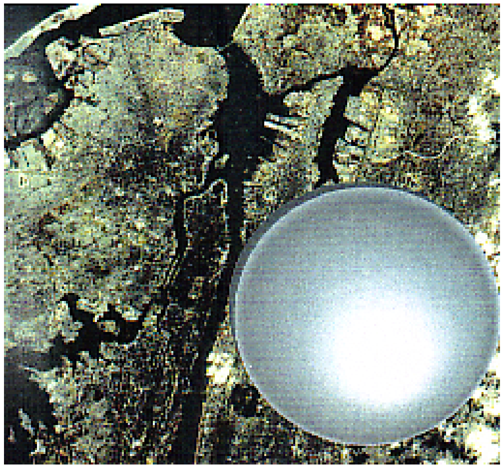
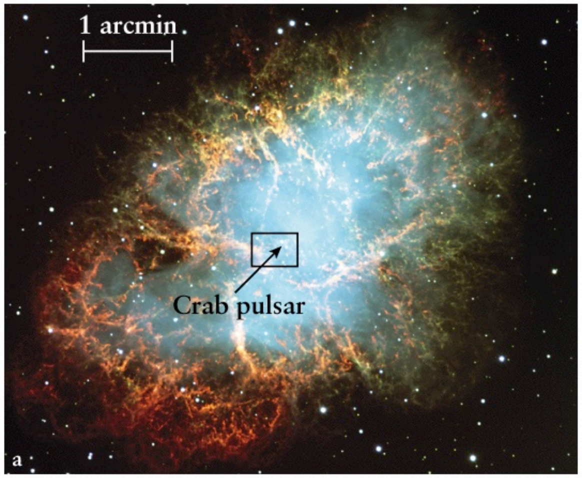




