

# AY1 Announcements

- Quiz 2: Tuesday Oct 29
  - Stellar properties, stellar structure, energy sources, evolution and end points,

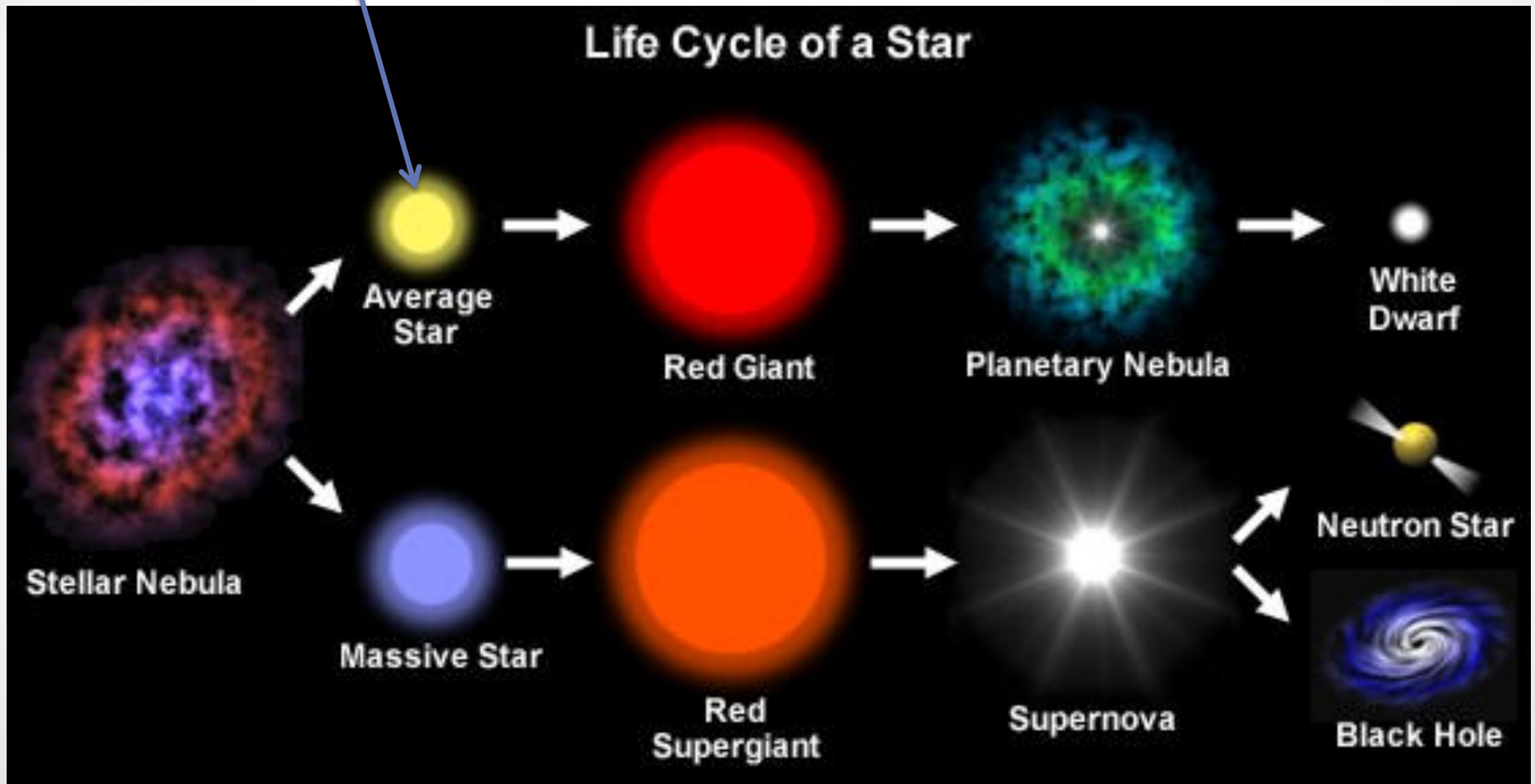
# Where are we?

- Stellar evolution of  $<8M_{\odot}$  stars (Red giants, planetary nebulae, white dwarfs)
- Stellar evolution of  $>8M_{\odot}$  stars (core-collapse supernovae)
- Finish off SNI predictions: Neutron stars and pulsars

REVIEW

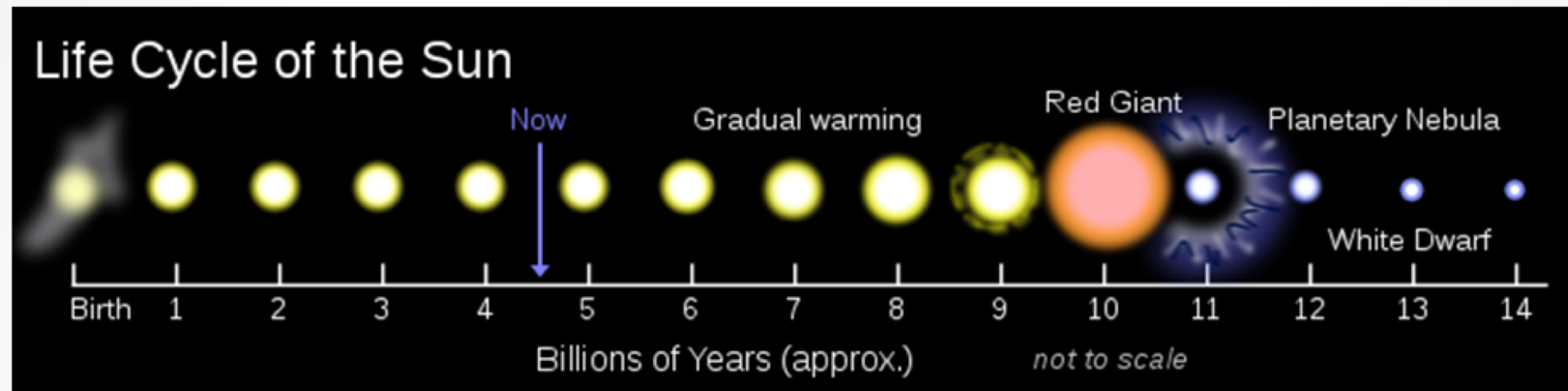
# Stellar Evolution

$0.1M_{\text{SUN}} - 8M_{\text{SUN}}$



## REVIEW

# Stars with initial mass $< 8M_{\text{Sun}}$

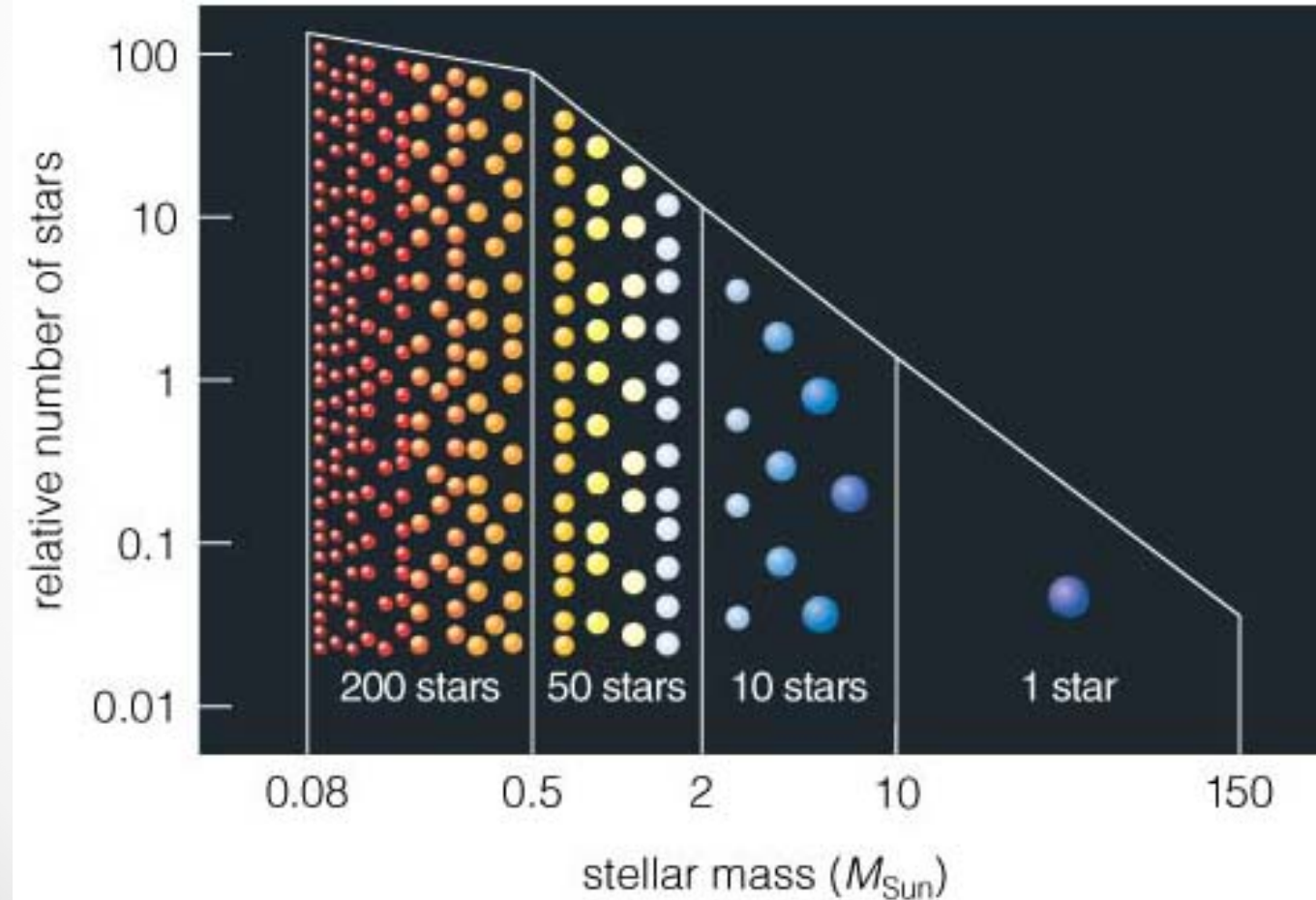


Approximately  $\frac{1}{2}$  of the initial main-sequence mass is sent back to the interstellar medium in stellar winds and (mostly) in the ejected planetary nebula

