

### The Life of a Star

- Gravity holds star together; pressure supports star against gravity.
- A star generates its supporting pressure from energy produced in its core by the conversion of hydrogen into helium.
- The hydrogen cannot last forever – consequently, the star must evolve (age).
- Once its fuel is exhausted, the star dies – quietly into a white dwarf or violently into a neutron star or black hole.
- The violent explosions of dying large stars seed interstellar space with materials for the next generation of stars and the elements vital to human life.

Higher luminosity leads to faster fuel usage. Faster fuel usage means a high-mass star burns out sooner than a low-mass star.

### The Life of a Star

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**Principles Governing the Structure of a Star**

- Gravity holds star together; pressure supports star against gravity. Gravity and pressure forces must balance (hydrostatic equilibrium).
- Pressure is created by high temperature in star's core.
- High temperature causes heat to flow from core to surface, where it escapes into space as the star's luminosity (starlight).
- Escaping heat is replenished by nuclear fusion in core. (Hydrogen fuses into helium, initially).
- Star eventually runs out of fuel.

Low-mass stars turn into white dwarfs. High-mass stars explode, leaving neutron star or black hole.

Note: High-mass stars require more pressure to support their greater mass. Greater pressure is produced by higher temperature. Higher temperature produces higher luminosity. Higher luminosity leads to faster fuel usage. Faster fuel usage means a high-mass star burns out sooner than a low-mass star.

### Mass Is the Key

Principles Governing the Structure of a Star

- 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.

Higher luminosity leads to faster fuel usage. Faster fuel usage means a high-mass star burns out sooner than a low-mass star.

### The Life of Our Sun

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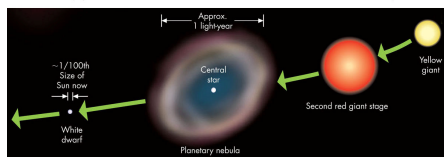
- The Sun was born out of an *interstellar cloud* that gravitationally collapsed over a time span of a few million years.
- Fusing hydrogen into helium in its core, the Sun will reside on the main sequence for 10 billion years and in the process convert 90% of its core hydrogen into helium.

### 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

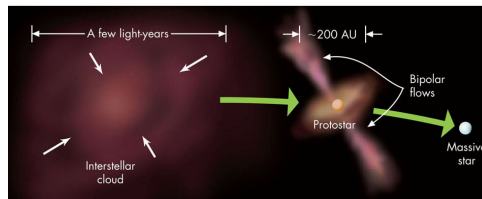
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- As the core's helium fuel begins to expire, the Sun will once again transform into a red giant, but only bigger than before
- The high luminosity of the red giant will drive the Sun's atmosphere into space leaving behind its bare core
- The core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

## The Life of a High-Mass Star

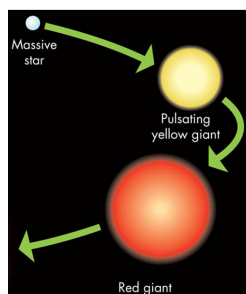
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- The early life of a high-mass star is similar to the Sun:
  - Collapses from an interstellar cloud and resides on the main sequence
  - Proceeds through these stages much faster than the Sun, spending less than 100 million years on the main sequence

## The Life of a High-Mass Star

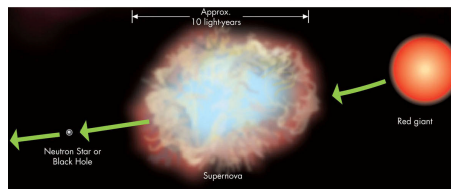
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- A high-mass star then passes through the pulsating yellow giant stage before it turns into a red giant
- In the red giant phase, the core begins to fuse one element into another creating elements as massive as iron

## The Life of a High-Mass Star

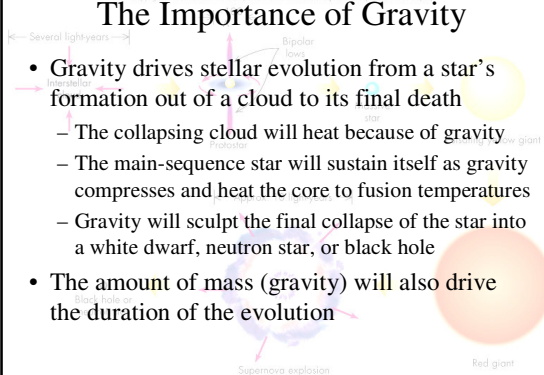
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- Once iron is reached, the core is out of fuel and it collapses
  - The star's heavy elements are blown into space along with its outer layers
  - A neutron star or black hole is left behind

