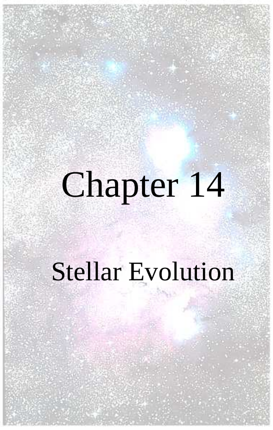
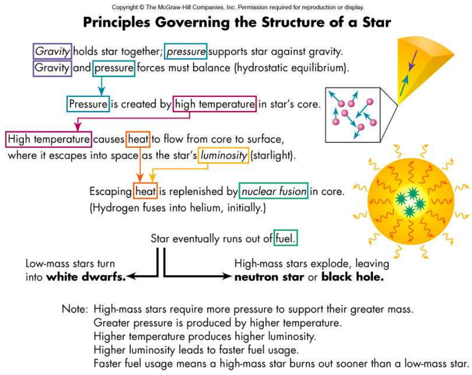


Chapter 14

Stellar Evolution

The Life of a Star



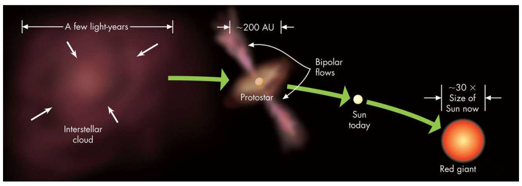
Mass Is the Key

- Stars require millions to billions of years to evolve – a time that is incredibly slow by human standards
- A star's evolution can be studied two ways:
  - Stellar models via computer calculations that take into account the relevant physics
  - Observations – different stars represent different snapshots in the life of a star
- The lifeline of a star is found to depend critically on its mass
- The possible endings of a star's life naturally divide stars into two groups: low-mass stars and high-mass stars, with the division set at about 10 solar masses

The Importance of Gravity

- Gravity drives stellar evolution from a star's formation out of a cloud to its final death
  - The collapsing cloud will heat because of gravity
  - The main-sequence star will sustain itself as gravity compresses and heat the core to fusion temperatures
  - Gravity will sculpt the final collapse of the star into a white dwarf, neutron star, or black hole
- The amount of mass (gravity) will also drive the duration of the evolution

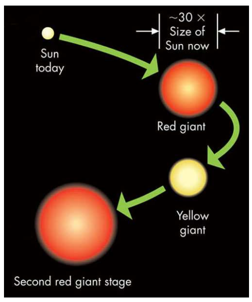
The Life of Our Sun



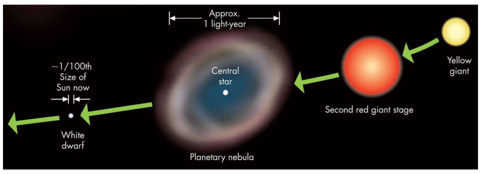
- The Sun was born out of an ***interstellar cloud*** that gravitationally collapsed over a time span of a few million years
- Fusing hydrogen into helium in its core, the Sun will reside on the main sequence for 10 billion years and in the process convert 90% of its core hydrogen into helium

The Life of Our Sun

- Starved of fuel, the core will shrink and grow hotter as the outer surface expands and cools transforming the Sun into a red giant
- After one billion years, the red giant's core will be hot enough to begin fusing helium
- The Sun will then transform into a pulsating yellow giant

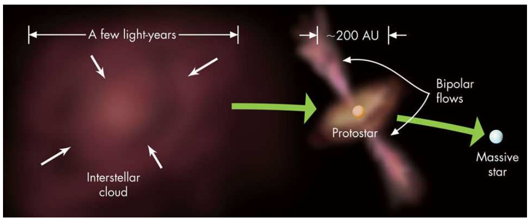


The Life of Our Sun



- As the core's helium fuel begins to expire, the Sun will once again transform into a red giant, but only bigger than before
- The high luminosity of the red giant will drive the Sun's atmosphere into space leaving behind its bare core
- The core will cool and dwindle into a white dwarf

