Astronomy 122

<u>This Class (Lecture 16):</u>

Stellar Evolution:
Post-Main Sequence

<u>Next Class:</u>

Stellar Evolution:
Post-Main Sequence

<u>Make-up Nightlabs!</u>

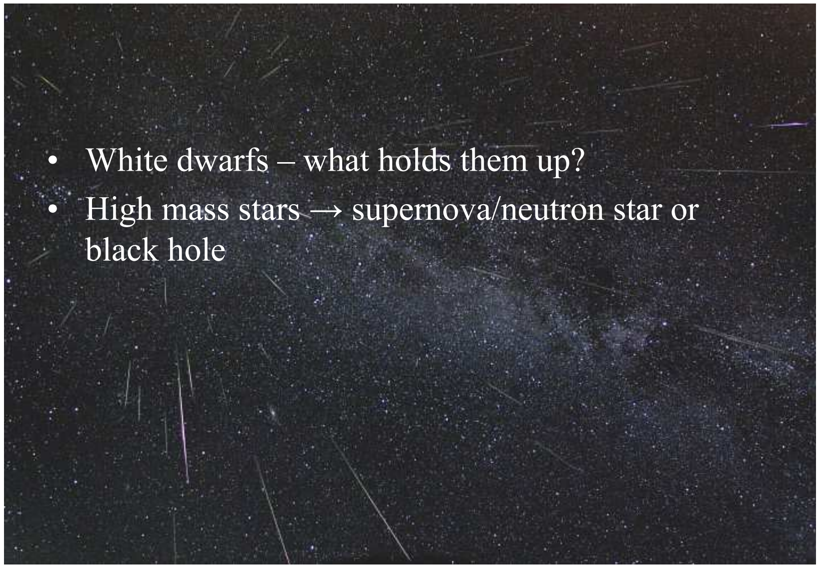
Nightlabs due in discussion class on March 29th.

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

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.

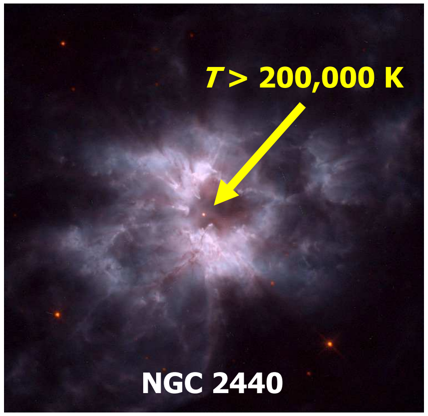
Outline



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

Low-Mass Star End Game

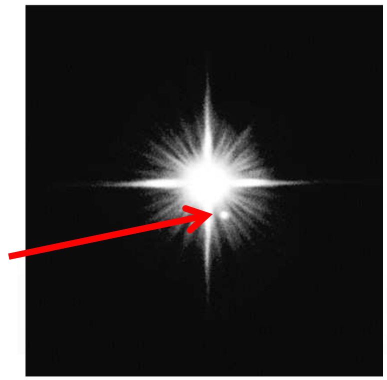
- "Superwind"
- Outer layers of the red giant star are cast off
  - Up to 40% of original mass
- The core remains, made of carbon/oxygen "ash" from helium fusion
  - The core is very hot, above 200,000 K
- Ultraviolet radiation from the core ionizes the cast off outer layers
  - Becomes a *planetary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



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^3!
  - Very hot, surface temperature >100,000 K
- Final fate - **White dwarf**
  - Slowly cools off over billions of years