## The Importance of Gravity

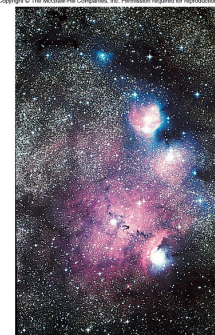
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- Gravity drives stellar evolution from a star's formation out of a cloud to its final death
  - The collapsing cloud will heat because of gravity
  - The main-sequence star will sustain itself as gravity compresses and heat the core to fusion temperatures
  - 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

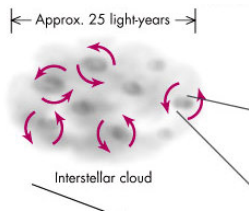
## Interstellar Gas Clouds

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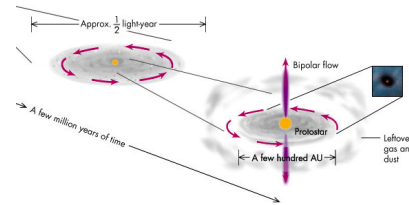
- General Characteristics
  - Gas: hydrogen (71%), helium (27%), others
  - Dust: microscopic particles of silicates, carbon, and iron
  - Temperature: Around 10 K

## Initial Collapse



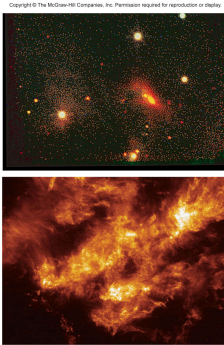
- Low temperature leads to too low pressure to support cloud against gravitational collapse
- Collapse may be triggered by collision with another cloud, a star explosion, or some other process
- Non-uniformity, clumpy nature of gas leads to formation of smaller, warmer, and denser clumps

## 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

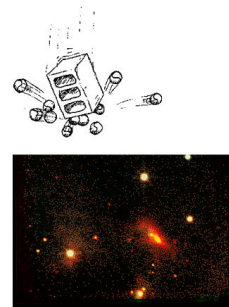
## Protostars



- 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

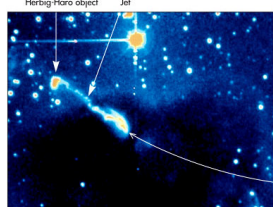
## Further Collapse

- 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

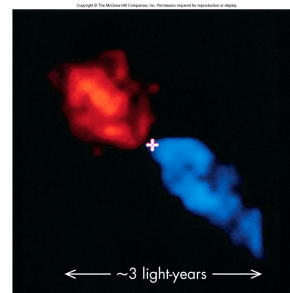


## Herbig-Haro Objects

- Long, thin jets squirt out from the young star, carving a cavity in the gas around the star and creating bright blobs, “Herbig-Haro objects”, where the jet hits surrounding, distant gas

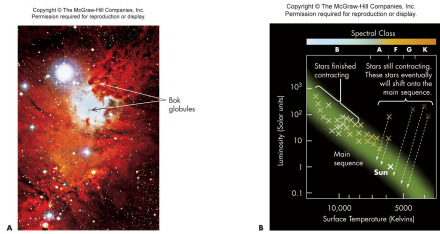


## Bipolar Flows



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

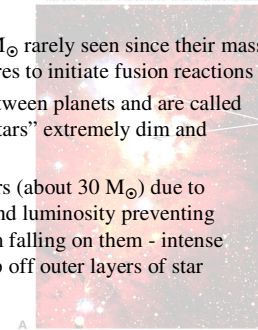
## T-Tauri Stars



- 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

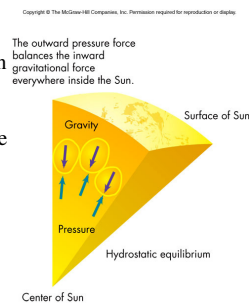
## Stellar Mass Limits

- 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



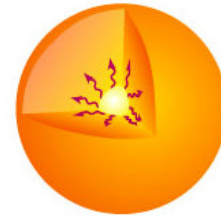
## A Star's Mass Determines Its Core Temperature