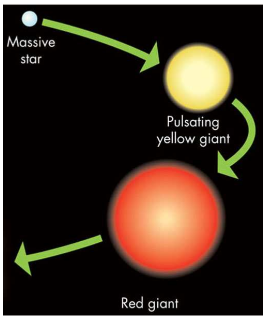
The Life of a High-Mass Star



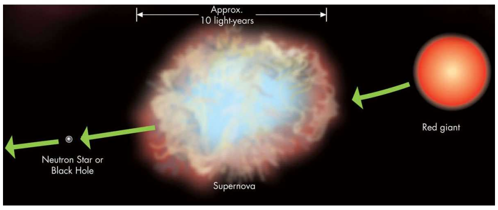
- The early life of a high-mass star is similar to the Sun:
  - Collapses from an interstellar cloud and resides on the main sequence
  - Proceeds through these stages much faster than the Sun, spending less than 100 million years on the main sequence

The Life of a High-Mass Star

- A high-mass star then passes through the pulsating yellow giant stage before it turns into a red giant
- In the red giant phase, the core begins to fuse one element into another creating elements as massive as iron



The Life of a High-Mass Star

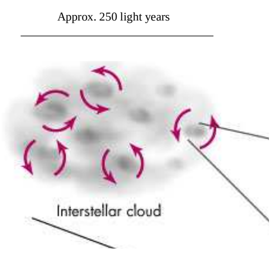


- Once iron is reached, the core is out of fuel and it collapses
  - The star's heavy elements are blown into space along with its outer layers
  - A neutron star or black hole is left behind

Interstellar Gas Clouds

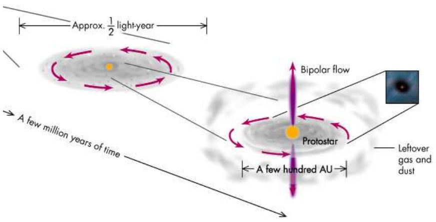
- General Characteristics
  - Gas: hydrogen (71%), helium (27%), others
  - Dust: microscopic particles of silicates, carbon, and iron
  - Temperature: Around 10 K

Initial Collapse



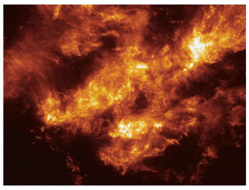
- Low temperature leads to too low pressure to support cloud against gravitational collapse
- Collapse may be triggered by collision with another cloud, a star explosion, or some other process
- Non-uniformity, clumpy nature of gas leads to formation of smaller, warmer, and denser clumps

To the Protostar Stage



- Rotating dense clumps flatten into disk
- About one million years: small, hot dense core at center of disk forms – a ***protostar***
- Stars generally form in groups – similar age

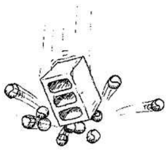
Protostars



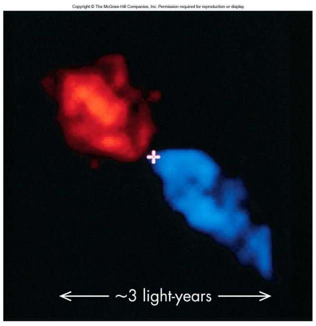
- Characteristics
  - Temperature: About 1500 K
  - Shine at infrared and radio wavelengths
  - Low temperature and obscuring dust prevents visible detection
  - May be found in “Bok globules”, dark blobs 0.2-2 lys across with masses of up 200 solar masses

Further Collapse

- Gravity continues to draw material inward
- Protostar heats to 7 million K in core and hydrogen fusion commences
- Collapse of core ceases, but protostar continues to acquire material from disk for 10^6 years
- In-falling material creates violent changes in brightness and ultimately a strong outflow of gas

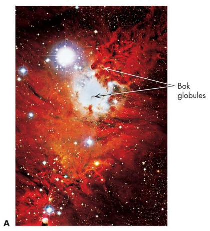


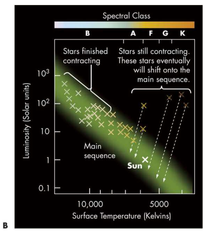
Bipolar Outflows



- Jets also create ***bipolar outflows*** around protostar
  - Easily seen at radio wavelengths
  - Clears away most gas and dust around protostar