Sirius B

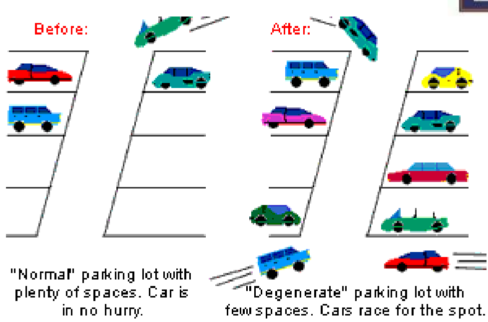


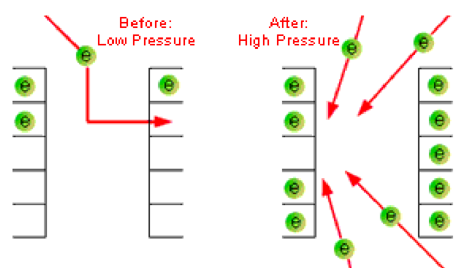
Electron Degeneracy

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

Degeneracy Pressure

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

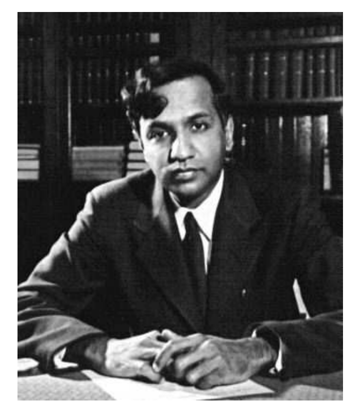




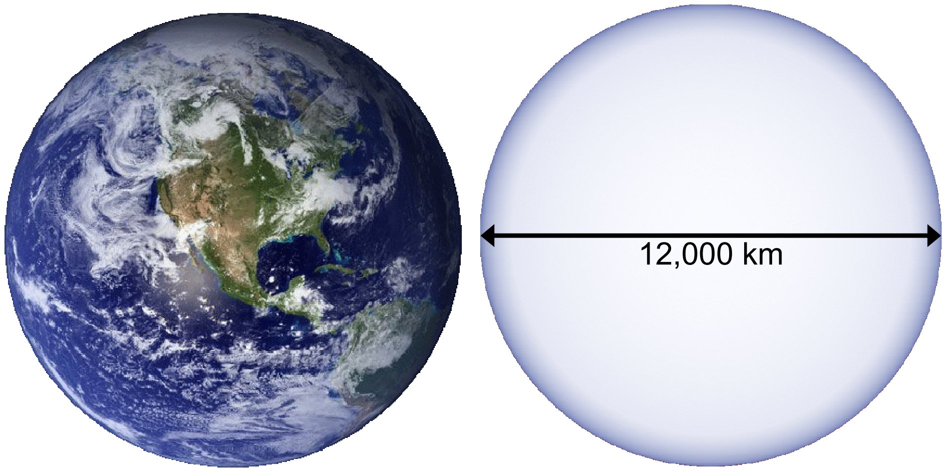
NASA

Chandrasekhar limit

- Maximum mass of a white dwarf (M ≅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!



Relative Size of White Dwarf

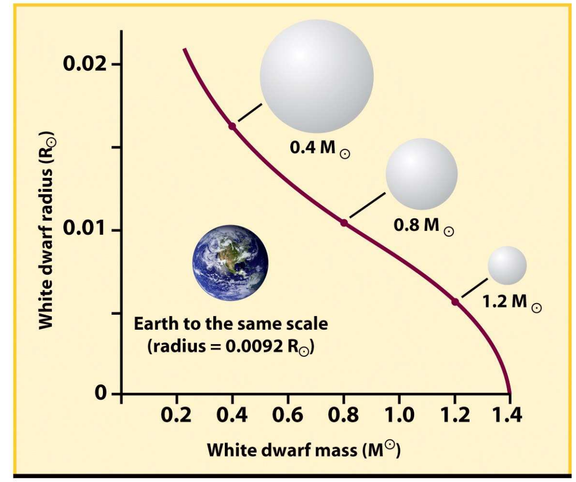


White dwarf– but will usually weigh about 0.6 Solar masses

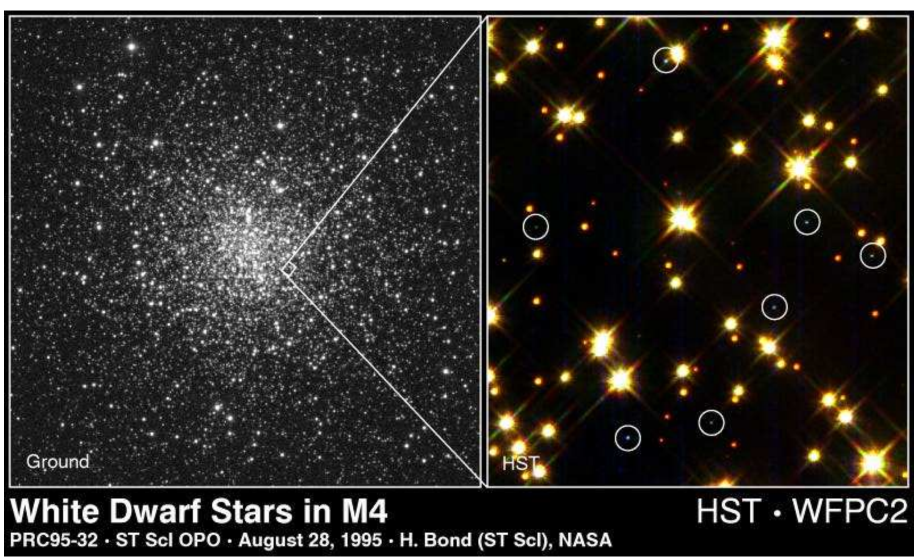
White Dwarfs are Weird

The more massive, the smaller!

Their radius *decreases* with mass!

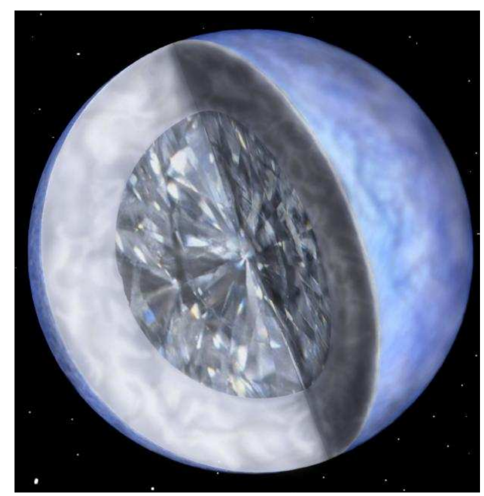


White Dwarves!