- 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



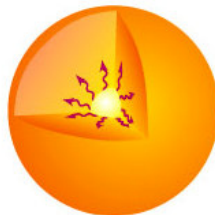
## Structure of High- and Low-Mass Stars

- 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

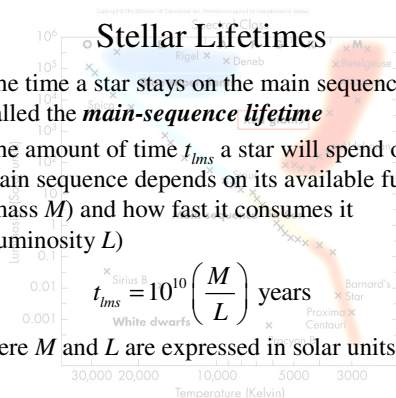


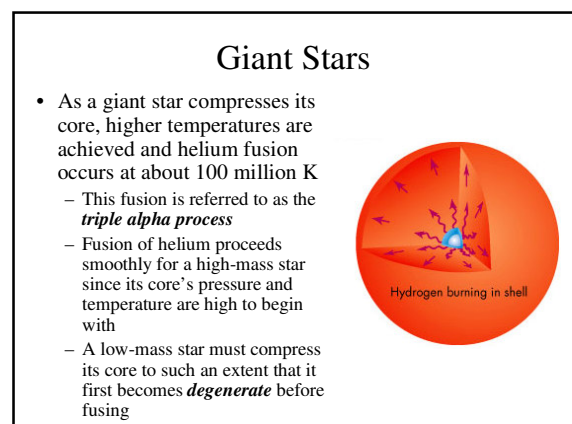
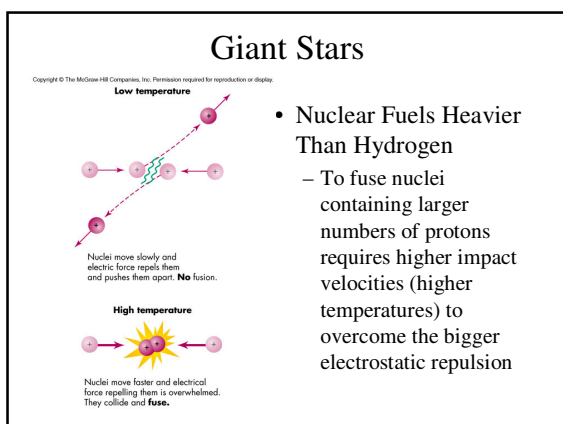
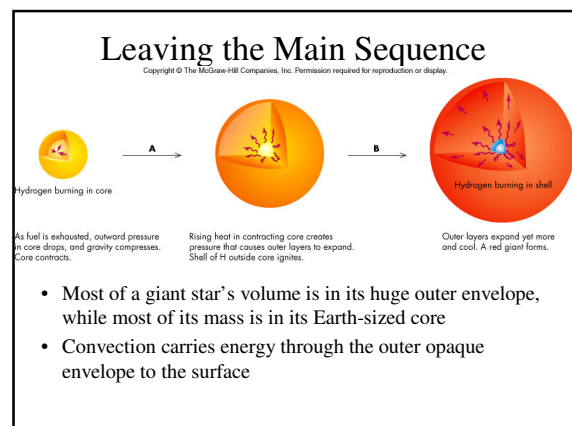
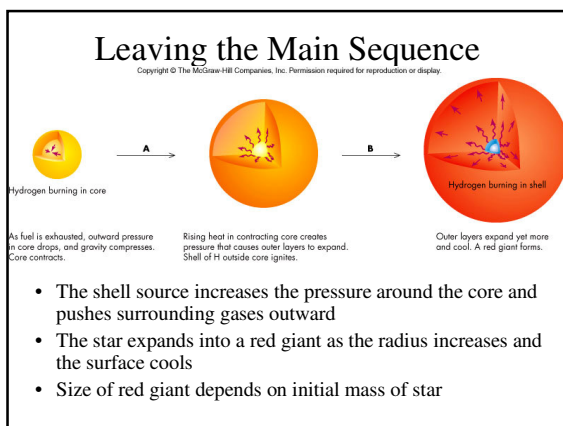
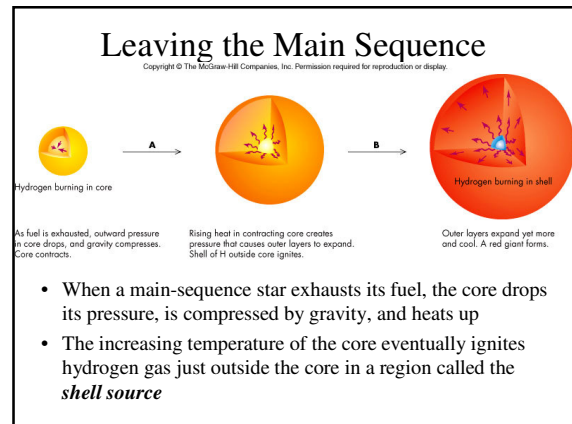
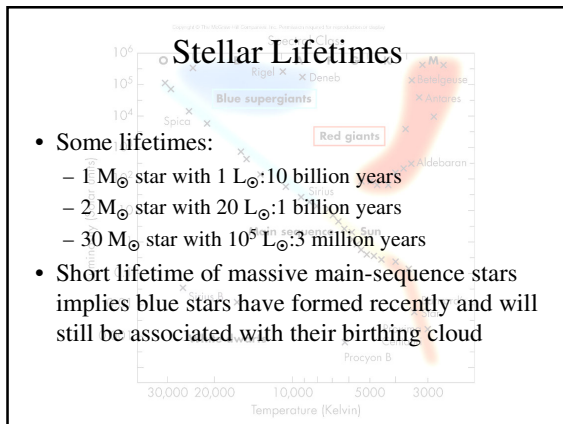
## Stellar Lifetimes