T-Tauri Stars





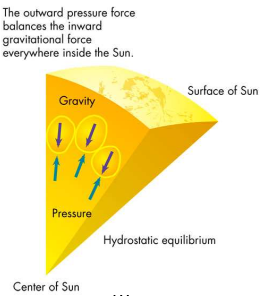
- Young stars still partially immersed in interstellar matter
- Vary erratically in brightness, perhaps due to magnetic activity
- Intense outward gas flows from surfaces
- Occupy H-R diagram just above main-sequence

Stellar Mass Limits

- Stars smaller than 0.1 $M_\odot$ rarely seen since their mass is too small for their cores to initiate fusion reactions
- Objects with masses between planets and are called brown dwarfs, “failed stars” extremely dim and difficult to observe
- Upper mass limit of stars (about 30 $M_\odot$) due to extreme temperatures and luminosity preventing additional material from falling on them - intense radiation may even strip off outer layers of star

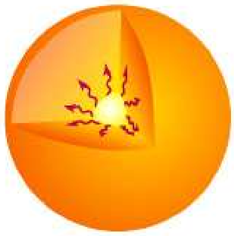
A Star's Mass Determines Its Core Temperature

- All other things being equal, a more massive star has a higher gravitational attraction than a less massive star
- Hydrostatic equilibrium then requires a higher gas pressure for the larger gravity of a massive star
- The higher pressure can be achieved, from the perfect gas law, by a higher temperature



Structure of High- and Low-Mass Stars

- Fusion in the core
  - Low mass stars: proton-proton chain
  - High mass stars: CNO cycle – carbon, nitrogen, and oxygen act as catalysts for H fusion at higher core temperatures



Structure of High- and Low-Mass Stars

- Energy transport from the core
  - Low mass stars: Inner radiative zone, outer convection layer
  - High mass stars: Inner convection zone, outer radiative layer
  - All stars: Outer layers of hydrogen gas are unavailable for fusion reactions in the core

Stellar Lifetimes

- The time a star stays on the main sequence is called the ***main-sequence lifetime***
- The amount of time t_{lms} a star will spend on the main sequence depends on its available fuel (mass M) and how fast it consumes it (luminosity L)

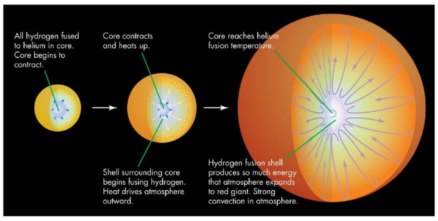
$$t_{lms} = 10^{10}\left(\frac{M}{L}\right) \text{ years}$$

- Here M and L are expressed in solar units

Stellar Lifetimes

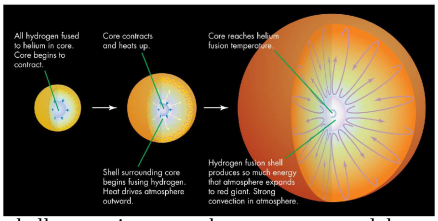
- Some lifetimes:
  - 1 $M_\odot$ star with 1 $L_\odot$:10 billion years
  - 2 $M_\odot$ star with 20 $L_\odot$:1 billion years
  - 30 $M_\odot$ star with 10^5 $L_\odot$:3 million years
- Short lifetime of massive main-sequence stars implies blue stars have formed recently and will still be associated with their birthing cloud

Leaving the Main Sequence



- When a main-sequence star exhausts its fuel, the core drops its pressure, is compressed by gravity, and heats up
- The increasing temperature of the core eventually ignites hydrogen gas just outside the core in a region called the ***shell source***

Leaving the Main Sequence



- The shell source increases the pressure around the core and pushes surrounding gases outward
- The star expands into a red giant as the radius increases and the surface cools
- Size of red giant depends on initial mass of star

