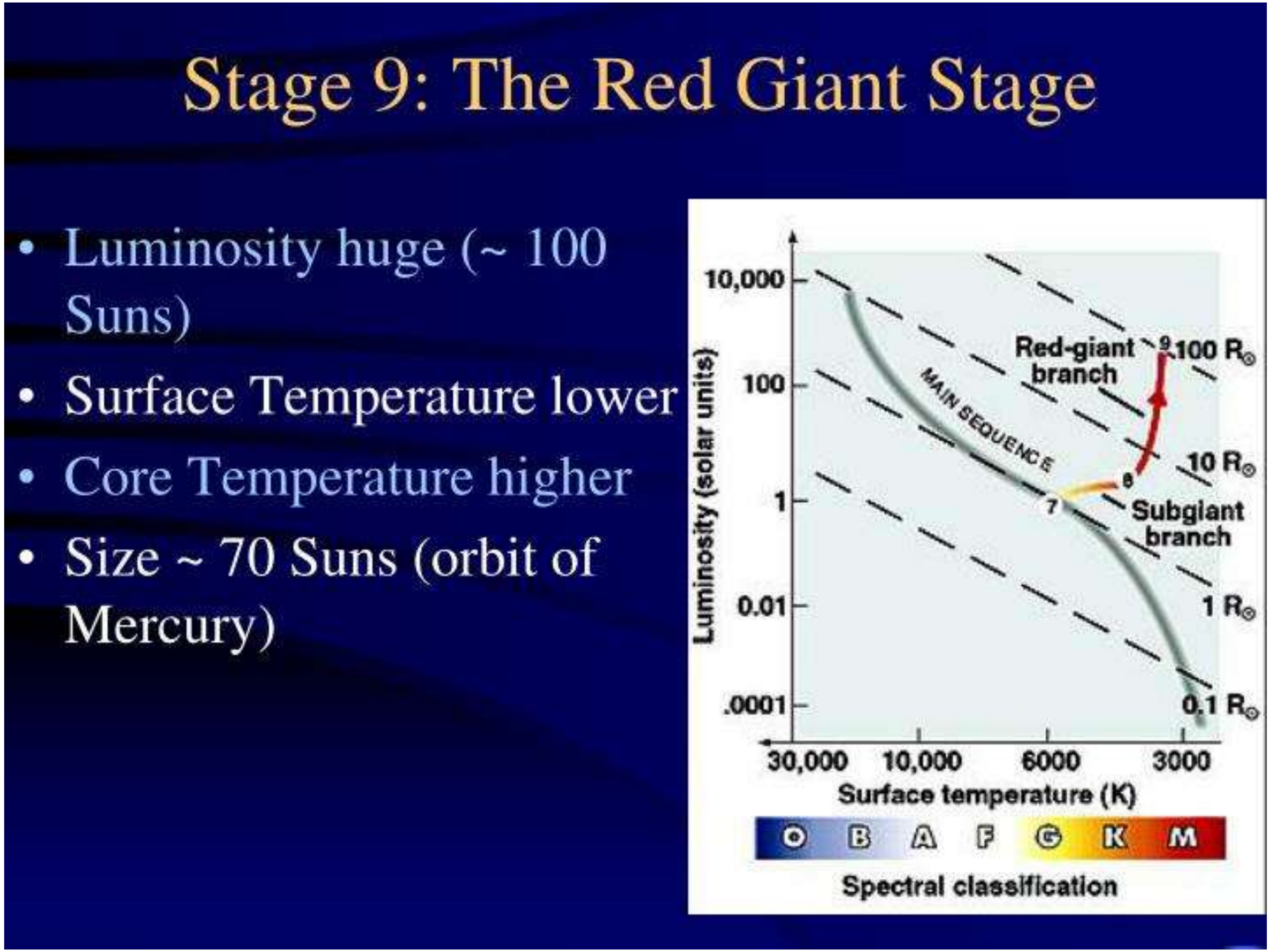
- A drop in pressure means that the core region of the star will contract slightly
- This will cause the temperature to go up again, and the fusion rate, for the remaining hydrogen in the core, jumps up (even though the core hydrogen is almost gone (a last gasp)-fused to **helium**
- The sharp rise in temperature also starts a **hydrogen burning shell** around the core, a region that before was too cool (less than 15 million degrees) to sustain fusion before



Stage 8: Hydrogen Shell Burning

- Cooler core → imbalance between pressure and gravity → core shrinks
- hydrogen shell generates energy too fast → outer layers heat up → star expands
- Luminosity increases
- Duration ~ 100 million years
- Size ~ several Suns