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

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

- Here  $M$  and  $L$  are expressed in solar units







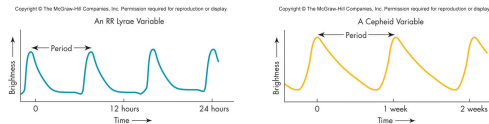
## Degeneracy in Low-Mass Giant Stars

- 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

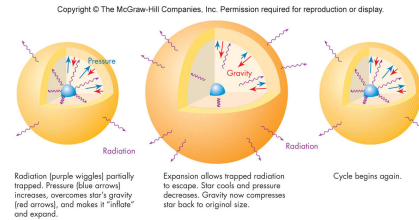
- The explosive energy converts the core back to a normal gas
  - The core expands and the star's surface shrinks
  - The red giant turns into a yellow giant
- Most luminous yellow giants on an H-R diagram are aging high-mass stars
- Less luminous yellow giants are low-mass stars that have completed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

## Variable Stars



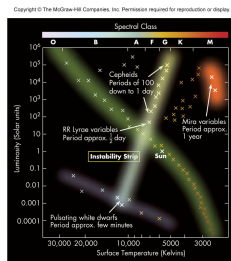
- Two important groups of variable (pulsating) stars:
  - RR Lyrae (first discovered in constellation of Lyra)
    - Mass comparable to Sun's with 40 times the luminosity
    - Periods of about half a day
  - Cepheid (first discovered in constellation of Cepheus)
    - More massive than Sun and about 20,000x 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

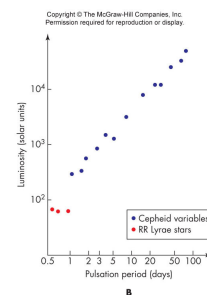
## The Instability Strip



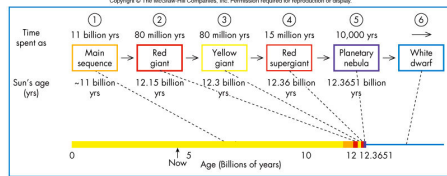
- The high “opacity” (ability to trap radiation) of a star's atmosphere only occurs in the limited **instability strip** of the H-R diagram