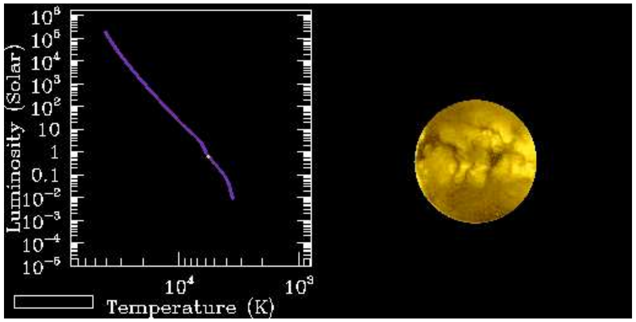


Stellar Diamonds!?!

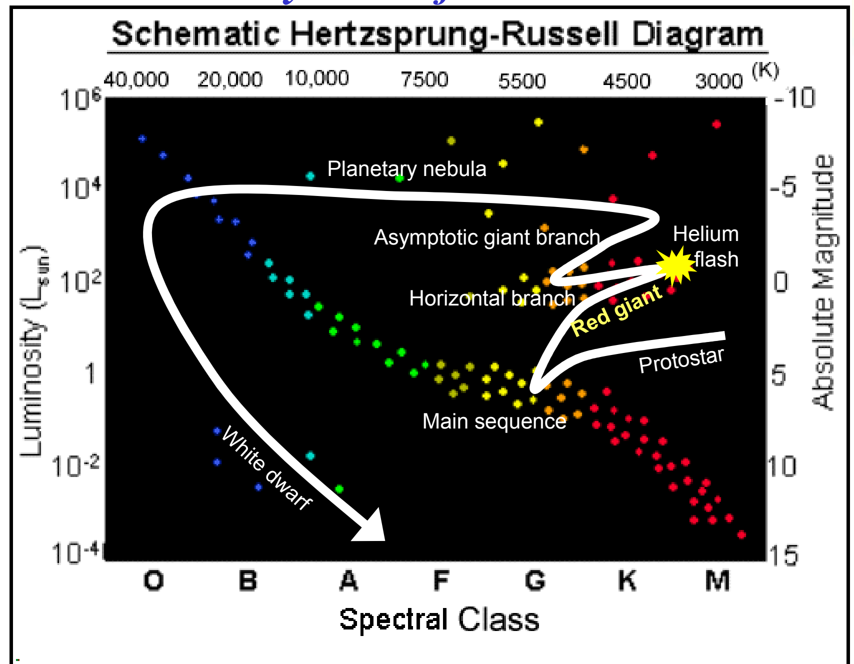
- The interior of the white dwarf crystallizes due to the extreme pressures
- Made mostly of carbon (some oxygen)
- Crystallized carbon = **a diamond**
  - With a blue-green tint from the oxygen
  - 10 billion trillion trillion carats!



The Life and Times of a Low-Mass Star

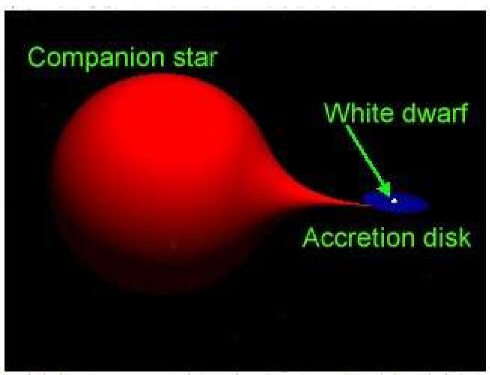


Evolutionary Path of a Solar-Mass Star

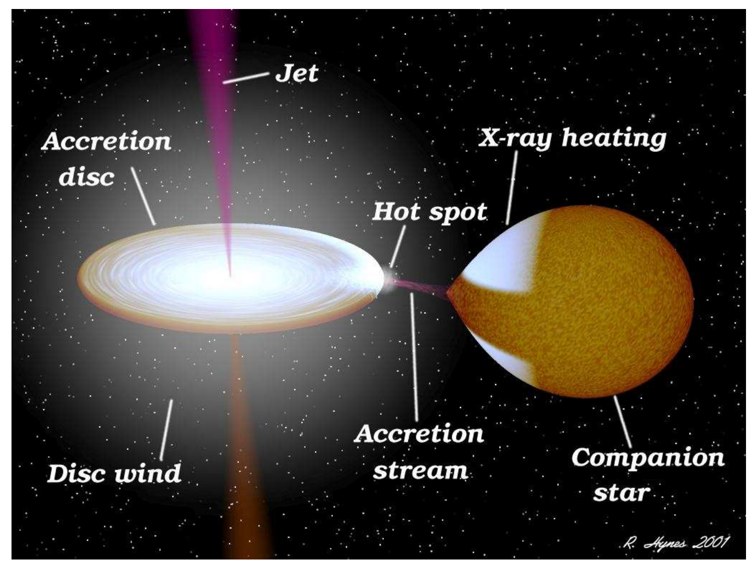


Binary Systems?

