Astronomy 210

This Class (Lecture 33):

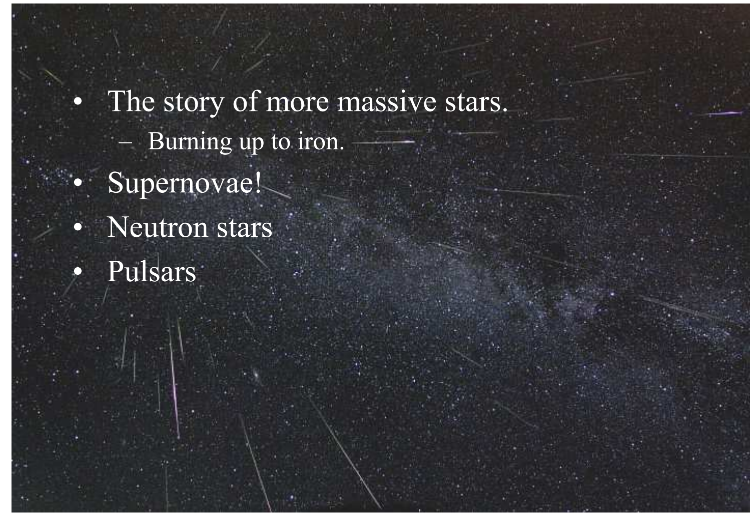
Life and Death of Other Stars

Stardial 2 is available.

Next Class:

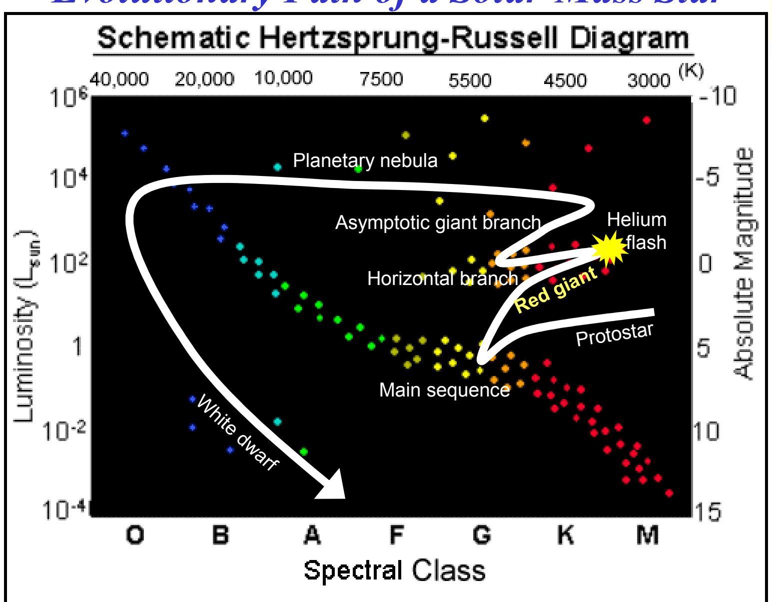
Supernovae and Neutron Stars

Outline

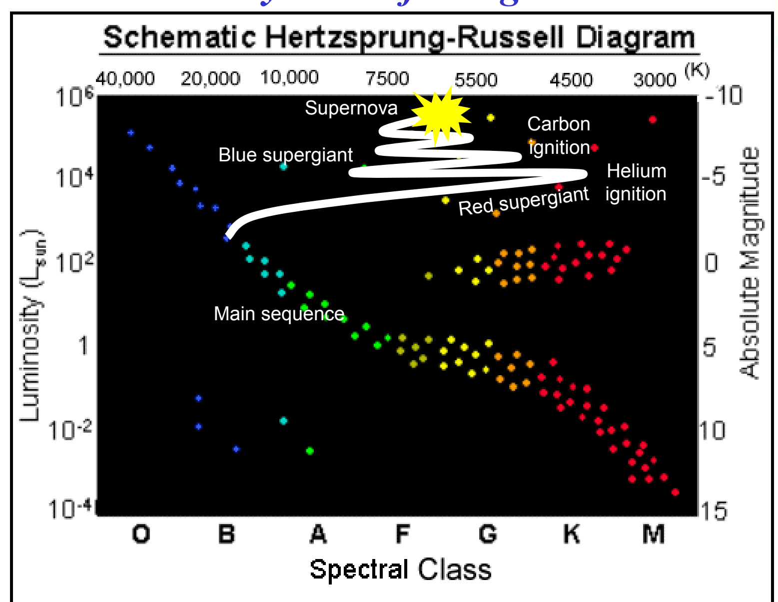


- The story of more massive stars.
  - Burning up to iron.
- Supernovae!
- Neutron stars
- Pulsars

Evolutionary Path of a Solar-Mass Star



Evolutionary Path of a High-Mass Star



Life Fast, Die Young

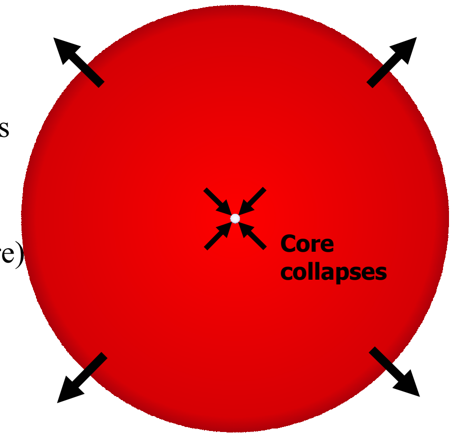
- High-mass stars: "gas guzzlers"
  - Very bright
  - Consume hydrogen fuel supply very quickly
  - Only live for millions of years on the main sequence

TABLE 11-1 Main-Sequence Lifetimes

Mass ($M_\odot$)	Surface temperature (K)	Luminosity ($L_\odot$)	Time on main sequence (10^6 years)	Spectral class
25	35,000	80,000	3	O
15	30,000	10,000	15	B
3	11,000	60	500	A
1.5	7,000	5	3,000	F
1.0 (Sun)	6,000	1	10,000	G
0.75	5,000	0.5	15,000	K
0.50	4,000	0.03	200,000	M

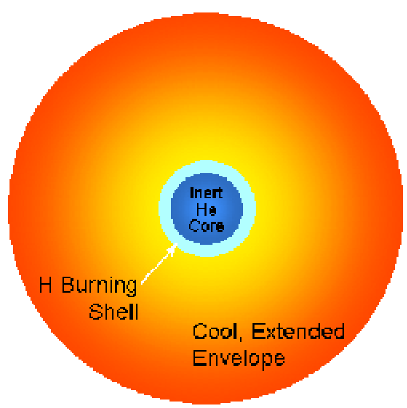
And when the Hydrogen Runs out?

- Similar to lower-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**



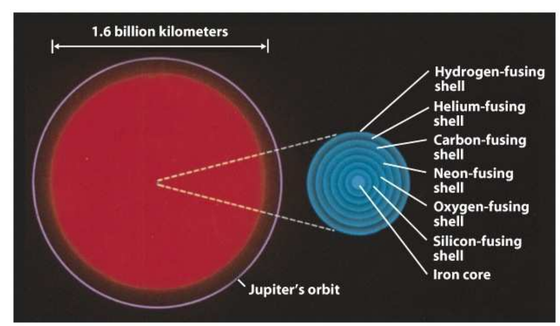
The Supergiant Phase

- 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, burning
- Ash of one cycle becomes fuel for the next
  - C+He ⇨ O
  - O+He ⇨ Ne
  - ... Up to iron
- Onion-skin like structure develops in the core

