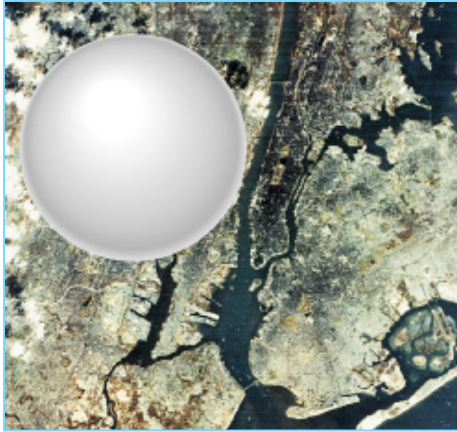


Last Section of AY4

- Last quiz: Thursday, December 2
- Optional Final: December 8, 4 - 7pm
- Neutron stars, pulsars, x-ray binaries
- Relativity
- Black Holes



Neutron Stars

- There is a last 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.
- Supported by neutron degeneracy (although there is an “atmosphere” of normal matter)

This is called neutron “star”



White dwarf
6000 km



Neutron Star
10 km

Neutron Stars: Predictions

- Neutron star mass: $> 1.4M_{\odot}$
- Neutron star radius: 10 - 80 km
- Neutron star density: 10^{14} grams/cm³
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

Neutron Star Spins

- The reason n-stars are predicted to be rapidly spinning is another Law of Physics called *'Conservation of Angular Momentum'*.
- Linear momentum is a property of a moving object and is a vector quantity: of a moving object to remain in motion. $\vec{p} = m \vec{v}$
- To change linear momentum $\vec{p} = m \vec{v}$ you need to exert a force on an object.

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' -> $\underline{\omega}$ (greek letter omega)
- 'mass distribution' -> Moment of inertia (\underline{I})

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

Conservation of Angular Momentum

- Conservation of angular momentum means:

Moment of Inertia \rightarrow

$$L_{initial} = L_{final}$$
$$I_i \omega_i = I_f \omega_f$$

Angular velocity \leftarrow

$$\frac{I_i}{I_f} = \frac{\omega_f}{\omega_i}$$

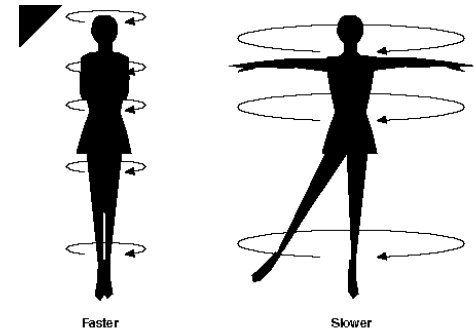
The diagram features a central blue-bordered box containing four equations. To the left of the box, the text 'Moment of Inertia' is followed by a yellow arrow pointing to the I_i term in the second equation. To the right, the text 'Angular velocity' is followed by a yellow arrow pointing to the ω_f term in the same equation. The first equation is $L_{initial} = L_{final}$. The second equation is $I_i \omega_i = I_f \omega_f$. The third equation is $\frac{I_i}{I_f} = \frac{\omega_f}{\omega_i}$. The fourth equation is $I_f \omega_i$.

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 km , by what factor does its spin rate increase?

- Conservation of angular momentum means:

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

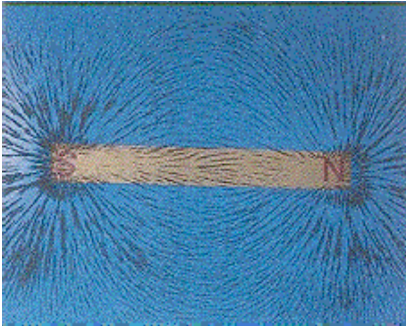
$$I_i \omega_i = I_f \omega_f$$

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

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

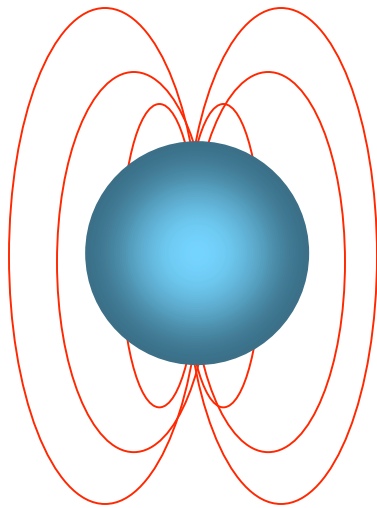
$$\omega_f = \frac{R_i^2}{R_f^2} \omega_i = \left(\frac{7 \times 10^5}{10} \right)^2 \omega_i = 4.9 \times 10^9 \omega_i$$

- 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



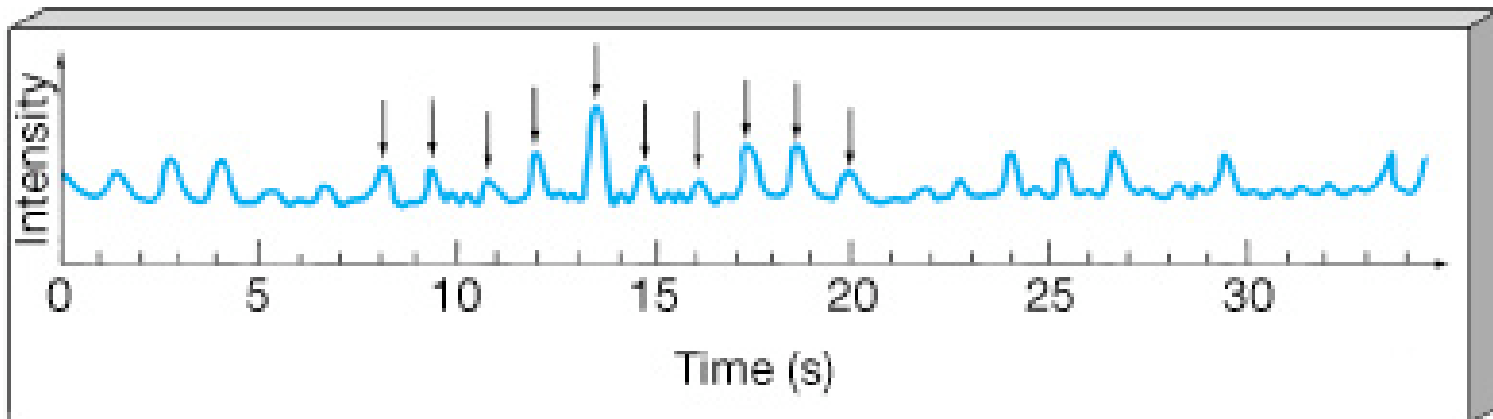
conserved, and the density of the field lines goes way up . This is the strength of the magnetic field.

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 (why?)
- 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

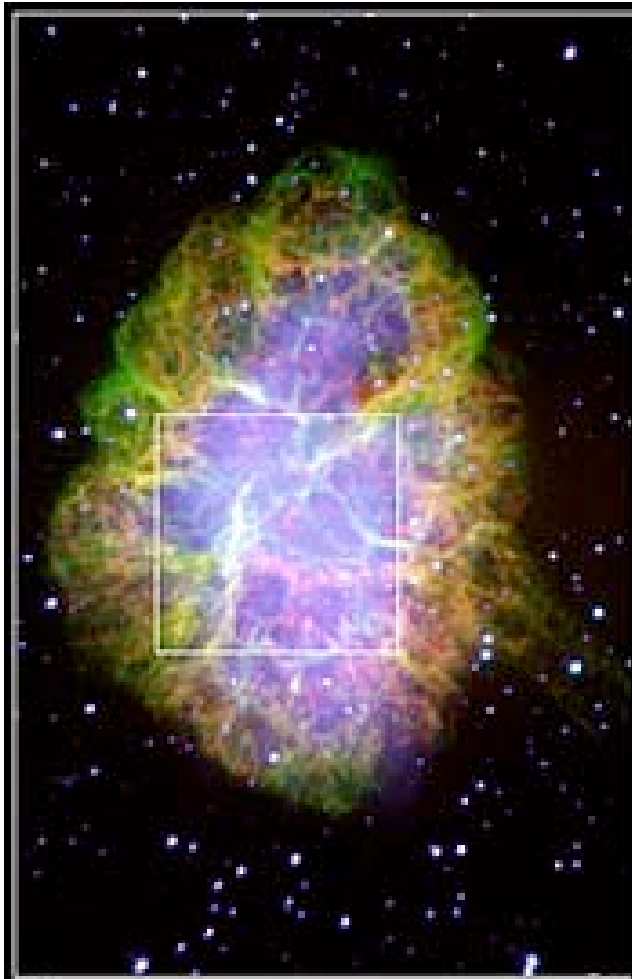


- Bell was a graduate student at the time. The source was assumed to be man made, but when no terrestrial source could be identified, they briefly considered an artificial extra-terrestrial source.
- When a second source was discovered (Cass A) they announced the discovery as a new phenomenon.