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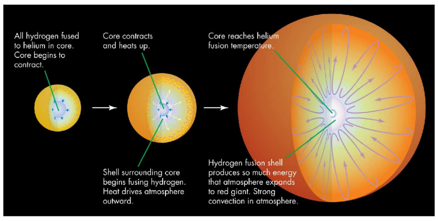
Leaving the Main Sequence



- Most of a giant star’s volume is in its huge outer envelope, while most of its mass is in its Earth-sized core
- Convection carries energy through the outer opaque envelope to the surface

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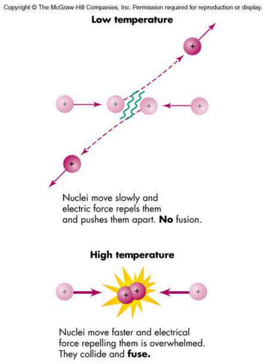
Giant Stars



- Nuclear Fuels Heavier Than Hydrogen
  - To fuse nuclei containing larger numbers of protons requires higher impact velocities (higher temperatures) to overcome the bigger electrostatic repulsion

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Giant Stars

- As a giant star compresses its core, higher temperatures are achieved and helium fusion occurs at about 100 million K
  - This fusion is referred to as the ***triple alpha process***
  - Fusion of helium proceeds smoothly for a high-mass star since its core’s pressure and temperature are high to begin with
  - A low-mass star must compress its core to such an extent that it first becomes ***degenerate*** before fusing

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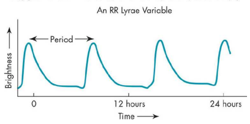
Degeneracy in Low-Mass Giant Stars

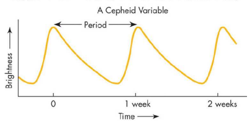
- Degenerate gas is so tightly packed that the electrons interact not as ordinary charged particles but according to laws of atomic physics
  - A consequence of these laws is that no two electrons of the same energy can occupy the same volume
  - The degenerate gas behaves more like a solid – it does not expand as its temperature rises
- When a degenerate, low-mass star begins to fuse helium, it will not expand
  - The core temperature increases exponentially
  - Helium fusion proceeds explosively in what is called a ***helium flash***

Yellow Giants

- The explosive energy converts the core back to a normal gas
  - The core expands and the star’s surface shrinks
  - The red giant turns into a yellow giant
- Most luminous yellow giants on an H-R diagram are aging high-mass stars
- Less luminous yellow giants are low-mass stars that have completed their first red giant stage
- Regardless of mass, many yellow giants pulsate in size and luminosity

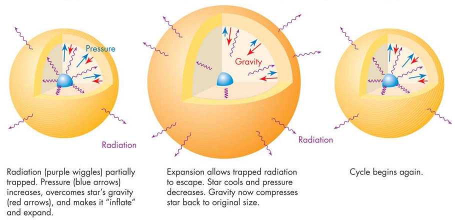
Variable Stars





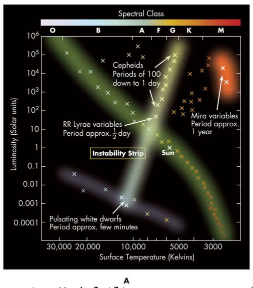
- Two important groups of variable (pulsating) stars:
  - RR Lyrae (first discovered in constellation of Lyra)
    - Mass comparable to Sun's with 40 times the luminosity
    - Periods of about half a day
  - Cepheid (first discovered in constellation of Cepheus)
    - More massive than Sun and about 20,000× more luminous
    - Periods from 1-70 days
- Other groups: Mira (pulsating red giants) and ZZ Ceti (pulsating white dwarfs)

Why Variable Stars Pulsate



- Giant stars pulsate because their atmospheres trap some of their radiated energy
  - This heats the atmosphere, which then expands and allows radiation to escape
  - Expanding atmosphere cools, then contracts trapping the radiation again