- 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

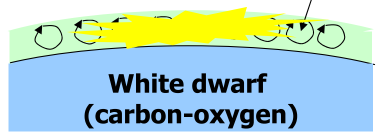


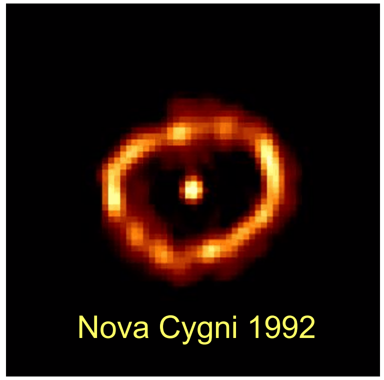
Binary Systems?



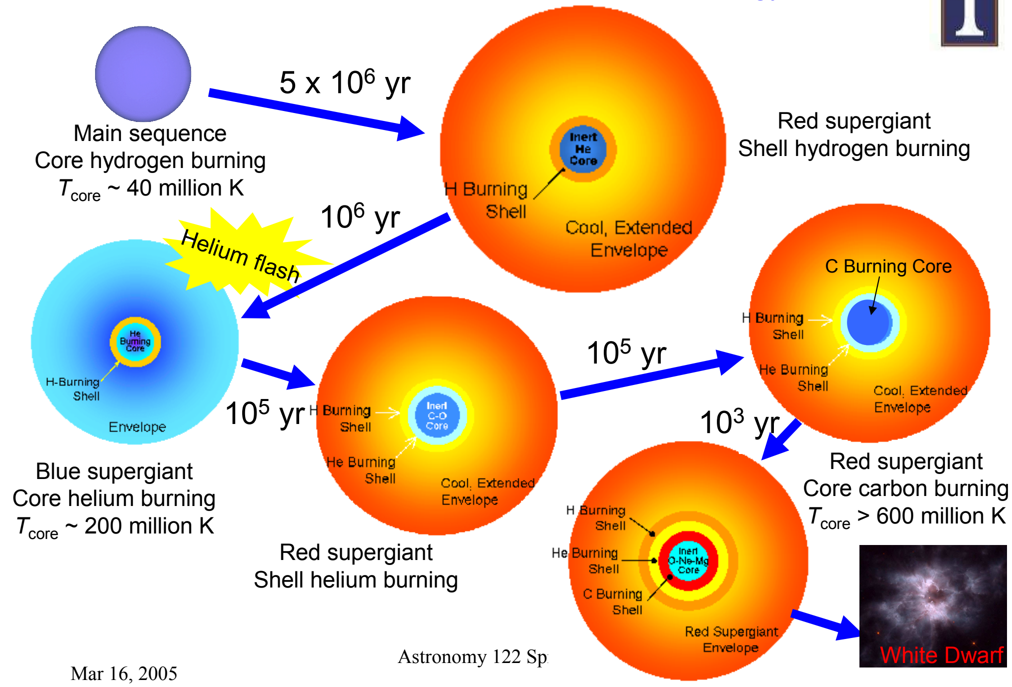
Novae

- 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

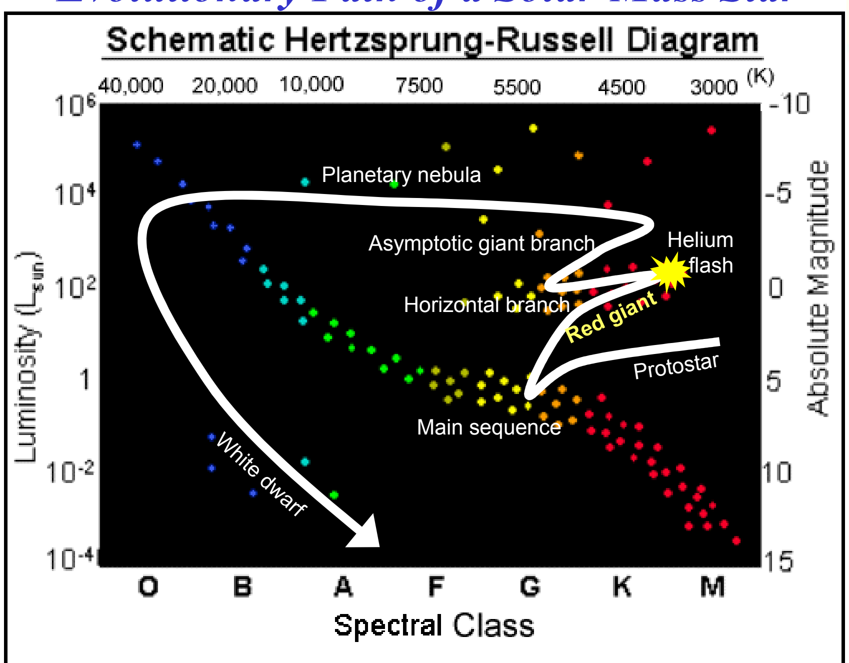




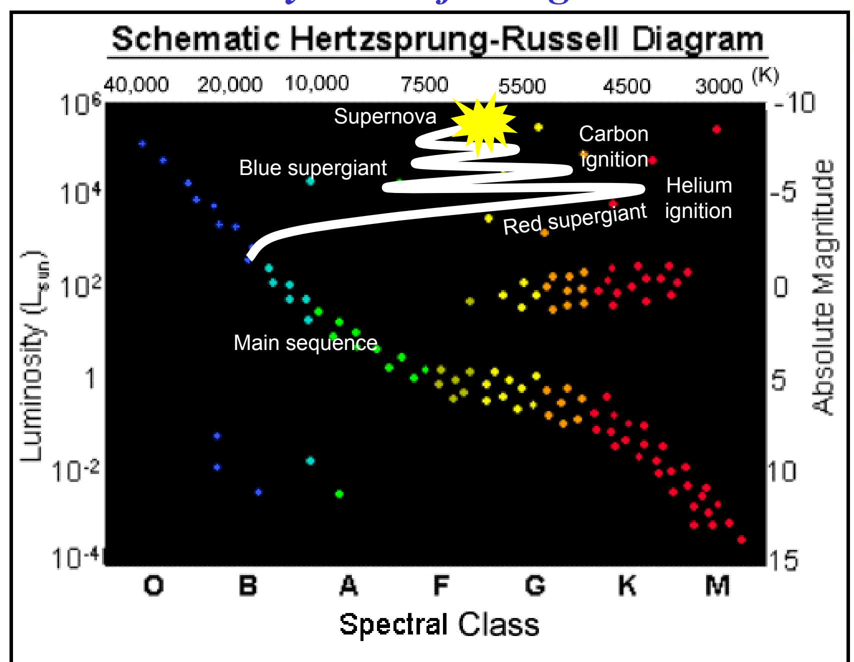