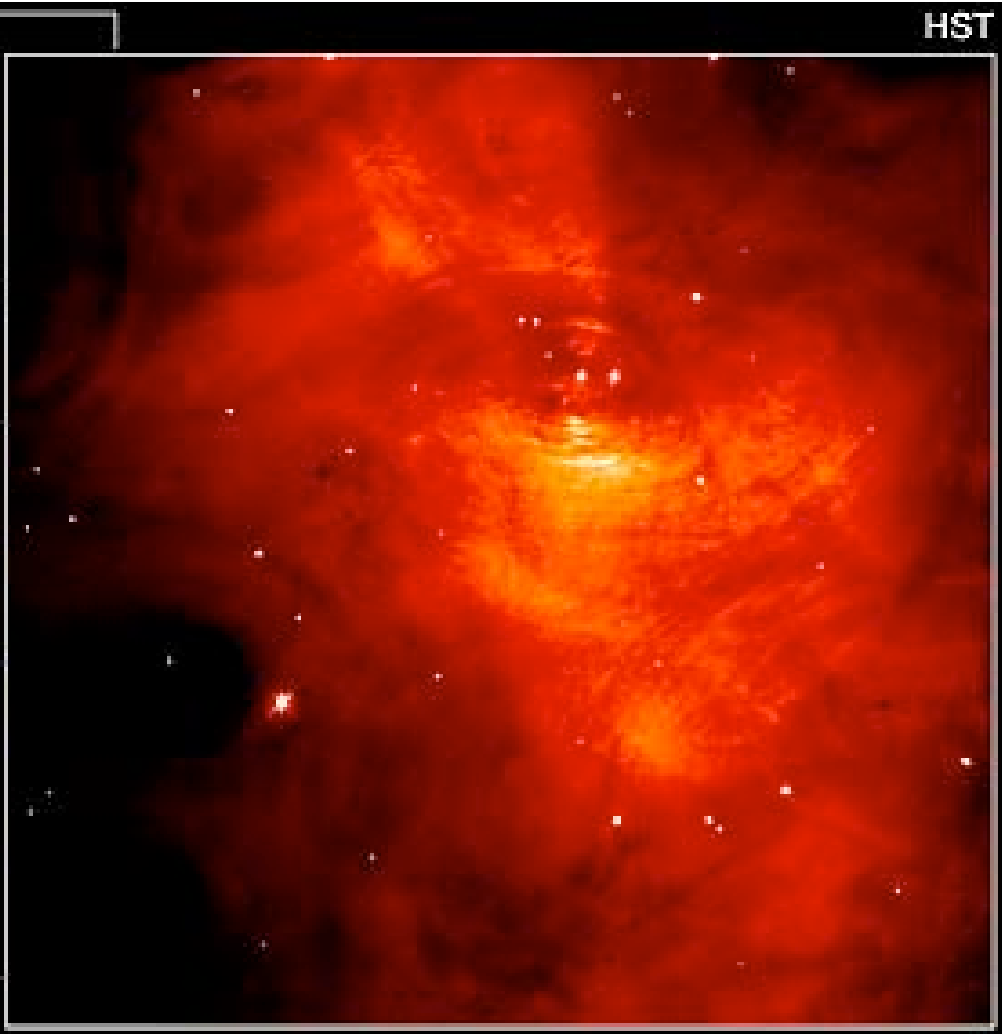
- The discovery led to a year of wild speculation, but explanations involving neutron stars quickly rose to the top.
- A pulsing source with period of 0.033 seconds was discovered in the Crab nebula.
- Big clue! Spin the Sun or Earth or a WD 30 times per second and they will be *torn apart*.
- *Need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

Pulsars

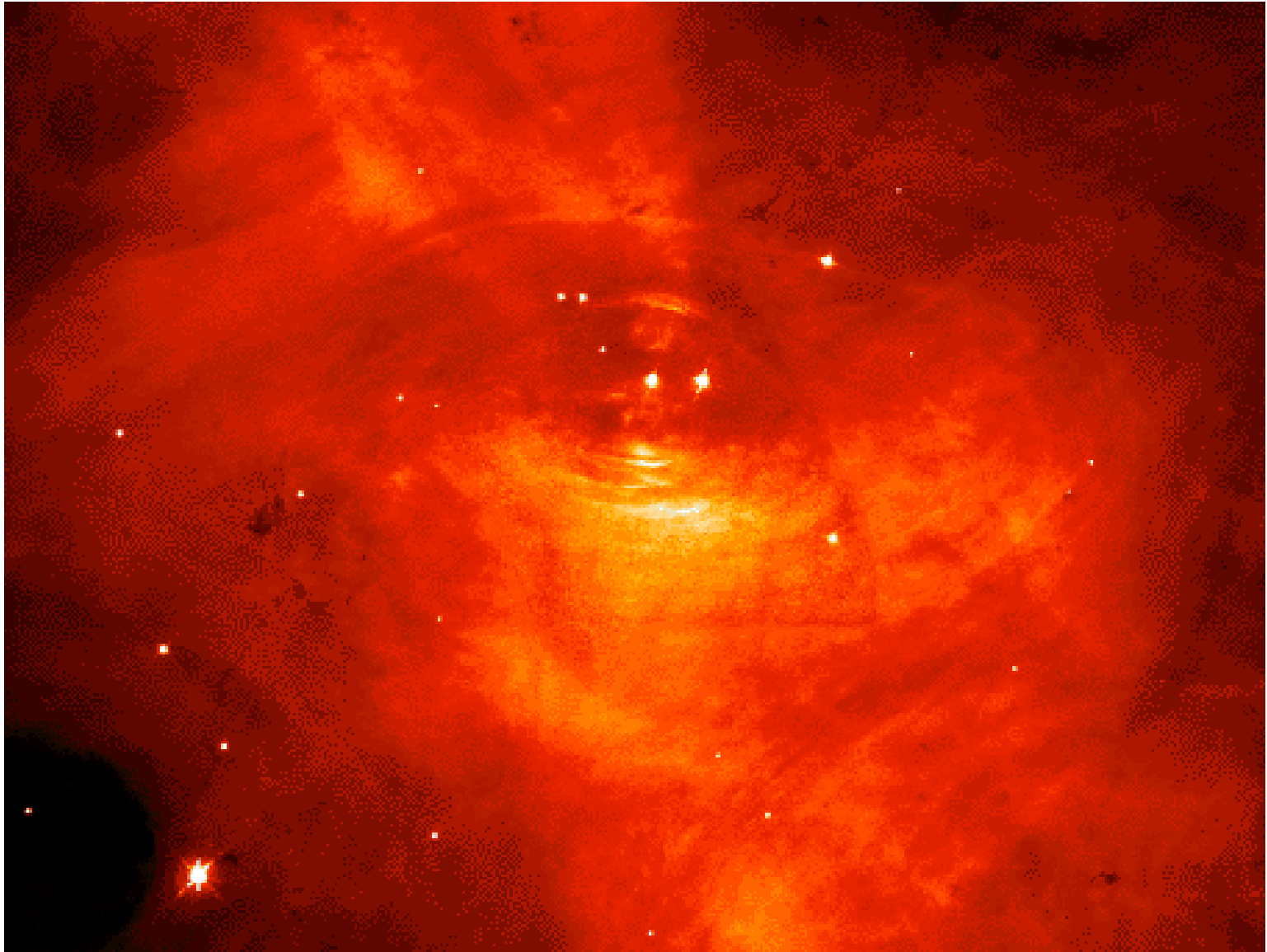
- The new objects were named ‘pulsars’ and it was soon discovered that they were slowly slowing down -- this provided the answer to the mystery of why the Crab Nebula was still glowing.
- There are now more than 1000 known pulsars in the Galaxy.