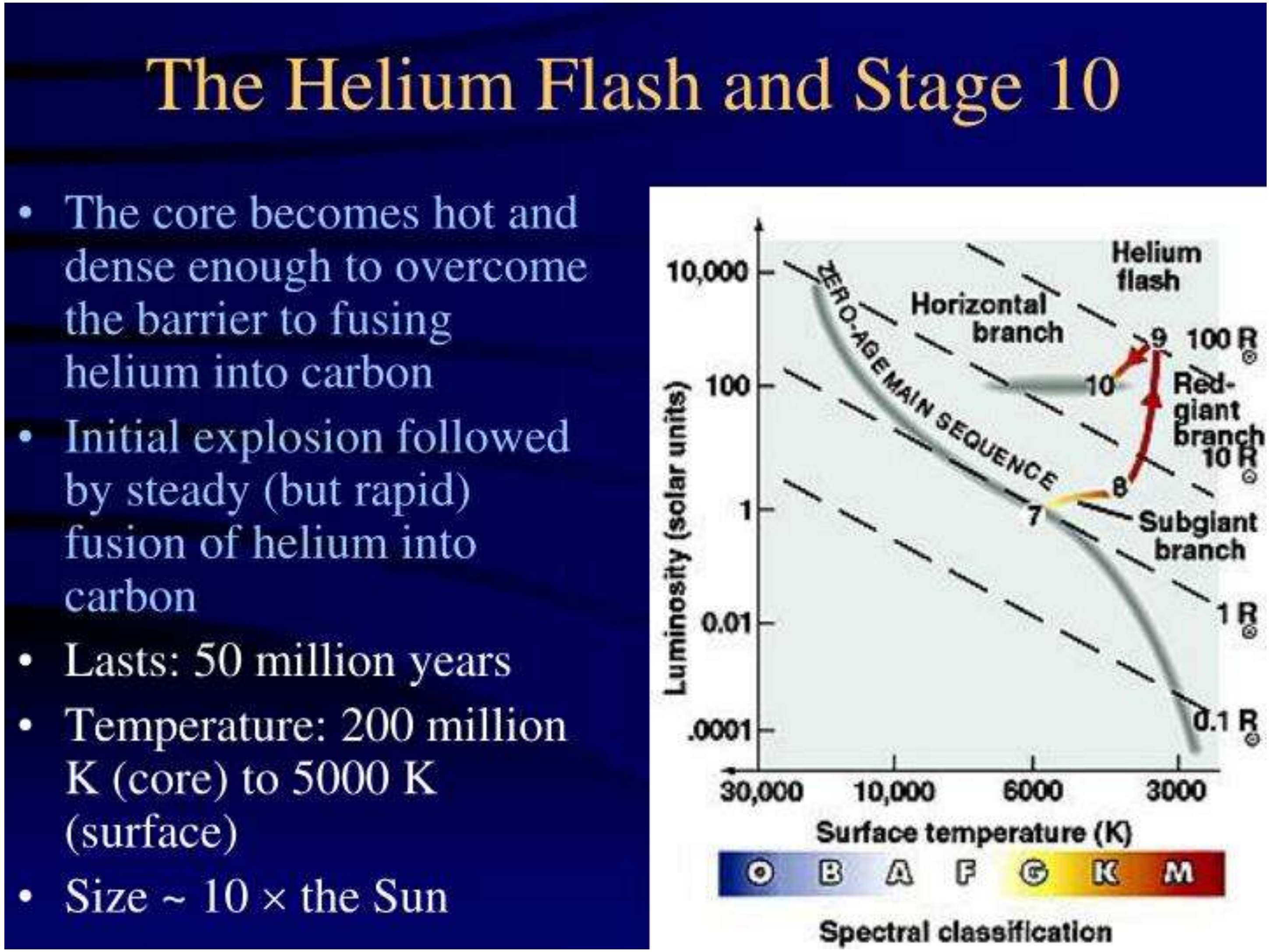
Red Giant Phase



Stage 9: The Red Giant Stage

- Luminosity huge (~ 100 Suns)
- Surface Temperature lower
- Core Temperature higher
- Size ~ 70 Suns (orbit of Mercury)

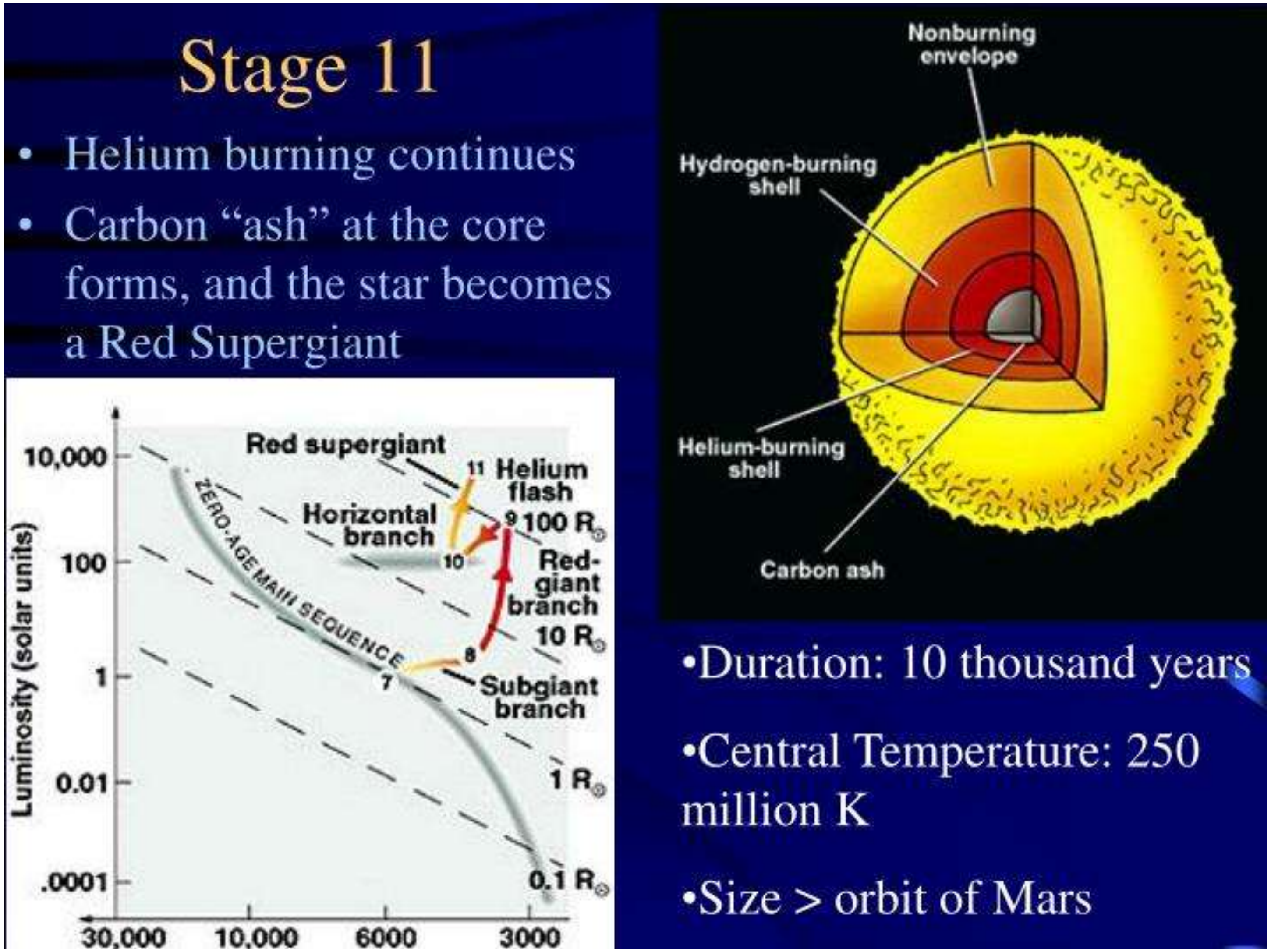
Horizontal Branch



The Helium Flash and Stage 10

- The core becomes hot and dense enough to overcome the barrier to fusing helium into carbon
- Initial explosion followed by steady (but rapid) fusion of helium into carbon
- Lasts: 50 million years
- Temperature: 200 million K (core) to 5000 K (surface)
- Size ~ 10 × the Sun