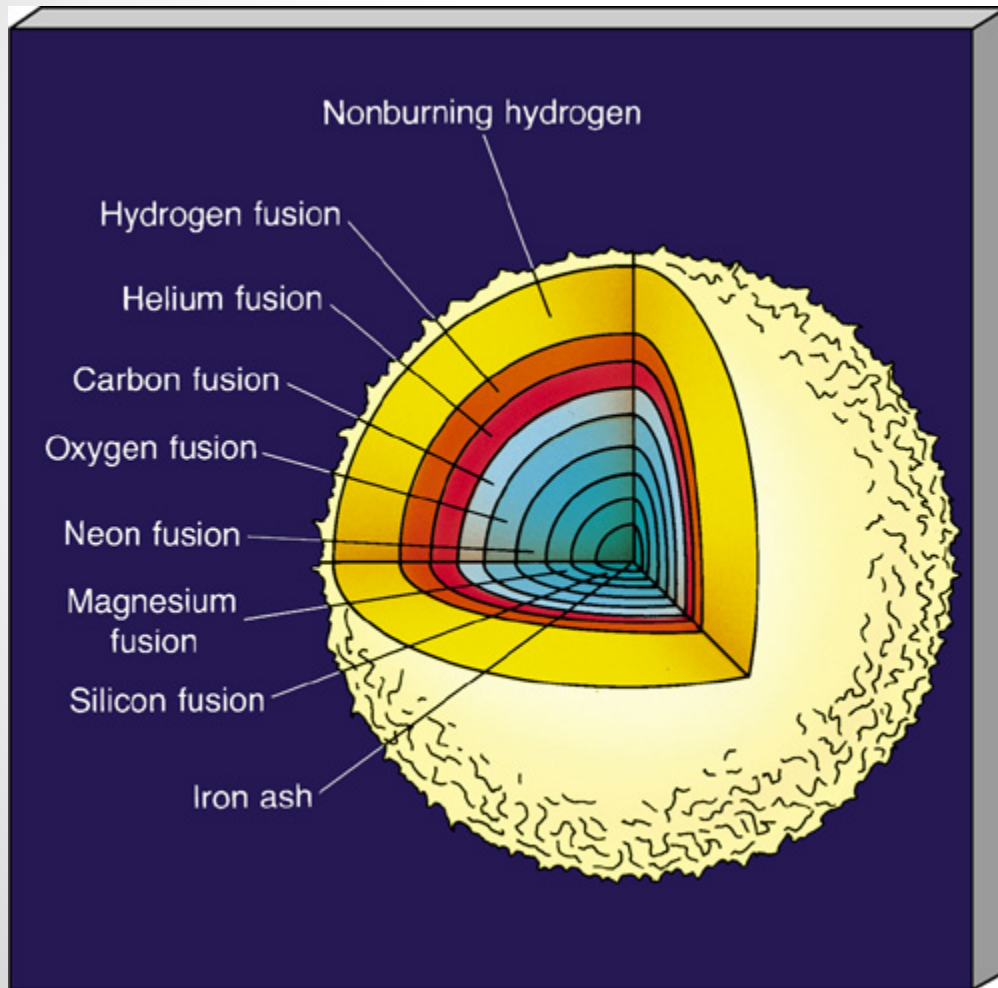
The material returned to the inter-stellar medium is enriched in He, Ca, O, Mg, and Ne (the exact mix depends on the initial main-sequence mass)

# The “initial mass function”

- The vast majority of stars are formed with an initial main-sequence mass that is  $<8M_{\text{Sun}}$

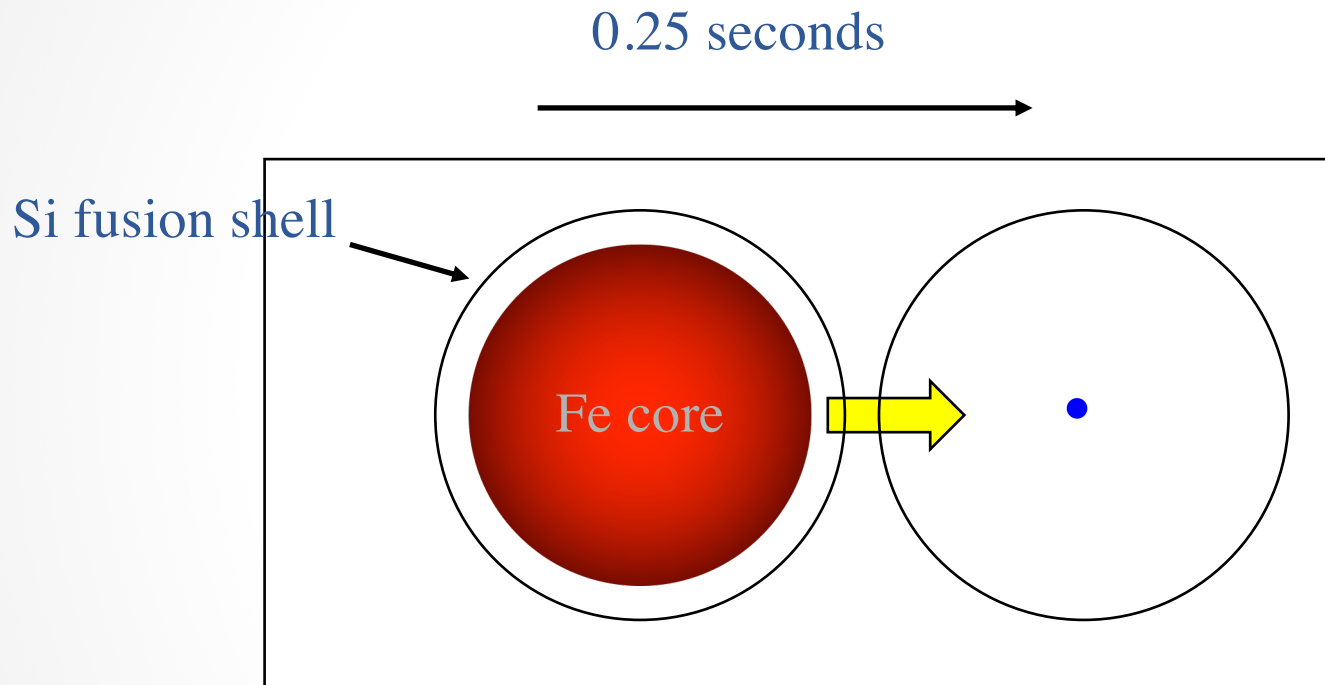


# Massive Star Evolution



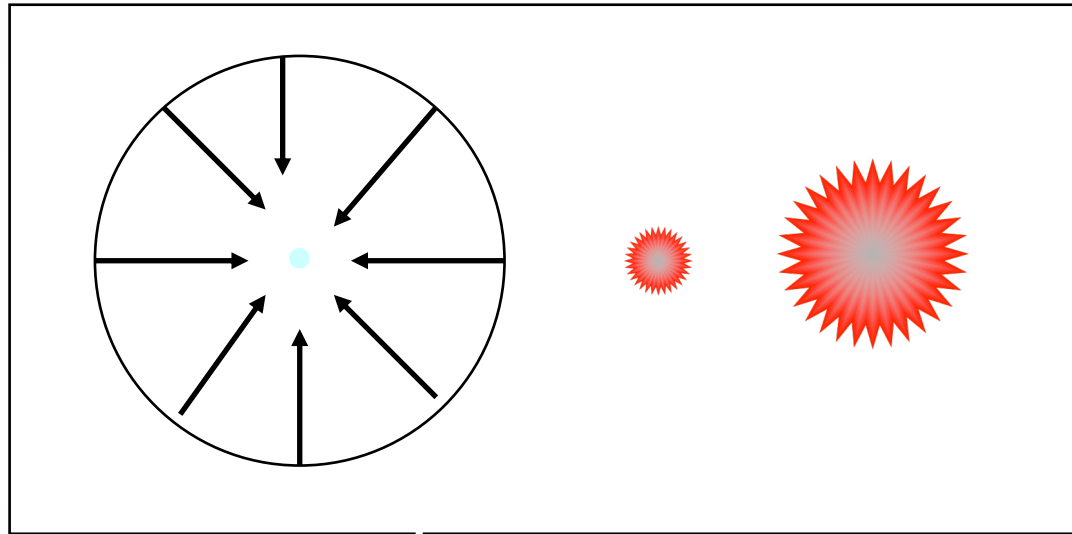
- The critical difference between low and high-mass star evolution is the core temperature.
- In stars with  $M > 8M_{\text{SUN}}$  the central temperature is high enough to fuse elements all the way to Iron (Fe)

# Core-Collapse in Massive Stars



- 1) Fe core exceeds  $1.4M$  and implodes
- 2) Temp reaches 5 billion K and photodisintegration begins to blast apart the Fe nuclei
- 3) Neutronization occurs:  $e^- + p^+ \rightarrow n^0 + \text{neutrino}$

# Core-Collapse in Massive Stars



- 4) Neutron ball is at `nuclear density' ( $>10^{17}$  kg/m<sup>3</sup>) and is much harder than any brick wall.
- 5) Infalling layers crash into neutron ball, bounce off, create a shock wave and, with help from the neutrinos, blast off the outer layers of the star at 50 million miles/hour.