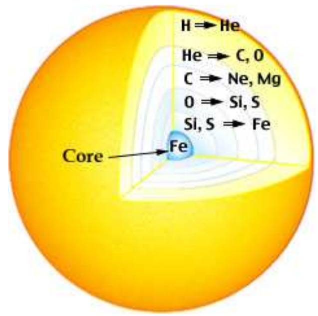


Iron – The End of the Road

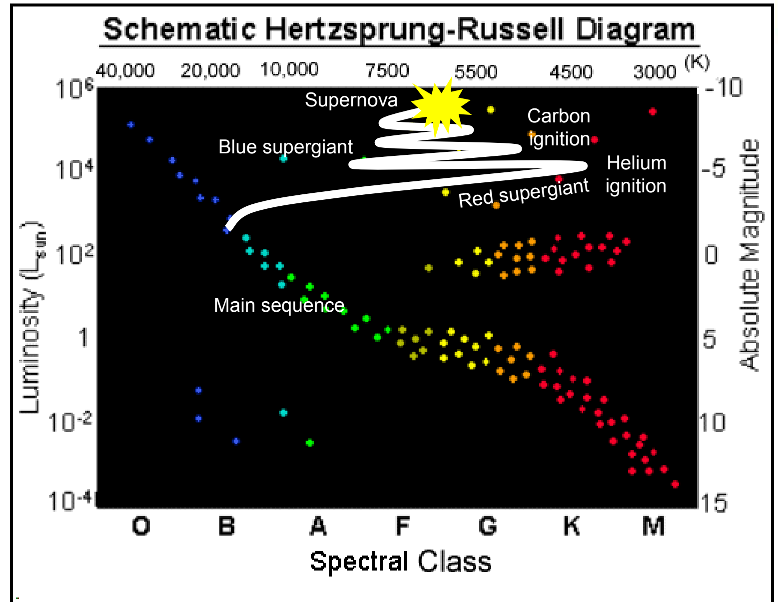
- Supergiants "burn" heavier and heavier atoms in the fusion process
- Each stage faster than the last
- After iron - no fuel left!
  - It requires energy to produce heavier atoms

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 $25 M_{Sun}$ star



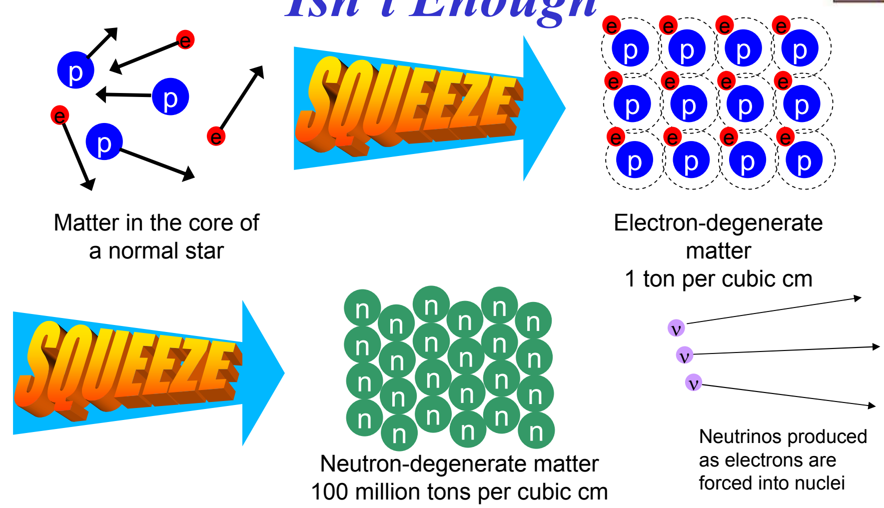
Evolutionary Path of a High-Mass Star



Core Collapse

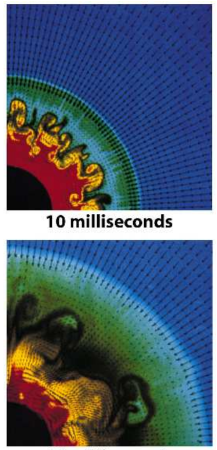
- Completely out of gas!
- Hydrostatic equilibrium is gone.
- The iron core of the star is supported by electron degeneracy pressure
  - Same pressure that supports a white dwarf
- Eventually, gravity will win…
  - This will happen when the core reaches 1.4 solar masses
  - Remember the Chandrasekhar limit
- When it goes over the limit – **core collapse!**
  - From 1,000 km across to 50 km in *1/10th of a second*
  - *Nearly 10% speed of light!*

When Electron Degeneracy Just Isn't Enough



Supernova!