## 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



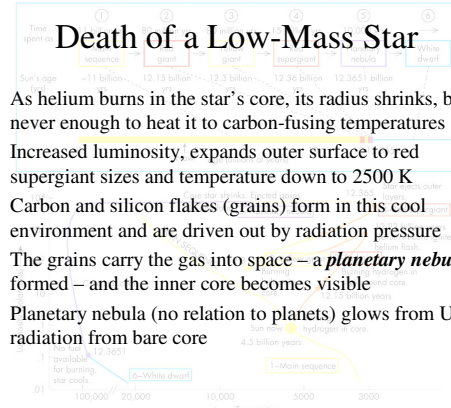
## The Death of Sun-like Stars



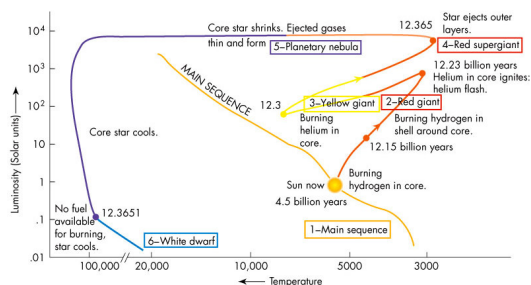
- Sun spends 11-12 billion years on the main-sequence consuming its hydrogen and becoming a red giant
- Subsequently, it spends about 100 million years fusing helium in its core

## 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

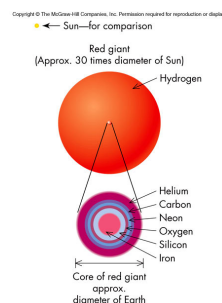


## Planetary Nebulae



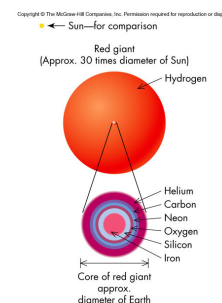
## Old Age of Massive Stars

- 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:  $4\text{He} + {}^{12}\text{C} = {}^{16}\text{O} + \gamma$  where  $\gamma$  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

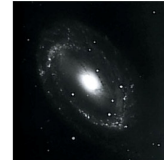
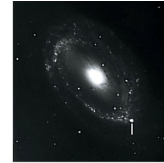


## Core Collapse of Massive Stars

- 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

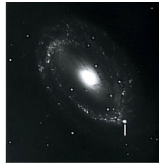
## Supernovae

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



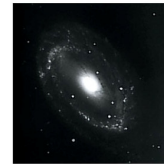
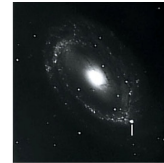
## Supernovae

- 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



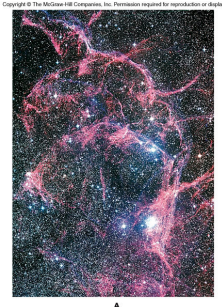
## Supernovae

- 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



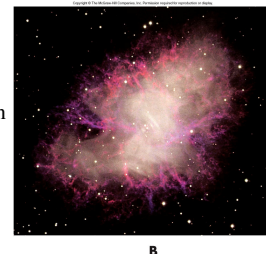
## Supernova Remnants

- 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



## Supernova Remnants

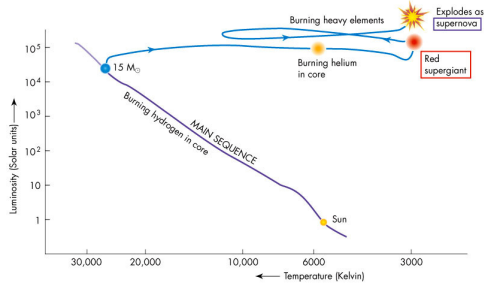
- Two well-known supernova remnants
  - *Crab Nebula* – Visual outburst witnessed by astronomers in China in 1054 A.D.
  - Supernova 1987A – Most recent visual supernova and a rare blue supergiant explosion





## Stellar Corpses

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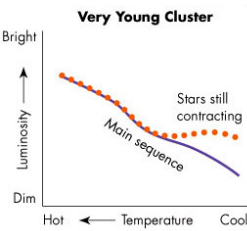
- Neutron star or black hole remains after supernova remnant dissipates

## 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 18<sup>th</sup> 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 20<sup>th</sup> 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

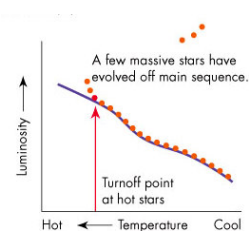
## Testing Stellar Evolution Theories

- 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



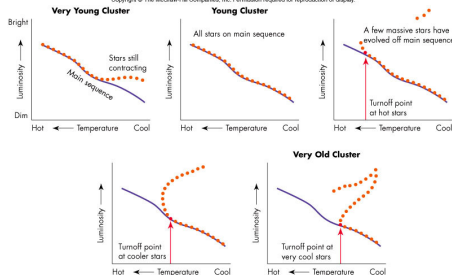
## Testing Stellar Evolution Theories

- 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

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