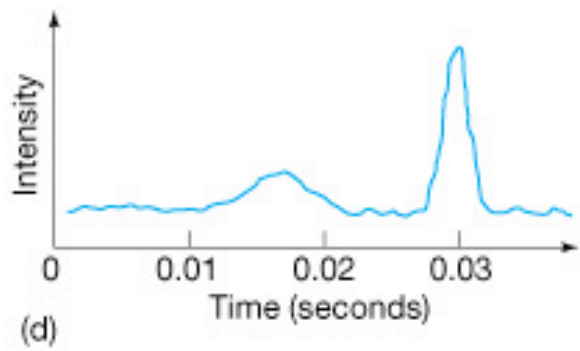
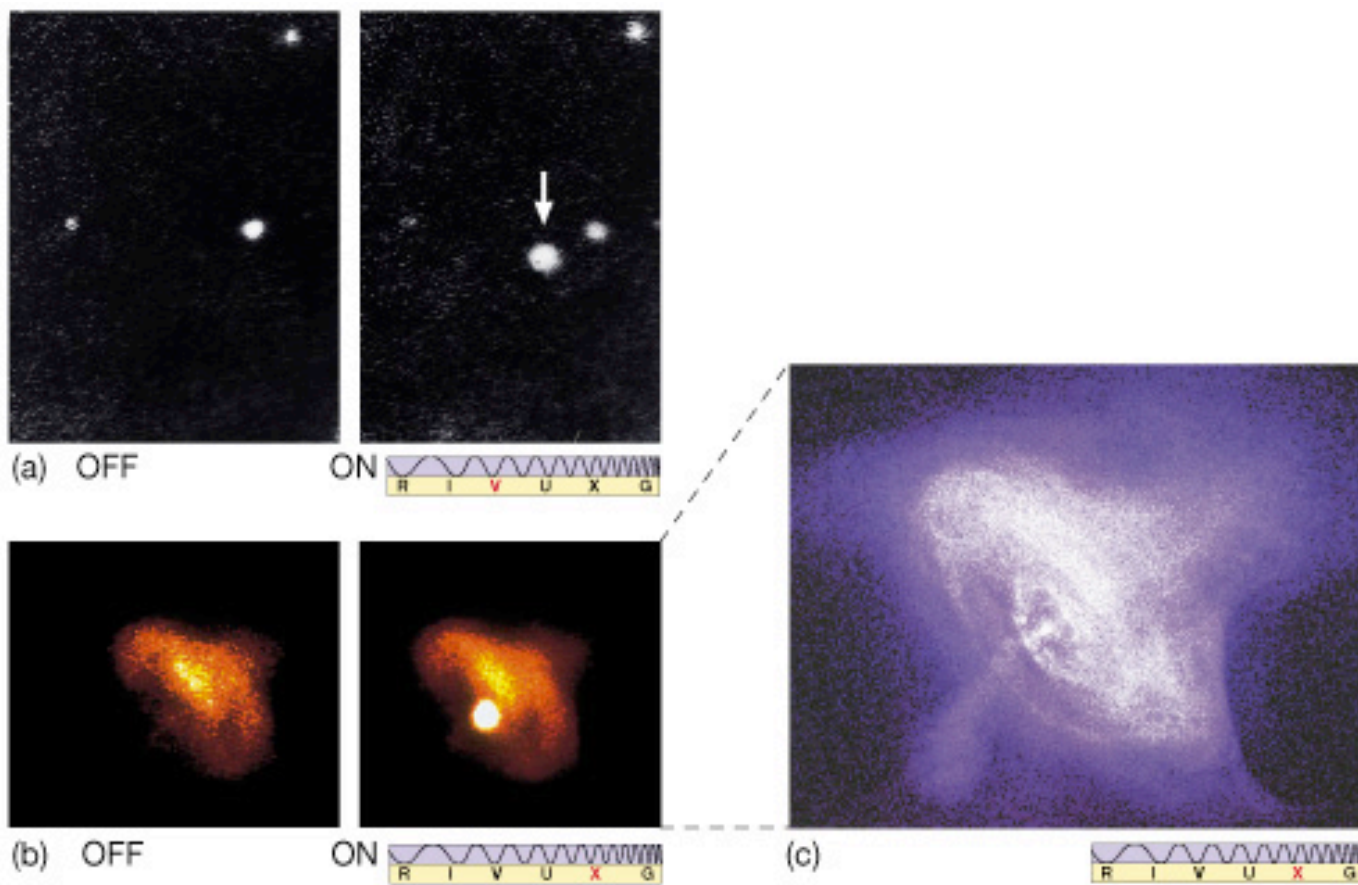