Evolution of an Intermediate-Mass (4 M_{Sun}) Star



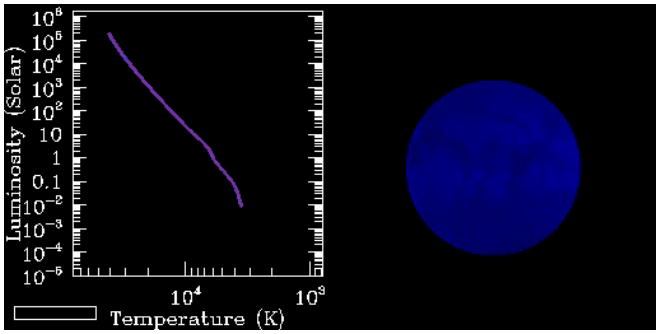
Evolutionary Path of a Solar-Mass Star



Evolutionary Path of a High-Mass Star

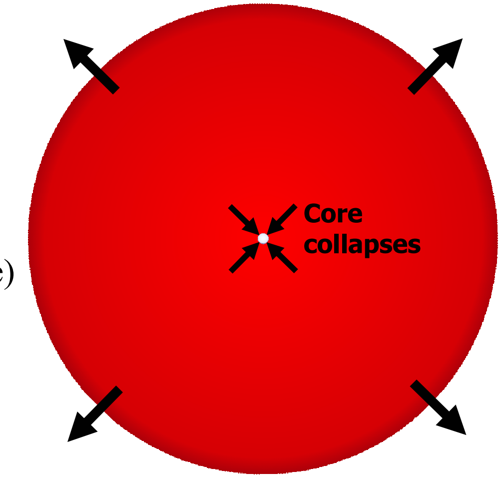


High Mass Stars (> 8 M_{sun})



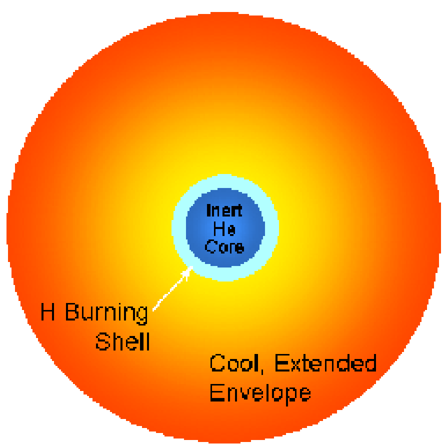
High Mass Stars (> 8 M_{sun}): when the Hydrogen Runs out?

