

# Astronomy 122



## This Class (Lecture 16):

Stellar Evolution:  
Post-Main Sequence

***Make-up Nightlabs!***

***Nightlabs due in discussion  
class on March 29<sup>th</sup>.***

## Next Class:

Stellar Evolution:  
Post-Main Sequence

Music: *We Are All Made of Stars* – Moby

Mar 16, 2005

Astronomy 122 Spring 2006

# Icko Lecture: Extra Credit



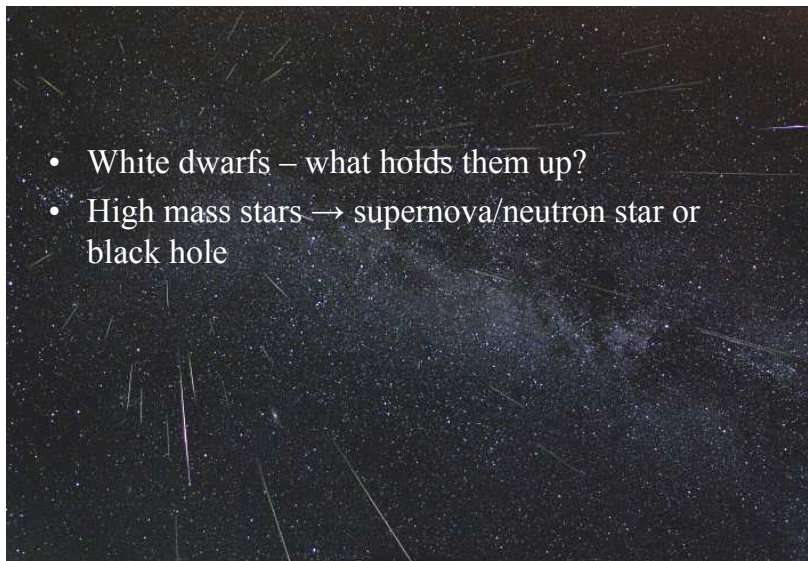
- "The Mars Exploration Rover Mission" by Dr. Steven Squyres, Goldwin Smith Professor of Astronomy at Cornell University
- Tuesday, March 28th at 7PM in Foellinger Auditorium
- Go to lecture and write a typed ~1 page analysis on the talk, make sure to discuss (1) what surprising thing you learned and (2) the most interesting aspect of the talk.
- Extra credit worth an extra 1% to your final grade.
- But, **do not walk out** of the talk until the questions have finished.



Mar 16, 2005

Astronomy 122 Spring 2006

# Outline



- White dwarfs – what holds them up?
- High mass stars → supernova/neutron star or black hole

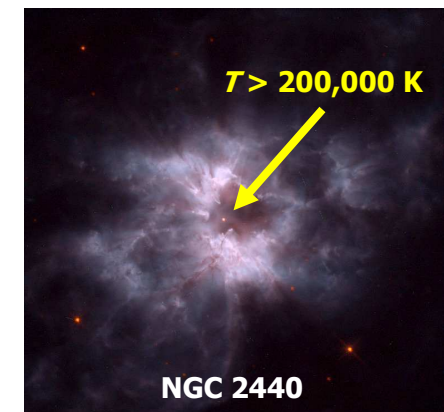
Mar 16, 2005

Astronomy 122 Spring 2006

# Low-Mass Star End Game



- “Superwind”
- Outer layers of the red giant star are cast off
  - Up to 40% of original mass
- The core remains, made of carbon/oxygen “ash” from helium fusion
  - The core is very hot, above 200,000 K
- Ultraviolet radiation from the core ionizes the cast off outer layers
  - Becomes a *planetary nebula*
  - *Unfortunate name, but some of the most beautiful objects in the sky.*



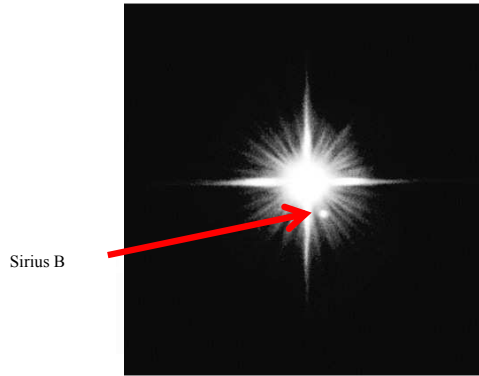
Mar 16, 2005

Astronomy 122 Spring 2006

# What About the Core?



- Nuclear fusion has stopped, and gravity begins to win the battle
- Core contracts to the size of the Earth
  - But its about 60% the Sun's mass!
  - Material in the core is compressed to a density of 1,000 kg/cm<sup>3</sup>!
  - Very hot, surface temperature >100,000 K
- Final fate - **White dwarf**
  - Slowly cools off over billions of years



Astronomy 122 Spring 2006

Mar 16, 2005

# Electron Degeneracy



- The electrons get so squashed together that they get pushed into *degenerate states*
  - This creates **pressure** to counteract gravity (Pauli exclusion)
  - Stops contraction



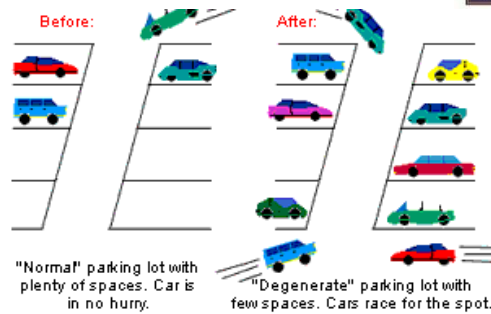
Astronomy 122 Spring 2006

Mar 16, 2005

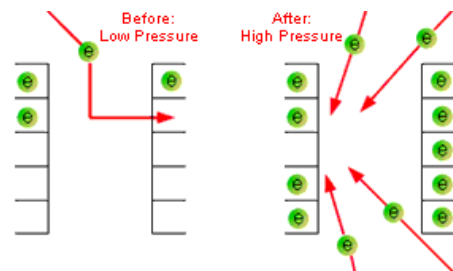
# Degeneracy Pressure



- ▶ Electrons are forced into higher energy levels than normal – all of the lower levels are taken
- ▶ Effect manifests itself as pressure



"Normal" parking lot with plenty of spaces. Car is in no hurry.  
"Degenerate" parking lot with few spaces. Cars race for the spot.



