Compton Lecture #7: Life On, In, and Around Neutron Stars

- Welcome!
- On the back table:
  - Lecture notes for today's lecture
  - Extra copies of last week's are on the back table
  - Sign-up sheets
    - please fill one out only if you're not already on the Compton Lectures mailing list or need to change your address
  - Luncheon Sign-up sheets
    - for lunch following the final lecture on Dec 13

- **No lecture Nov 29th or Dec 6th!**

Stars: Their Life and Afterlife

Life On, In, and Around Neutron Stars

Brian Humensky

68th Series, Compton Lecture #7

November 22, 2008

Outline

- Degenerate gases
- Neutron stars
- Pulsars
- Pulsar Wind Nebulae

Key Points to Take Away

- Neutron stars form from the collapse of massive stars and are supported against gravity by degenerate-neutron pressure.
- Pulsars are spinning neutron stars with strong magnetic fields.
  - Radio pulses probably originate near the magnetic poles.
  - High-energy pulses (optical, X-ray, gamma ray) can also be seen – origins still unclear.
  - The Fermi gamma-ray observatory will provide a wealth of new information about pulsars.
- Pulsar wind nebulae are clouds of energetic particles that form from the winds coming off of pulsars.
  - Visible from radio through TeV gamma rays in some cases.
  - The Crab Nebula is the classic example – brightest steady TeV gamma-ray source.

Degenerate Gases

Comparison: Ideal vs Degenerate Gases

- Ideal gas: particles are point-like, no long-range interactions
- Pressure proportional to density, temperature:

  $p \propto n * T / V$

  - pressure driven by random thermal motions of particles
  - pressure → 0 as temperature → 0
- Self-regulating
- Describes familiar gases well (air, Sun, …)

- Degenerate gas: inherently quantum mechanical
  - particles occupy discrete “states” (position/momentum)
  - Fermi exclusion principle: no two particles can be in same state
  - particles fill states from lowest energy up
  - Heisenberg uncertainty principle: position and momentum cannot both be known arbitrarily well

    $\Rightarrow \Delta x * \Delta p \sim \hbar$
  - High density ⇒ high momenta
  - Pressure dictated by density, independent of temperature
  - Pressure > 0 at $T = 0$!

White Dwarfs and Degenerate Electrons

- White dwarfs are supported by degenerate-electron pressure
  - states filled to point where some electrons have very high momenta
- If fusion starts, temperature rises
  - fusion rate rises with temperature

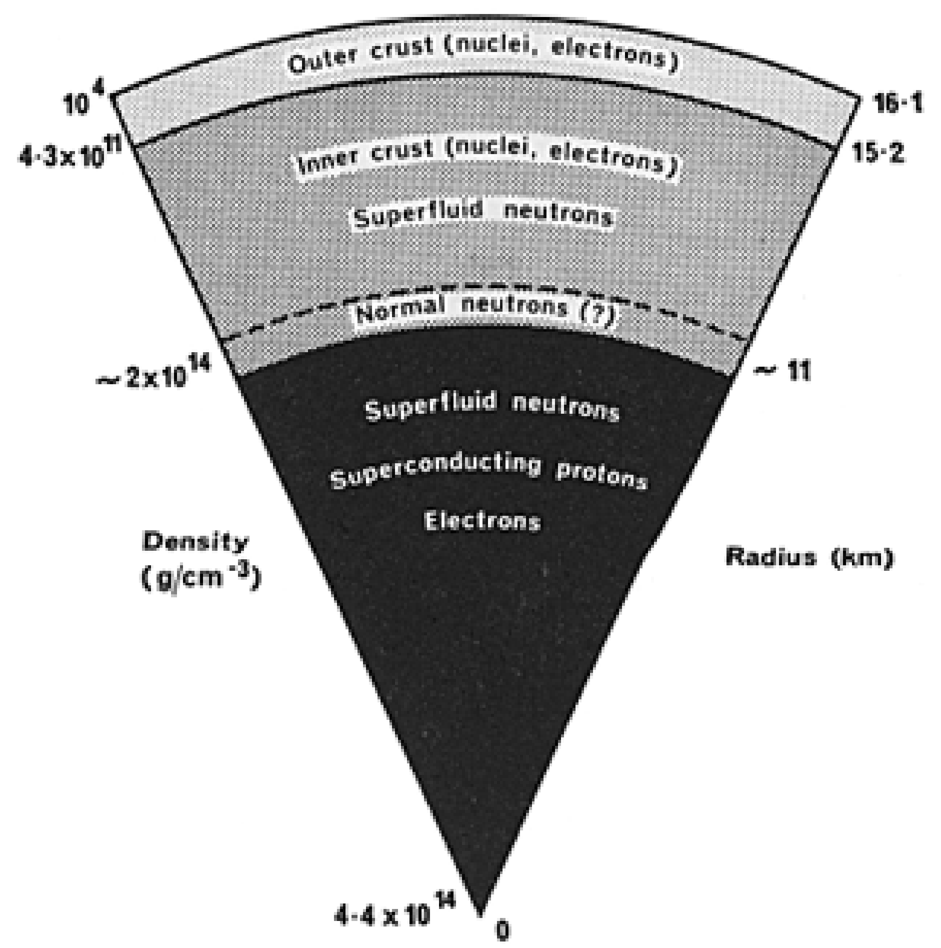
    → runaway process unless there's a way to control temperature
- Ideal gas: rise in temperature increases pressure and gas expands, cools – self-regulating
- Degenerate gas: rise in temperature does *NOT* affect pressure – no way to cool! (until it's too late)

Neutron Stars

How Neutron Stars Form

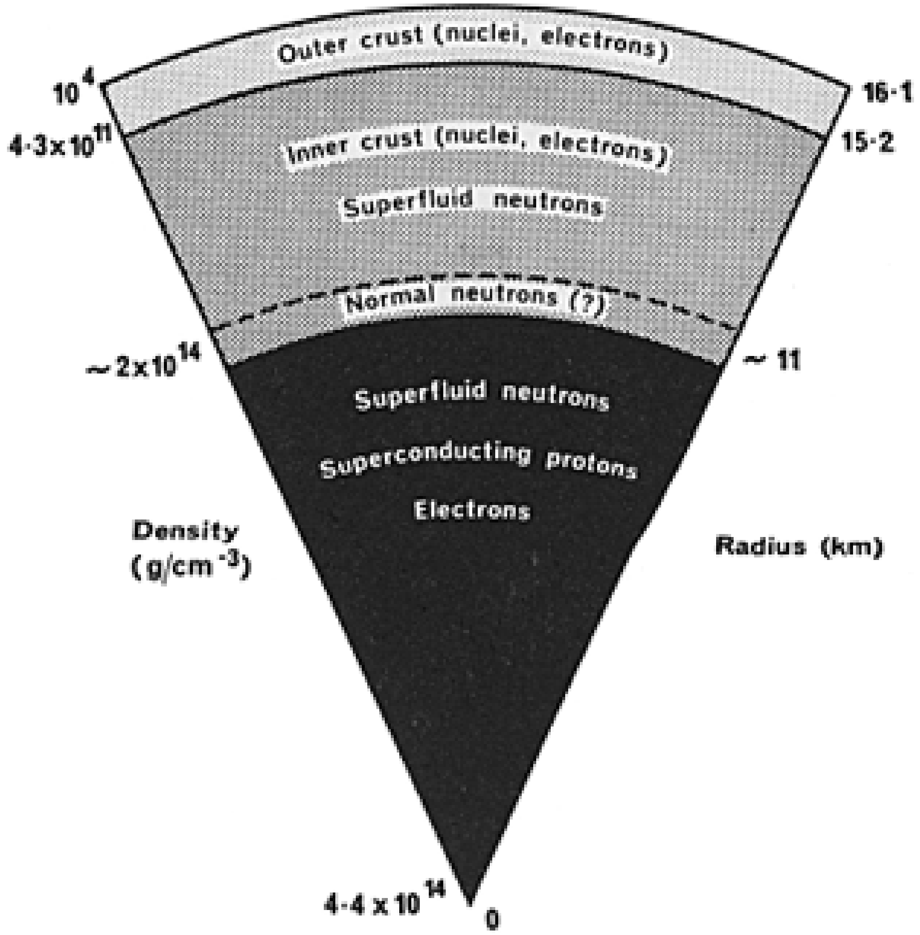
- Collapsed cores of massive stars ~ 8 – 20+ $M_\odot$
- Following supernova, neutron-rich matter coalesces, cools ⇒ neutron star
- Asymmetric explosions ⇒ “kick” of ~ 400 – 500 km/s
- Mass range of ~ 1.4 – 2.1 $M_\odot$
  - $\gtrsim 1.4\ M_\odot$ to overcome electron degeneracy pressure
  - $\lesssim 2 - 3\ M_\odot$ for support by neutron degeneracy pressure
    - otherwise collapse to black hole → next week