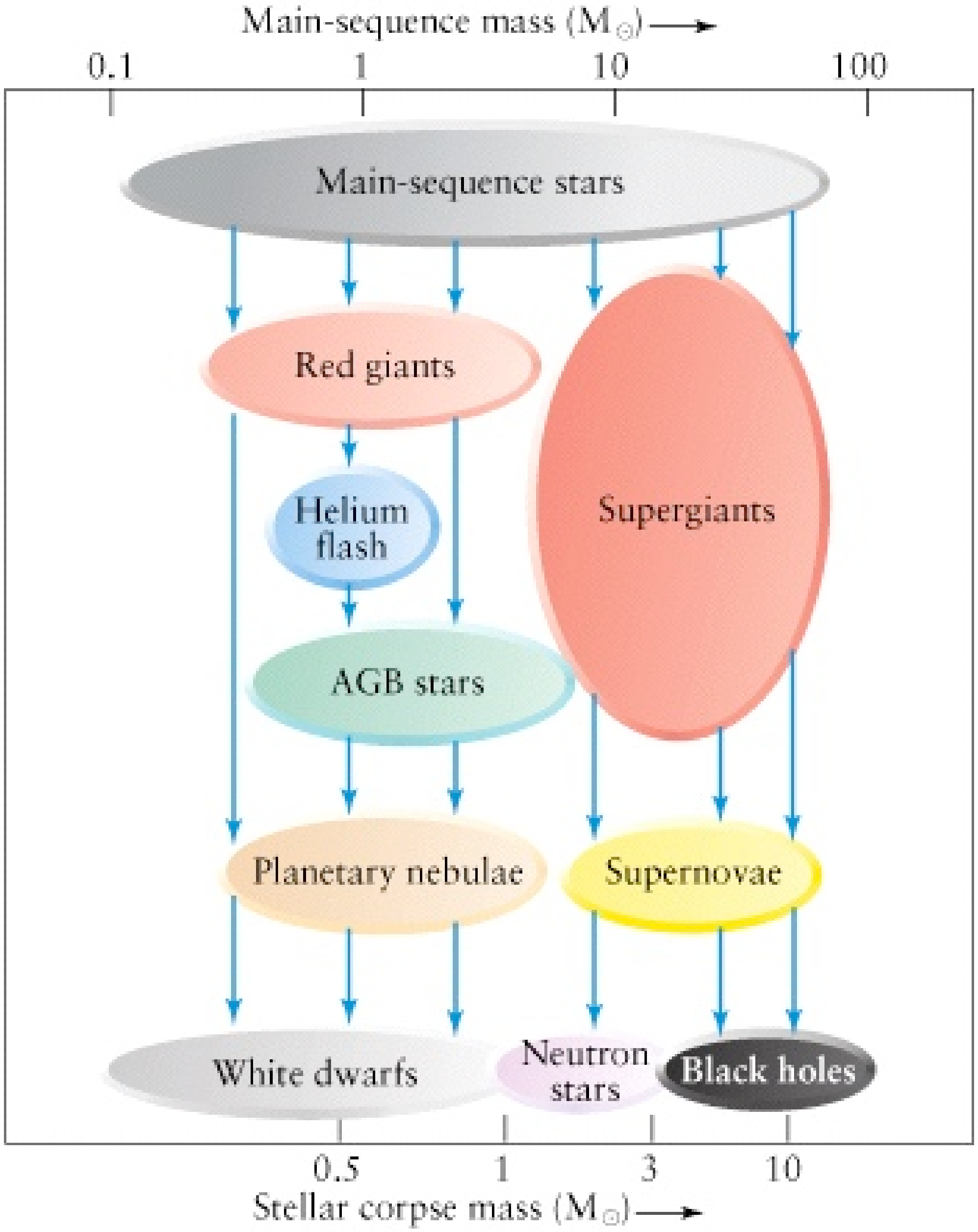
Neutron Stars

Astro. 191, GWU