Astronomy 122 Spring 2006

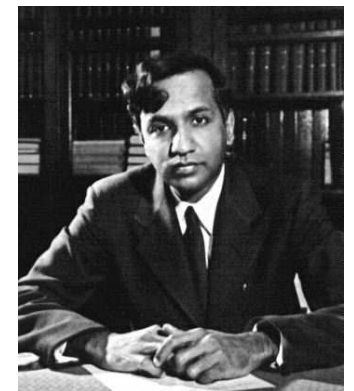
NASA

Mar 16, 2005

# Chandrasekhar limit



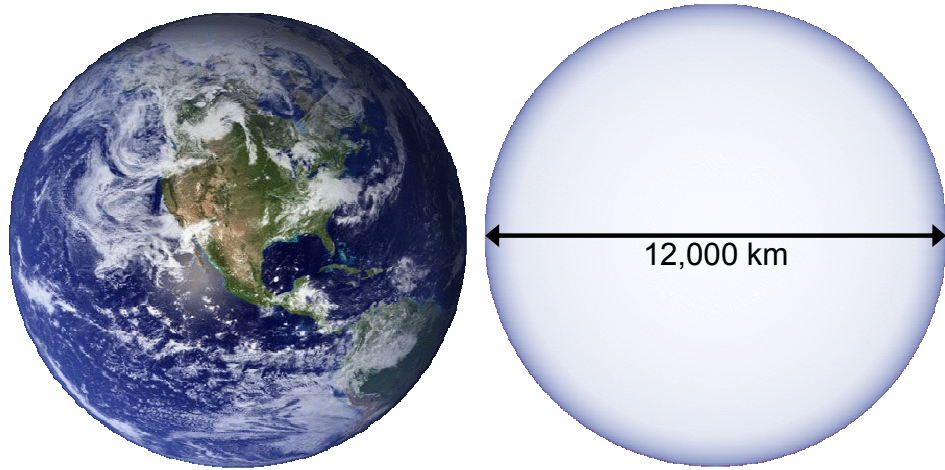
- Maximum mass of a white dwarf ( $M \cong 1.4$  solar masses).
- No white dwarf observed is over this.
- If mass is higher, the white dwarf can not support itself with electron degeneracy, and it collapses more! Gravity is a harsh mistress!



Astronomy 122 Spring 2006

Mar 16, 2005

## Relative Size of White Dwarf



White dwarf— but will usually weigh about 0.6 Solar masses

Mar 16, 2005

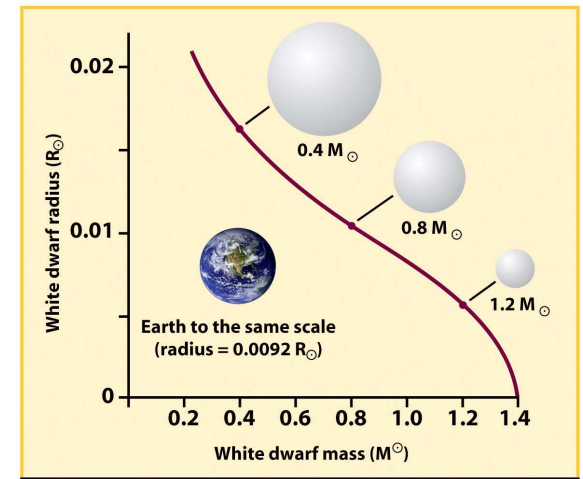
Astronomy 122 Spring 2006

## White Dwarfs are Weird



The more massive, the smaller!

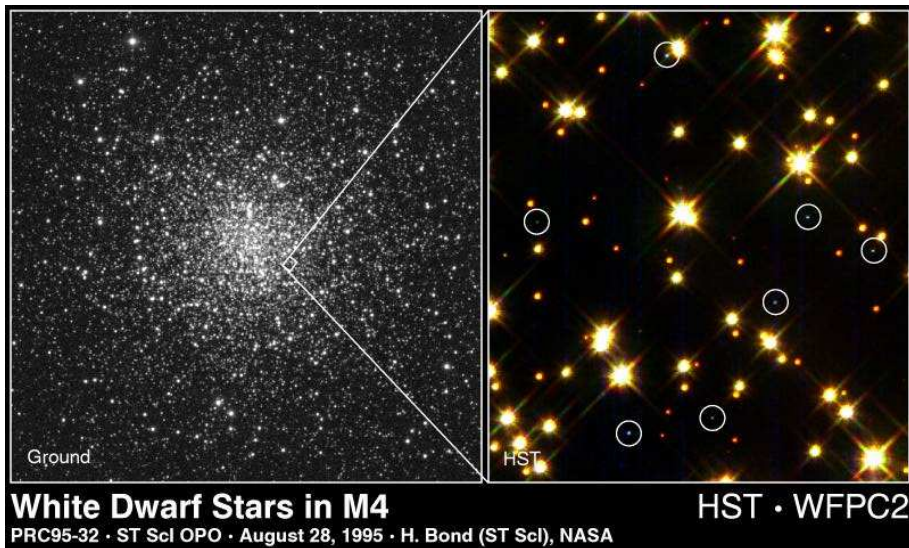
Their radius *decreases* with mass!