Palomar

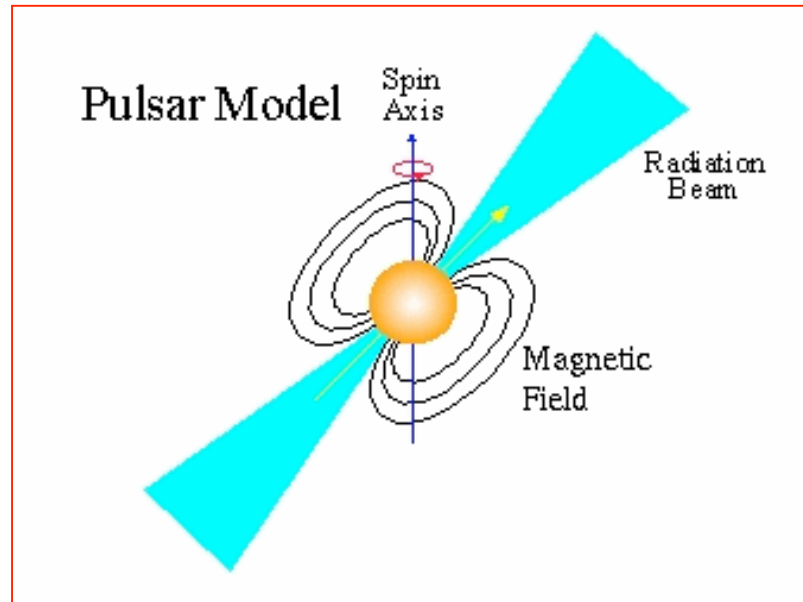


HST





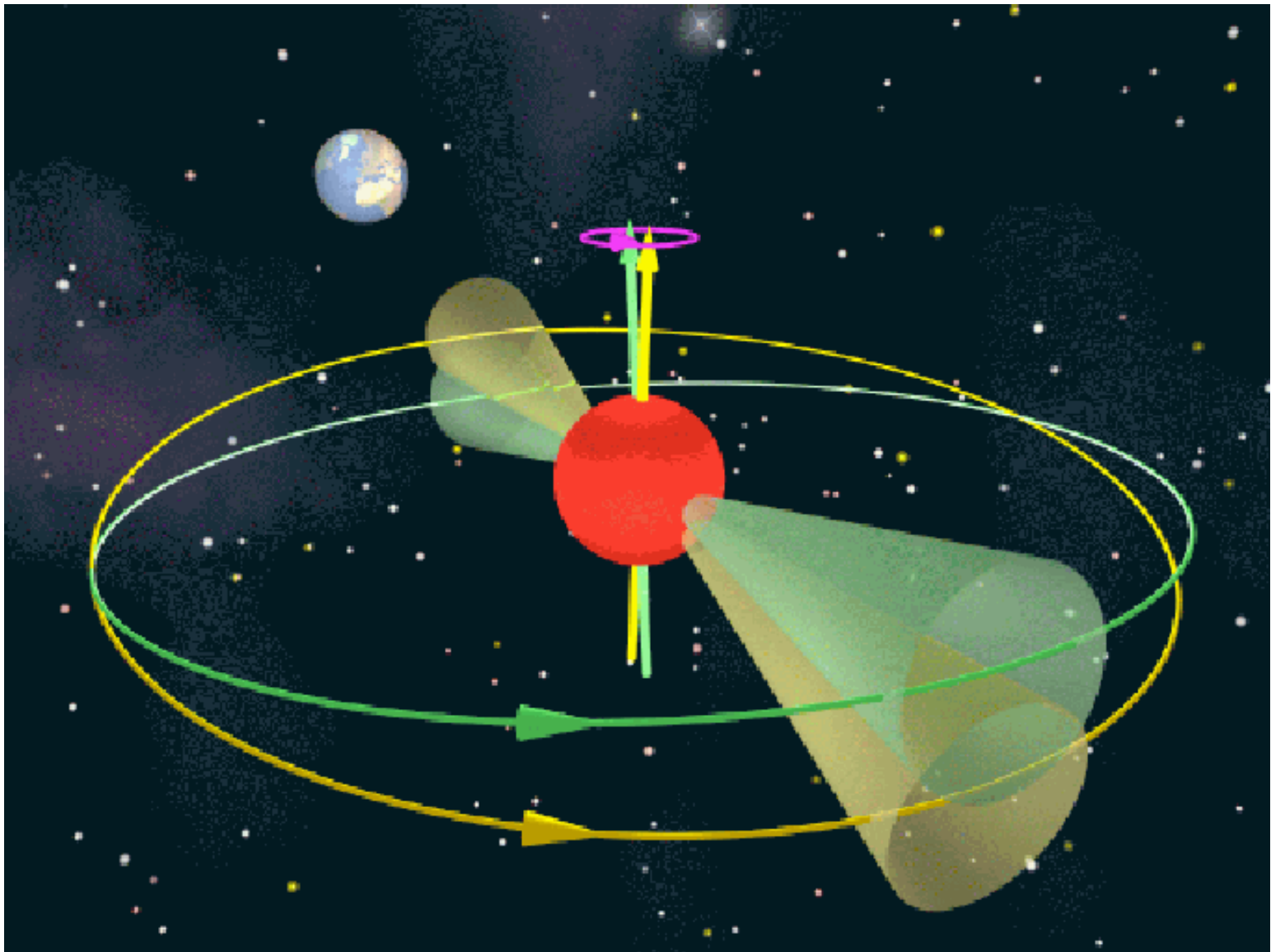
Pulsars: The Lighthouse Model



- 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?

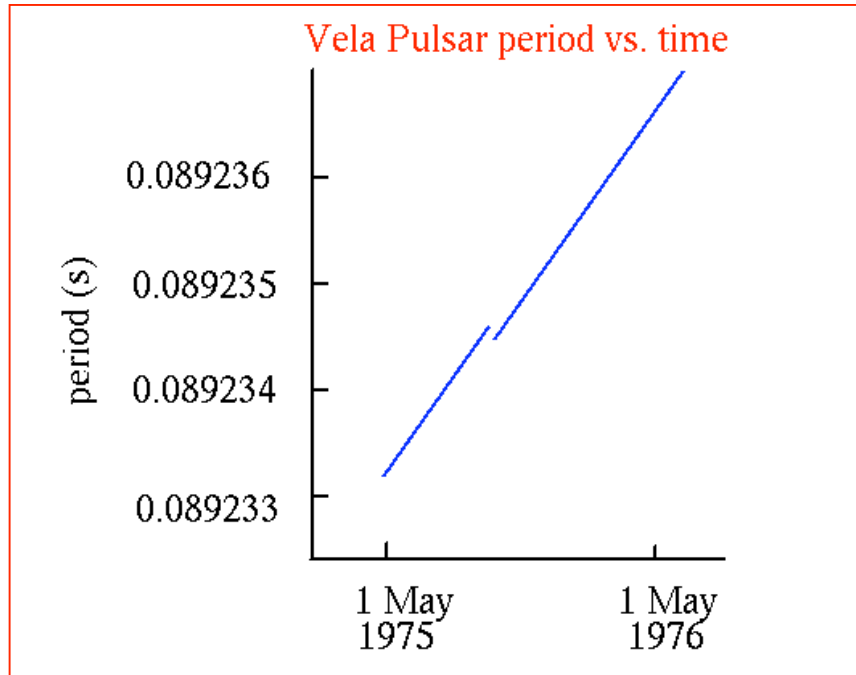
Lighthouse model

- 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.