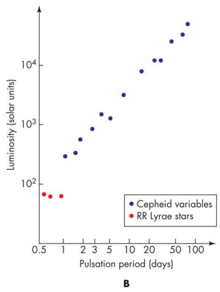
The Instability Strip



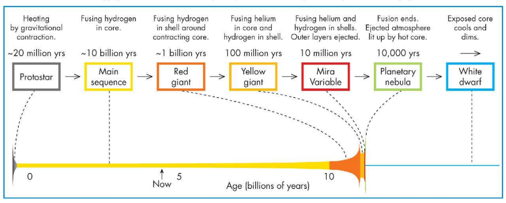
- The high "opacity" (ability to trap radiation) of a star's atmosphere only occurs in the limited ***instability strip*** of the H-R diagram

The Period-Luminosity Law

- Many pulsating stars obey a law that relates their luminosity to their period of pulsation – the longer the period, the more luminous the star
- Reason: Larger stars are more massive and have less surface gravity



The Death of Sun-like Stars

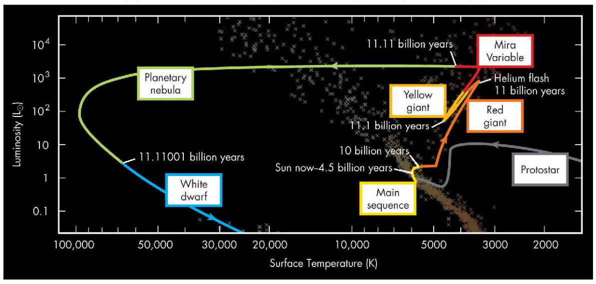


- Sun spends 11-12 billion years on the main-sequence consuming its hydrogen and becoming a red giant
- Subsequently, it spends about 100 million years fusing helium in its core

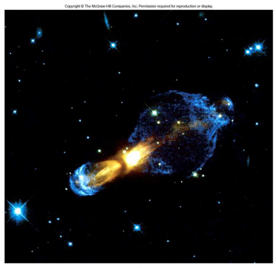
Death of a Low-Mass Star

- As helium burns in the star's core, its radius shrinks, but never enough to heat it to carbon-fusing temperatures
- Increased luminosity, expands outer surface to red supergiant sizes and temperature down to 2500 K
- Carbon and silicon flakes (grains) form in this cool environment and are driven out by radiation pressure
- The grains carry the gas into space – a ***planetary nebula*** is formed – and the inner core becomes visible
- Planetary nebula (no relation to planets) glows from UV radiation from bare core

Death of a Low-Mass Star

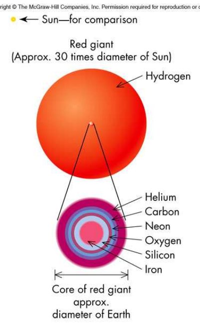


Planetary Nebulae



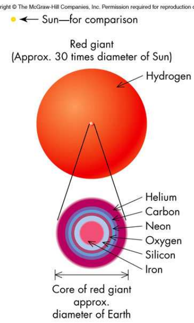
Old Age of Massive Stars

- Massive stars do not stop with helium fusion – a variety of nuclear reactions creates heavier elements
- Formation of heavy elements by nuclear burning processes is called ***nucleosynthesis***
- It is proposed that all elements in the universe heavier than helium were created by massive stars



Nucleosynthesis

- Typical fusion process: ^{4}He + ^{12}C = ^{16}O + γ where γ is a gamma ray photon
- As the temperature of the core increases, heavier elements are fused forming concentric layers of elements
- Iron is the heaviest element fused (at about 1 billion K) - larger elements will not release energy upon being fused
- A massive star (30 $M_{\odot}$) may take less than 10 million years to develop its Earth-sized iron core



Core Collapse of Massive Stars

- The inability of iron to release energy upon fusing signals the end of a massive star's life
- As the star's core shrinks, protons and electrons merge to form neutrons and the core is transformed into a sphere of neutrons
- The loss of electrons in the creation of the neutrons causes the core pressure to drop suddenly – nothing remains to support the star, so its inner layers collapse
- In a matter of seconds the Earth-sized iron core is transformed into a 10-km, extremely dense ball of neutrons
- The outer layers of the star, now not supported as well, collapse and heat to billions of degrees as they slam into the neutron core

Supernovae

- The gas pressure surges and thrusts the outer layers back into space in a gigantic explosion – a ***supernova***