Mar 16, 2005

Astronomy 122 Spring 2006

## White Dwarves!



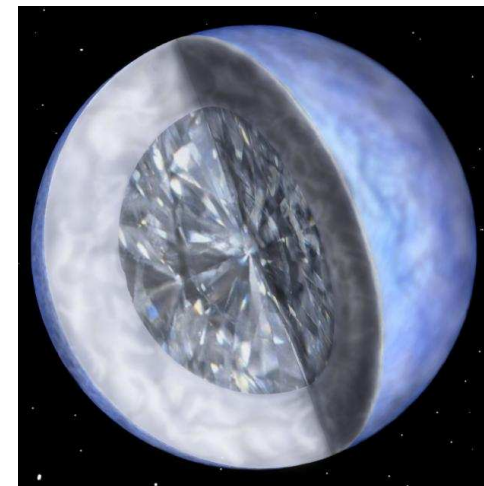
Mar 16, 2005

Astronomy 122 Spring 2006

## Stellar Diamonds!?!



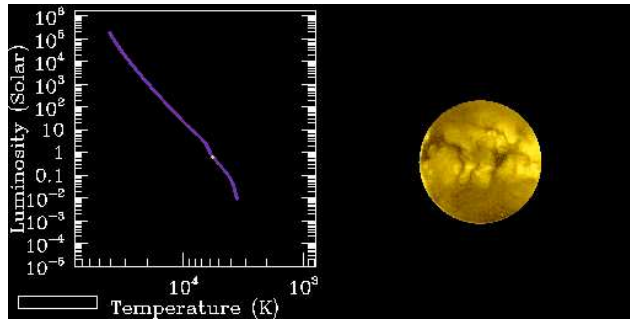
- The interior of the white dwarf crystallizes due to the extreme pressures
- Made mostly of carbon (some oxygen)
- Crystallized carbon = **a diamond**
  - With a blue-green tint from the oxygen
  - 10 billion trillion trillion carats!



Mar 16, 2005

Astronomy 122 Spring 2006

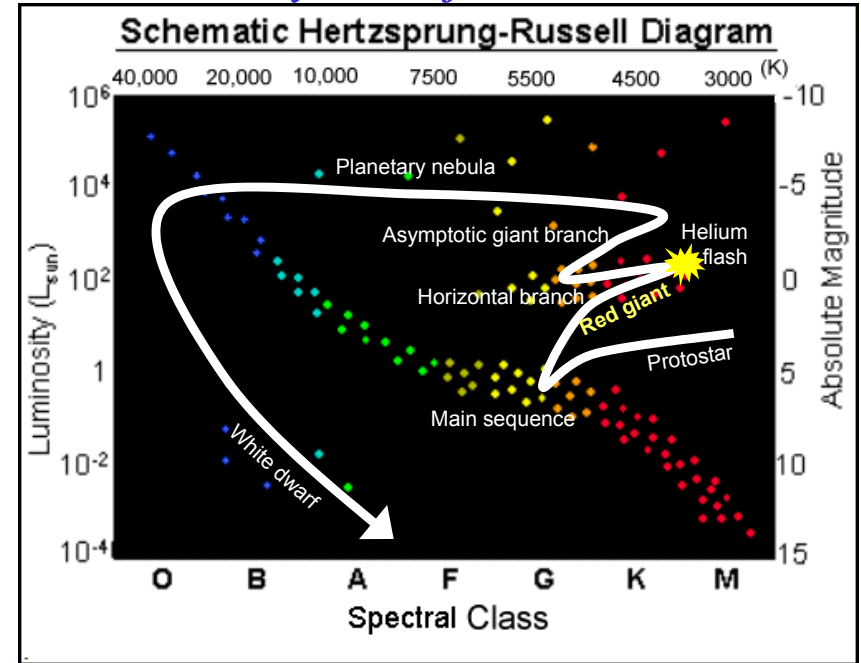
# The Life and Times of a Low-Mass Star



Mar 16, 2005

Astronomy 122 Spring 2006 <http://rainman.astro.uiuc.edu/ddr/stellar/beginner.html>