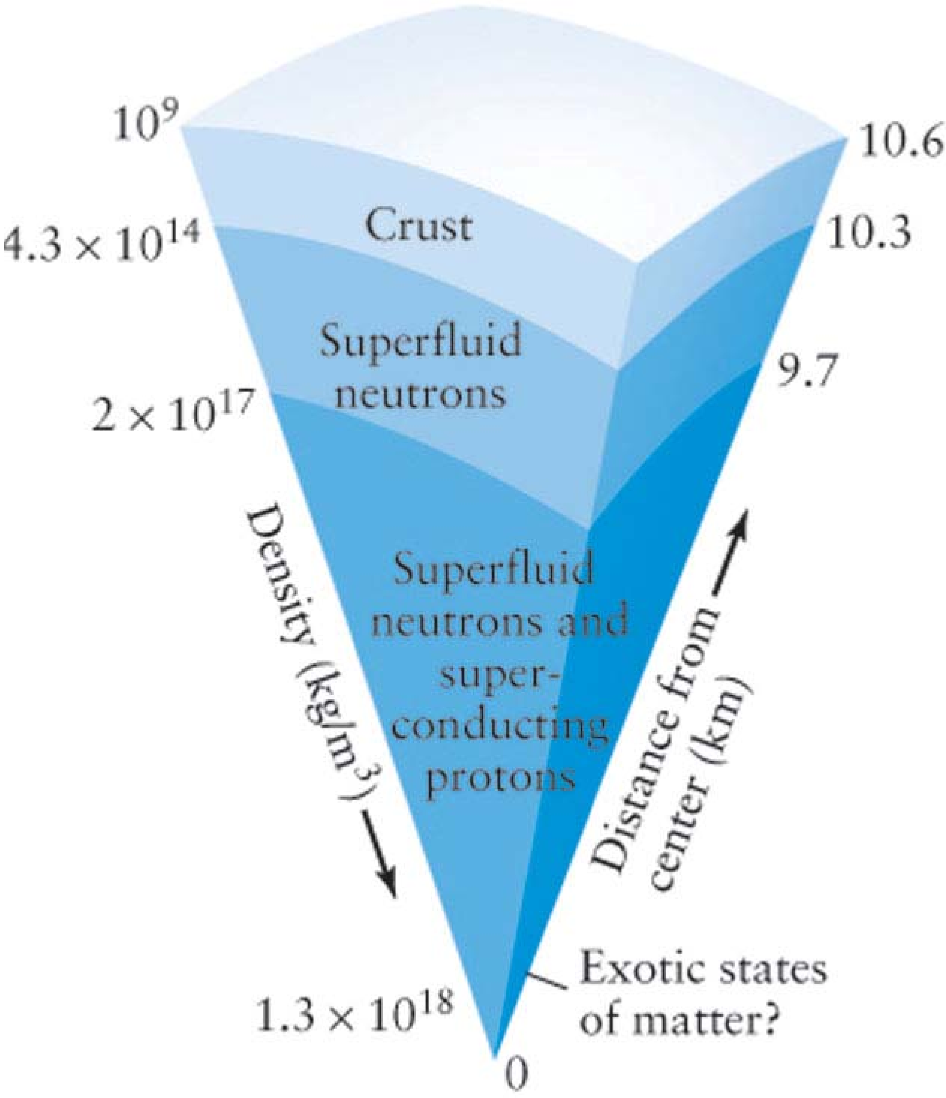
Neutron Star Interiors



- Outer Crust: solid, similar to a white dwarf:
  - heavy nuclei in a Coulomb lattice + degenerate electrons
- Inner Crust: transition region
  - neutron-rich nuclei, relativistic degenerate electrons, degenerate neutrons
- Neutron liquid:
  - superfluid neutrons
  - superconducting protons
  - normal electrons

Neutron Star Interiors





- Wee bit of uncertainty…

Pulsars

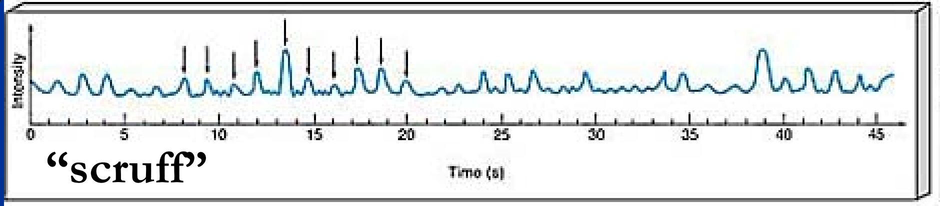
What is a Pulsar?

- A pulsar is a neutron star that emits ***radio*** pulses
- Pulses of radio waves occur regularly
  - Typically a few times per second, but fastest pulse a few hundred times a second (period ~ 1-2 ms)
  - Emission is synchrotron or curvature radiation
- Pulsars spin fast ⇒ must be small
  - Radio pulsars are rapidly rotating ***neutron stars***
  - Centrifugal forces would tear apart larger stars
    - even NS would break up for periods $\lesssim 0.5$ ms

The Discovery of Pulsars

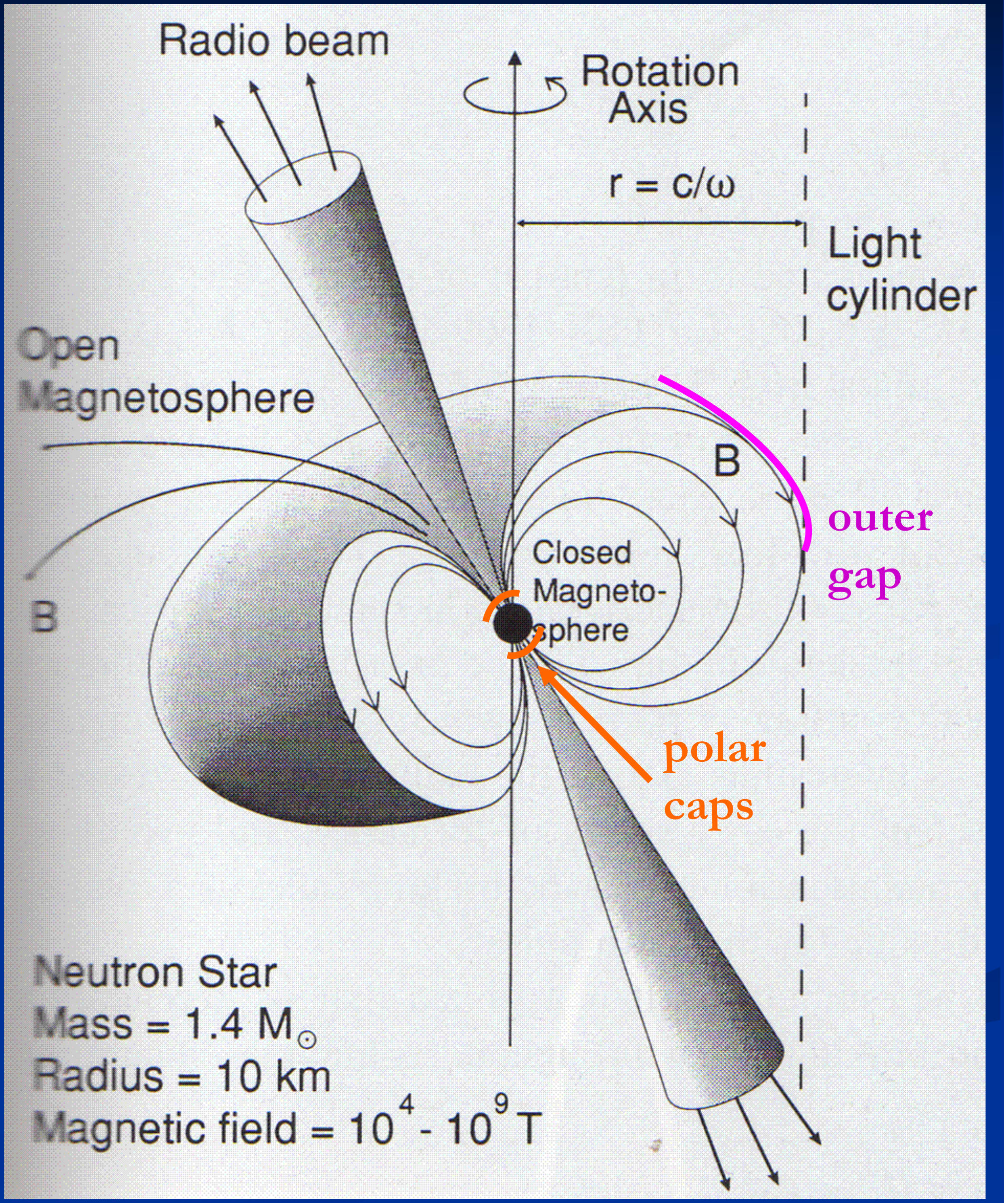
- Pulsars were discovered in 1968 by Antony Hewish and his student Jocelyn Bell
  - using a new radio telescope to search for quasars
  - periodic “scruff” looked different than normal man-made interference or quasar signals
  - first pulsar: Little Green Men?
  - within months found 3 more in different directions ⇒ not aliens
- Hewish won the 1974 Nobel Prize