Red Supergiant



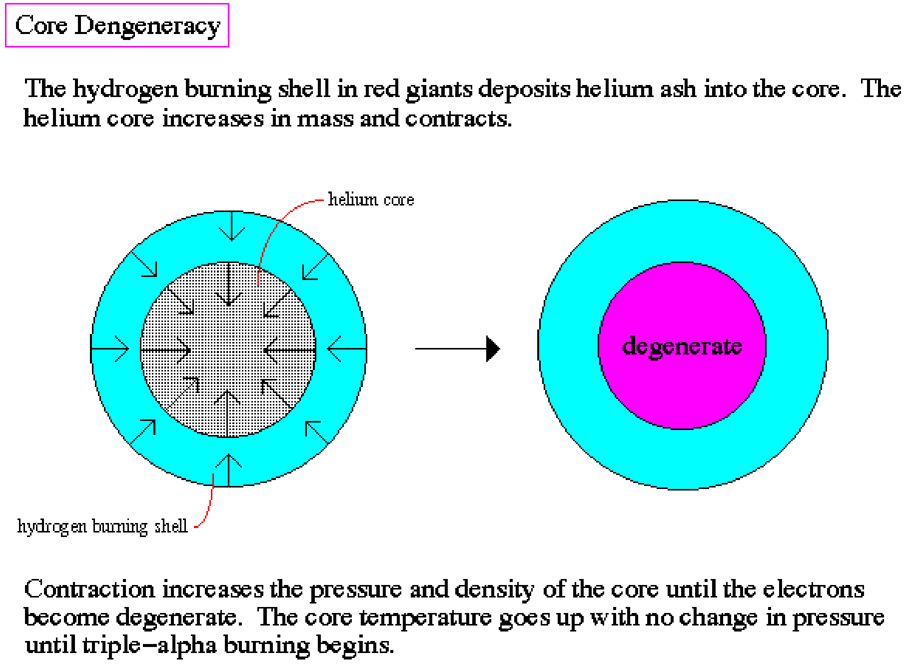
Stage 11

- Helium burning continues
- Carbon "ash" at the core forms, and the star becomes a Red Supergiant

- Duration: 10 thousand years
- Central Temperature: 250 million K
- Size > orbit of Mars

After the Red Giant Phase

- A star's evolution after the **red giant** phase depends on its mass
- For stars from 1 to 2 solar masses, the hydrogen burning shell eats its way outward leaving behind more **helium ash**
- The core becomes more massive and contracts
- Contraction heats the core, it becomes more dense
- The density of the core increases to where the electrons and helium nuclei become **degenerate**
- Electron and Neutron degeneracy are stellar applications of the **Pauli Exclusion Principle**
  - No two nucleons can occupy identical states
- The core begins to act more like a liquid than a gas, it becomes incompressible
- Further contraction stops



Core Dengeneracy

The hydrogen burning shell in red giants deposits helium ash into the core. The helium core increases in mass and contracts.

Contraction increases the pressure and density of the core until the electrons become degenerate. The core temperature goes up with no change in pressure until triple−alpha burning begins.

Main Sequence Stars – Leaving the Main Sequence

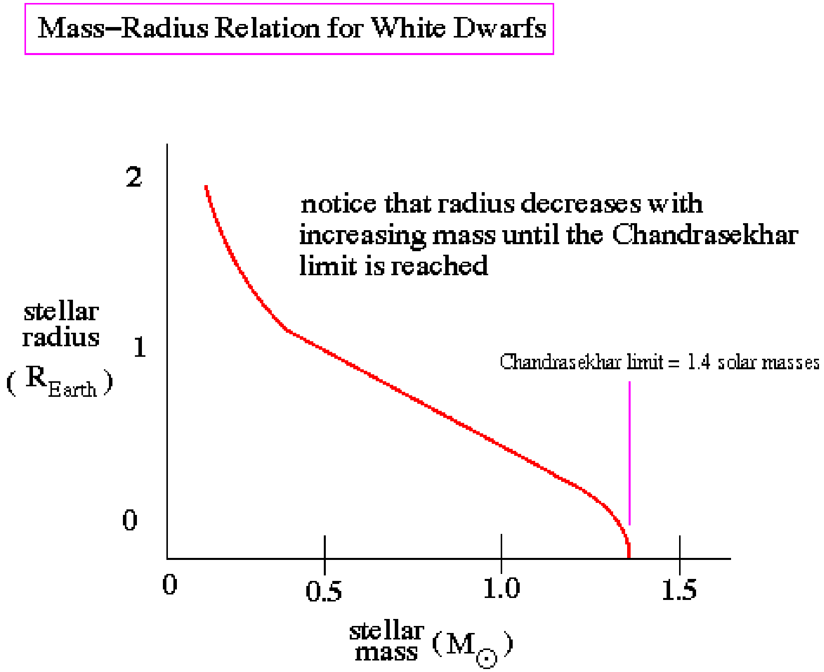
- At this point, the **hydrogen burning shell** becomes the sole source of energy in the dying star
- Once the hydrogen burning shell is created, the star makes a small jump off the main sequence in the H-R diagram
- It becomes slightly brighter and slightly cooler
- The drop in **surface temperature** is because the envelope of the star expands a small amount, increasing the surface area
- This increased surface area also increases the luminosity of the star

$$L = \underbrace{4\pi R^2} \sigma T_{\text{eff}}^4$$

- Once the last of the hydrogen is used up in the core of an aging main sequence star, fusion stops in the core and the temperature drops and the core collapses
- The collapsing core converts **gravitational energy** (potential energy) into **thermal energy** (kinetic energy)
- This energy is directed into the hydrogen burning shell, which expands to consume more fuel in the star's interior
- This whole process takes several million years but, in the end, the main sequence star becomes either a **red supergiant** or **a red giant**, depending on its initial mass