# Evolutionary Path of a Solar-Mass Star

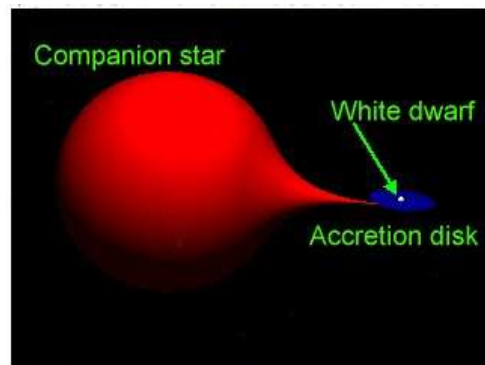


Mar 16, 2005

# Binary Systems?



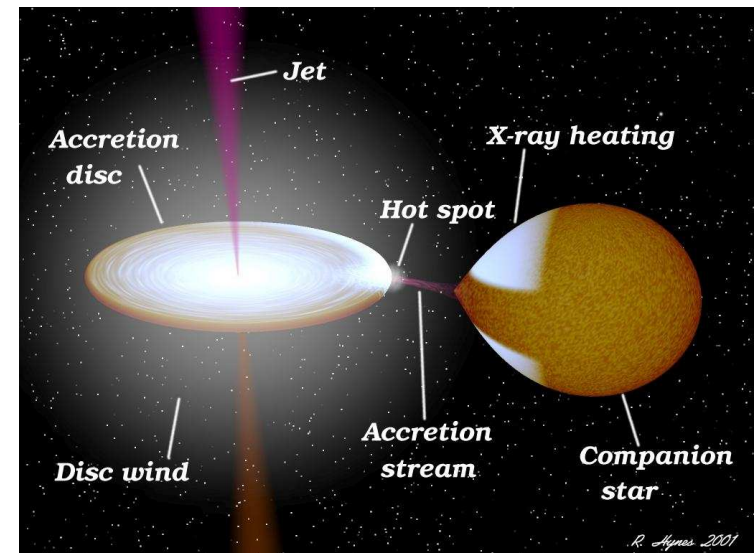
- In a close binary pair of stars with slightly different masses, the higher mass star evolves into a white dwarf first
- Later, the other star evolves into a red giant
- White dwarf then steals mass from its giant companion!
- Creates a dense layer of hydrogen gas on the white dwarf's surface



Mar 16, 2005

Astronomy 122 Spring 2006

# Binary Systems?



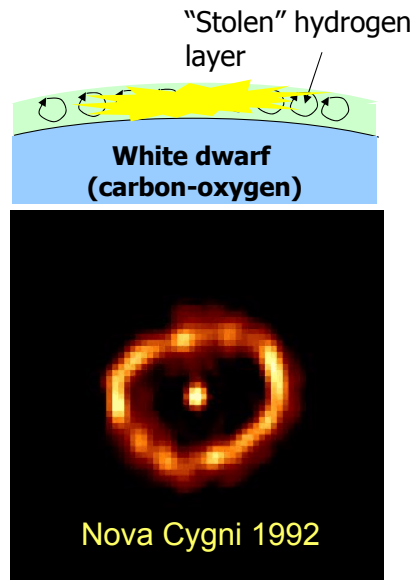
Mar 16, 2005

Astronomy 122 Spring 2006

# Novae



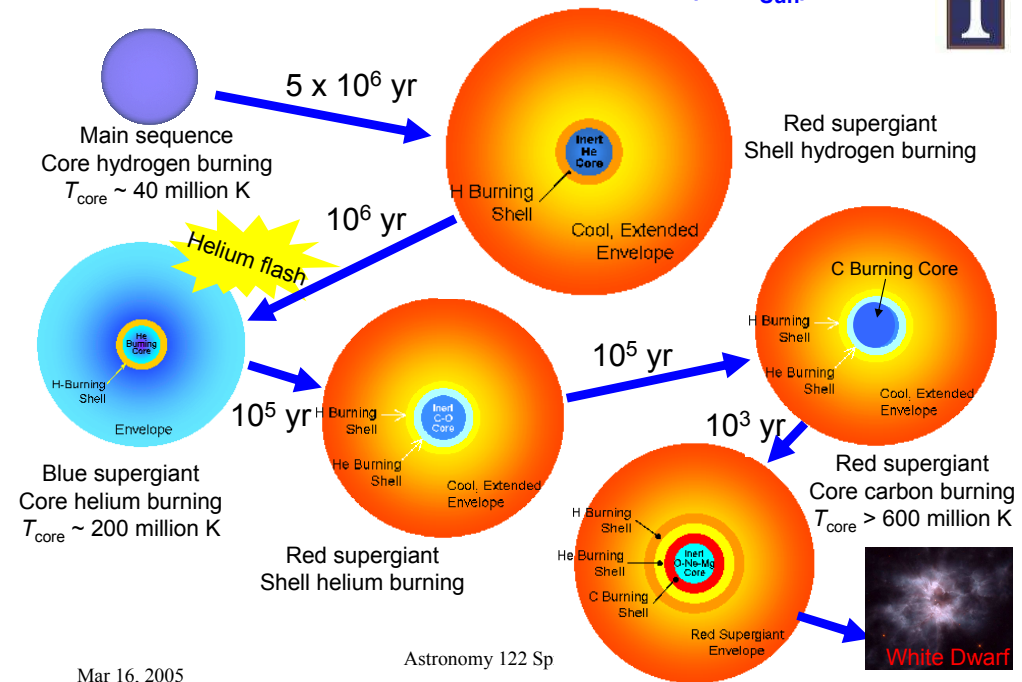
- If enough material piles up onto the surface of a white dwarf, can undergo explosive nuclear fusion
- White dwarf blows off this envelope and brightens by 100 – 1000 times
- Fades over a period of months
- This is called a **nova** (from Latin for “new”)
- Common, about 20 per year in our galaxy