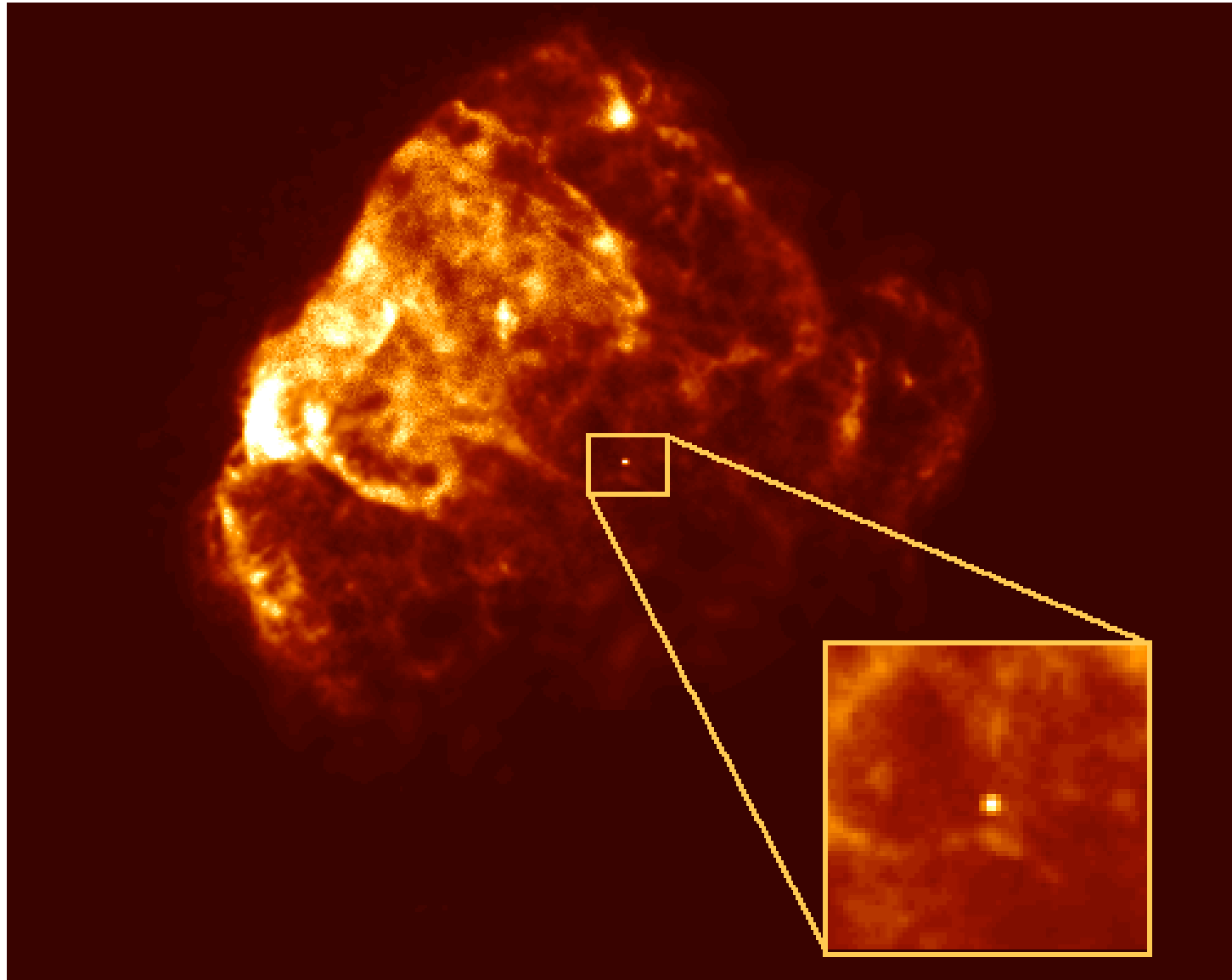
Pulsars

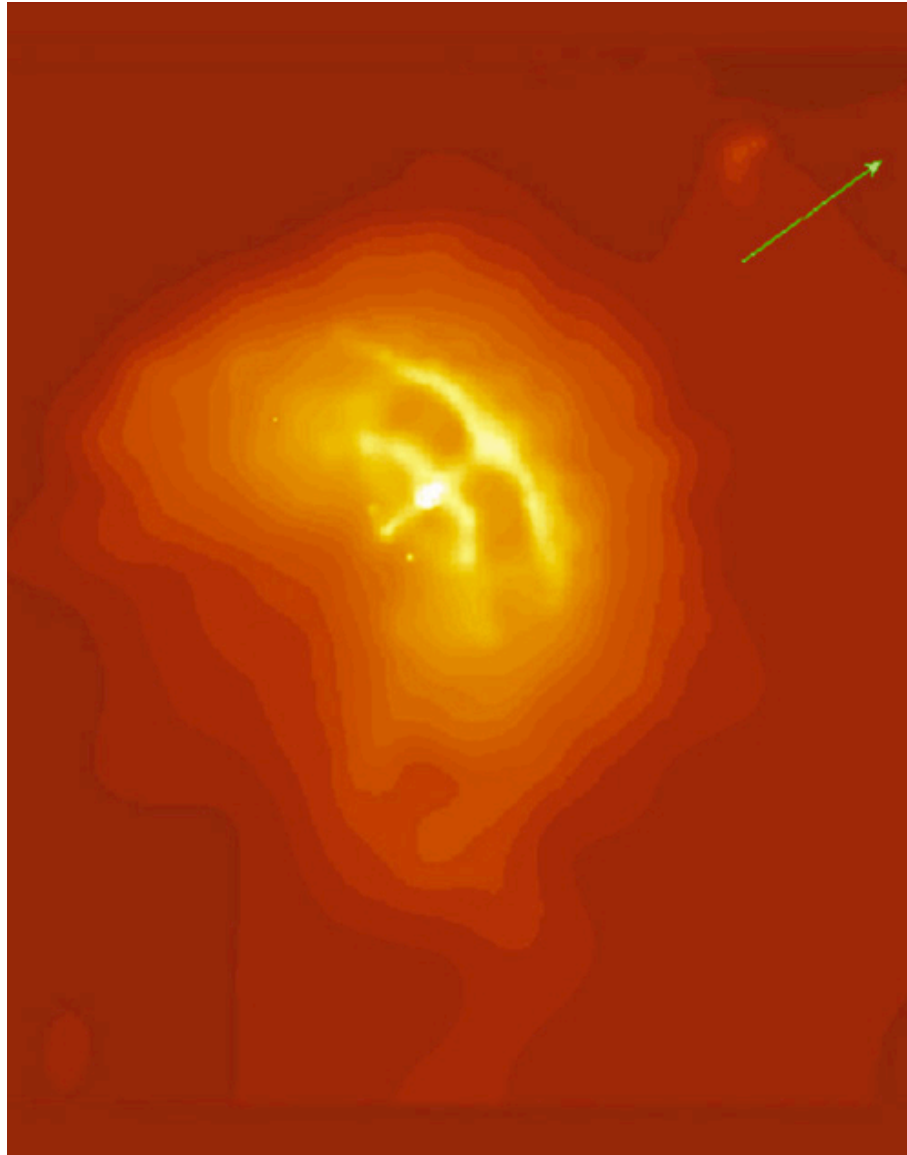
- The period of the Crab pulsar is decreasing by 3×10^{-8} seconds each day. The rotational energy is therefore decreasing and the amount of the

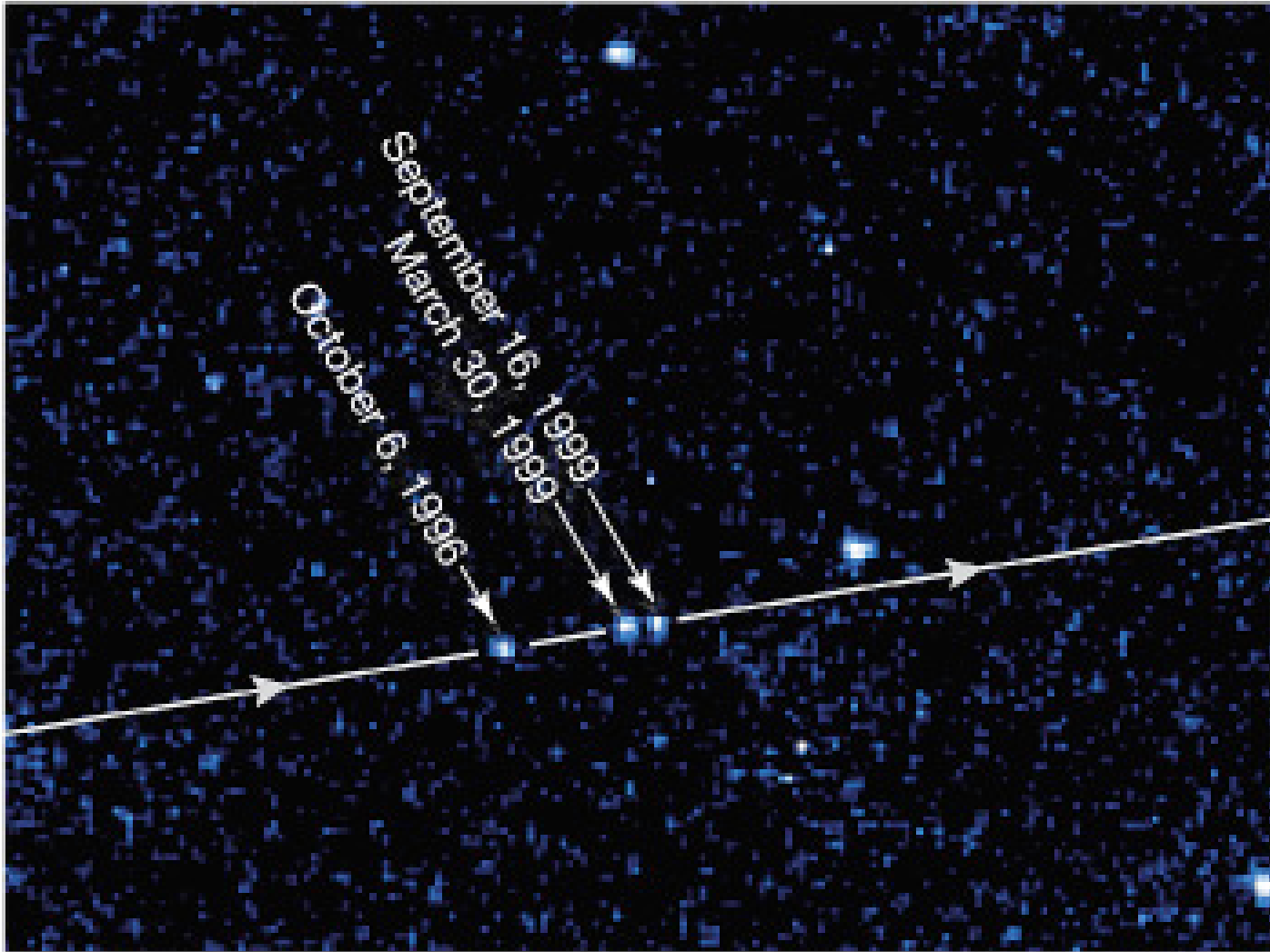


decrease in rotation energy is equal to the luminosity of nebula. Old pulsars spin more slowly.