Supernovae

- Elements synthesized by nuclear burning are mixed with the star's outer layers as they expand into space
  - Speeds may exceed 10,000 km/sec
  - Materials mix with interstellar matter to be recycled into a new generation of stars
  - Free neutrons from the explosion synthesize heavier elements (e.g., gold, platinum, uranium
  - A supernova releases neutrinos in large quantities

Supernovae

- In a few minutes, more energy is released than during the star's entire life
- It brightens to several billion times the luminosity of the Sun – a luminosity larger than all the stars in the Milky Way combined

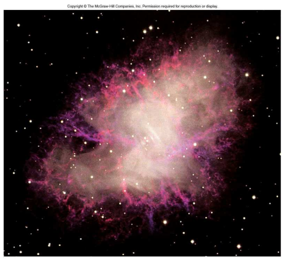
Supernova Remnants

- The huge, glowing cloud of debris that expands from a supernova explosion sweeping up interstellar material as it goes is called a ***supernova remnant***
  - During a 1-100 year time frame, a supernova will expand from 0.03 ly to several light-years in diameter
  - Supernova remnants have a more ragged look compared to planetary and other nebulae

A

Supernova Remnants

- Two well-known supernova remnants
  - ***Crab Nebula*** – Visual outburst witnessed by astronomers in China in 1054 A.D.
  - Supernova 1987A – Most recent visual supernova and a rare blue supergiant explosion



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Stellar Corpses

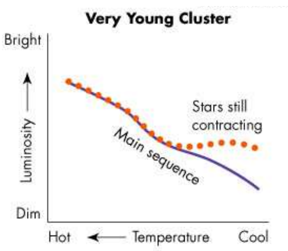
- Neutron star or black hole remains after supernova remnant dissipates

History of Stellar Evolution Theories

- Aristotle wrote more than 2000 years ago that stars are heated by their passage through the heavens, but never considered that they evolved
- In the 18th century, Immanuel Kant described the Sun as a fiery sphere, formed from the gases gravitated to the center of a solar nebula
- In the 1850s and 1860s, Lord Kelvin and Hermann von Helmholtz used the physics of gases and gravity to mathematically determine the pressure and temperature profiles inside a star, but were unable to find a suitable energy source to maintain the profiles
- The 20th century brought the physics of atoms and relativity to the problem of stellar evolution
  - Sir Arthur Eddington recognized the importance of mass as a source of energy and the need to account for energy transport
  - By 1940s, the need for computers to solve the problem of stellar evolution was recognized

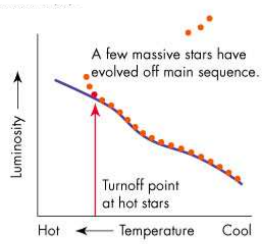
Testing Stellar Evolution Theories

- The best demonstration that modern theory is correct comes from comparing the H-R diagrams of real star clusters with theoretically determined diagrams
  - All stars within a cluster form at about the same time and are therefore about the same age
  - Depending on the age of the cluster, some stars will be on the main sequence and others will not

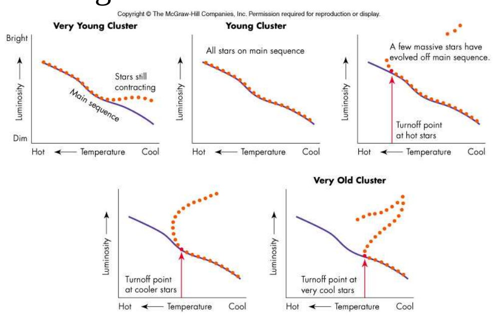


Testing Stellar Evolution Theories

- Since more massive stars evolve faster and in a well-defined fashion (at least theoretically speaking), the stars on or off the main sequence will not be random – a cluster of stars will show a distinctive pattern that is tied to the individual evolutionary tracks of the stars
- Real stars from a given cluster and plotted on an H-R diagram in fact show these distinctive patterns



Testing Stellar Evolution Theories



- This success now allows astronomers to date clusters by determining a cluster's "***turnoff point***"