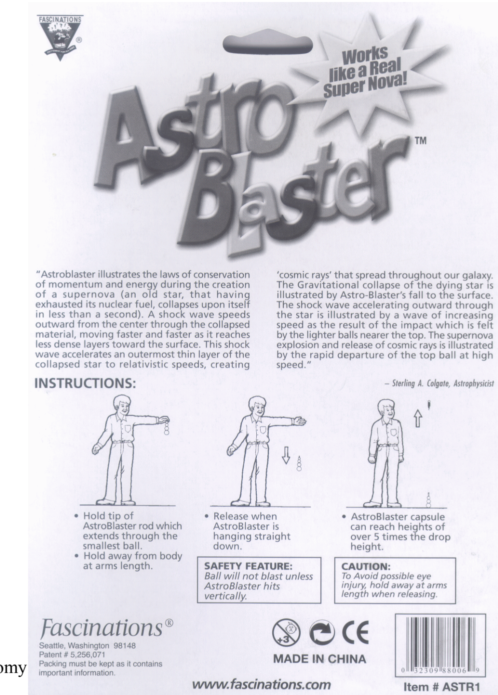
- Core basically becomes a large atomic nucleus– ultra-high density!
- During collapse, envelope “bounces” of stiff core and produces a shock wave
  - Material is so dense, that it is opaque to the neutrinos produced
  - Neutrinos give the shock a “kick”
  - Rips the outer layers of the star apart
- 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

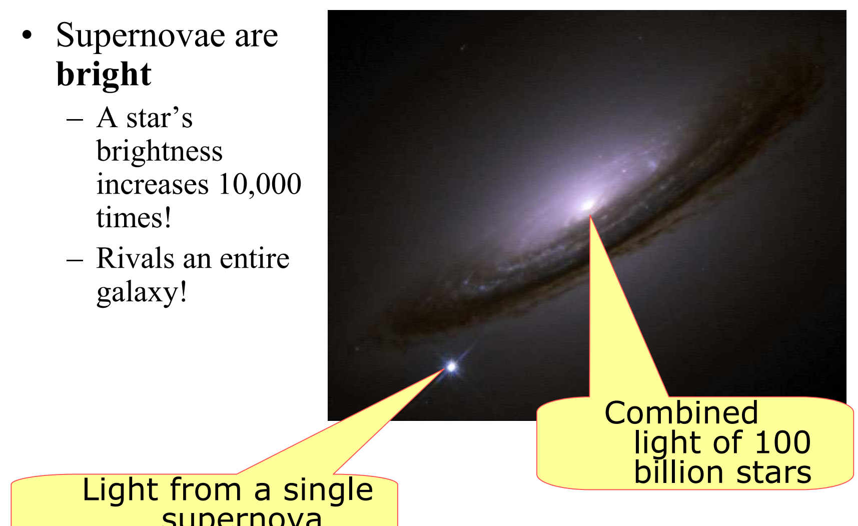
AstroBlaster!



Supernova!