- 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.



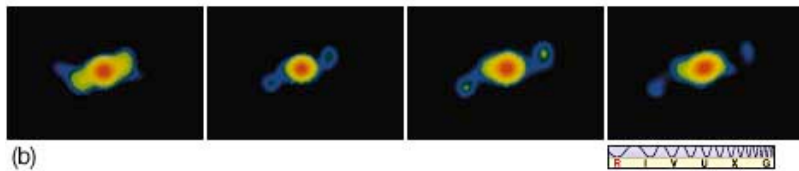
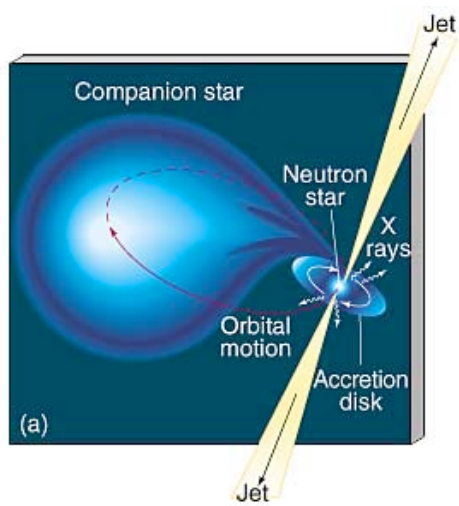




Pulsars

- Do all SN remnants have pulsars?
- No - some SN remnants are from SNI
- No - some rotating neutrons stars will have beams that don't intersect the Earth

Milli-sec Pulsars and X-ray Binaries



- Since the first x-ray telescopes went into space on rockets it has been known that there are **Luminous X-ray** stars.
- In 1982, the first of many milli-second pulsars was discovered

- The two phenomenon are connected.
- When a neutron stars has a close companion, it pulls material through the L1 point. This material flies down to the surface of the n-star and crashes onto the surface, releasing LOTS of gravitational potential energy. This energy comes out mostly as x-rays and is modulated with the n-stars spin.

Mass-transfer and N-stars

- Some of the x-ray binaries have allowed a measurement of the neutron star mass:

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

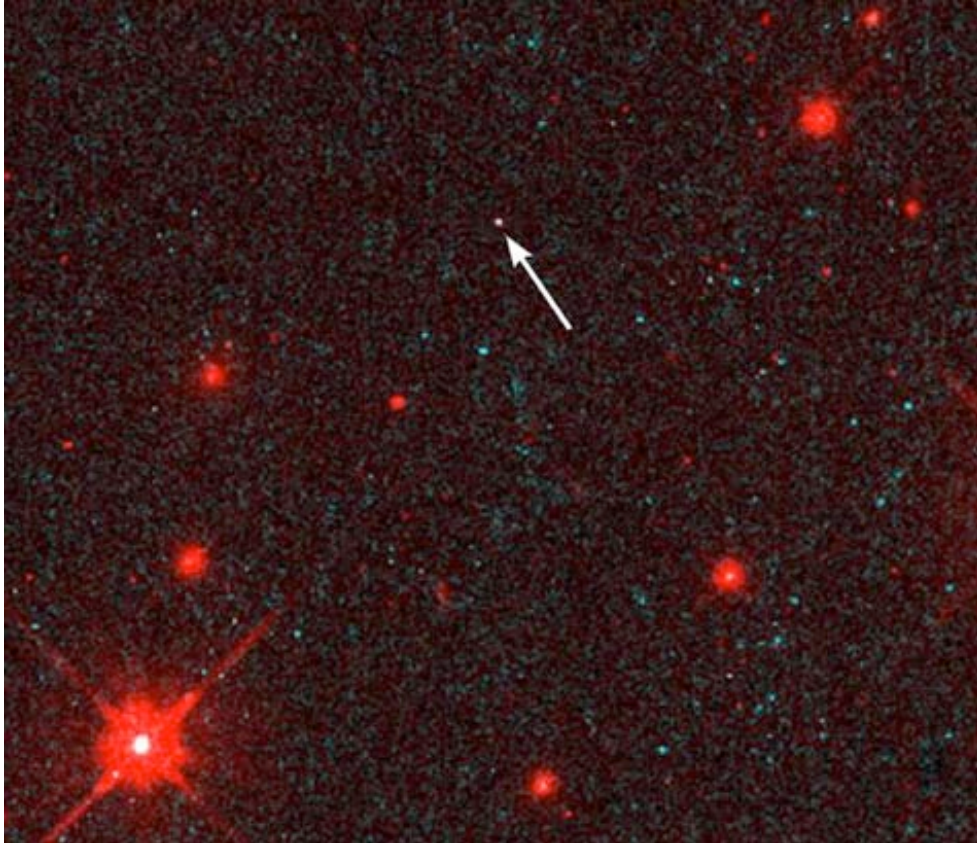
This is good! Neutron stars are all supposed to be more massive than the Chandrasekar limit and there is even reason to expect them to be close to this limit as that is what initiated the core collapse in a SNII

Millisecond Pulsars

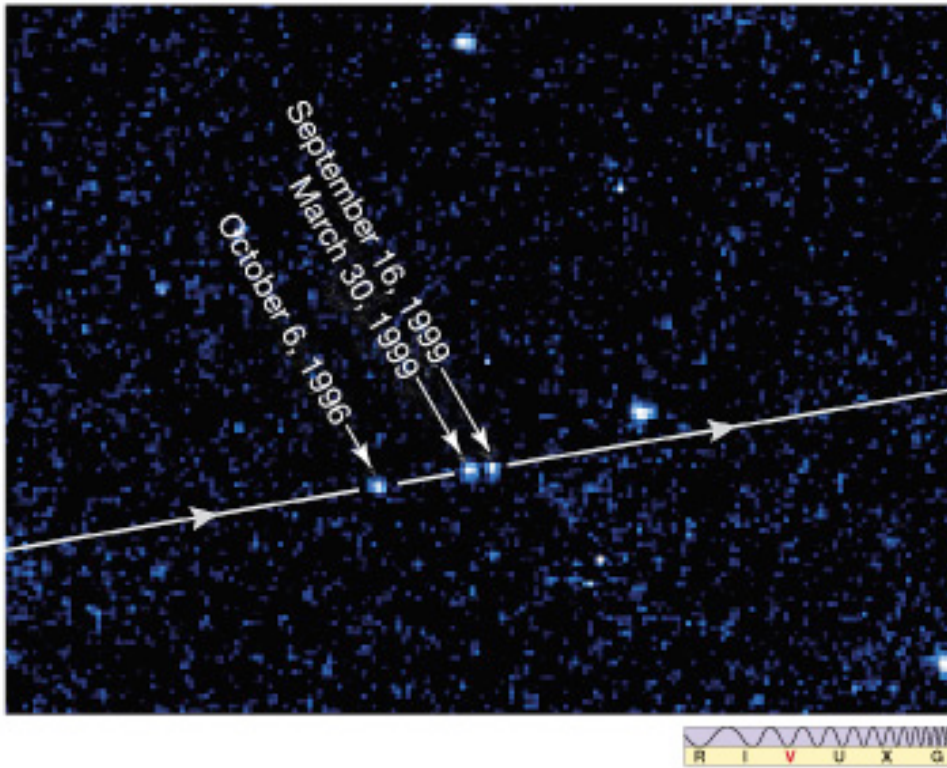
- The discovery of pulsars that were spinning more than 100 times per second (the first was spinning 640 times per second) threw the field for a loop. When some millisecond pulsars were discovered in old star clusters it was even more confusing.
- Eventually it was determined that all millisecond pulsars were in close binary systems and were 'spun up' by accreting material.