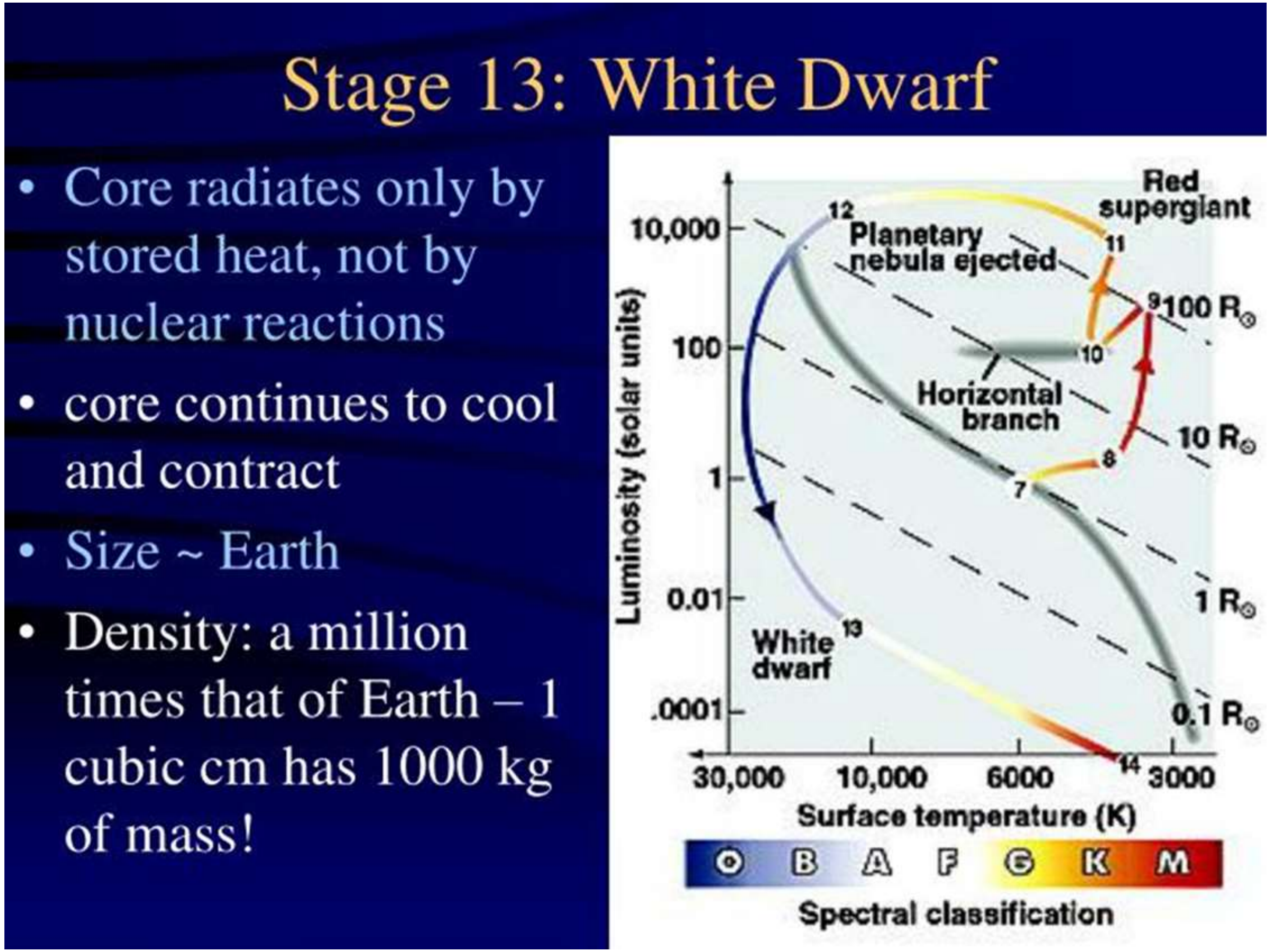
After the Red Giant Phase

- For stellar masses less than about 1.44 solar masses, the energy from the gravitational collapse is not sufficient to produce the neutrons (protons +electrons) of a neutron star- the collapse is halted by electron degeneracy to form **white dwarfs**
- This maximum mass for a white dwarf is called the **Chandrasekhar limit**
- Above 1.44 solar masses, enough energy is available from the gravitational collapse to force the combination of electrons and protons to form neutrons
- As the star contracts further, all the lowest neutron energy levels are filled and the neutrons are forced into higher and higher energy levels, filling the lowest unoccupied energy levels
- This creates an effective pressure which prevents further gravitational collapse, forming a **neutron star**
- For masses greater than ~2.3 solar masses, even neutron degeneracy can't prevent further collapse and it continues toward the black hole state



- Mass less the ~1.4 solar mass—**White Dwarf**
- Mass more than ~1.4 solar mass- **Neutron Star**
- Mass more than ~2.3 solar mass- **Black Hole**
  - **Tolman–Oppenheimer–Volkoff limit**

After the Red Giant Phase

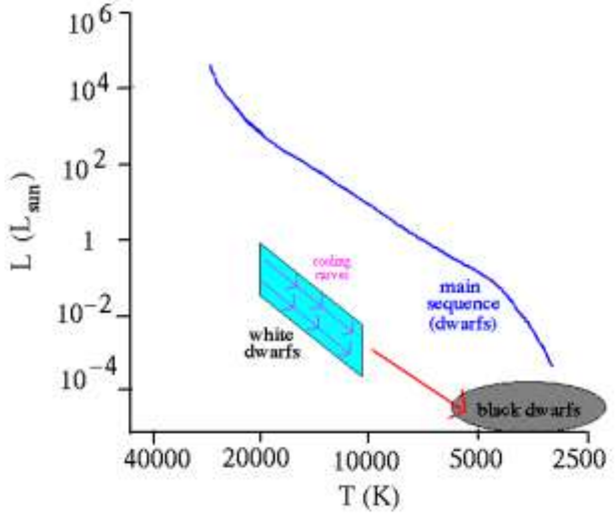


Stage 13: White Dwarf

- Core radiates only by stored heat, not by nuclear reactions
- core continues to cool and contract
- Size ~ Earth
- Density: a million times that of Earth – 1 cubic cm has 1000 kg of mass!