Jocelyn Bell at the radio telescope where pulsars were discovered (1968)



Pulsars: The Basic Picture

- Intense, dipole magnetic field
- Magnetic poles and rotation axis can have any relative orientation
- Light cylinder
  - radius at which speed of light required to rotate with pulsar
    - separates open and closed magnetic field lines
- Pulsed emission from polar cap (radio) or “outer gap” near light cylinder



Neutron Star
Mass = 1.4 $M_\odot$
Radius = 10 km
Magnetic field = $10^4 - 10^9$ T

So what we see is…

- If the arrangement of the neutron star’s rotation axis and magnetic poles cause the poles to sweep past the earth, we see a pulsar
- Pulsars make excellent clocks
  - spin down slowly: period grows by ~ ns/day
    - radiation powers Pulsar Wind Nebula
  - occasional “glitches”

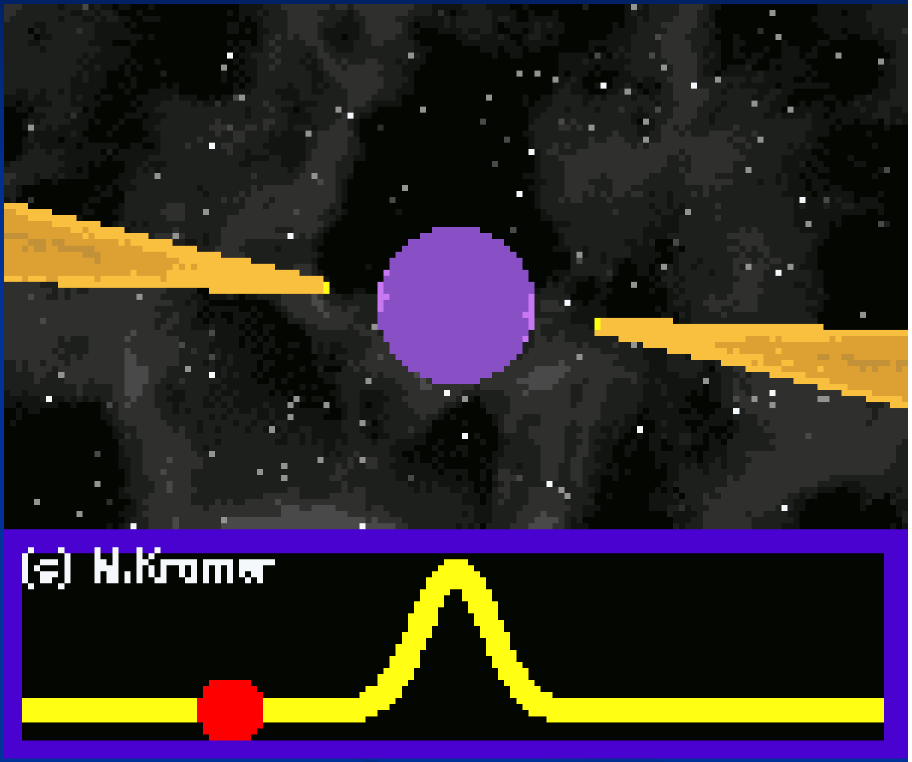
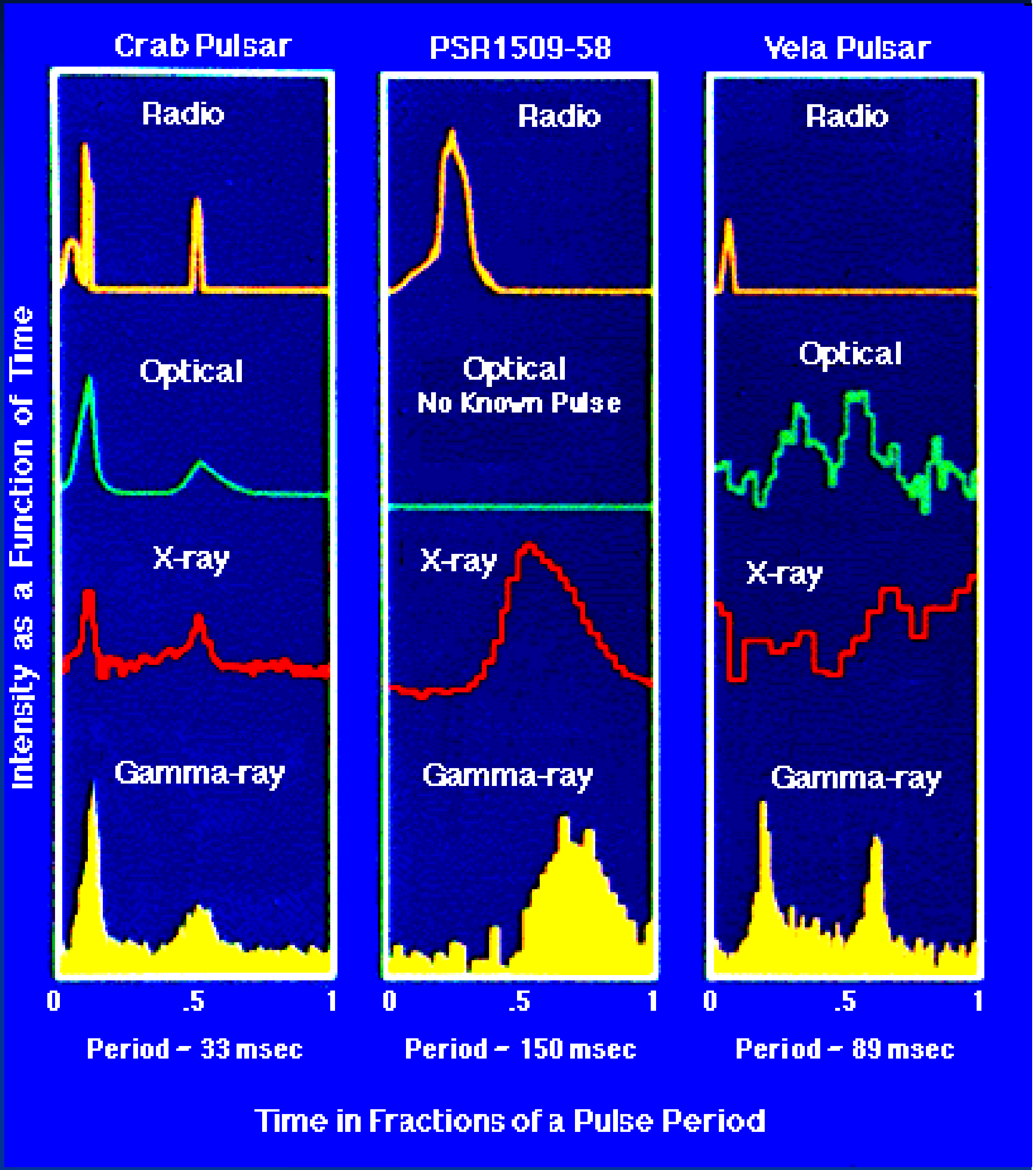