Astronomy 122 Spring 2006

Mar 16, 2005

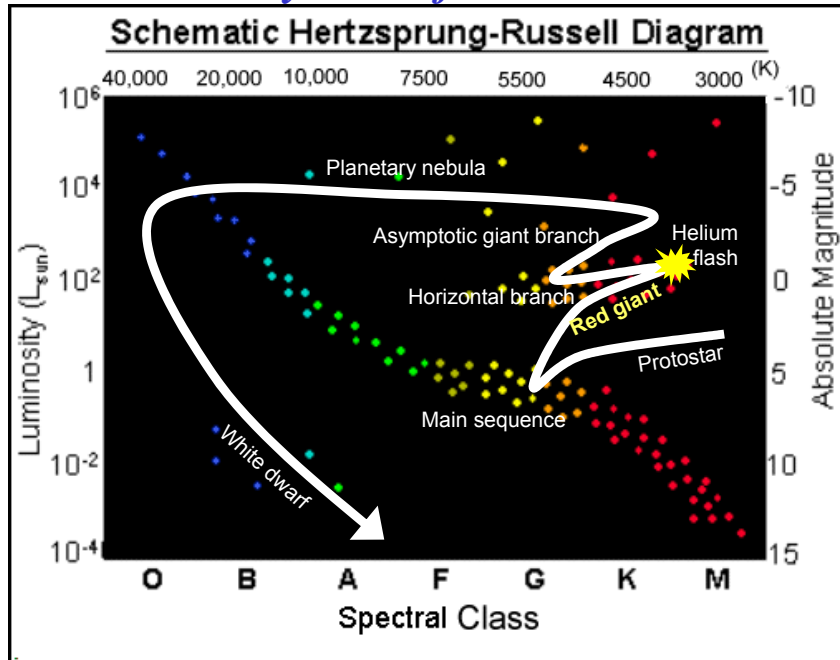
# Evolution of an Intermediate-Mass ( 4 M<sub>Sun</sub>) Star



Astronomy 122 Sp

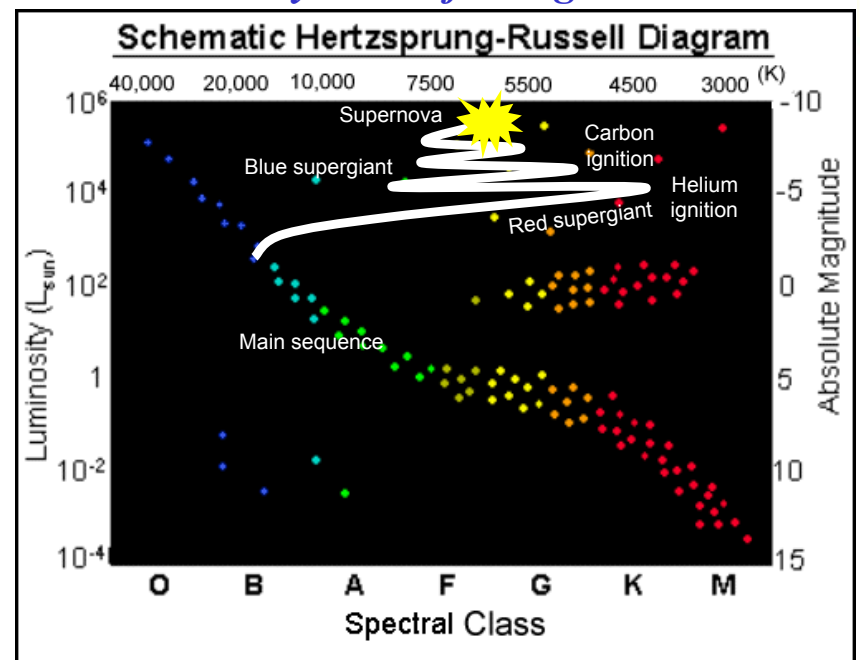
Mar 16, 2005

# Evolutionary Path of a Solar-Mass Star



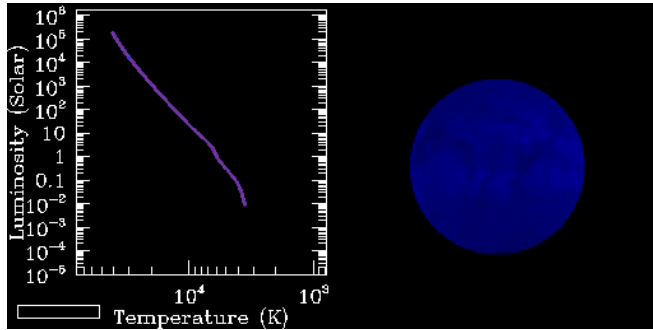
Mar 16, 2005

# Evolutionary Path of a High-Mass Star



Mar 16, 2005

# High Mass Stars ( $> 8 M_{sun}$ )



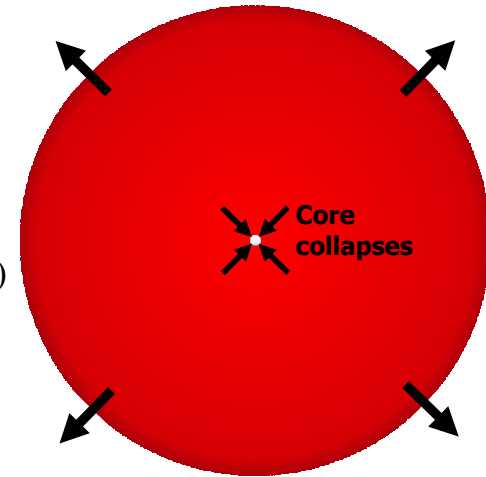
Mar 16, 2005

Astronomy 122 Spring 2006

# High Mass Stars ( $> 8 M_{sun}$ ): when the Hydrogen Runs out?



- Similar to intermediate-mass stars in the first few stages
- When the hydrogen supply runs out the core starts to contract
- Hydrogen shell burning (around the helium core) starts
- The outer envelope expands quickly becoming a **red supergiant**