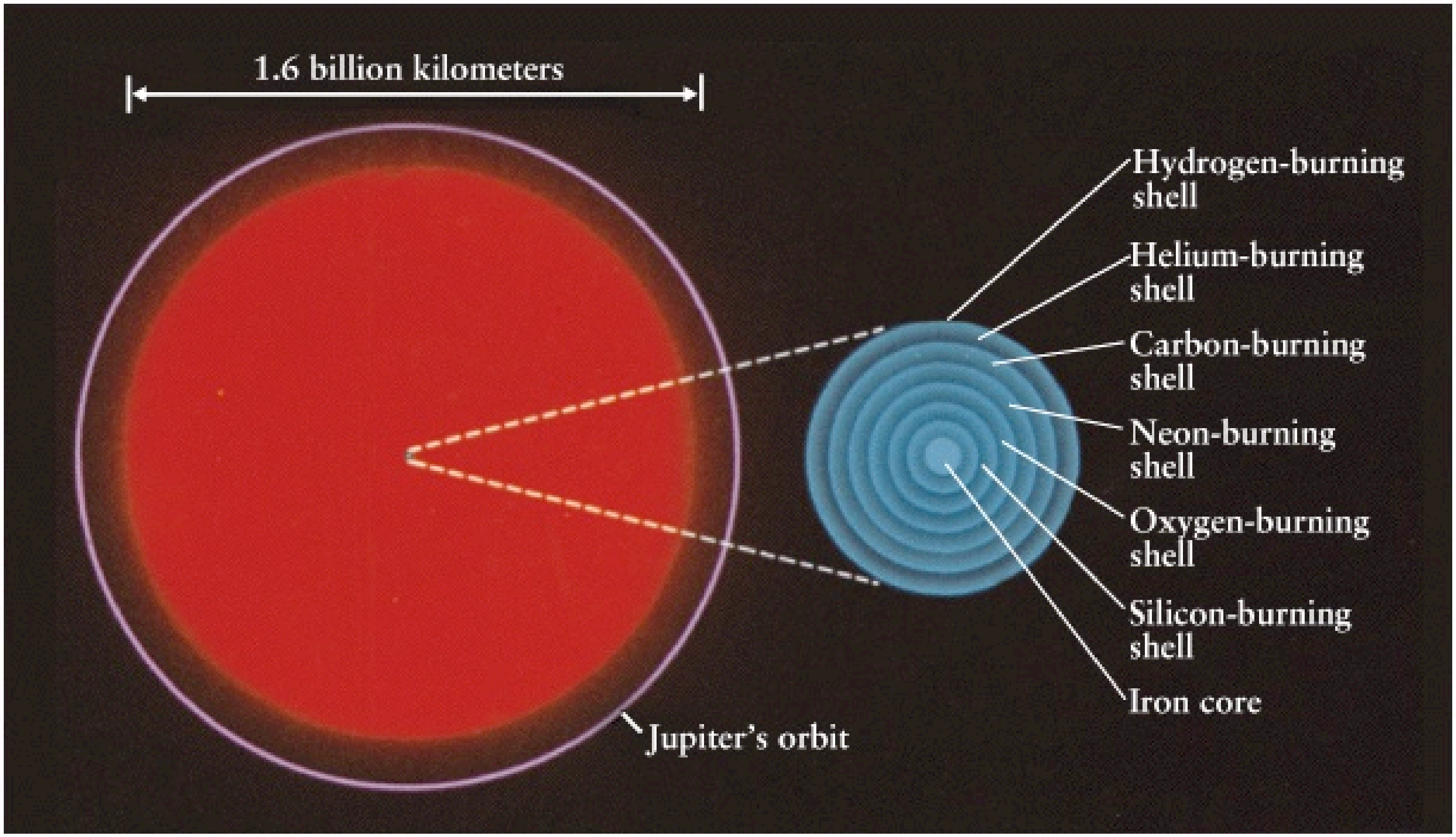
(guest lecture)