- 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**



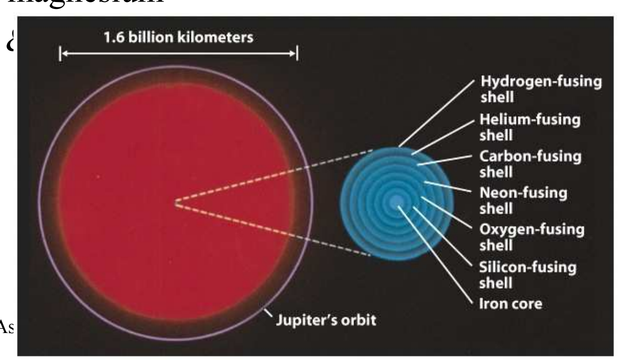
The Supergiant Phase

- 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**



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 ⇨ oxygen, neon, sodium, & magnesium
  - neon ⇨ oxygen & magnesium
  - oxygen ⇨ silicon &
  - silicon ⇨ iron
- Onion-skin like structure develops in the core

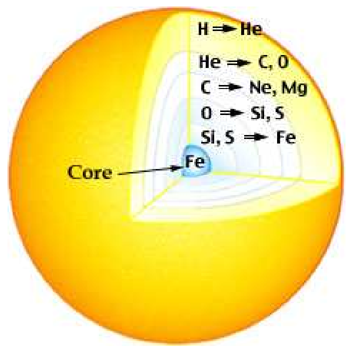


Iron – The End of the Road

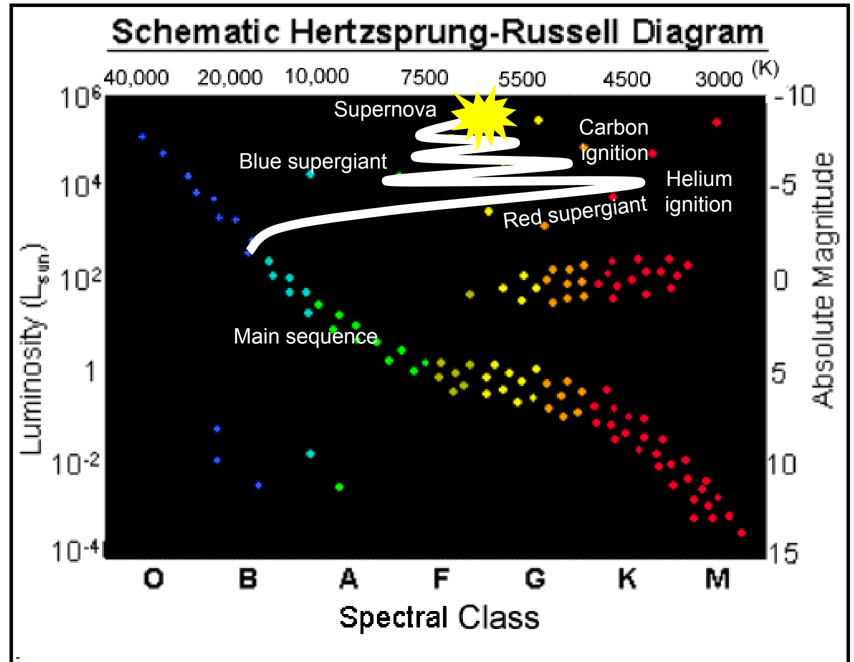
- Supergiants “burn” heavier and heavier atoms in the fusion process
- Each stage faster than the last
- After iron - no fuel left!
  - It requires energy to produce heavier atoms