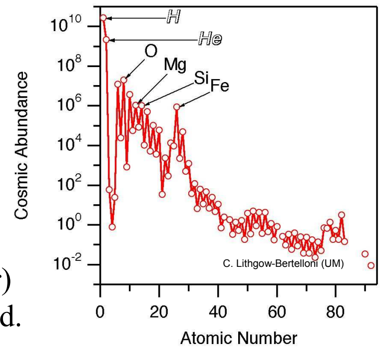
Bright as a Galaxy

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

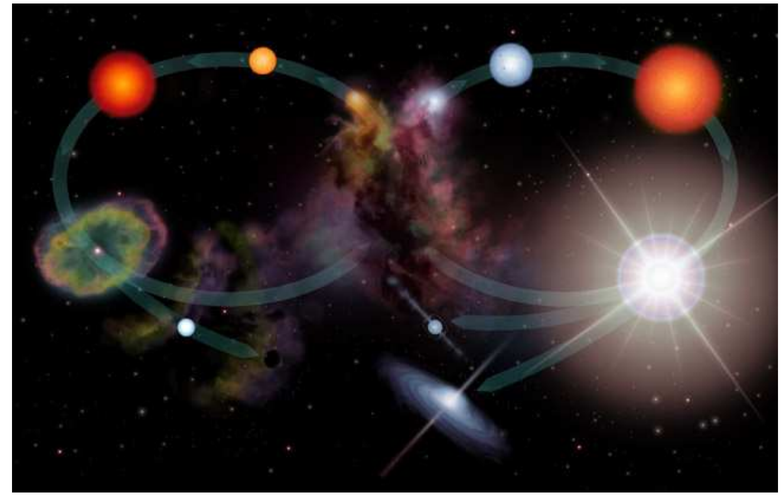


Making Heavy Elements

- 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.**



Stellar Evolution Cycle

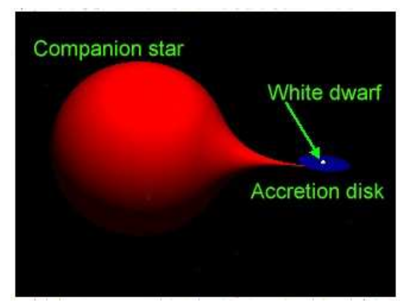


Stellar Evolution Cycle

- 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

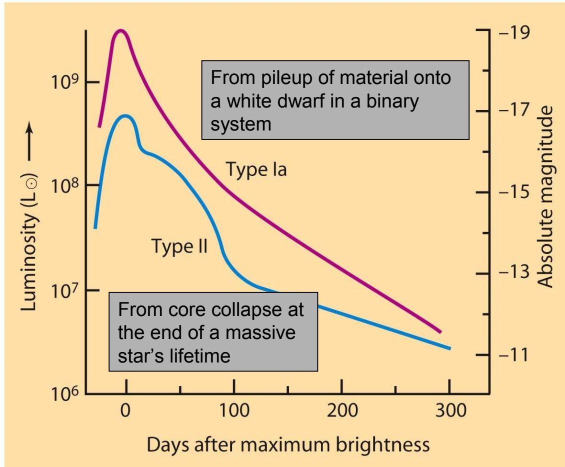
Another Way to Make a Supernova

- If a white dwarf in a binary system steals enough matter, it can go over the Chandrasekar Limit
- The white dwarf collapses under its own gravity
- Carbon and oxygen fuse into iron and nickel
- Star rips itself apart in a thermonuclear explosion
  - White dwarf is destroyed



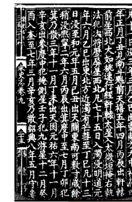
Bright Supernovae

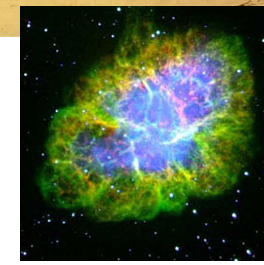
- Core-collapse supernovae are called Type II
- Type Ia supernovae are brighter than Type II's!



Supernova Explosions in Recorded History

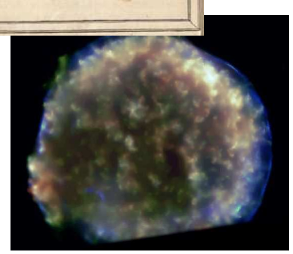
- 1054 AD
- Europe: no record
- China: "guest star"
- Anasazi people
  - Chaco Canyon, NM
  - Rock Paintings
- Modern view of this region of the sky:
  - **Crab Nebula** — a supernova remnant
- Massive star supernova





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)