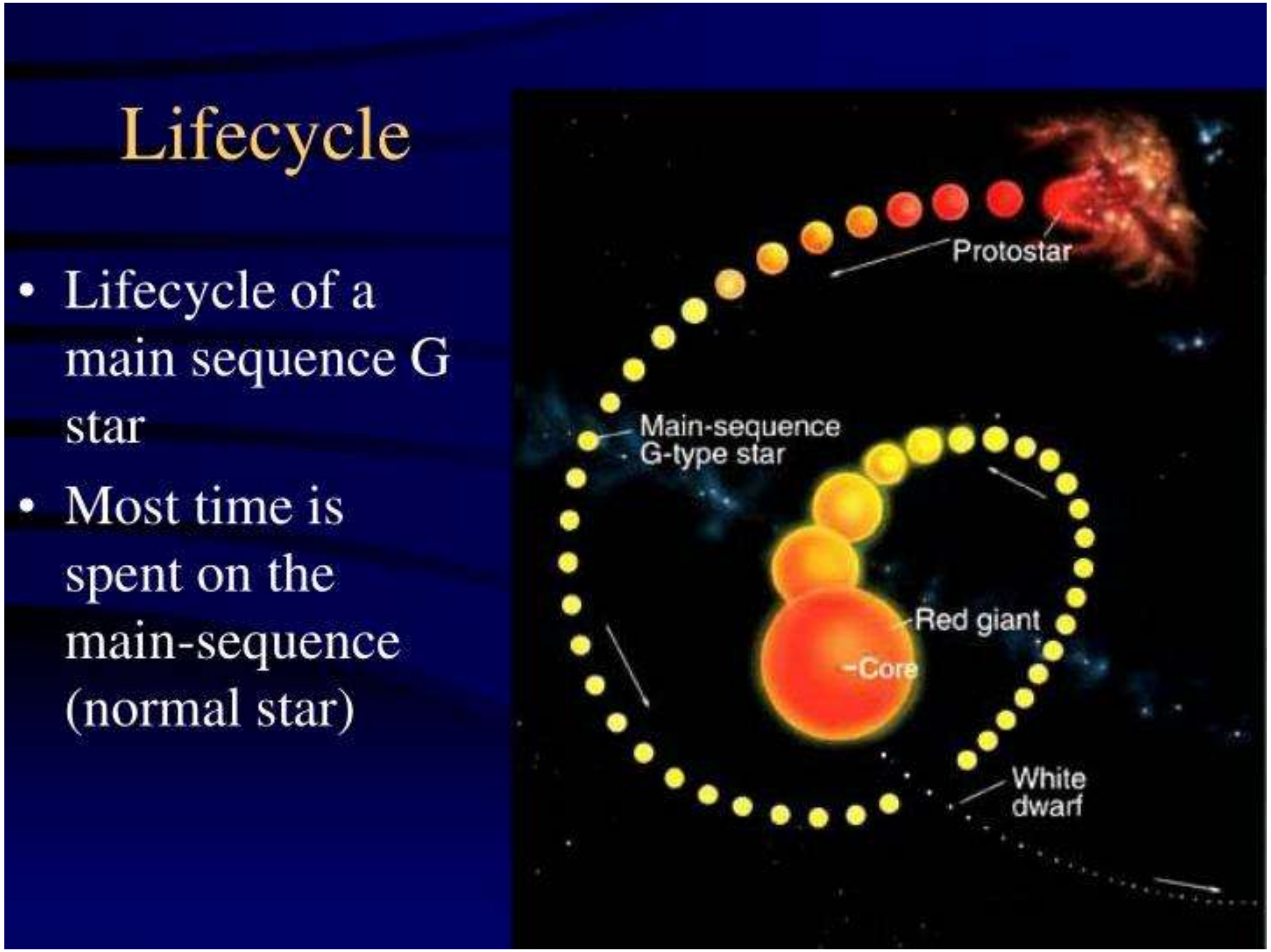
After the Red Giant Phase

- **White dwarfs** are quite common, being found in binary systems and in clusters
- Since they are remnants of stars born in the past, their numbers build up in the Galaxy over time
- Once a white dwarfs contracts to its final size, it no longer has any nuclear fuel available to burn
- So, as time passes, the white dwarf cools by radiating its energy outward
- Higher mass white dwarfs are small in size, and therefore radiate energy slower than larger, small mass white dwarfs
- Radiative cooling is one way for a white dwarf to cool, another way is neutrino cooling
- At very high temperatures, around 30 million degrees K, gamma-rays can pass near electrons and produce a pair of neutrinos



- The cooling process is very slow for white dwarfs
- After a billion years the typical white dwarf is down to 0.001 the luminosity of the Sun
- But the end result is unstoppable as the white dwarf will eventually give up all its energy and become a solid, crystal **black dwarf**

Lifecycle of a Main Sequence G Star

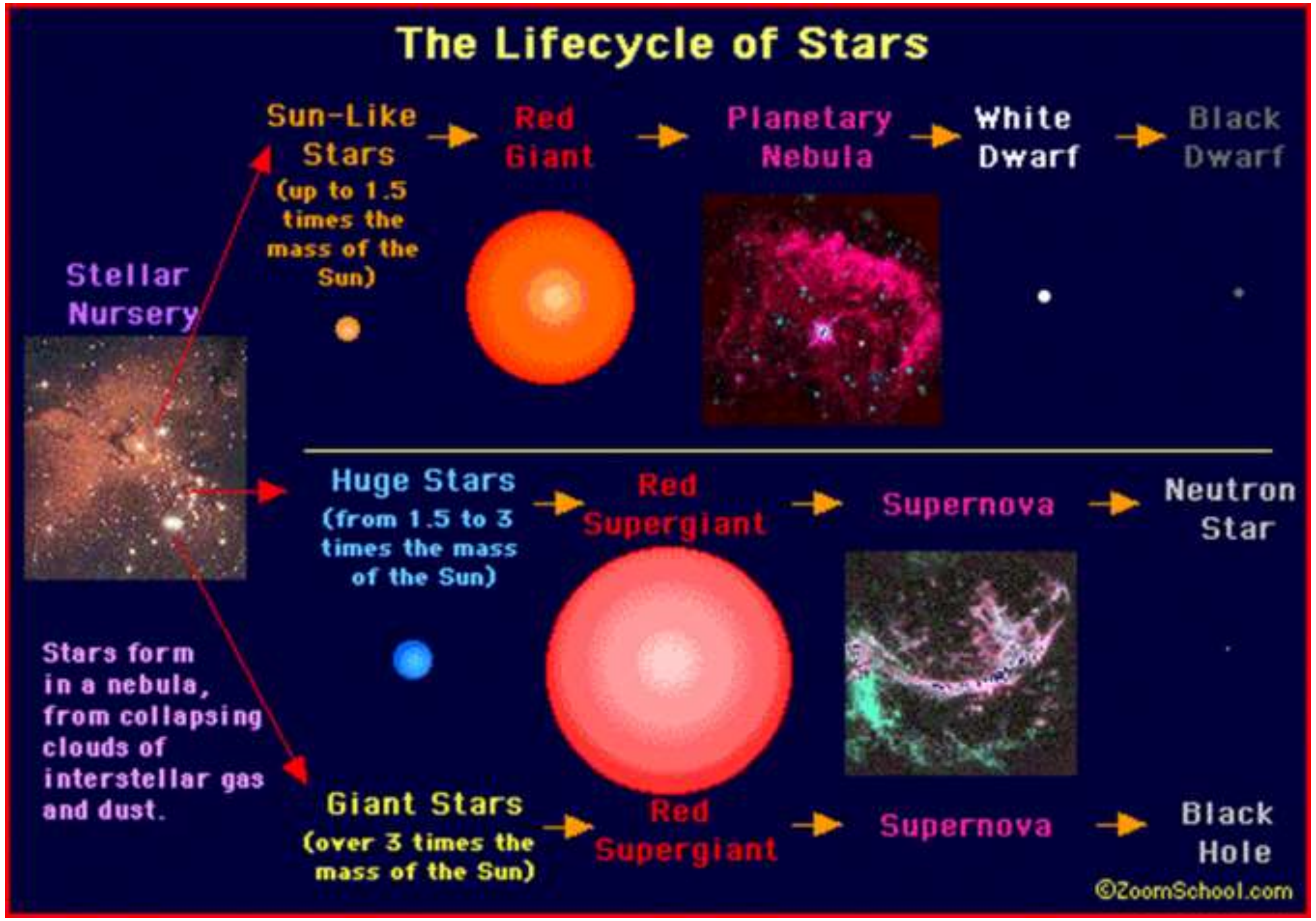


Lifecycle

- Lifecycle of a main sequence G star
- Most time is spent on the main-sequence (normal star)