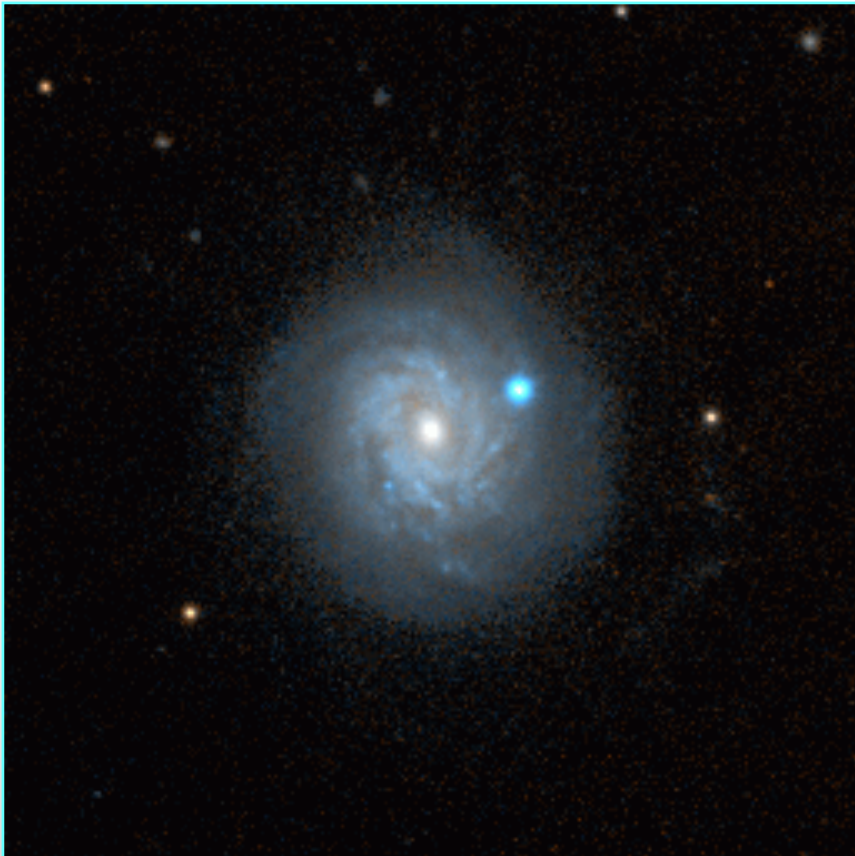


# Supernovae II

- Expect:
  - Association with massive stars/star formation
  - Rapidly expanding debris cloud
  - $10^8$  times the optical luminosity of the Sun
  - Chemically-enriched debris
  - Extremely dense 1.4 solar mass neutron ball left behind

# Supernova II

- Seen near spiral arms, SN1987A identified star that blew up and it was a massive blue super giant



# Neutron Stars

- There is another test of SNII theory
- If the scenario is correct, there should be a VERY dense, VERY hot ball of neutrons left behind after the explosion.
- Object is supported by neutron degeneracy (although there is an “atmosphere” of normal matter)
- Call this a Neutron star (although like a White Dwarf it is not a star)



White dwarf  
Radius=6000 km



Neutron Star  
Radius=10 km



# Neutron Stars: Predictions

- Neutron star mass:  $> 1.4M_{\text{Sun}}$  (collapse triggered)
- Neutron star radius: 10 - 80 km
- Neutron star density:  $10^{14}$  grams/cm<sup>3</sup>  
100 million tons/thimble (all of humanity)
- Initial Temperature:  $>2,000,000\text{k}$
- Neutron star remnant will be spinning rapidly and have a huge magnetic field

# Conservation of Angular Momentum

- Any spinning object has 'angular momentum' which depends on how fast it is spinning and how the object's mass is distributed.
- 'how fast':  $\omega$  (greek letter omega)
- 'mass distribution': Moment of inertia ( $I$ )

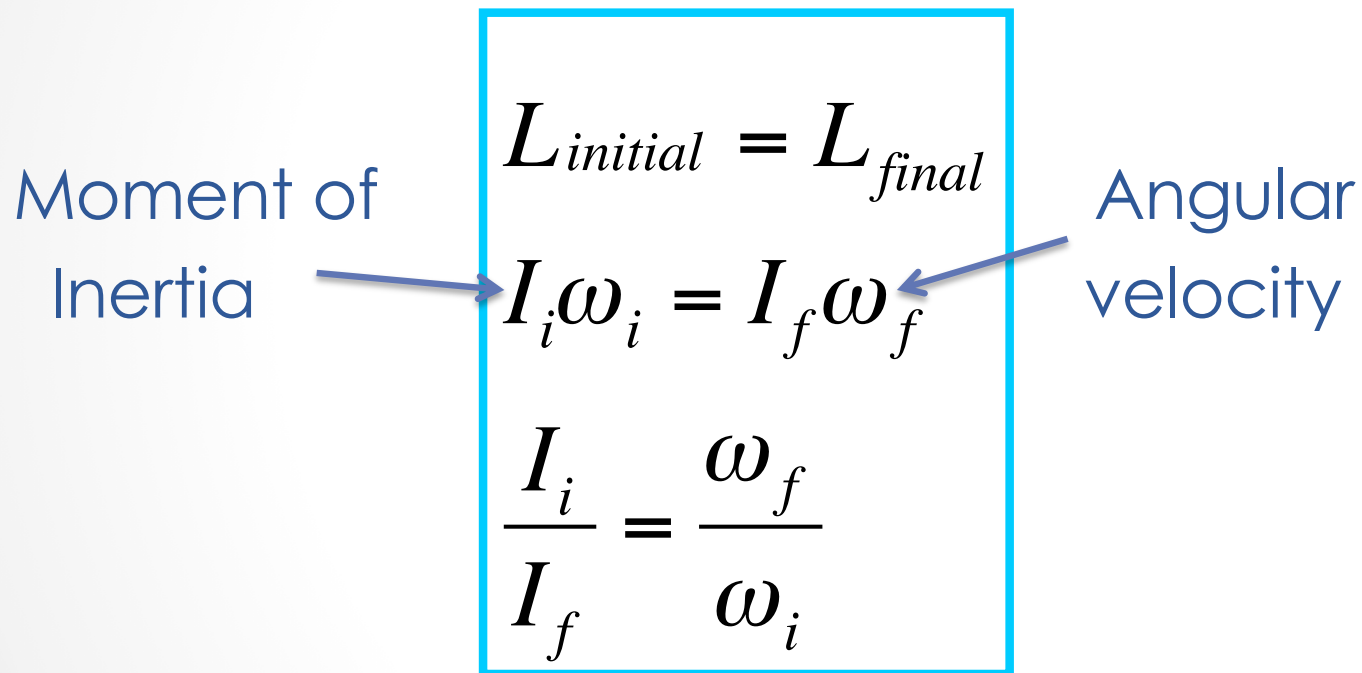
$$\vec{L} = I \vec{\omega}$$

# Conservation of Angular Momentum

- Conservation of angular momentum means:

Moment of Inertia

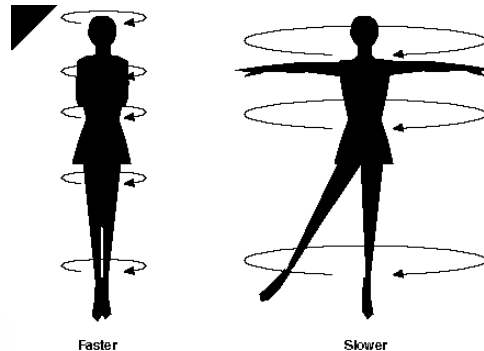
Angular velocity

$$L_{initial} = L_{final}$$
$$I_i \omega_i = I_f \omega_f$$
$$\frac{I_i}{I_f} = \frac{\omega_f}{\omega_i}$$
A diagram illustrating the conservation of angular momentum. It features a central blue-bordered box containing three equations. The top equation is  $L_{initial} = L_{final}$ . The middle equation is  $I_i \omega_i = I_f \omega_f$ . The bottom equation is  $\frac{I_i}{I_f} = \frac{\omega_f}{\omega_i}$ . To the left of the box, the text "Moment of Inertia" is written, with a blue arrow pointing from it to the  $I_i$  term in the middle equation. To the right of the box, the text "Angular velocity" is written, with a blue arrow pointing from it to the  $\omega_f$  term in the middle equation.

# Conservation of Angular Momentum

- Think about those ice skaters. With arms out, a skater has a large moment of inertia. Pulling his/her arms in reduces the moment of inertia.

Arms out: large  $I$ , low spin rate  
Arms in: small  $I$ , high spin rate





# Conservation of Angular Momentum

- The moment of inertia for a solid sphere is:

$$I = \frac{2}{5} MR^2$$

- If a sphere collapses from a radius of  $7 \times 10^5 \text{ km}$  to a radius of  $10 \text{ km}$ , by what factor does its spin rate increase?

$$L_{initial} = L_{final}$$

$$I_i \omega_i = I_f \omega_f$$

$$\frac{2}{5} MR_i^2 \omega_i = \frac{2}{5} MR_f^2 \omega_f$$

$$R_i^2 \omega_i = R_f^2 \omega_f$$

$$\omega_f = \frac{R_i^2}{R_f^2} \omega_i = \left( \frac{7 \times 10^5}{10} \right)^2 \omega_i = 4.9 \times 10^9 \omega_i$$

Sun rotates at 1 rev/month. Compress it to 10km and conserve L, it will spin up to 1890 revolutions/second (and fly apart)

# Magnetic Fields

Magnetic field lines are also conserved. When the core collapses, the field lines are conserved, and the density of the field lines goes way up. This is the strength of the magnetic field.