Samar Safi-Harb

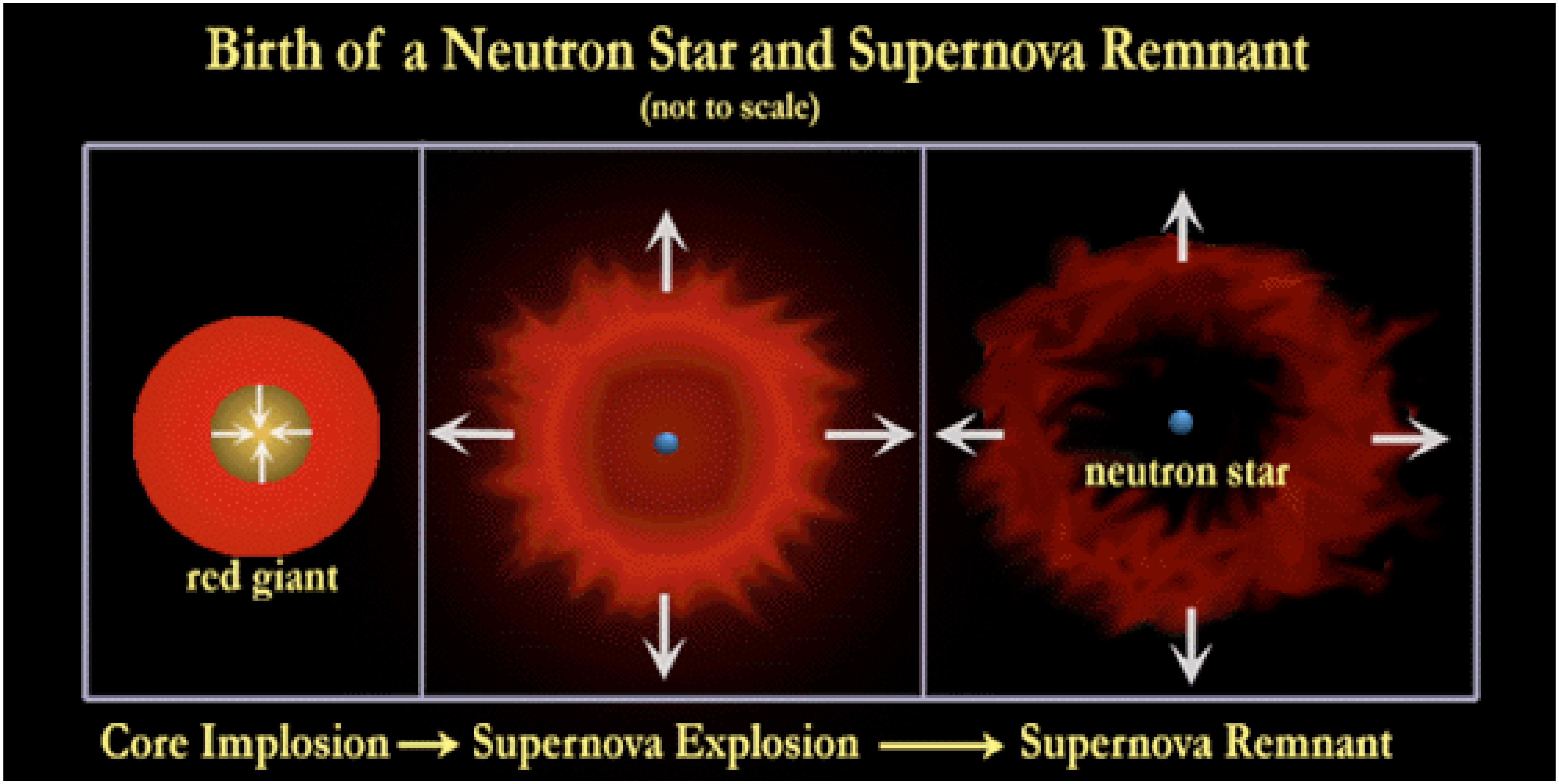
samar@physics.umanitoba.ca


Main-sequence mass ($M_\odot$) →
0.1
1
10
100
Main-sequence stars
Red giants
Helium flash
AGB stars
Supergiants
Planetary nebulae
Supernovae
White dwarfs
Neutron stars
Black holes
0.5
1
3
10
Stellar corpse mass ($M_\odot$) →

The Structure of a Massive Star before its death



Type II (core-collapse) Supernova



History: Baade and Zwicky

Walter Baade

"With all reserve, we advance the view that a *supernova* represents the transition of an ordinary star into a *neutron star* consisting mainly of neutrons…

Baade & Zwicky (1934)

Just 2 yrs after the discovery of the neutron!

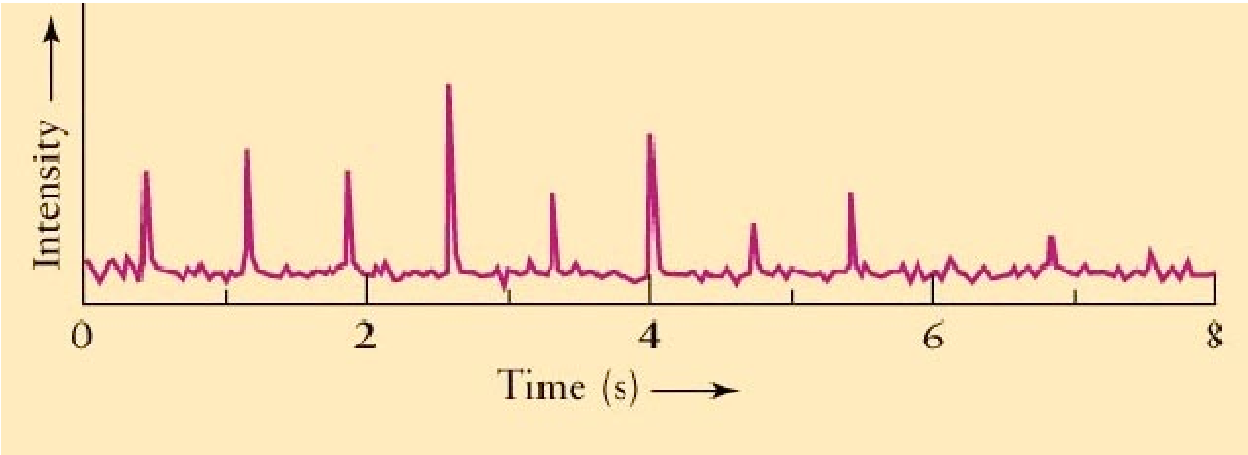

Fritz Zwicky

Jocelyn Bell

- J. Bell: Ph.D. student of Antony Hewish in Cambridge
- Radio telescope to detect quasars
- Periodic Signal: P=1.3373011 s

☺ Little Green Man!