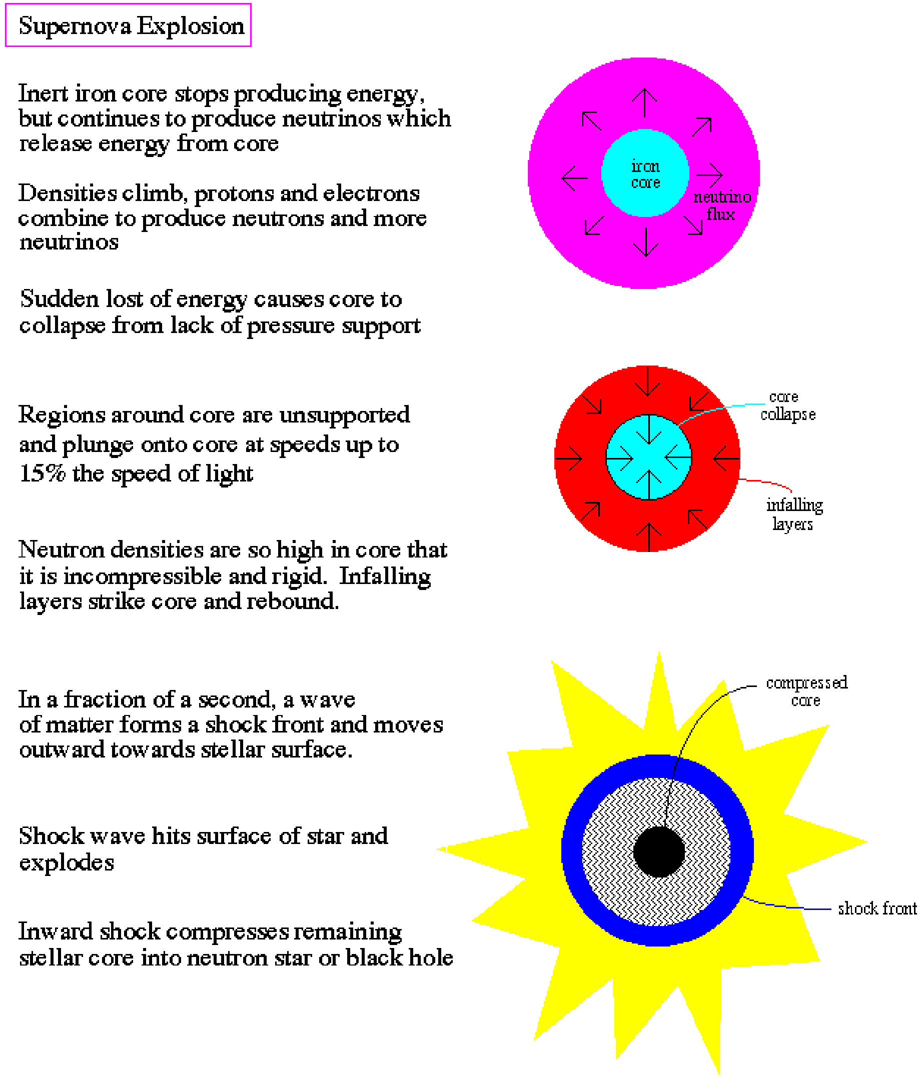
Fate of Stars

- The fate of a star depends on its initial main sequence mass
- **Lower mass** stars pass through the red phase creating a planetary nebula finally becoming a white dwarf
- **Large mass** stars pass through the red supergiant phase exploding as a supernova before becoming either neutron star or a black hole



Supernovae

- Once the silicon burning phase of a high mass star has produced an **iron core** the fate of the star is sealed
- Since iron will not fuse to produce more energy, energy is lost by the productions of neutrinos through a variety of nuclear reactions
- Neutrinos, which interact very weakly with matter, immediately leave the core taking energy with them
- As the core shrinks, it increases in density
- Electrons are forced to combine with protons to make neutrons and more neutrinos, called neutronization
- The core cools more, and becomes an extremely rigid form of matter
- This entire process only takes 1/4 of a second



Supernova Explosion

Inert iron core stops producing energy, but continues to produce neutrinos which release energy from core

Densities climb, protons and electrons combine to produce neutrons and more neutrinos

Sudden lost of energy causes core to collapse from lack of pressure support

Regions around core are unsupported and plunge onto core at speeds up to 15% the speed of light

Neutron densities are so high in core that it is incompressible and rigid. Infalling layers strike core and rebound.

In a fraction of a second, a wave of matter forms a shock front and moves outward towards stellar surface.