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_{sun} star



Evolutionary Path of a High-Mass Star

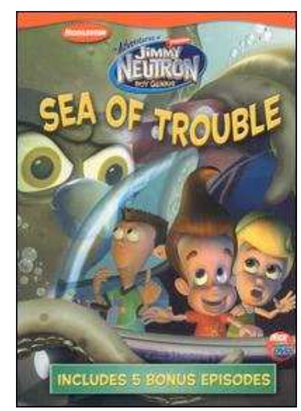


Core Collapse

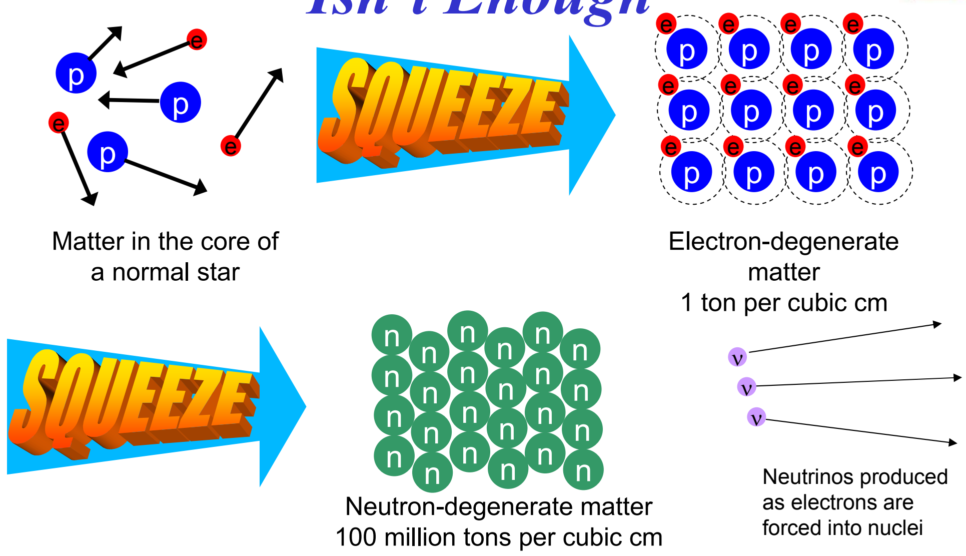
- Completely out of gas!
- Hydrostatic equilibrium is gone.
- The iron core of the star is supported by electron degeneracy pressure
  - Same pressure that supports a white dwarf
- Eventually, gravity wins…
  - This happens when the core reaches 1.4 solar masses
  - Remember the Chandrasekhar limit
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

Core Collapse

- When core is greater than 1.4 M_{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

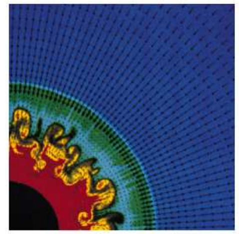


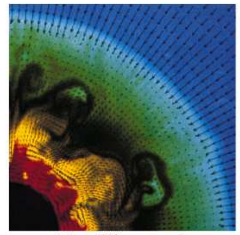
When Electron Degeneracy Just Isn't Enough



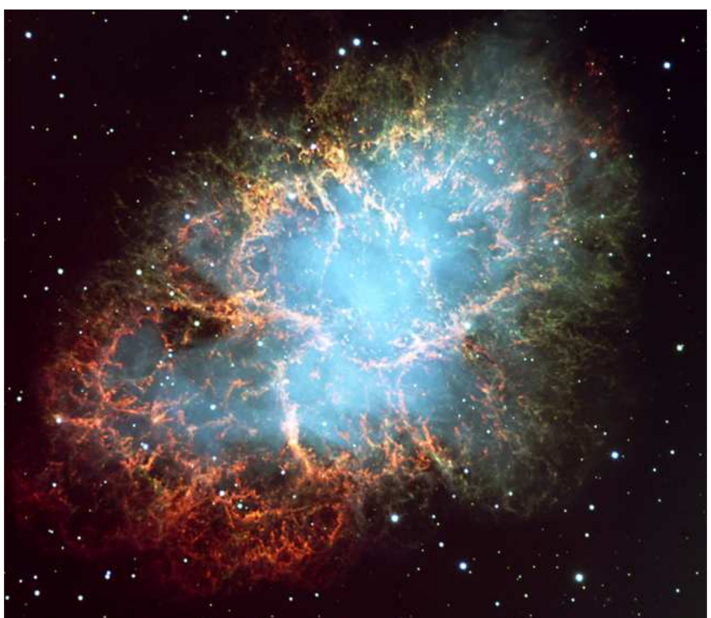
Supernova!

- 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,

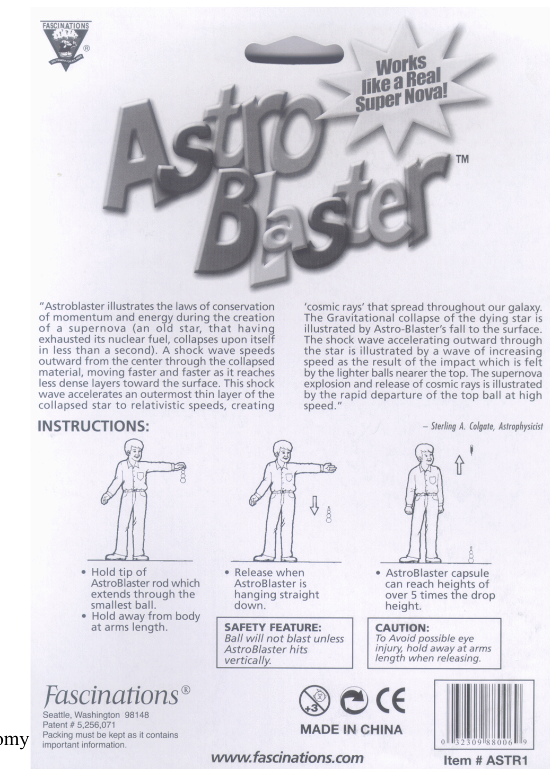

10 milliseconds


20 milliseconds

Game Over!