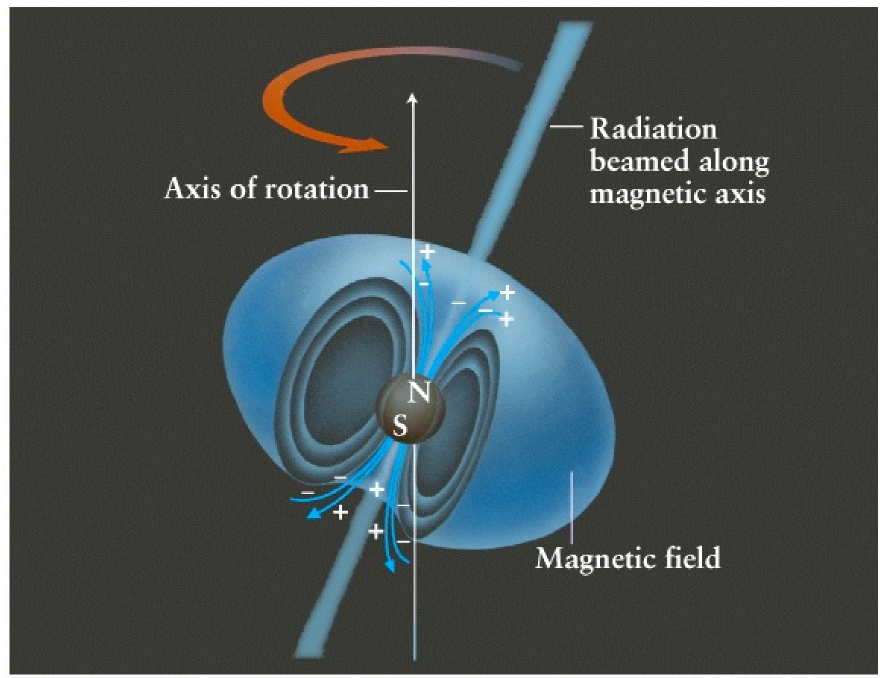
➡ "Pulsating Stars" : A. Hewish: Nobel Prize (1974)



Neutron Stars as Extreme Objects

- M~1.4 solar masses
- R~10 km
- □~5 x 10^{14} g/cc
- B~10^{9} - 10^{15} G
- P~millisec to seconds
- T(surface)>10^{6} K
- X-ray emitters

Lighthouse Model



Estimating B and P

- Conservation of magnetic flux: B . R^2

- Conservation of angular momentum: I . □ or I/P (I is the moment of inertia~2/5 MR^2)

Degenerate Stars

- For an ideal (ordinary) gas, the pressure is proportional to the temperature: $PV = N\,k\,T$

For a degenerate gas, this is NOT the case!

- White Dwarfs and Neutron Stars are degenerate stars supported by electron and neutron *degeneracy pressure*, respectively.
- The heavier the star is, the smaller it is!

Estimating the electron degeneracy pressure

- Heisenberg's uncertainty principle

$$\Delta x \Delta p \geq \hbar$$

- Pauli's exclusion principle:
  - No two fermions can occupy the same quantum state: $\Delta x \sim n_e^{-1/3}$

- Pressure: $P = 1/3 \int n(p) p v dp$

Degenerate Pressure

$$P = \frac{1}{5m}\left(\frac{3h^3}{8\pi}\right)^{2/3} n^{5/3} \qquad (1)$$

$$P = \frac{hc}{4}\left(\frac{3}{8\pi}\right)^{1/3} n^{4/3} \qquad (2)$$

For a non-relativistic and a fully relativistic particle, respectively --> P is a function of the density.