Image Credit: Michael Kramer (University of Manchester)

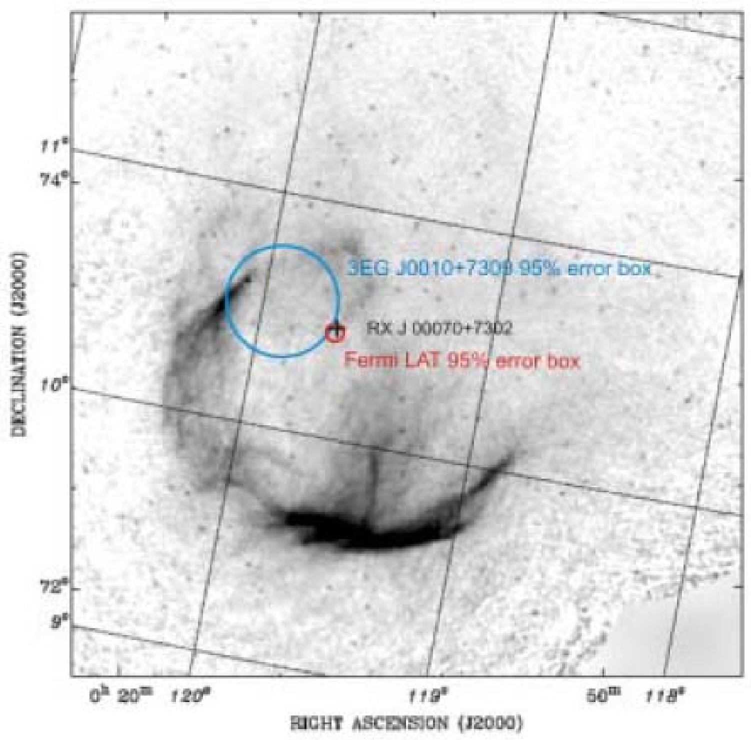
Pulsing Across the Spectrum

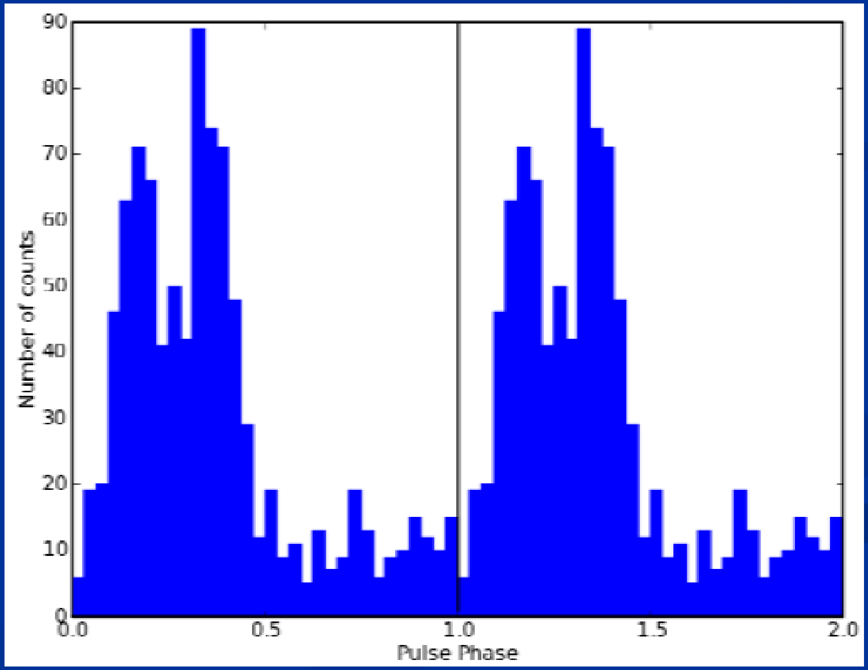
- Optical, X-ray, and gamma-ray pulses have been seen from many pulsars as well
- Great variety in structure of pulses
  - Viewing geometry
  - Size, location of emitting region
- Radio pulses mainly (?) from polar regions
- High-energy pulses…
  - polar cap region?
  - “outer gap” near light cylinder?



More Pulsars!

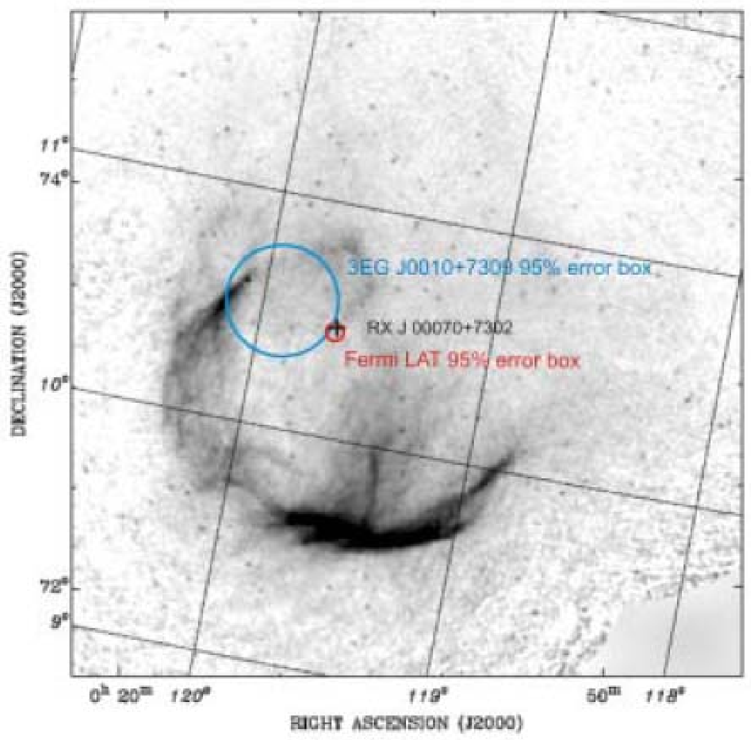
- Over 1700 radio pulsars have been found so far.
  - compared to $\lesssim$ 10 so far in gamma rays: will change rapidly with Fermi!
- Geminga: radio-quiet pulsar discovered in X-rays
- CTA 1: radio-quiet pulsar discovered by Fermi in gamma rays within weeks after launch

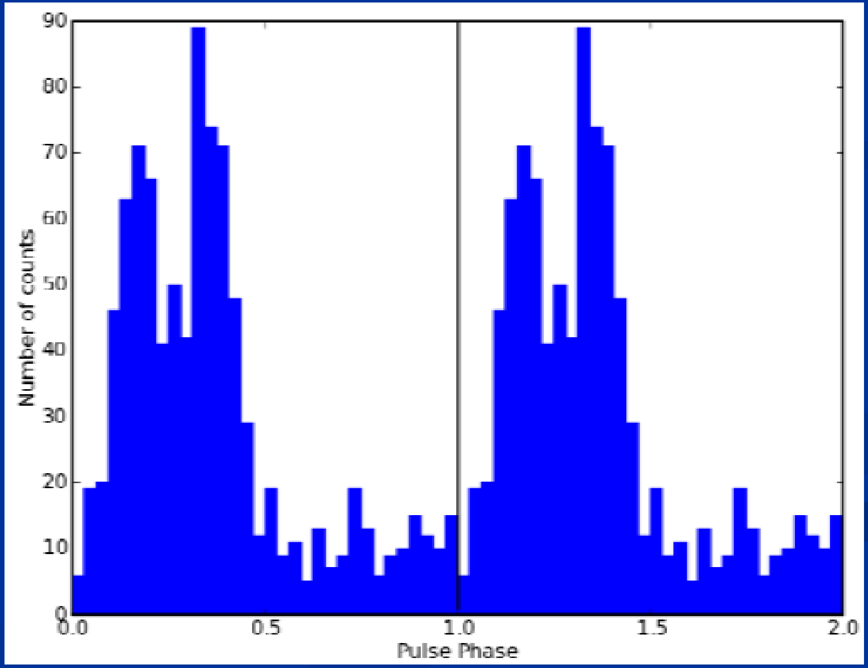




More Pulsars!