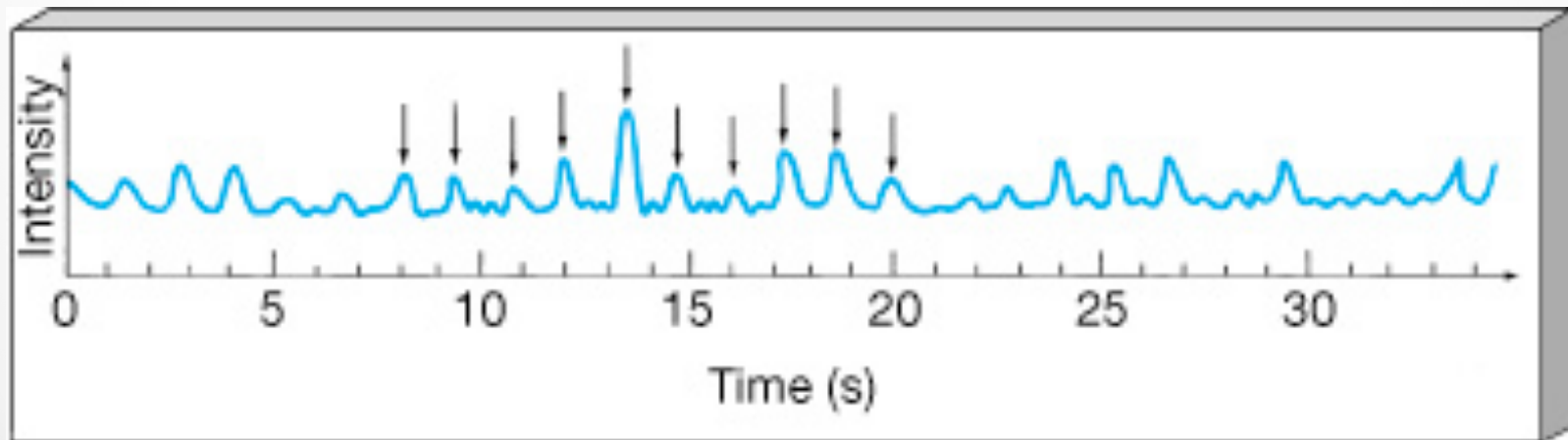


# Neutron Stars

- The possibility of n-stars was discussed way back in the 1930's but for many decades it was assumed they would be impossible to detect because the surface area was so tiny the total radiation will be small
- But, in 1967, Jocelyn Bell and Tony Hewish set up a rickety barbed-wire fence in the farmland near Cambridge England to do some routine radio observations.

# LGMs

- Bell and Hewish discovered a source in Vela that let out a pulse every 1.3 seconds. Then they realized it was accurate to 1.337 seconds, then 1.3372866576 seconds. They soon realized that the best clocks of the time were not accurate enough to time the object. They called it ‘LGM’.



# First Pulsar



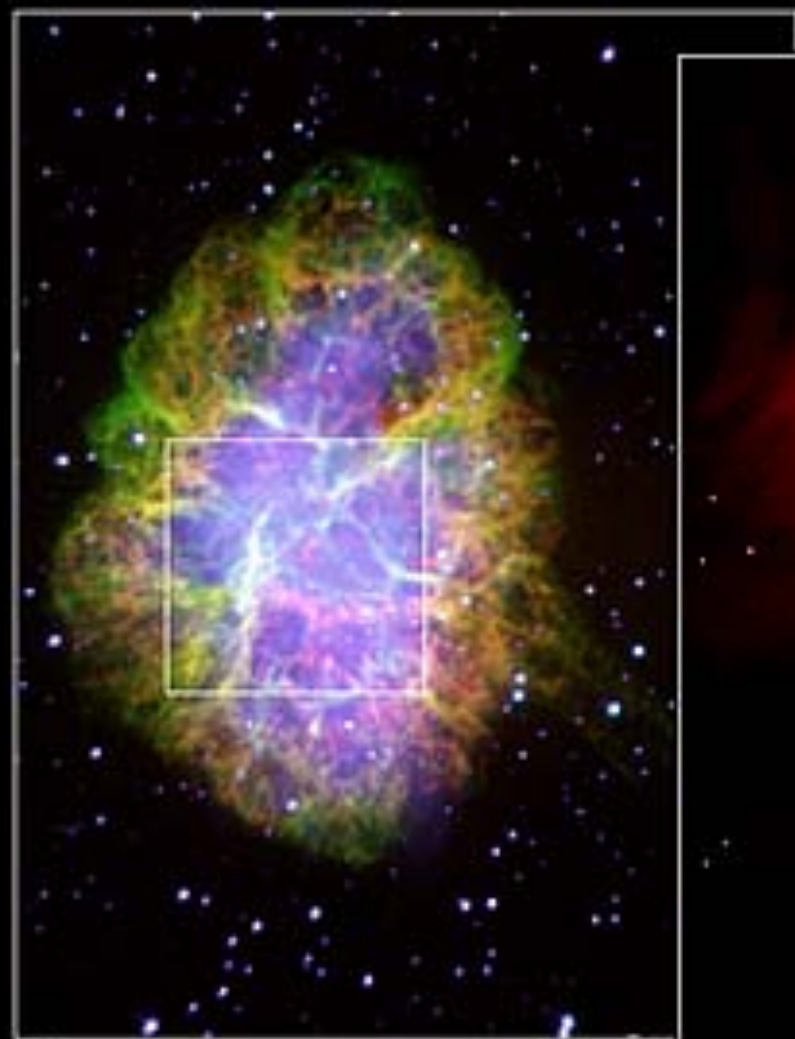
- Bell was a graduate student at the time. The source was assumed to be man made, but when no terrestrial source could be identified, they briefly considered an artificial extra-terrestrial source.
- When a second source was discovered (Cass A) they announced the discovery as a new phenomenon.

- The discovery led to a year of wild speculation, but explanations involving neutron stars quickly rose to the top.
- A pulsing source with period of 0.033 seconds was discovered in the Crab nebula.
- Big clue! Spin the Sun or Earth or a WD 30 times per second and they will be *torn apart*.
- *Need a small object with very large material strength.*

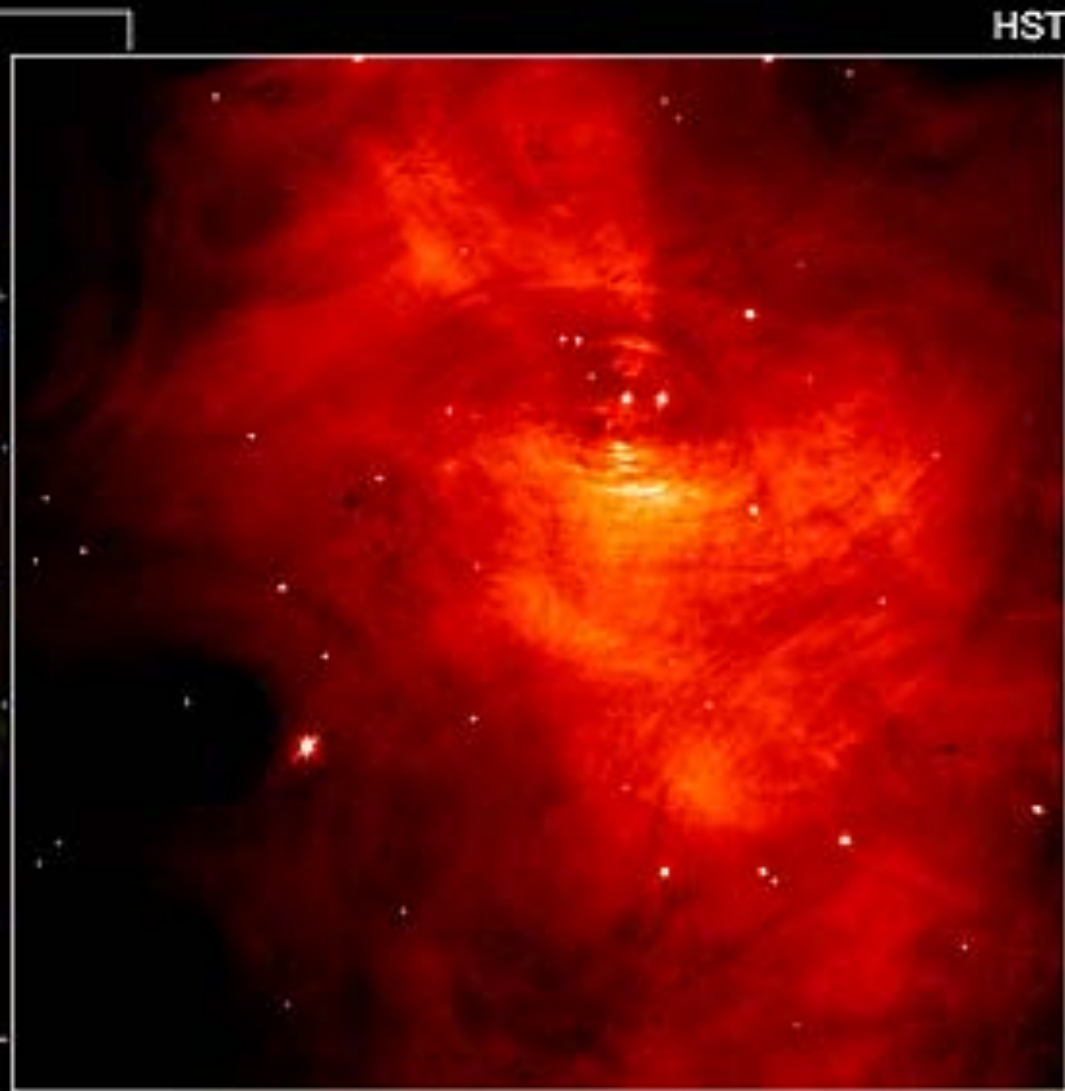
# Pulsars

- The new objects were named ‘pulsars’ and it was soon discovered that they were slowly slowing down -- this provided the answer to the mystery of why the Crab Nebula was still glowing.
- There are now more than 2000 known pulsars in the Galaxy.
- [Pulsar map](#)