Radius of a degenerate star

$$R_{wd} \sim \frac{(18\pi)^{2/3}}{10} \frac{\hbar^2}{G m_e M_{wd}^{1/3}} \left[\frac{Z}{A} \frac{1}{m_H}\right]^{5/3}$$

$$R_{ns} \sim \frac{(18\pi)^{2/3}}{10} \frac{\hbar^2}{G M_{ns}^{1/3}} \left(\frac{1}{m_H}\right)^{8/3}$$

Z and A are the number of protons and nucleons, respectively.
Note as M increases, the radius decreases.

Magnetic Field

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right) = I \cdot \Omega \cdot \dot{\Omega}$$

$$= \frac{2}{3c^3}|m|^2 \Omega^4 \sin^2 \alpha$$

$\Omega = 2\pi f = 2\pi/P$

$-d\Omega/dt = 2\pi (dP/dt) P^2$

$I = 0.4\ M\ R^2$

$$B = \sqrt{\frac{3c^3}{8\pi^2} \frac{I}{R^6 \sin^2 \alpha} P \dot{P}} = 3.2 \cdot 10^{19} \sqrt{P \dot{P}} \text{ Gauss}$$

□ = < (rotation, magnetic axes), assume 90 degrees.

Braking Index (n)

$$\dot{\Omega} = -k\ \Omega^{n}$$

$$\tau = \frac{P}{2\dot{P}}\left[1 - (P_0/P)^{n-1}\right]$$

τ is the spin-down age of the pulsar,

P_0 is the period at birth (t=0)

P is the *current* period

For a magnetic dipole: n=3

$$\dot{\Omega} = -\frac{2m^2 sin^2(\alpha)}{3Ic^3}\Omega^3$$

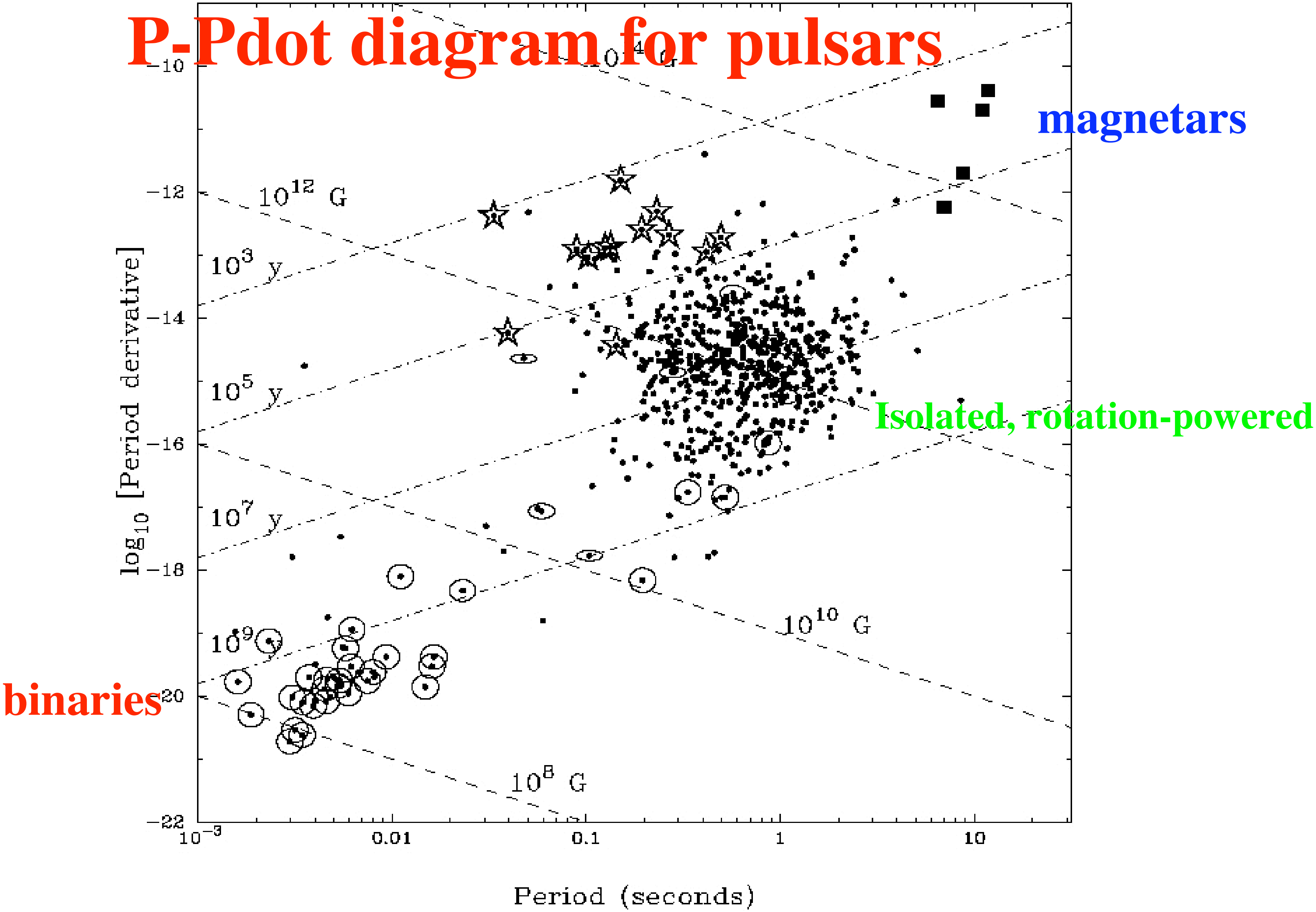
$$\tau = \frac{P}{2\dot{P}}[1 - (P_0/P)^2]$$