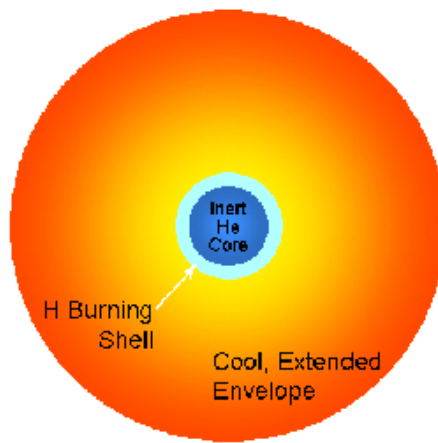
Mar 16, 2005

Astronomy 122 Spring 2006

# The Supergiant Phase



- Outer envelope of the star grows larger and cooler
  - Up to 5 AU in size!
  - Unlike a low mass star, brightness does not increase dramatically
- Eventually, core is hot enough that it can fuse helium atoms together (non-degen gas, so no flash)
  - Star contracts and heats up
  - Now a **blue supergiant**



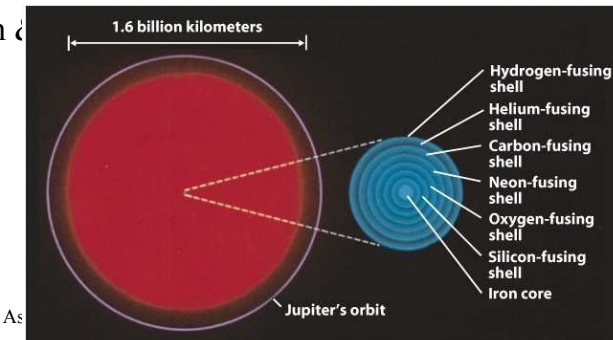
Mar 16, 2005

Astronomy 122 Spring 2006

# Massive Stars: Cycles of Fusion



- Helium fusion is not the end for massive stars
- Cycles of core contraction, heating, ignition
- Ash of one cycle becomes fuel for the next
  - carbon  $\Rightarrow$  oxygen, neon, sodium, & magnesium
  - neon  $\Rightarrow$  oxygen & magnesium
  - oxygen  $\Rightarrow$  silicon
  - silicon  $\Rightarrow$  iron
- Onion-skin like structure develops in the core



Mar 16, 2005

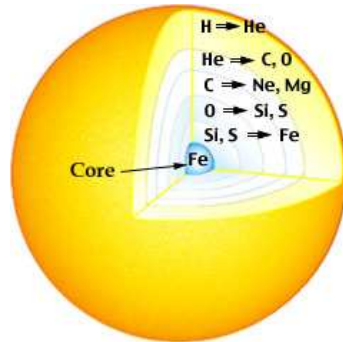
As

# Iron – The End of the Road



- Supergiants “burn” heavier and heavier atoms in the fusion process
- Each stage faster than the last
- After iron - no fuel left!
  - It requires energy to produce heavier atoms

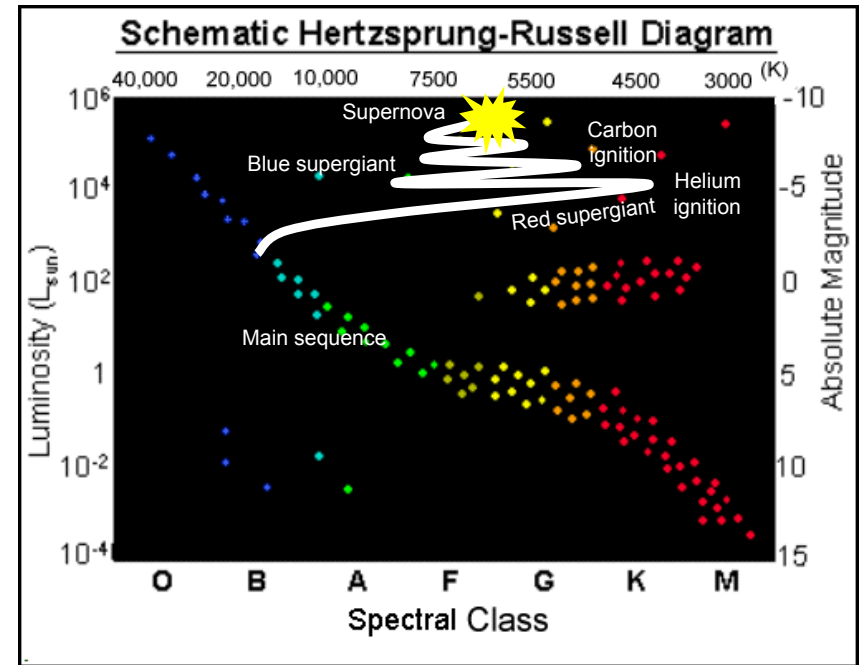
Stage	Temperature	Duration
H fusion	40 million K	7 million yr
He fusion	200 million K	500,000 yr
C fusion	600 million K	600 yr
Ne fusion	1.2 billion K	1 yr
O fusion	1.5 billion K	6 mo
Si fusion	2.7 billion K	1 day



Values for a  $25M_{\text{sun}}$  star  
Sun Astronomy 122 Spring 2006

Mar 16, 2005

# Evolutionary Path of a High-Mass Star



Mar 16, 2005

# Core Collapse



- **Completely out of gas!**
- Hydrostatic equilibrium is gone.
- The iron core of the star is supported by electron degeneracy pressure
  - Same pressure that supports a white dwarf
- Eventually, gravity wins...
  - This happens when the core reaches 1.4 solar masses
  - Remember the Chandrasekhar limit
  - The core has nuclear density!
    - It Earth has same density, it would be 1000 feet in diameter.