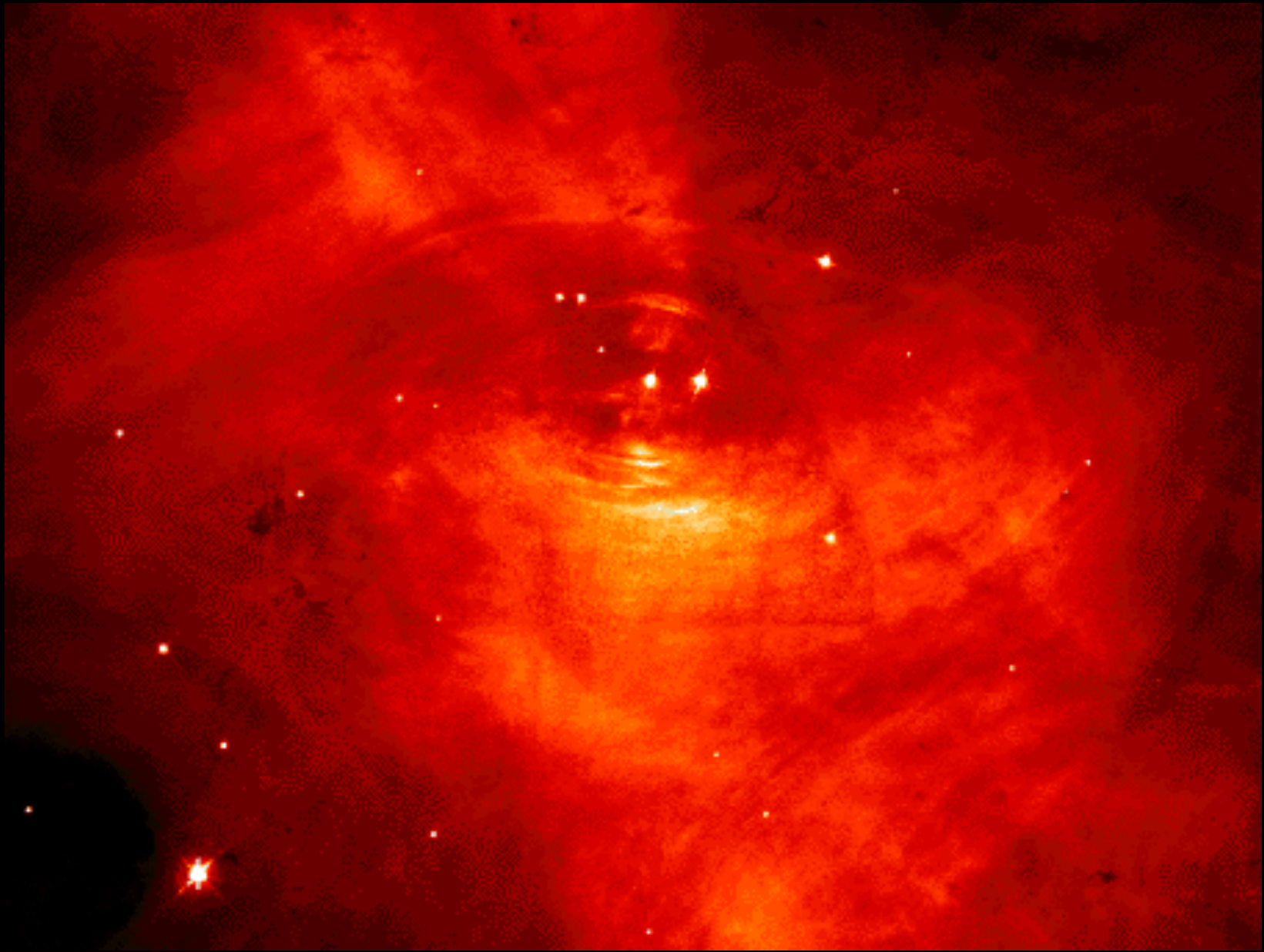


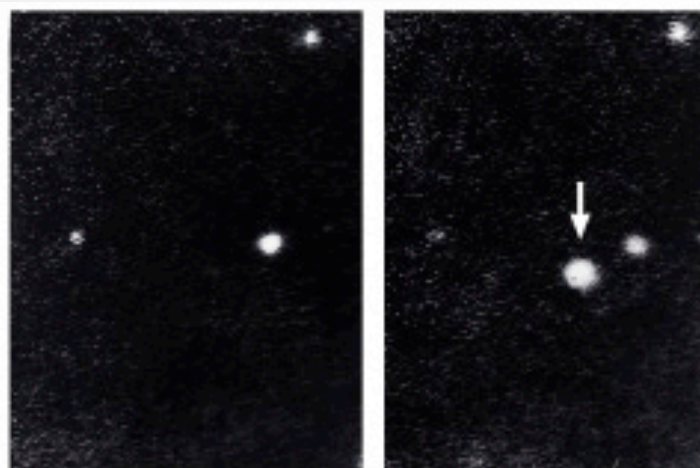


Palomar



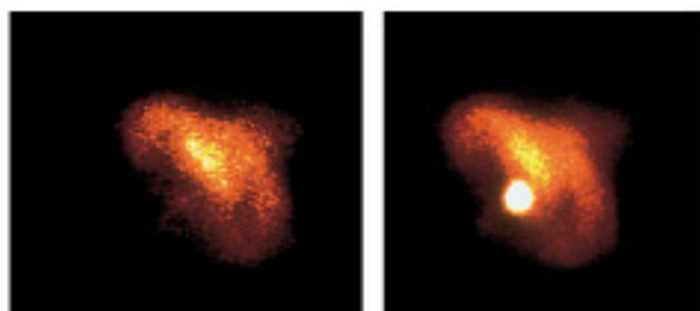
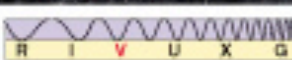
HST





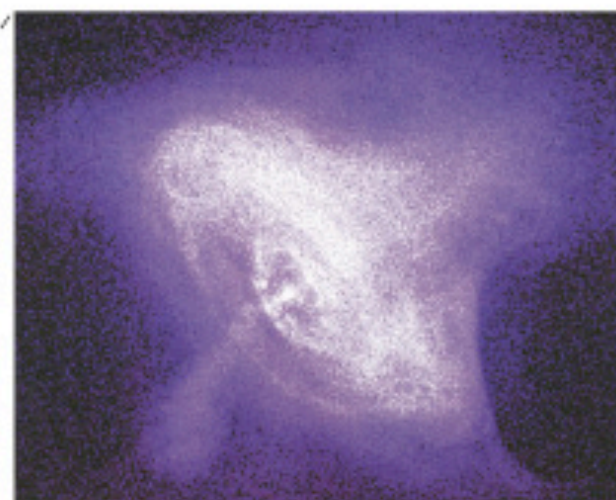
(a) OFF

ON

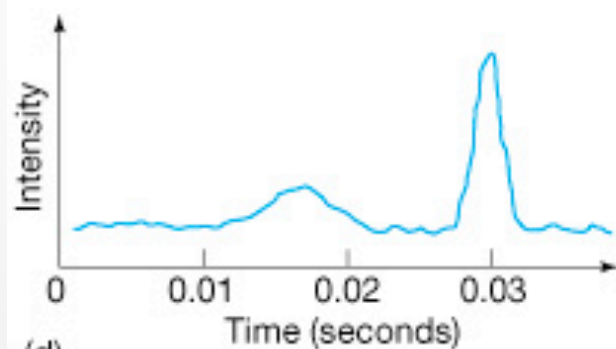
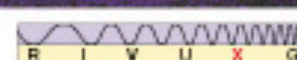


(b) OFF

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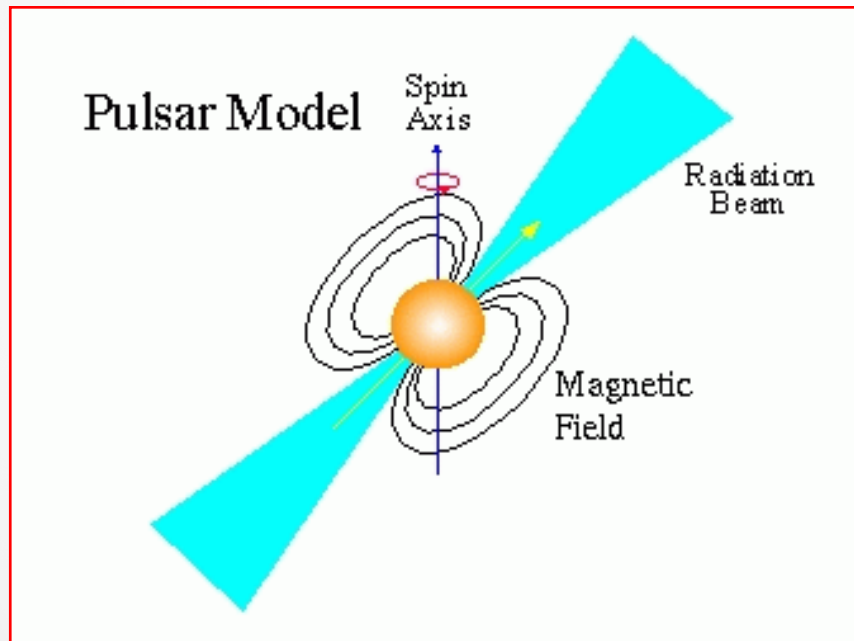


(c)



(d)

# Pulsars: The Lighthouse Model

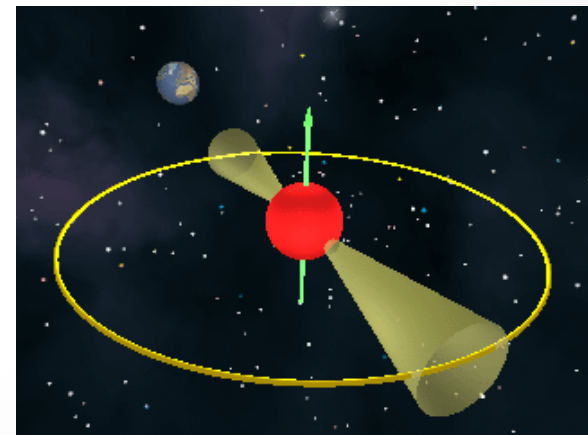


- So, what is the pulsing all about?
- The key is to have a misalignment of the nstar magnetic and spin axes?
- What do you call a rotating powerful magnetic field?