For P >> $P_{0,}$

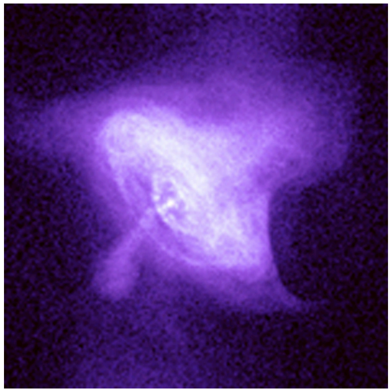
$$\tau = \frac{P}{2\dot{P}}$$

Spin-down age~period/(2*period derivative)

P-Pdot diagram for pulsars



Rotation-Powered Pulsars



Crab Pulsar and its nebula

- P = 33.3 ms
- dP/dt = 4.21 10^{-13} s/s

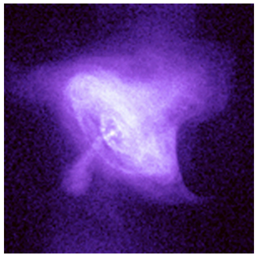
Rotation-powered isolated pulsar

- dE/dt = -5 10^{38} erg/s ~

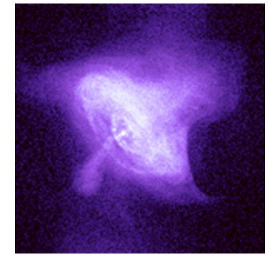
Power required to power the nebula

- Spin-down age = P/2Pdot = 1.3 kyr
- SN 1054 AD 950 years
- "young" SNR
- B ~ 4 . 10^{12} G

-->typical for Crab-like (rotation-powered pulsars)