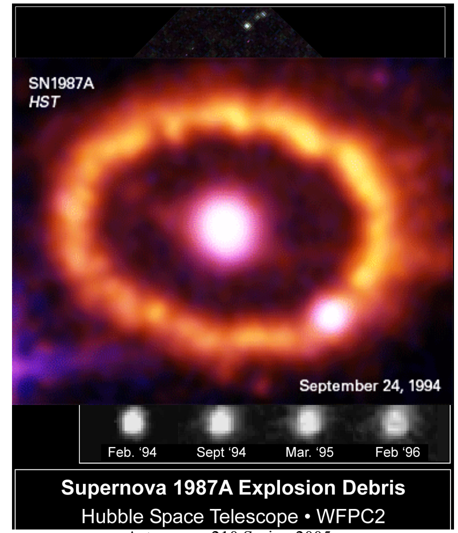
Supernova 1987A

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 10 secs about 20 ν.

Supernova 1987A - Today

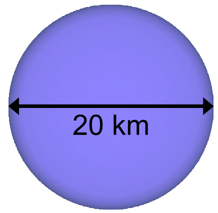


Game Over!

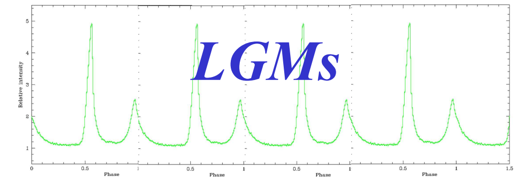
Supernova Leftovers

- What's left of the star's core after a Type II supernova?
- A **neutron star**
  - About 1.4 – 2 solar masses
  - Very small diameter – around 20 km!
  - Composed of a sea of neutrons
    - Supported by *neutron degeneracy pressure!*
    - Teaspoon of neutron star material on Earth would weigh almost 1 billion tons!!!!
  - Surface gravity – 200 billion times that on Earth
  - Escape velocity – of half the speed of light

Relative Sizes of Stellar Corpses

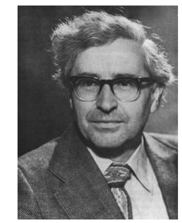


Neutron star



LGMs

Jocelyn Bell Burnell



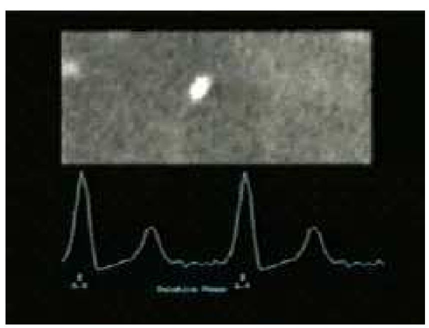
Anthony Hewish

- In the late 1960s, Jocelyn Bell discovered radio pulses from the constellation Vulpecula that repeated regularly
  - Every 1.337… seconds
- What could it be?
- Perfect timing, but no real encoding of signal.
- Jokingly called LGMs, then Pulsars.

http://www.radiosky.com/rspplsr.html

Pulsars

- What could it be?
  - Pulses were too fast to be a variable star
- What can they be?
- A rotating star?



Rotating Star?

Max possible rotation rate at equator: when gravity balances centripetal acceleration.

$$v_c = \sqrt{\frac{GM}{R}}$$

But

$$v_c = \frac{2\pi R}{P}$$

so

Rotating Star?

Solve for P

$$= \frac{4\times10^5\ \text{s}}{\sqrt{\rho}} \quad \rho \text{ in kg/m}^3$$

Rotating Star?

For shortest possible pulsar known of P=1 ms

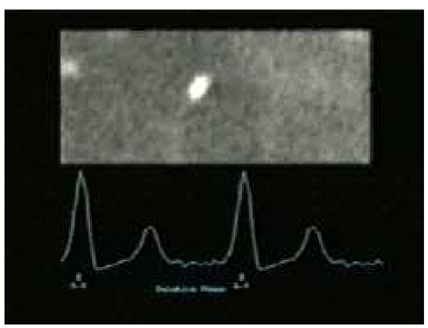
$$P = \frac{4\times10^5\ \text{s}}{\sqrt{\rho}} \quad \rho \text{ in kg/m}^3$$

$$\Rightarrow \rho_{\min} \geq \ 10^{17}\ \text{kg/m}^3$$

Must be a neutron star! $V_{esc} > 1/3$ c!