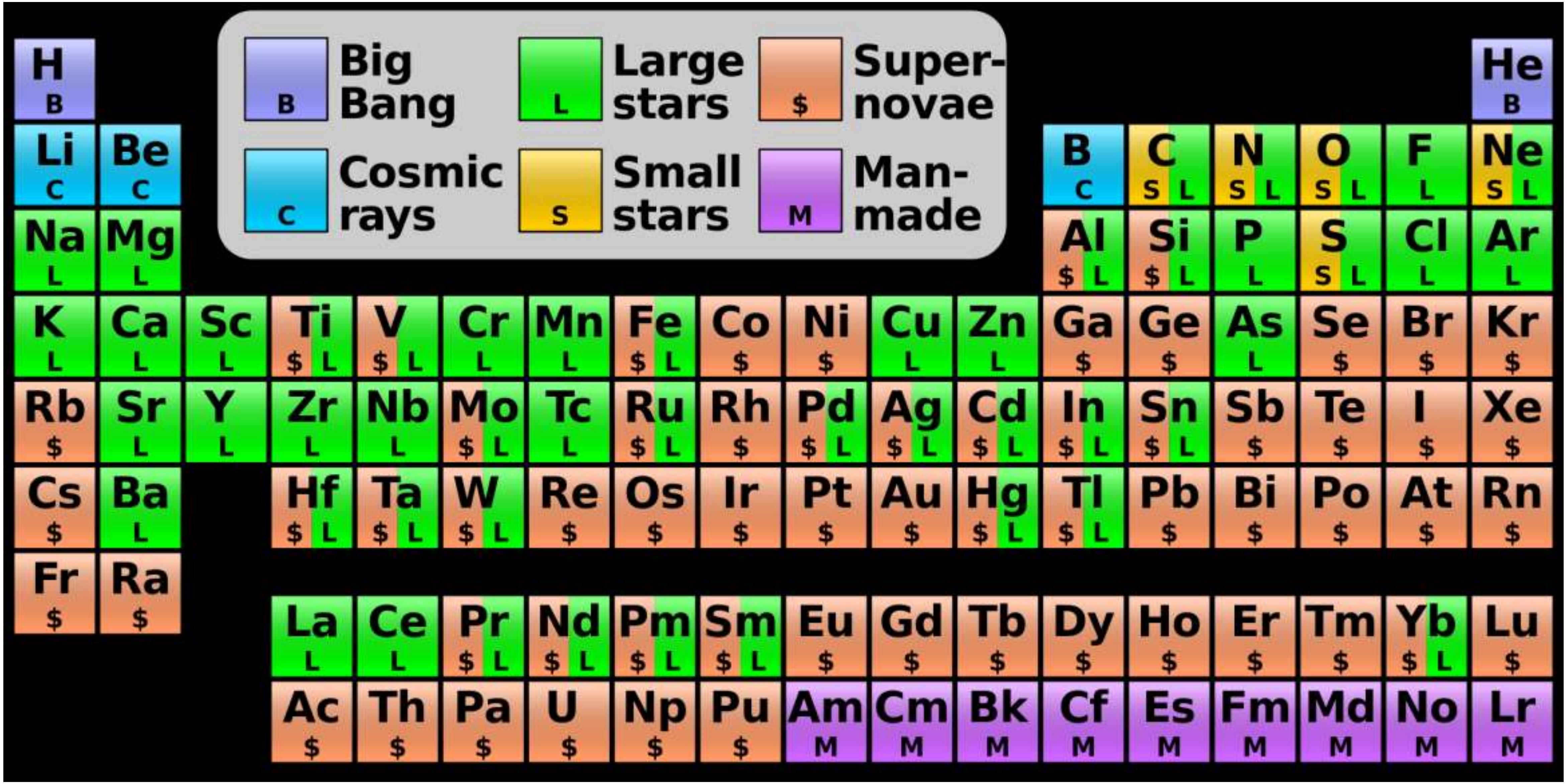
Shock wave hits surface of star and explodes

Inward shock compresses remaining stellar core into neutron star or black hole

Supernovae in stars with 8 M_{Sun} < M < 20 M_{Sun}

- When the **supernova** begins the **iron core** collapses rapidly under free-fall and becomes denser.
- When the density is very high, protons and electrons can combine together to form neutrons and neutrinos:
  $p + e^- \to n + nu$
- The neutrinos escape since they don't interact well with matter and carry off energy
- The resulting neutron gas collapses until the density is extremely high
- When the density becomes higher than about **10^{14} g per cubic cm**, neutron degeneracy pressure provides an outward pressure which suddenly halts the gravitational collapse
- The core of neutrons held stable by neutron degeneracy pressure is called a **neutron star**
- The outer layers are still collapsing inwards at this point and collapsing layers collide with the hard surface of the newly formed neutron star
- This collision causes a violent rebound and a shock wave bounces outwards, colliding with the outer layers of the star
- This expanding wave carries an extraordinary amount of energy
- This energy can provide the fuel which allows the **endothermic fusion** reactions to create very high mass elements such as **Uranium**
- Supernovae are responsible for **all** the elements with masses larger than **iron** found on Earth
- These supernova explosions are extremely bright

Sources of The Elements



B Big Bang

L Large stars

$ Super-novae

C Cosmic rays

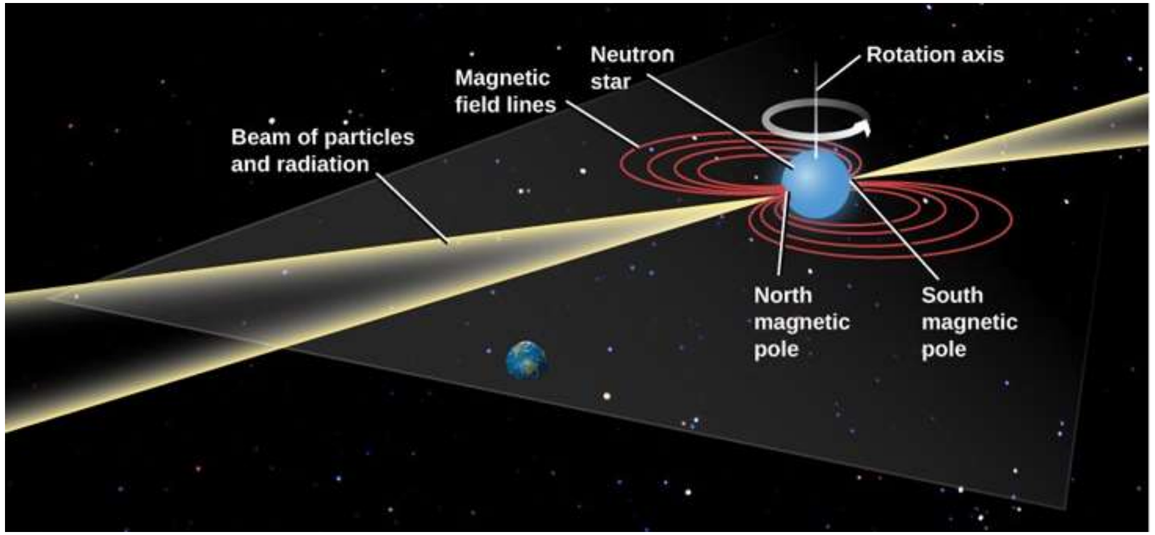
S Small stars

M Man-made

H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al $ L	Si $ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti $ L	V $ L	Cr L	Mn L	Fe $ L	Co $	Ni $	Cu L	Zn L	Ga $	Ge $	As L	Se $	Br $	Kr $
Rb $	Sr L	Y L	Zr L	Nb L	Mo $ L	Tc L	Ru $ L	Rh $	Pd $ L	Ag $ L	Cd $ L	In $ L	Sn $ L	Sb $	Te $	I $	Xe $
Cs $	Ba L		Hf $ L	Ta $ L	W $ L	Re $	Os $	Ir $	Pt $	Au $	Hg $ L	Tl $ L	Pb $	Bi $	Po $	At $	Rn $
Fr $	Ra $																
			La L	Ce L	Pr $ L	Nd $ L	Pm $ L	Sm $ L	Eu $	Gd $	Tb $	Dy $	Ho $	Er $	Tm $	Yb $ L	Lu $
			Ac $	Th $	Pa $	U $	Np $	Pu $	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