Detecting Neutron Stars

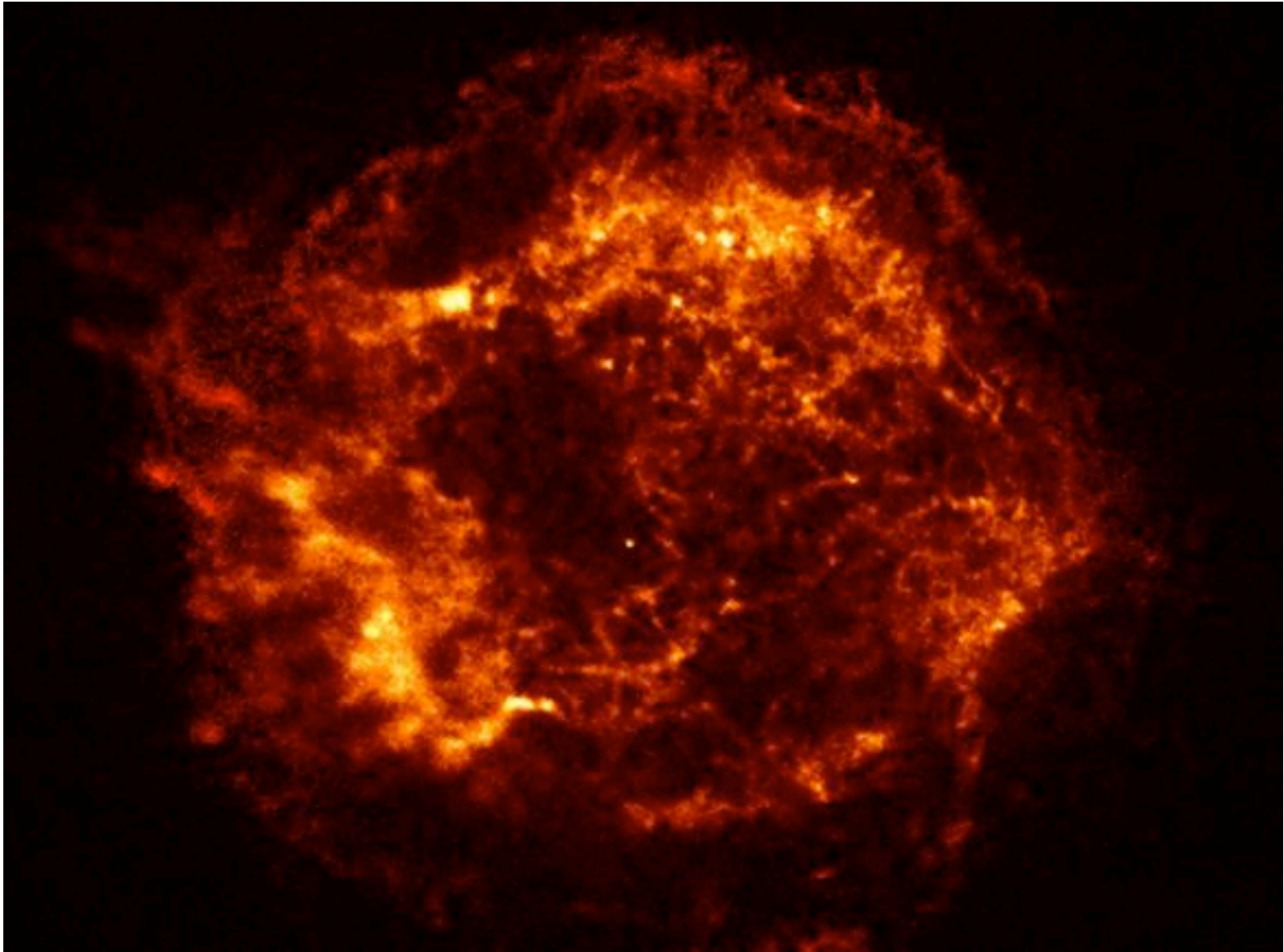
- Detecting n-stars via their photospheric emission is difficult.
- N-stars are VERY hot, but have a tiny surface area so have low luminosity.
- Initial temperature may be greater than 3,000,000k so a very young n-star will emit most of its Planck radiation in X-rays.