- Emission mechanism for high energies:
  - Polar caps: predicts narrow emission beam ⇒ sharper pulse peaks and fewer total pulsars discovered
  - Outer gap: predicts wide emission beam ⇒ wider pulses and more total pulsars discovered
  - CTA 1 appears to favor outer gap-type models
  - How many more will Fermi find?

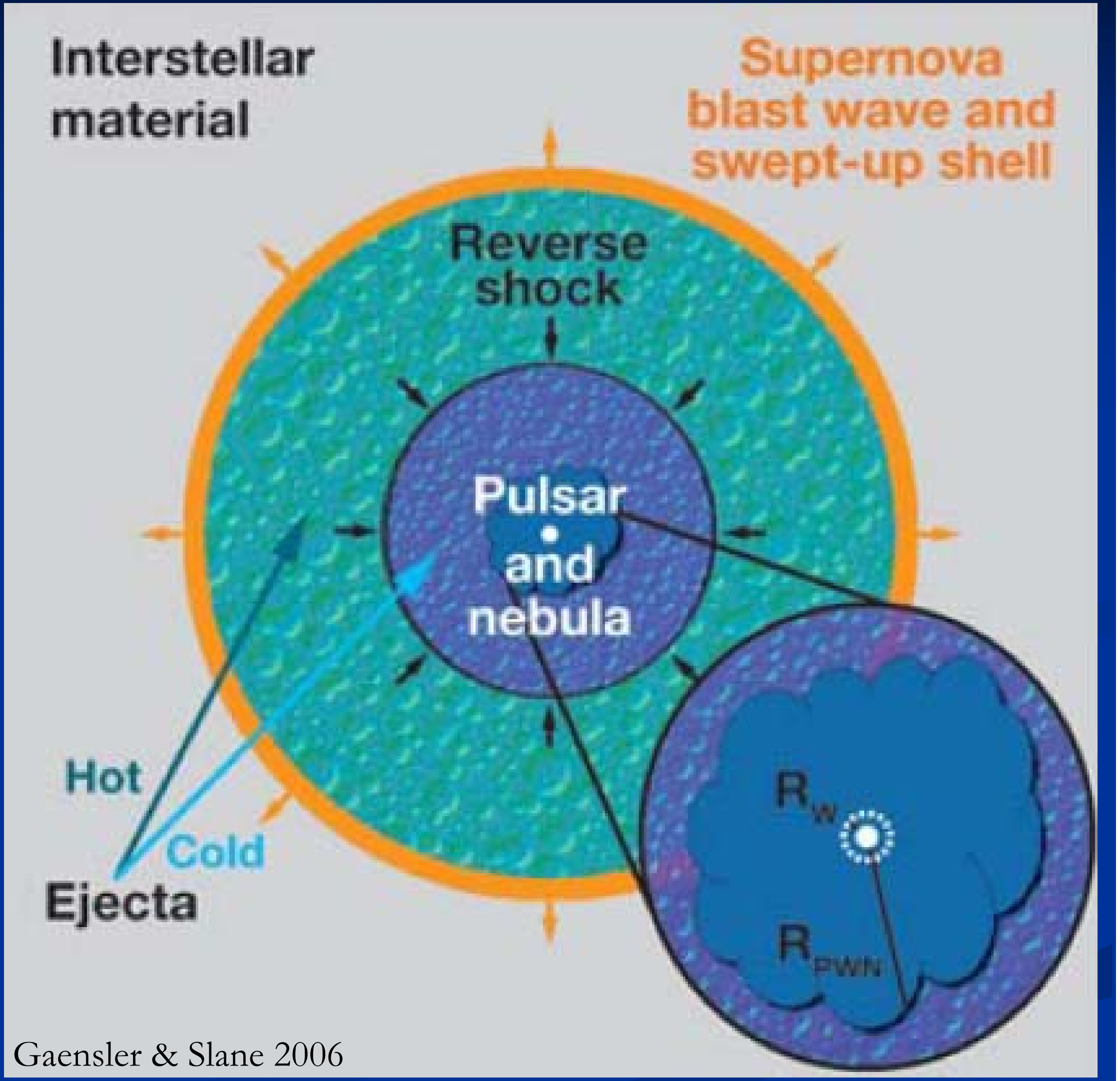




Pulsar Wind Nebulae

What is a Pulsar Wind Nebula?

- A Pulsar Wind Nebula is a cloud of electrons, positrons, and ions flowing away from the pulsar.
- The particles are
  - accelerated by the pulsar
  - and again where the nebula collides with the interstellar medium.
- Emits synchrotron radiation
  - radio → X-ray
  - gamma rays: inverse Compton



Gaensler & Slane 2006

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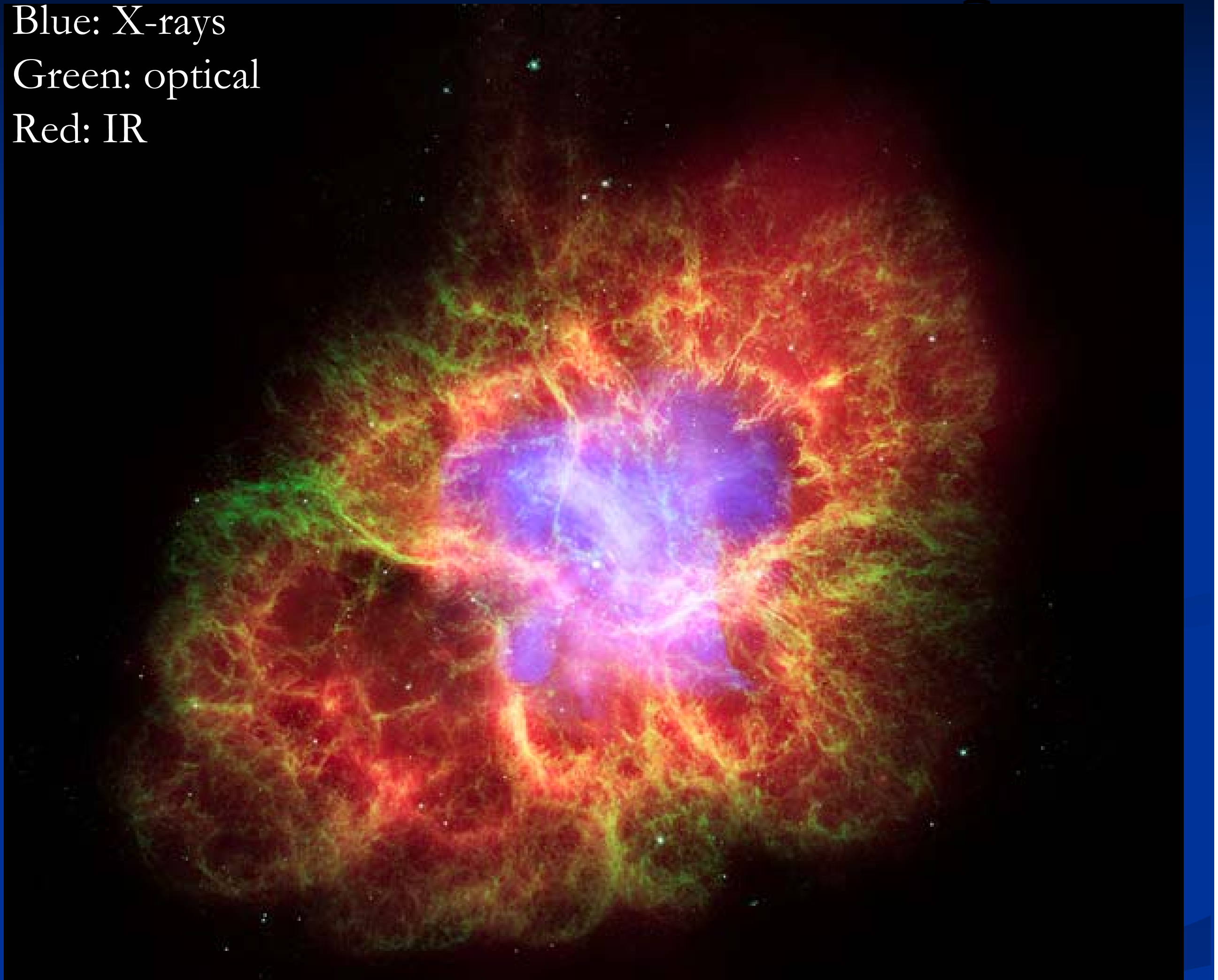
SNR G21.5-0.9 in X-rays (Matheson & Safi-Harb 2005)