# Lighthouse model

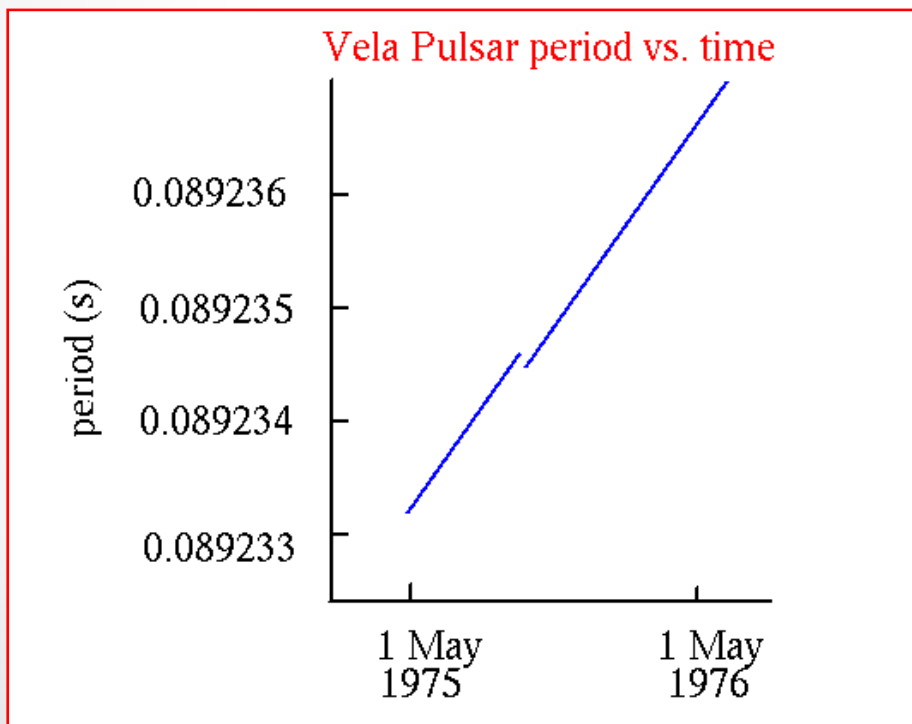
- A rotating magnetic field is called a generator. The pulsar is a dynamo which is typically about  **$10^{29}$  times** more powerful than all the powerplants on Earth. The huge electric field rips particles off the surface and accelerates them out along the magnetic field axis.

The misalignment of the magnetic and spin axes results in a lighthouse-like effect as the beam sweeps past the Earth once per rotation period.



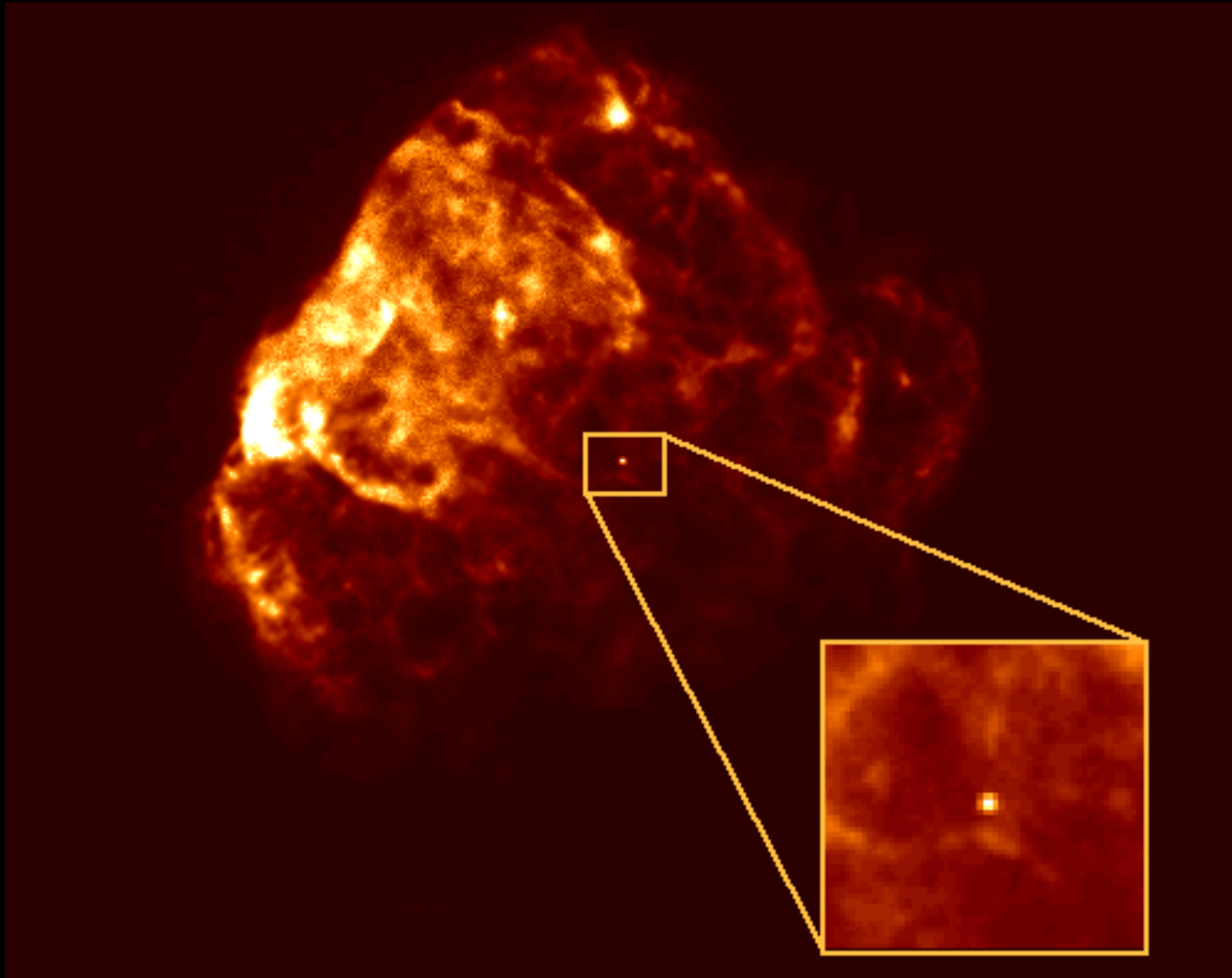
# Pulsars

- The period of the Crab pulsar is decreasing by  $3 \times 10^{-8}$  seconds each day. The rotational energy is therefore decreasing and the amount of the

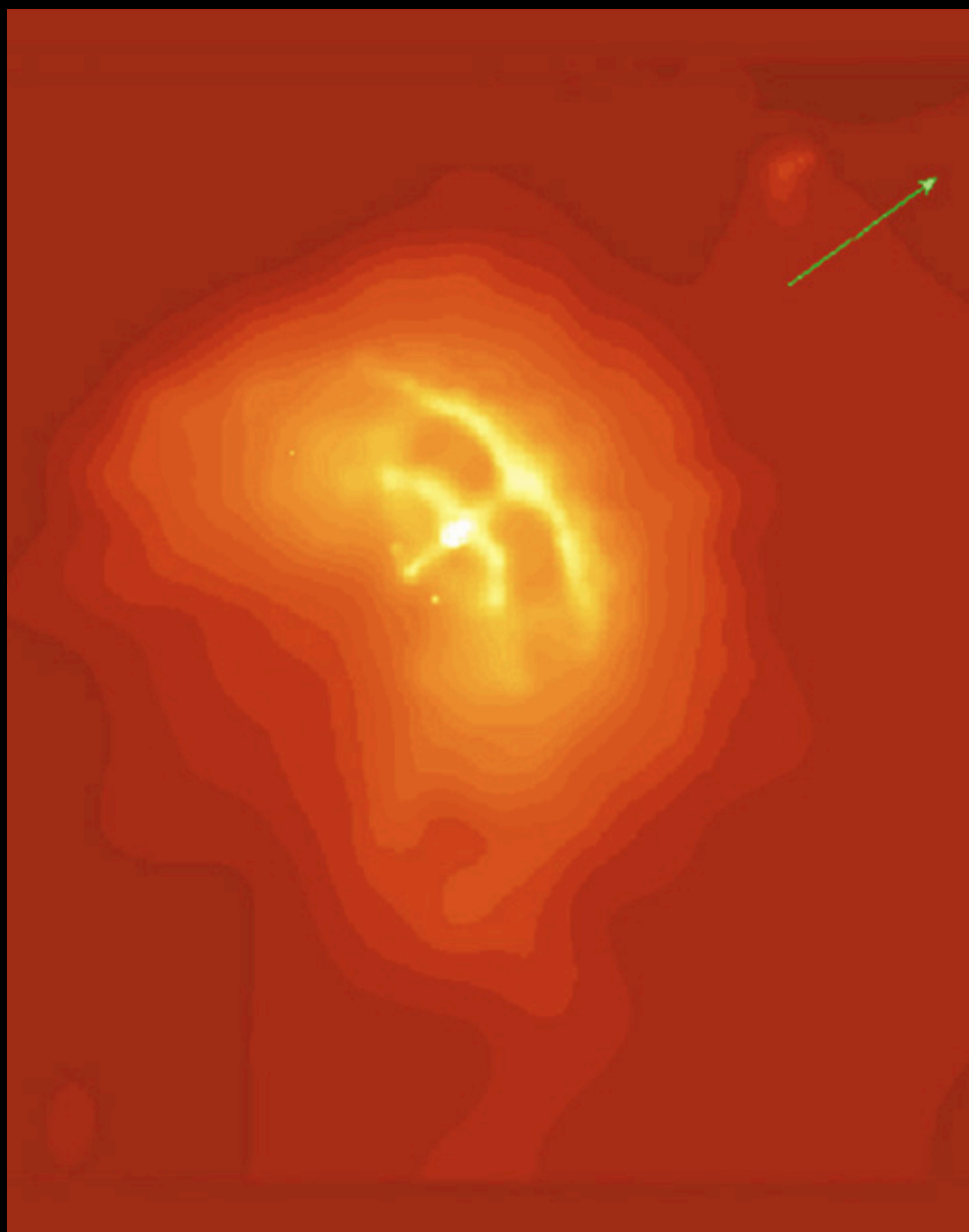


decrease in rotation energy is equal to the luminosity of nebula. Old pulsars spin more slowly.