Fate of Stars- Neutron Stars

- A **neutron star** is a dense stellar corpse consisting of closely packed degenerate neutrons
- A neutron star typically has a diameter of about 20 km, a mass of less than 3 times solar mass, a magnetic field 10e12 times stronger than that of the Sun, and a rotation period of roughly 1 second
- A neutron star consists of a super fluid , super conducting core surrounded by superfluid mantle and a thin ,brittle crust
- Intense beams of radiation emanate from regions near the north and south magnetic poles of a neutron star
- These beams are produced by streams of charged particles moving in the star's intense magnetic field
- When the beams are directed toward the neutron star is a **pulsar**



- Neutron stars can have their magnetic poless perpendicular to their axis of rotation

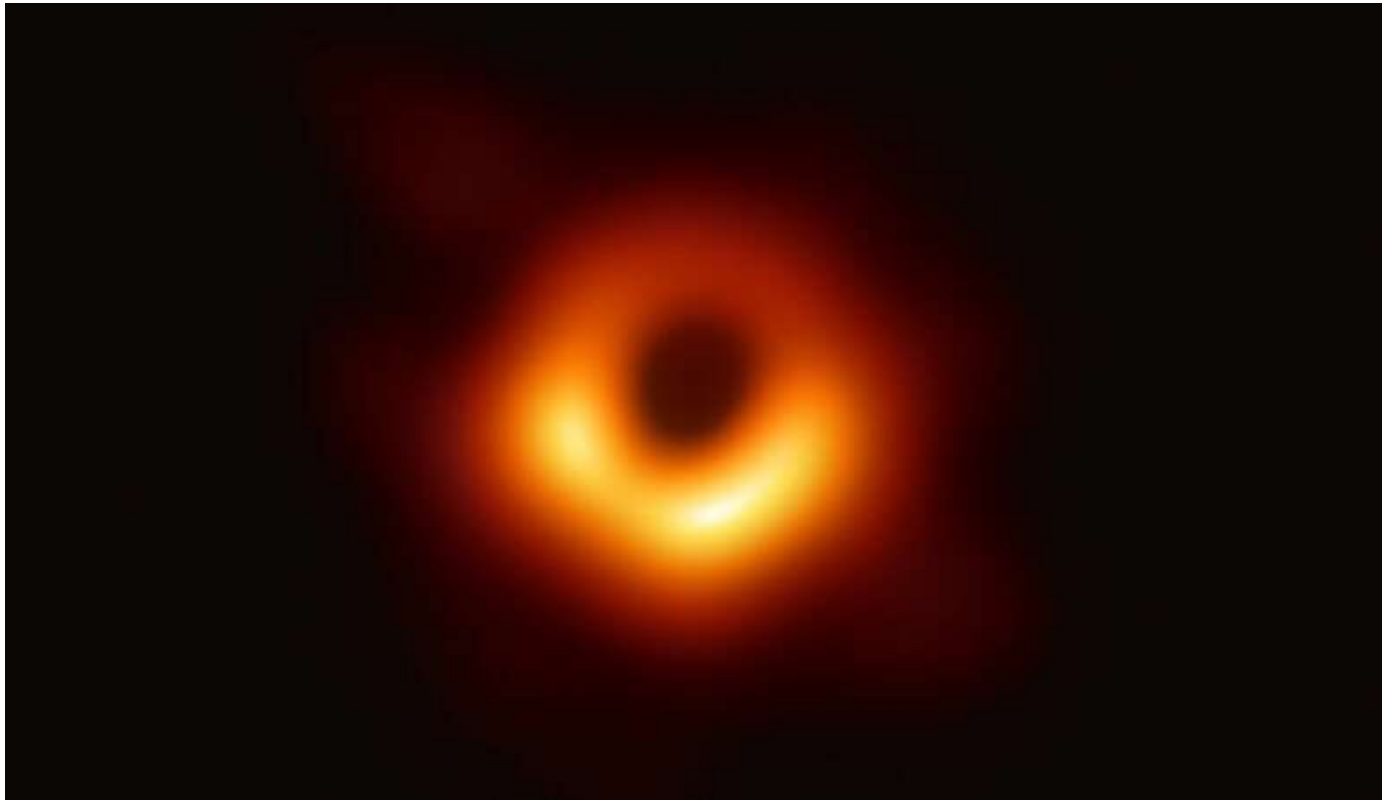
Fate of Stars-Black Holes

- **Black hole** is a body of extremely intense gravity from which nothing, not even light, can escape
- A black hole can be formed by the death of a massive star
- When such a star has exhausted the internal thermonuclear fuels in its core at the end of its life, the core becomes unstable and gravitationally collapses inward upon itself, and the star’s outer layers are blown away
- The crushing weight of constituent matter falling in from all sides compresses the dying star to a point of “zero volume” and “infinite density” called the **singularity**
- Details of the structure of a black hole are calculated from **Einstein’s general theory of relativity**
- The singularity constitutes the center of a black hole and is hidden by the object’s “surface,” the **event horizon**
- Inside the event horizon the escape velocity (velocity required for matter to escape from the gravitational field) exceeds the speed of light
- Not even rays of light can escape into space
- The radius of the event horizon is called the **Schwarzschild radius**, after **Karl Schwarzschild**, who in 1916 predicted the existence of collapsed stellar bodies that emit no radiation
- The size of the Schwarzschild radius is proportional to the mass of the collapsing star
- For a black hole with a mass 10 times as great as that of the Sun, the radius would be 30 km

Quasar---Quasi-stellar radio source

- **Quasars** are astronomical objects of very high luminosity found in the centers of some galaxies
- The brightest quasars can outshine all of the stars in the galaxies in which they reside
- Making them visible even at distances of billions of light-years
- Quasars are among the most distant and luminous objects known
- Quasars are apparently powered by gravitational accretion onto supermassive black holes
- “Supermassive” means from roughly a million to a few billion times the mass of the Sun
- Supermassive black holes reside at the center of many large galaxies
- In about 5–10 percent of these galaxies, gas tumbles into the deep gravitational well of the black hole and is heated to incandescence as the gas particles pick up speed and pile up in a rapidly rotating “accretion disk” close to the horizon of the black hole
- There is a maximum rate at which a black hole can accrete matter before the heating of the infalling gas results in so much outward pressure from radiation that the accretion stops
- The black hole in an active nucleus accretes a few solar masses of matter per year
- Which, is sufficient to account for a typical quasar with a total luminosity of about 10^{39} watts
  - The Sun’s luminosity is about 4×10^{26} watts

Fate of Stars- Black Holes



In 2019, the **Event Horizon Telescope Collab**oration released this first-ever image of a black hole, at the heart of galaxy M87. The image shows the shadow of the monster on its accretion disk

Next session

The Sun