The Crab Nebula – Classic Example

- Nebula is the remnant of SN 1054
    - No shell yet detected
- Image 8 arcmin ~ 0.13° across
- X-ray torus is shock front
- Filaments, arcs indicate magnetic fields

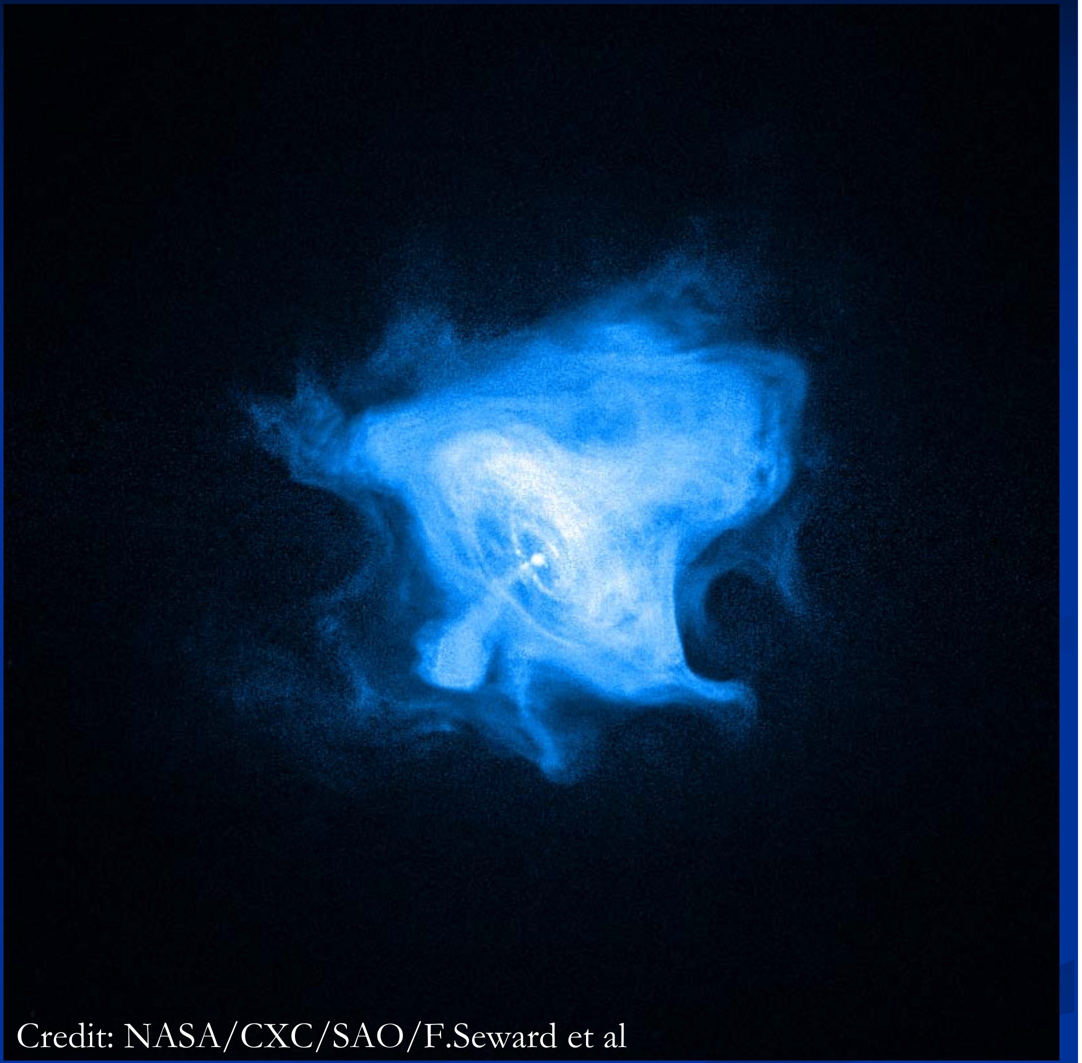


Blue: X-rays
Green: optical
Red: IR

Credit: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/ESA/ASU/J.Hester & A.Loll; Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehrz

The Crab in X-rays

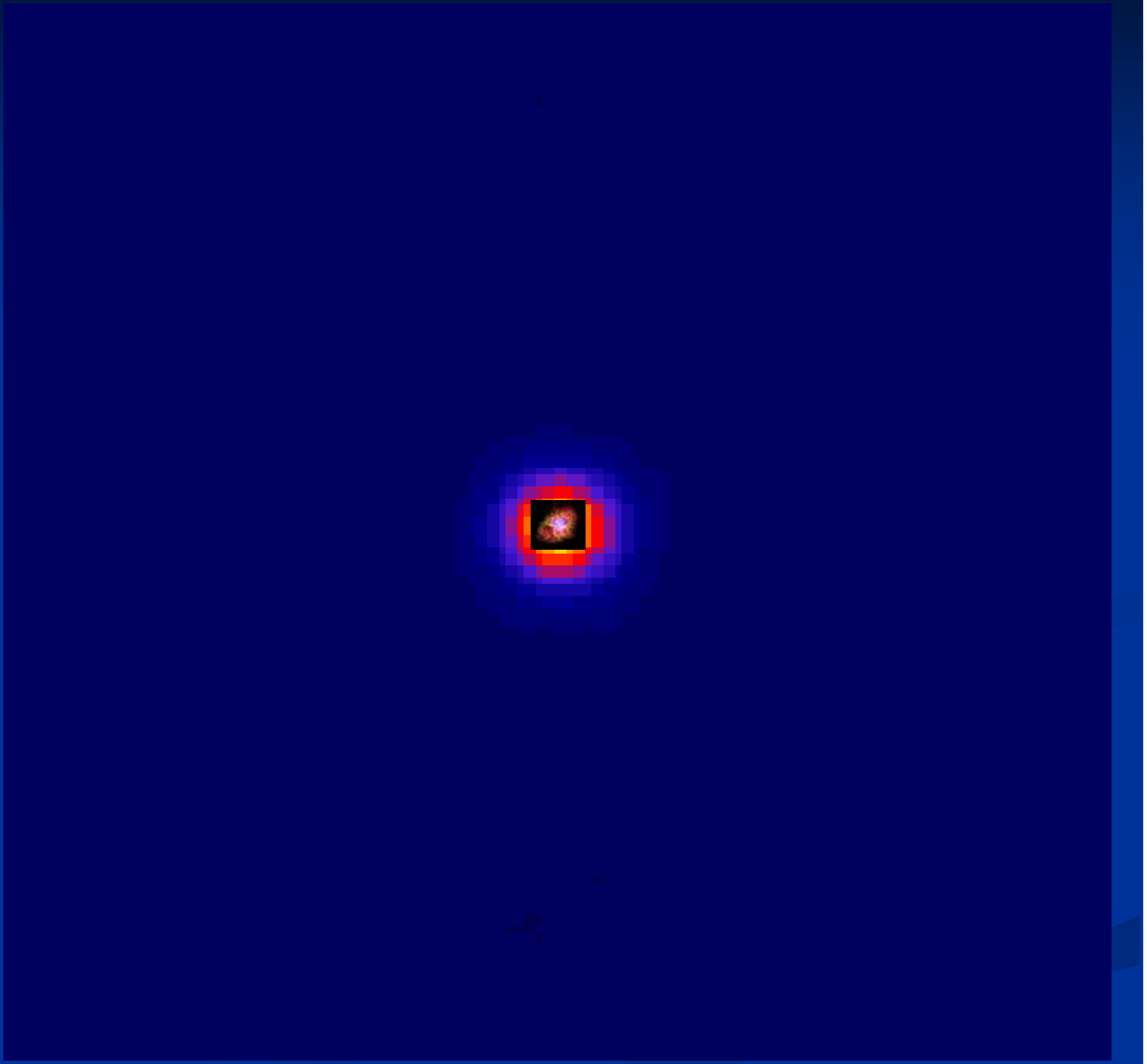
- Image from the Chandra X-ray satellite
- Shows extent of X-ray-emitting nebula
- Synchrotron radiation
- Energetic $e^{\pm}$ travel speedily along magnetic field lines, slowly across them
    - Creates filaments, arcs