- There is a mysterious cutoff in pulsar periods at 4 seconds. The Crab will slow to this in about 10 million years. The pulsar will turn off. Although the n-star will still be there, it will be essentially invisible.
- Most pulsars have large space velocities. This is thought to be due to asymmetric SNII explosions.







# Neutron stars in binary systems

- Some neutron stars were discovered in binary systems that allowed measurement of the n-star mass:

In 10 of 11 cases,  $M=1.44M_{\text{Sun}}$

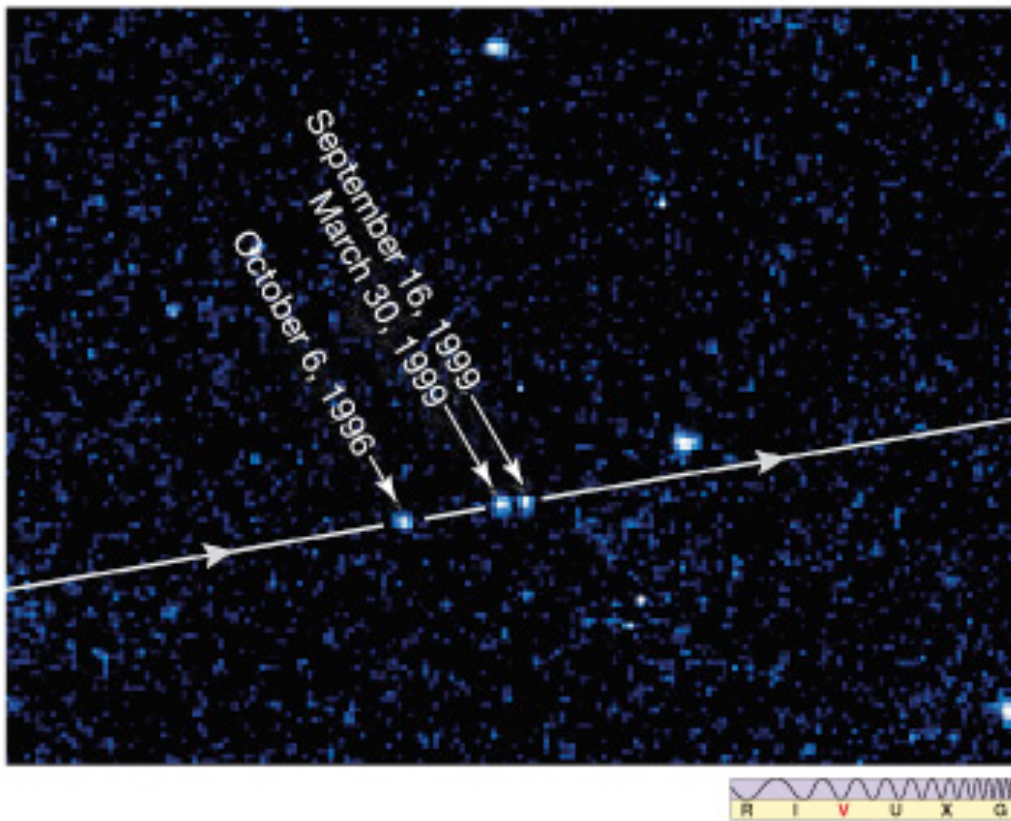
- This is good! Neutron stars are all supposed to be more massive than the Chandrasekar limit and there is even reason to expect them to be close to this limit as that is what initiated the core collapse in a SNII

# Detecting Neutron Stars

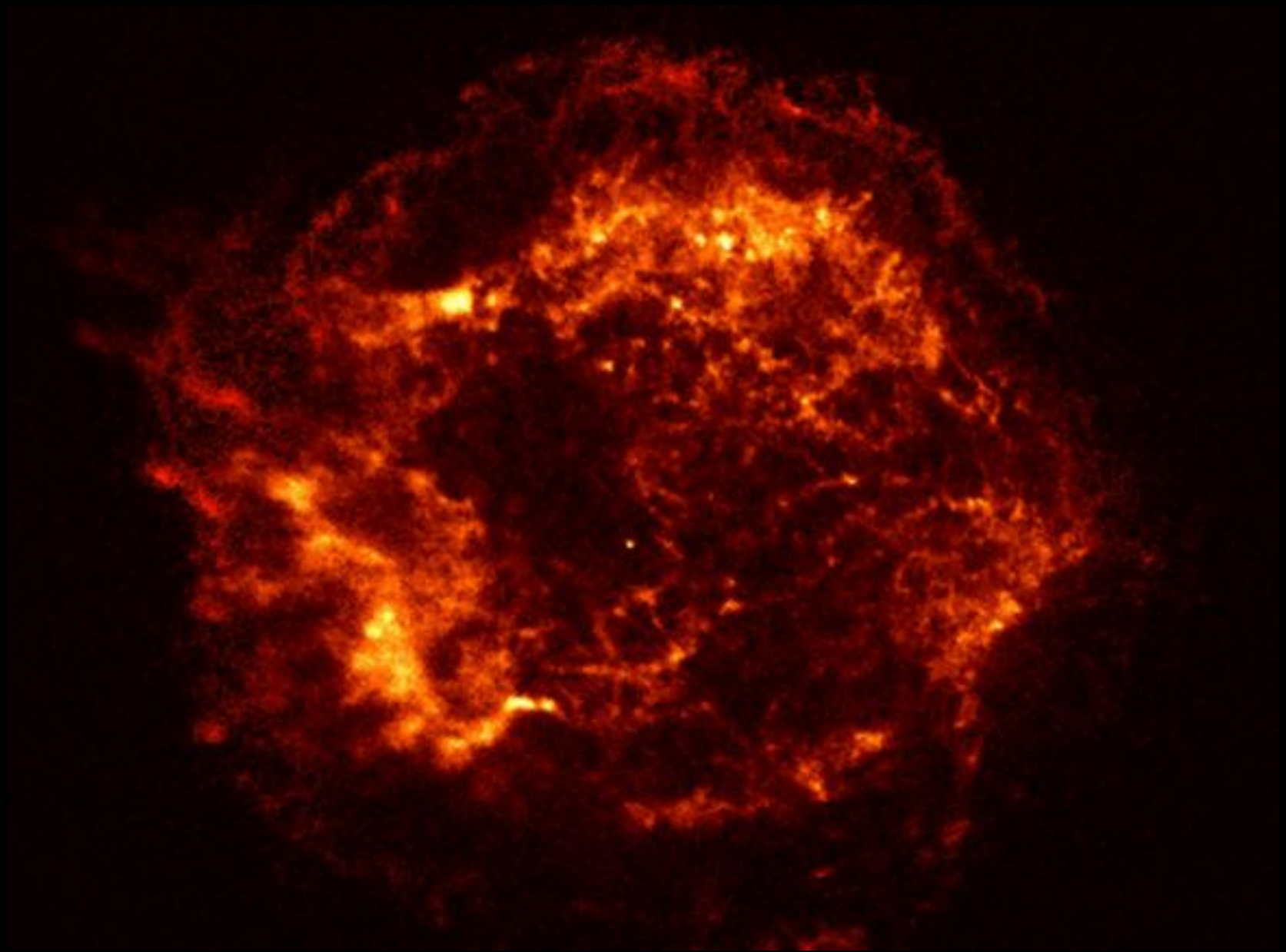
- Detecting n-stars via their photospheric emission is difficult.
- N-stars are VERY hot, but have a tiny surface area so have low luminosity.
- Initial temperature may be greater than 2,000,000k so a very young n-star will emit most of its Planck radiation in X-rays.