Pulsars

- What could it be?
  - Pulses were too fast to be a variable star
- Very precise, better than atomic clocks.
- P from 1s to 1ms!
- Could they be something spinning?
  - Would have to be small to be spinning that fast
- They must be spinning neutron stars!



What are Pulsars?

- When the core collapses, its spin and magnetic field strength increases
- Typically
  - Surface field strength over 1 trillion times that of the Earth
  - Rotation rate up to 1000 times per second
- Magnetic field beams radiation into space
- If the Earth is in the beam's path, we see the pulsar

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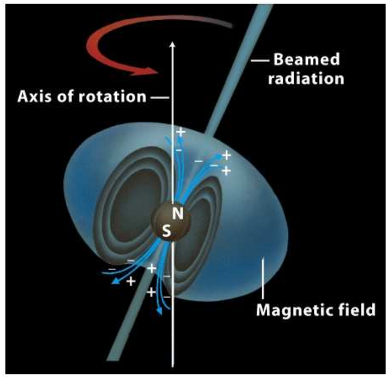
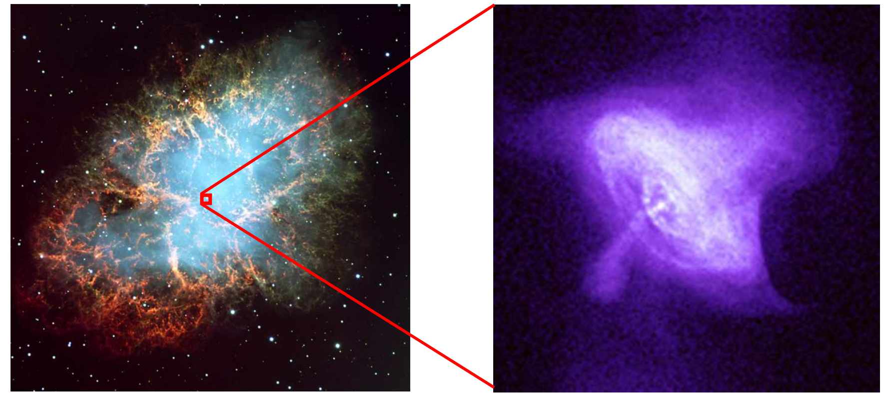


Crab Nebula – Remnant of the Supernova of 1054



Optical - ESO

X-ray - Chandra

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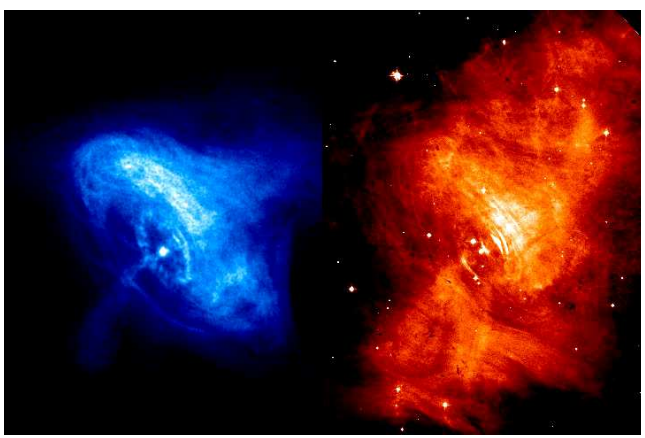

When Neutron Degeneracy Isn't Enough

- Maximum neutron star mass
  - About 3.0 M_{Sun}
- Beyond this mass, neutron degeneracy cannot stop gravity
- Nothing left to stop total collapse– gravity rules!
- A **black hole… $v_{esc} > c$**

Stellar Evolution Recap