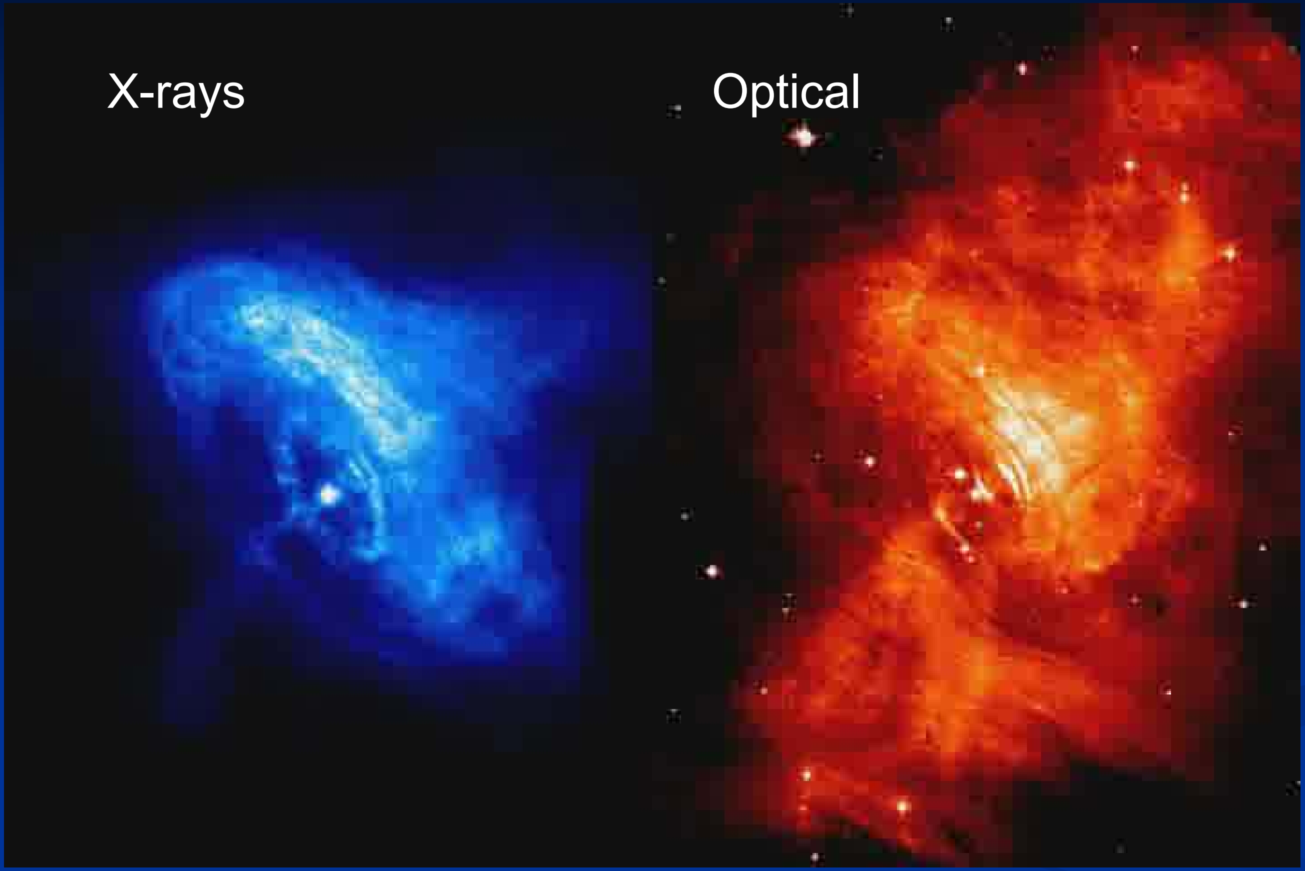
Credit: NASA/CXC/SAO/F.Seward et al

The Crab Nebula in TeV Gamma Rays

- The Crab is the brightest steady TeV gamma-ray source
- Looks like a point source in gamma rays
  - Where do the gamma rays come from?
  - Maximum energy?
- Pulsed gamma rays?
  - Seen by EGRET, Fermi satellites
  - Recently detected by MAGIC from ground



The Crab Nebula: The Movie



- Wisp moves out from inner ring at half speed of light, merges with outer ring
- Images taken November, 2000 – April, 2001

Credit: X-ray: NASA/CXC/ASU/J.Hester et al.;
Optical: NASA/HST/ASU/J.Hester et al.

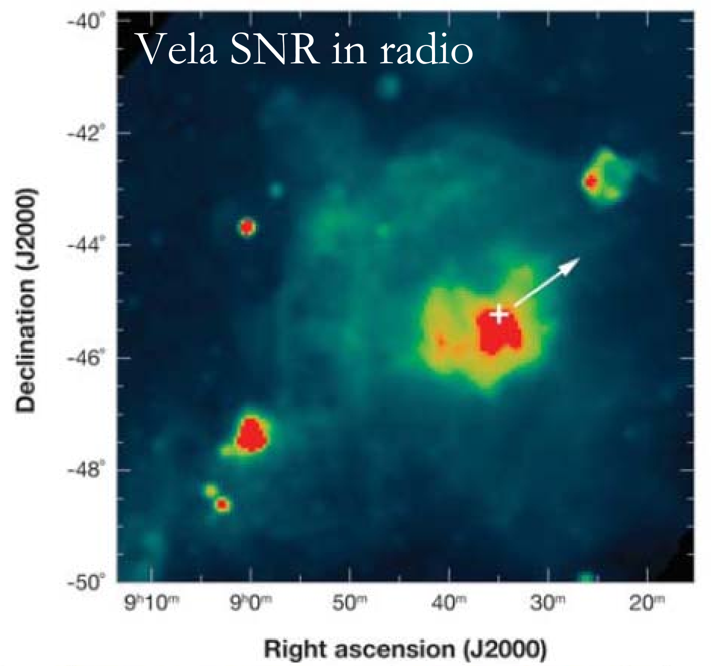
PWN Evolution: Youth

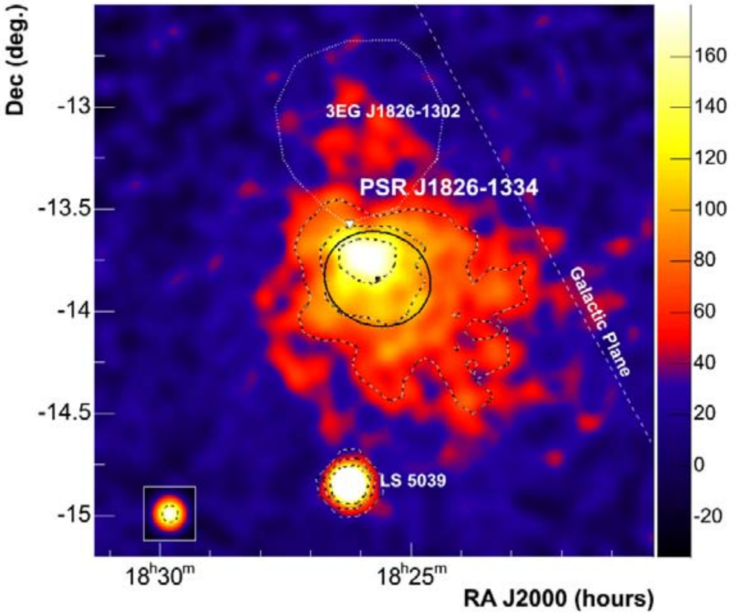
- Wind from pulsar drives shock into SNR interior
- Initially, nebula expands quickly
- Powered by charged particles and magnetic fields from pulsar at center
- SNR G21.5-0.9: a young, composite remnant