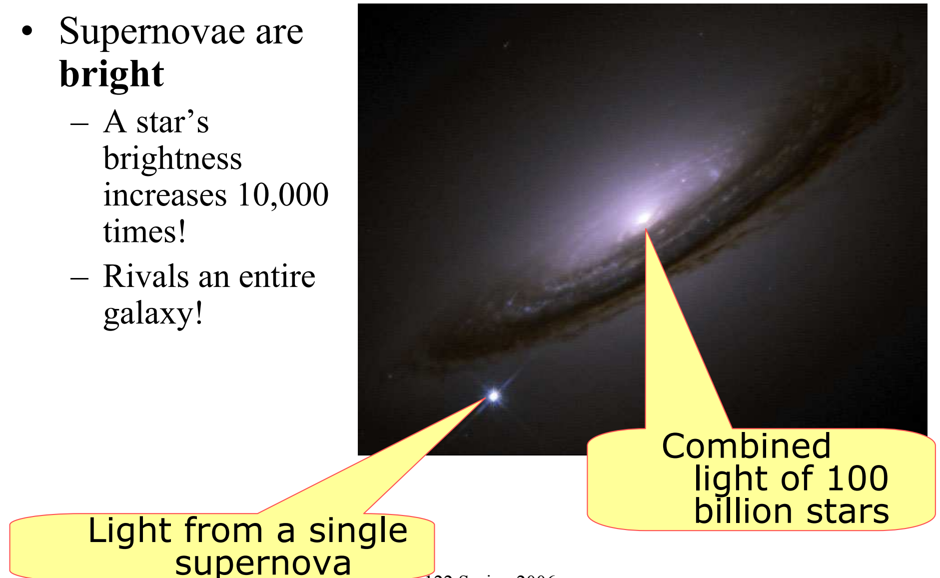
AstroBlaster!



Supernova!

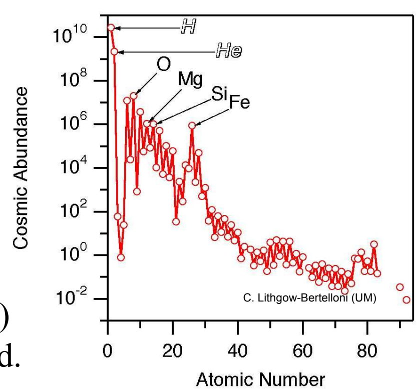
Bright as a Galaxy

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



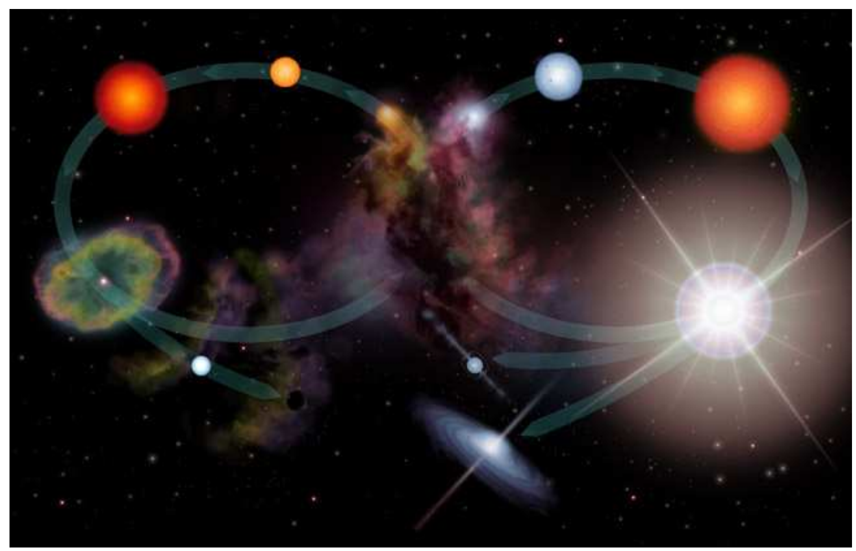
Making Heavy Elements

- 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.**



Delenn, B5

Stellar Evolution Cycle

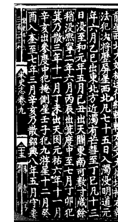


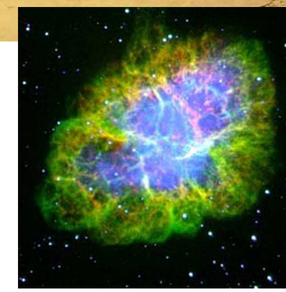
Stellar Evolution Cycle

- 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

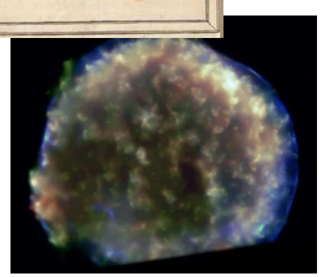




Supernova Explosions in Recorded History

- 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)



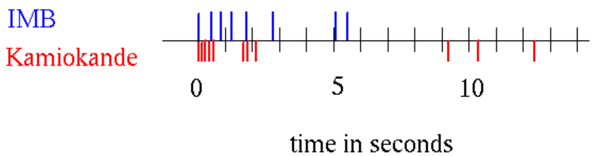


Supernova 1987A

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.



Supernova 1987A - Today