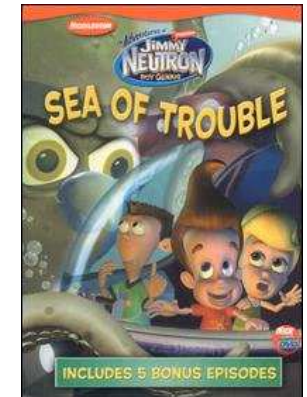
Mar 16, 2005

Astronomy 122 Spring 2006

# Core Collapse



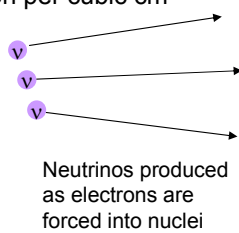
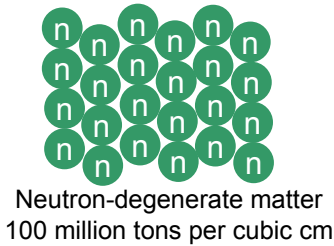
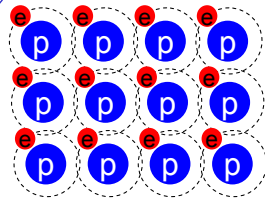
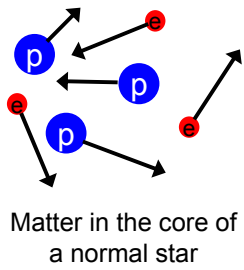
- When core is greater than  $1.4 M_{\text{sun}}$  – **core collapse!**
  - From 1,000 km across to 50 km in *1/10th of a second*
  - **Nearly 10% speed of light!**
- The core is transformed into a sea of neutrons
  - Electrons are squeezed into protons, neutrinos released



Mar 16, 2005

Astronomy 122 Spring 2006

# When Electron Degeneracy Just Isn't Enough



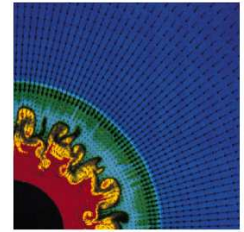
Mar 16, 2005

Astronomy 122 Spring 2006

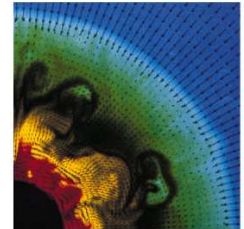
# Supernova!



- Core basically becomes a large atomic nucleus– ultra-high density!
- During collapse, envelope “bounces” of stiff core and produces a shock wave
  - Material is so dense, that it is opaque to the neutrinos produced
  - Neutrinos give the shock a “kick”
  - Rips the outer layers of the star apart
- Star explodes in a **supernova**
- Releases a tremendous amount of energy
  - 99% of the energy in the form of neutrinos
- >90% of the mass of star is ejected into space!
  - Fast, hot,



10 milliseconds



20 milliseconds

Mar 16, 2005

Astronomy 122 Spring 2006

# Game Over!



Mar 16, 2005

# AstroBlaster!

Works like a Real Super Nova!

**AstroBlaster™**

"Astroblaster illustrates the laws of conservation of momentum and energy during the creation of a supernova (an old star, that having exhausted its nuclear fuel, collapses upon itself in less than a second). A shock wave speeds outward from the center through the collapsed material, moving faster and faster as it reaches less dense layers toward the surface. This shock wave accelerates an outermost thin layer of the collapsed star to relativistic speeds, creating 'cosmic rays' that spread throughout our galaxy. The gravitational collapse of the dying star is illustrated by Astro-Blasters' fall to the surface. The shock wave accelerating outward through the star is illustrated by a wave of increasing speed as the result of the impact which is felt by the lighter balls nearer the top. The supernova explosion and release of cosmic rays is illustrated by the rapid departure of the top ball at high speed."

— Sterling A. Calgate, Astrophysicist

**INSTRUCTIONS:**

- Hold tip of AstroBlaster rod which extends through the smallest ball.
- Release when AstroBlaster is hanging straight down.
- AstroBlaster capsule can reach heights of over 5 times the drop height.

**SAFETY FEATURE:** Ball will not blast unless AstroBlaster hits vertically.

**CAUTION:** To avoid possible eye injury, hold away at arms length when releasing.

Fascinations®  
Seattle, Washington 98148  
Patent # 5,258,071  
Packaging must be kept as it contains important information.

MADE IN CHINA

www.fascinations.com

Item # ASTR1

Mar 16, 2005

Astronomy



# Supernova!



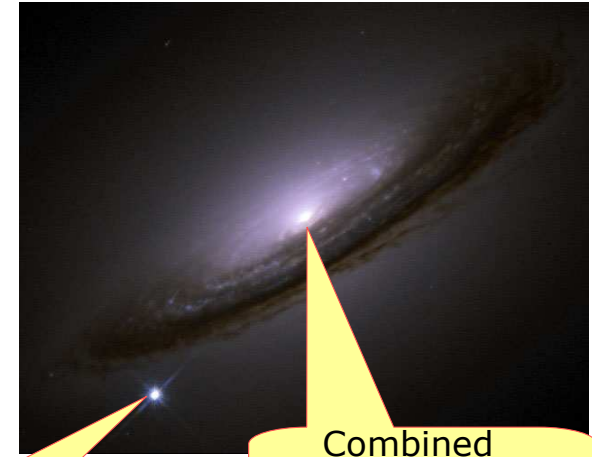
Mar 16, 2005

Astronomy 122 Spring 2006

# Bright as a Galaxy



- Supernovae are **bright**
  - A star's brightness increases 10,000 times!
  - Rivals an entire galaxy!