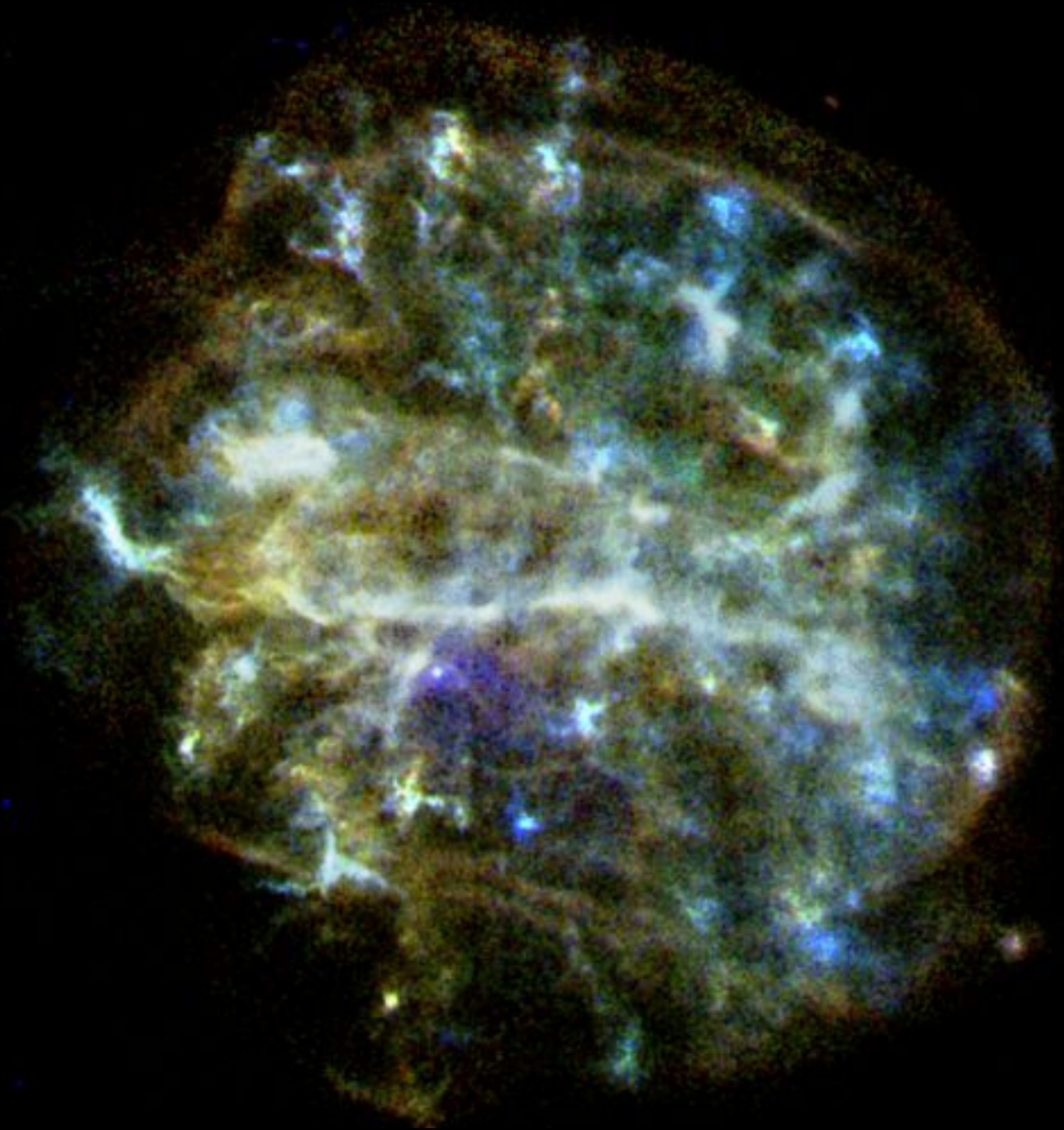


- First isolated n-star observed in photospheric light was discovered in 1997.
- $T_{\text{surface}} = 700,000$
- Estimated age is  $10^6$  years.
- This is combined x-ray through visible light image

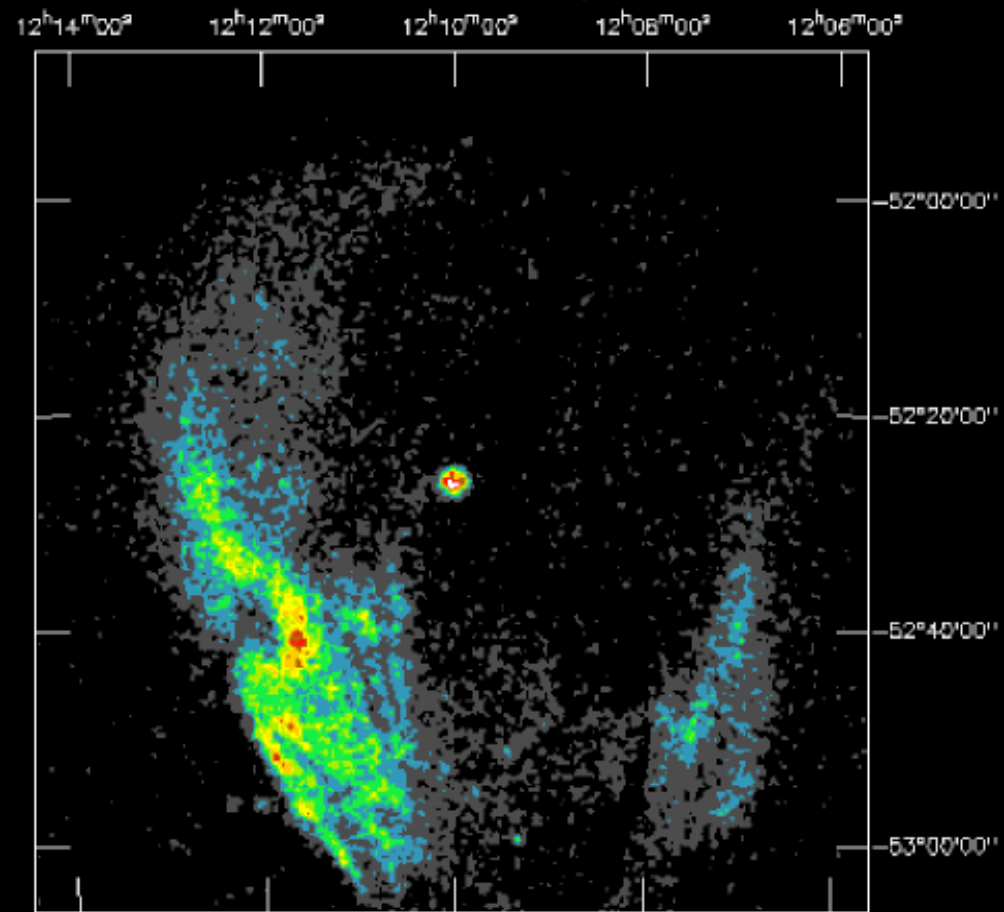


- In 2017 there are about 6 isolated n-stars known that are seen in the light of their Plank radiation.
- Most are very nearby (<300 pc) and traveling VERY fast.

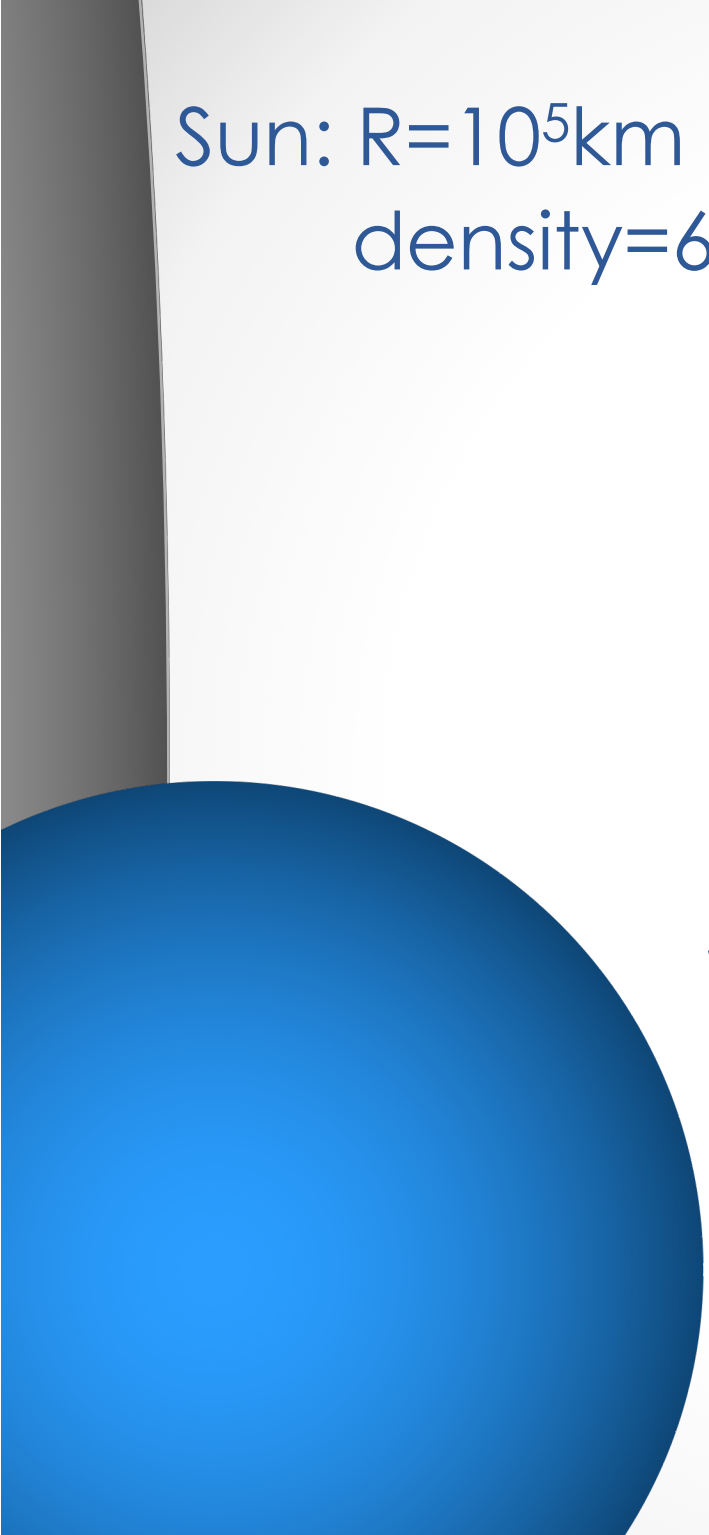




G296.5+10.0 - SE  
ROSAT PSPC 1993 Jul 21 Exposure: 5798 s







Sun:  $R=10^5\text{km}$   
density= $6\text{ gram/cm}^3$

Neutron `star' :  $R=20\text{km}$   
• density= $10^{14}$   
Mass  $> 1.4M_{\odot}$

White Dwarf:  $R=6000\text{km}$   
density= $10^6$   
Mass  $< 1.4M_{\odot}$

- End of material for Quiz 2