SNR G21.5-0.9 in X-rays (Matheson & Safi-Harb 2005)
~ 1000 yrs old

PWN Evolution: Encountering the SNR

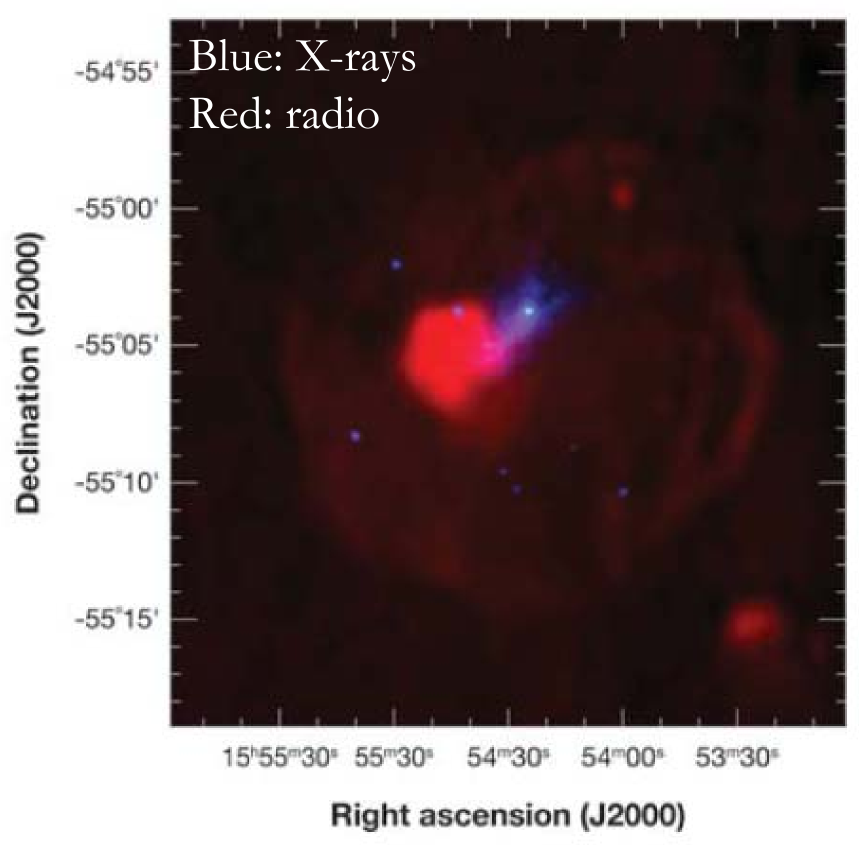
- After SNR enters Sedov phase, the Reverse Shock from the SNR can interact with the PWN
  - reverse shock crushes, distorts PWN
  - PWN bounces back – several oscillations over thousands of years
  - Meanwhile pulsar is migrating from birth place…
  - Vela SNR:
    - distorted pulsar wind nebula
    - pulsar offset from center
    - pulsar direction does not point to center!
  - HESS J1825 – TeV nebula similar to Vela


Vela SNR in radio

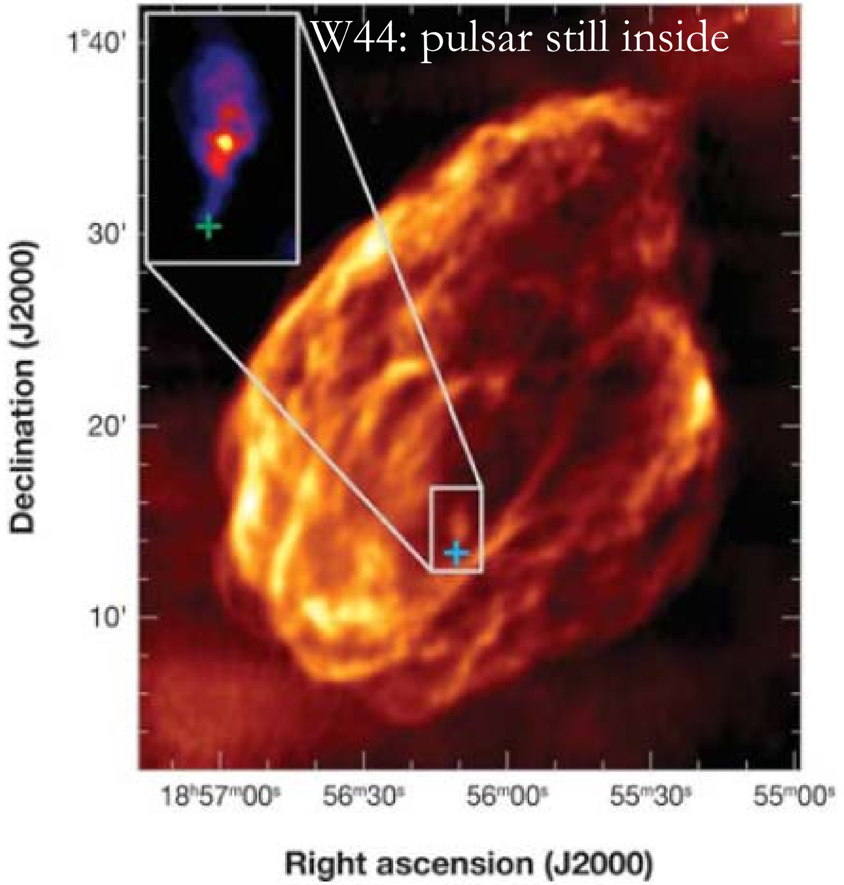


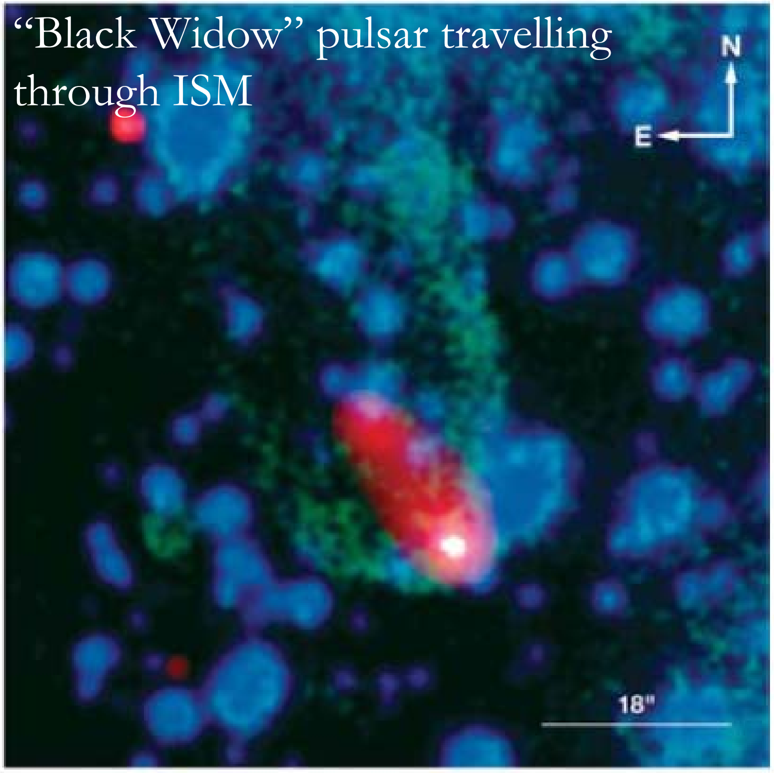
PWN Evolution: Making a run for it

- Pulsar born with a kick will eventually exit the SNR, trailing its nebula behind
- SNR G327.1-1.1
  - large, faint radio shell
  - bright radio "relic" pulsar wind nebula
  - neutron star in X-rays



Old PWN: Leaving the Remnant Behind


W44: pulsar still inside


“Black Widow” pulsar travelling through ISM

- As pulsar approaches / passes shell of remnant, it becomes supersonic – surrounded by a bow shock
- Exits supernova remnant after ~40,000 years
- In ISM, eventually nebula fades from view…

Summary

- Neutron stars form from the collapse of massive stars and are supported against gravity by degenerate-neutron pressure.
- Pulsars are spinning neutron stars with strong magnetic fields.
  - Radio pulses probably originate near the magnetic poles.
  - High-energy pulses (optical, X-ray, gamma ray) can also be seen – origins still unclear.
  - The Fermi gamma-ray observatory will provide a wealth of new information about pulsars.
- Pulsar wind nebulae are clouds of energetic particles that form from the winds coming off of pulsars.
  - Visible from radio through TeV gamma rays in some cases.
  - The Crab Nebula is the classic example – brightest steady TeV gamma-ray source.

- Next week: Black holes and X-ray binaries, followed by luncheon
  - Luncheon sign-up deadline: December 8th.
- **No lecture Nov 29th or Dec 6th!**