Light from a single supernova

Combined light of 100 billion stars

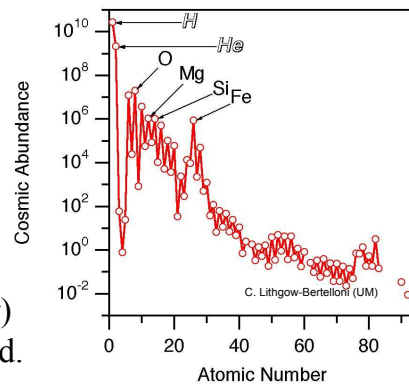
Mar 16, 2005

Astronomy 122 Spring 2006

# Making Heavy Elements



- During the explosion, energy-consuming fusion reactions are possible
- Heavy elements up to plutonium (& beyond?) are produced
- Dominant product: iron
- These by-products are *blasted* into space (>90% of star)
- Ejection is fast, hot, and enriched.
- Supernovae provide much of the building blocks for planets... and us!
- **We are recycled supernova debris!**
- **Star stuff.**



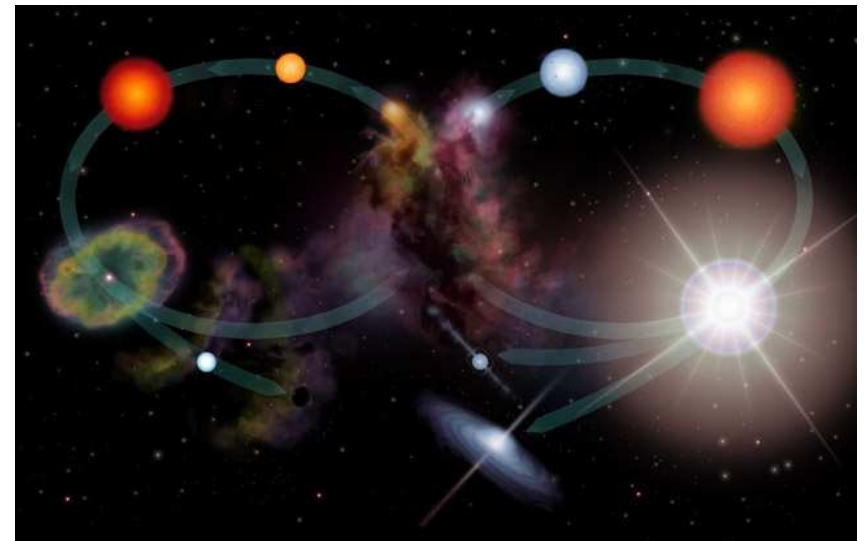
Mar 16, 2005

Astronomy 122 Spring 2006

DeLenn, B5



# Stellar Evolution Cycle



Mar 16, 2005

Astronomy 122 Spring 2006

# Stellar Evolution Cycle



- Stars form out of the interstellar medium
- They manufacture helium, carbon, nitrogen and more in their interiors by nuclear fusion
- Heavier elements (iron, lead, uranium, etc..) are made by supernovae
- Stars give these processed materials back to the interstellar medium when they die
- The processed materials are included in the gas and dust out of which the next generation of stars and planets will form

# Supernova Explosions in Recorded History



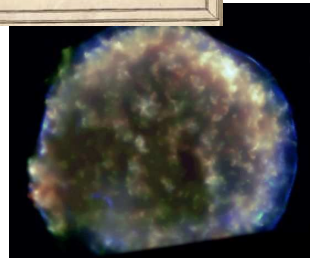
- 1054 AD
- Europe: no record
- China: “guest star”
- Anasazi people
  - Chaco Canyon, NM
  - Rock Paintings
- Modern view of this region of the sky:
  - **Crab Nebula** — a supernova remnant
- Massive star supernova



# Supernova Explosions in Recorded History



- November 11, 1572
- Recorded by Tycho Brahe
  - Called it a “**nova stella**” (new star)
- For about two weeks the supernova could be seen in the daytime!
- Modern view (X-rays):
  - Tycho’s Supernova Remnant
- Probably a white dwarf supernova (Ia)



# Supernova 1987A



Before

Feb. 23, 1987

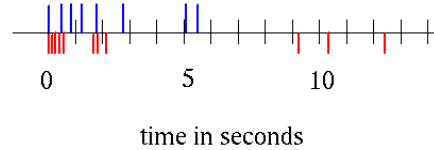
# Supernova 1987A



- Supernova are rare
- Only about ~3/century in a galaxy.
- Last was 400 yrs ago (Tycho)
- 1987A happened in the satellite galaxy LMC (150,000 lyrs away)
- Star was about 20  $M_{\odot}$
- Detected neutrinos from the core (most of explosion energy) for 13 secs about 20 detected.

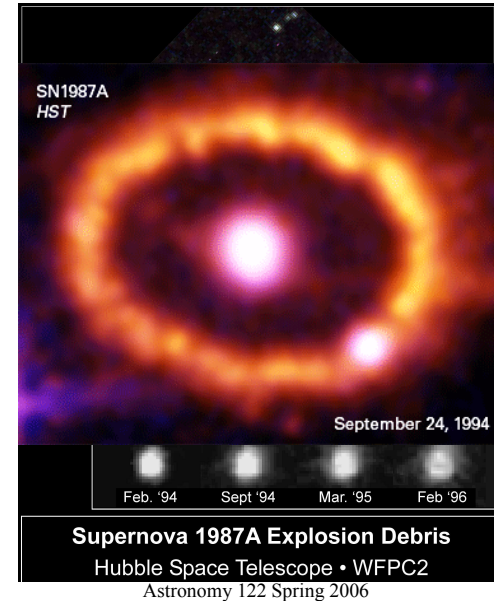


IMB  
Kamiokande



Mar 16, 2005

# Supernova 1987A - Today



Mar 16, 2005