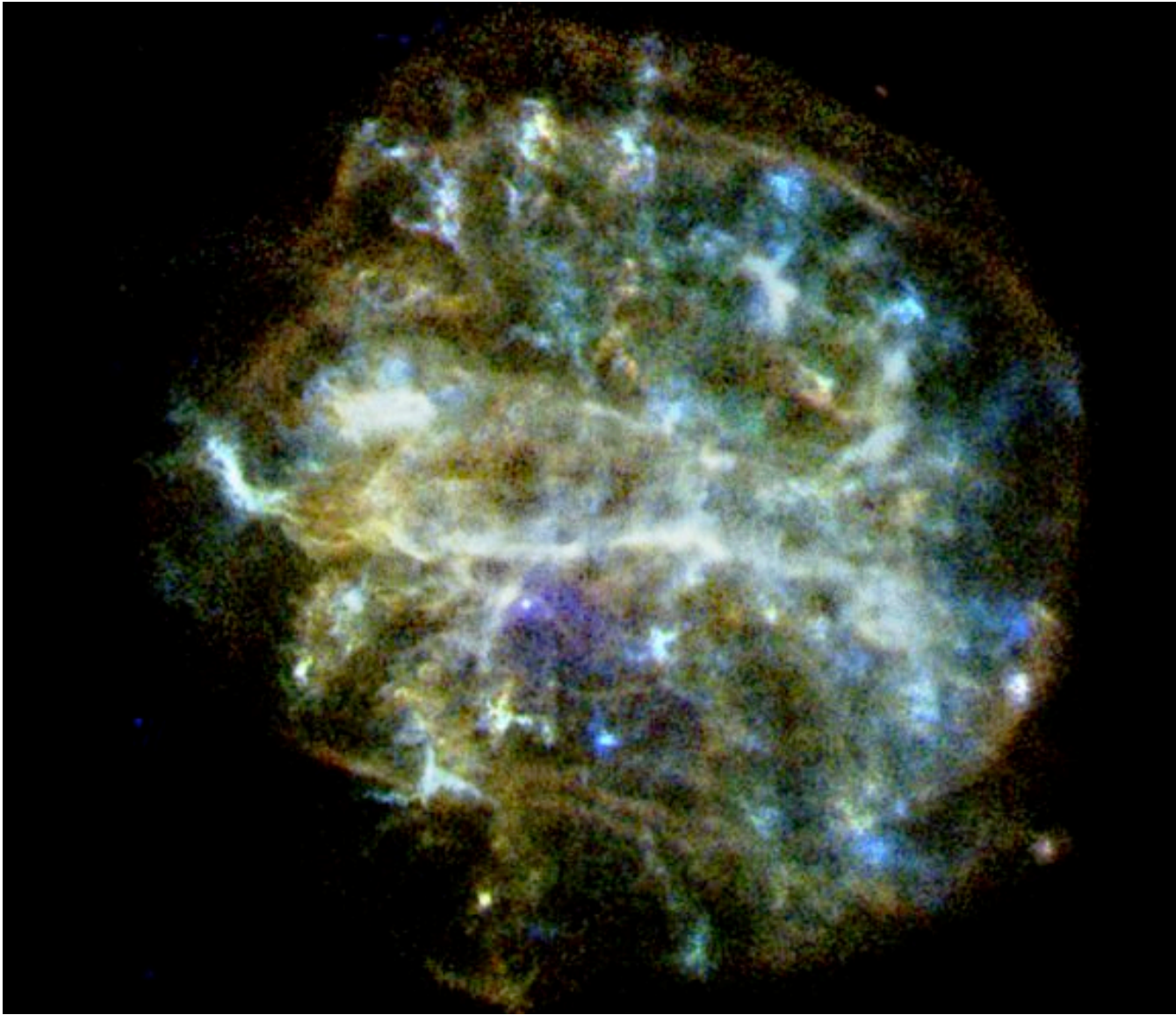


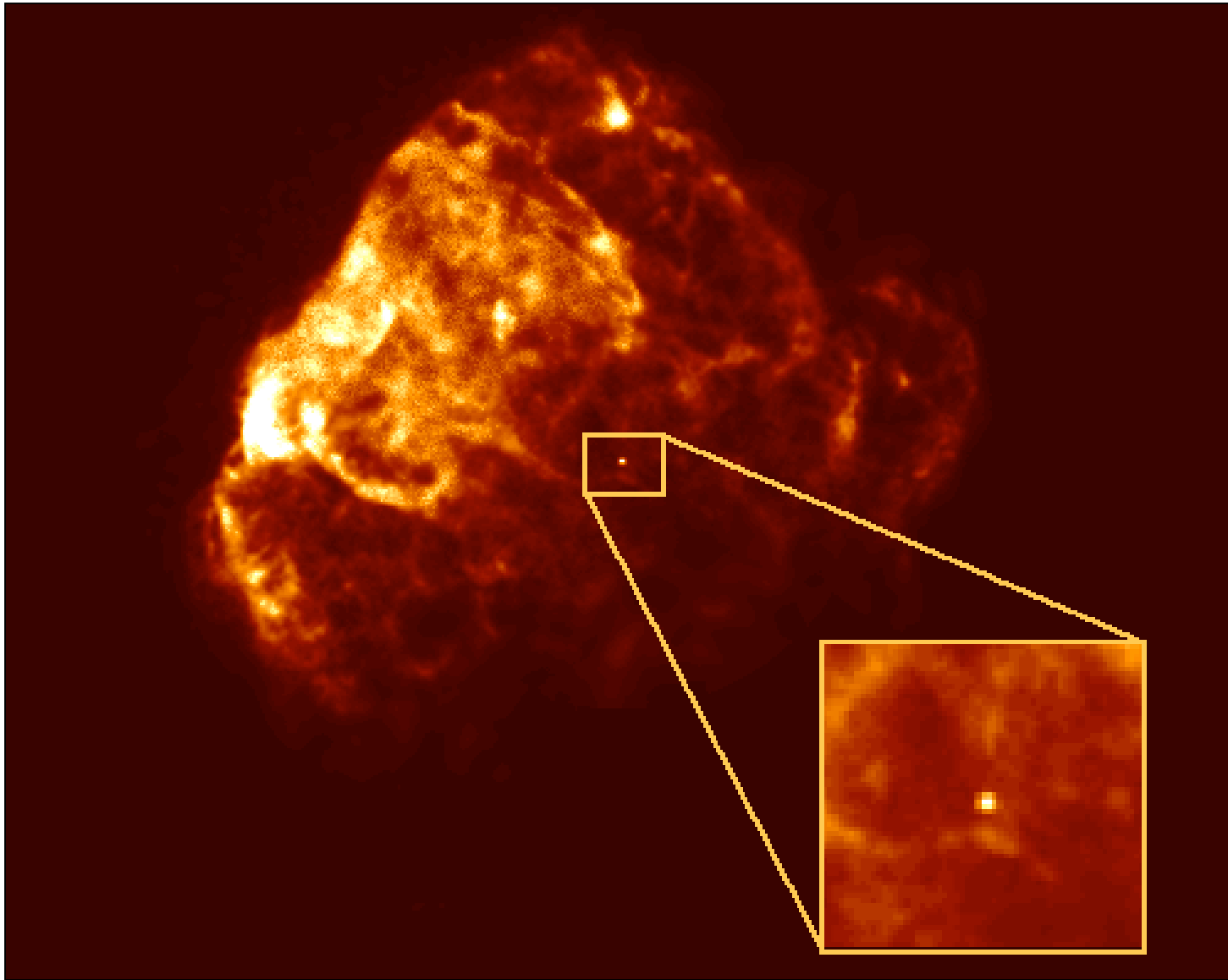
- First isolated n-star observed in photospheric light was discovered in 1997.
- $T_{\text{surface}} = 700,000$
- Estimated age is 10^6 years.
- This is combined x-ray through visible light image



- In 2002 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.

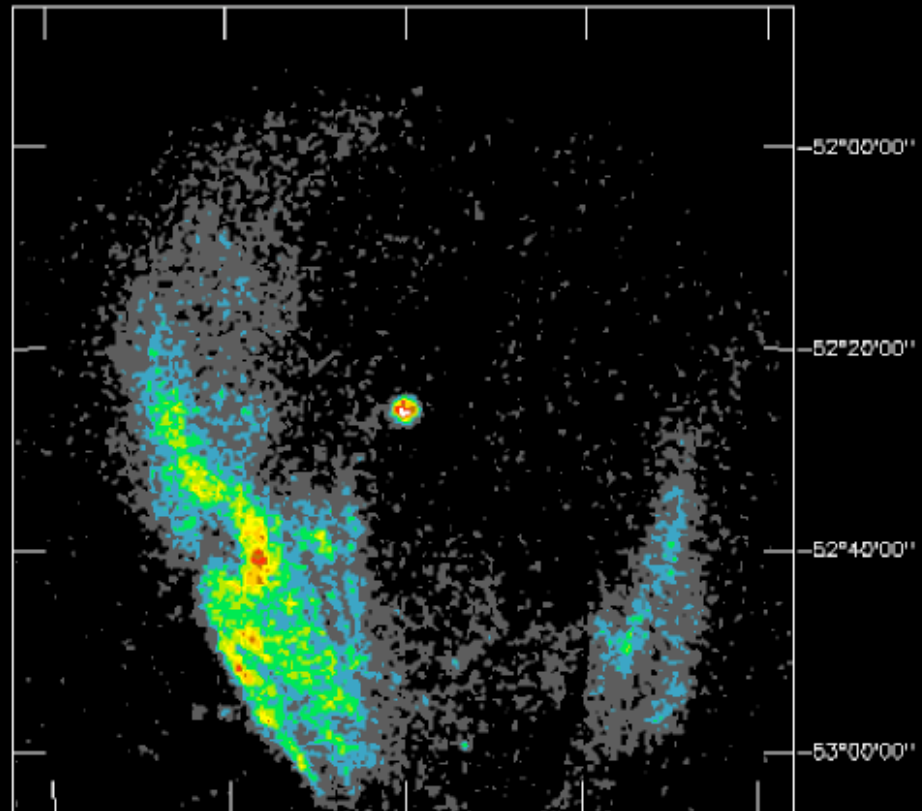






Puppis A remnant with 2 millionK n-star racing away at 600 km.sec. Estimated age is 6000 years.

G296.5+10.0 - SE
ROSAT PSPC 1993 Jul 21 Exposure: 5798 s
12^h14^m00^s 12^h12^m00^s 12^h10^m00^s 12^h08^m00^s 12^h06^m00^s





Sun: $R=10^5\text{km}$

density= 6 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 $< 1.4M_{\odot}$



Is there a limit to neutron degeneracy?

- Yes! Gravity wins the final battle. The current best estimate for the maximum mass of a neutron-degenerate star is $3M_{\odot}$.
- If a neutron star exceeds this mass it will collapse into an infinitely small volume called a **black hole**.
- But, this story starts with Einstein's theories of **special and general relativity**.