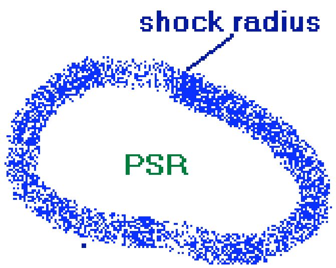


Plerions=Pulsar Wind nebulae



Plerion= □□□□□□ = ‘full’: Synchrotron nebula powered by the spin-down energy of the pulsar

$$\frac{\dot{E}}{\Omega r_s^2 c} = P_c$$



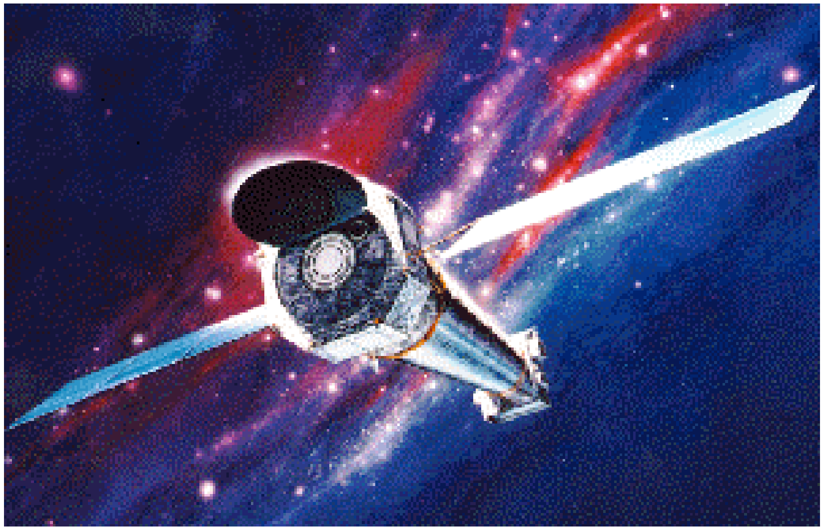
- $\dot{E}$ → spin down energy of the pulsar
- Ω → solid angle
- r_s → shock radius
- c → speed of light
- P_c → confining pressure:
  - a) Ram Pressure: □v^2 <u>bow shock nebula</u>
  - b) Ambient (SNR) material

CHANDRA X-ray observatory

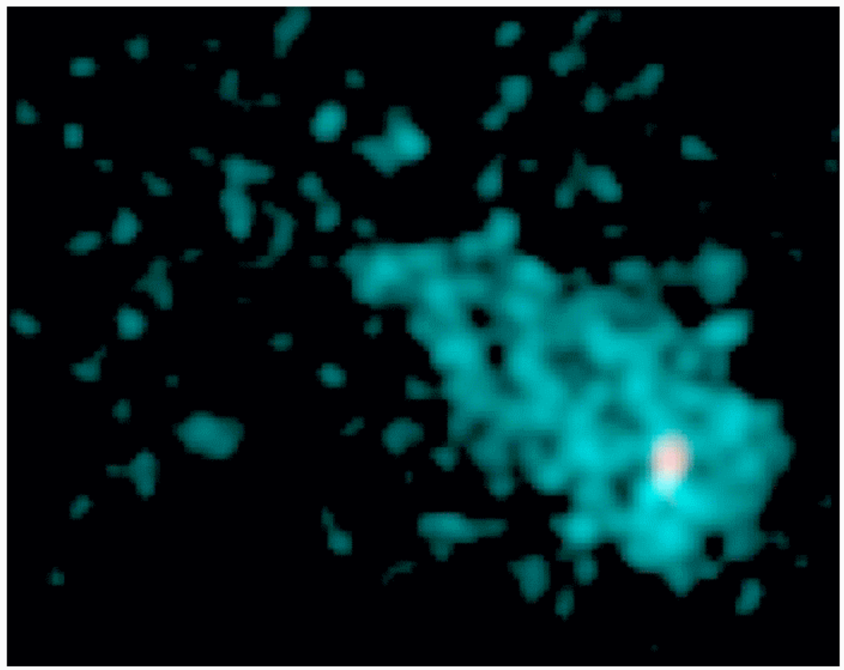
- NASA mission launched in July 1999

- 0.5-10 keV
- 0.5” angular resolution

- HST for X-ray astronomers!!



A bow-shock nebula in IC443 discovered by high-school kids!

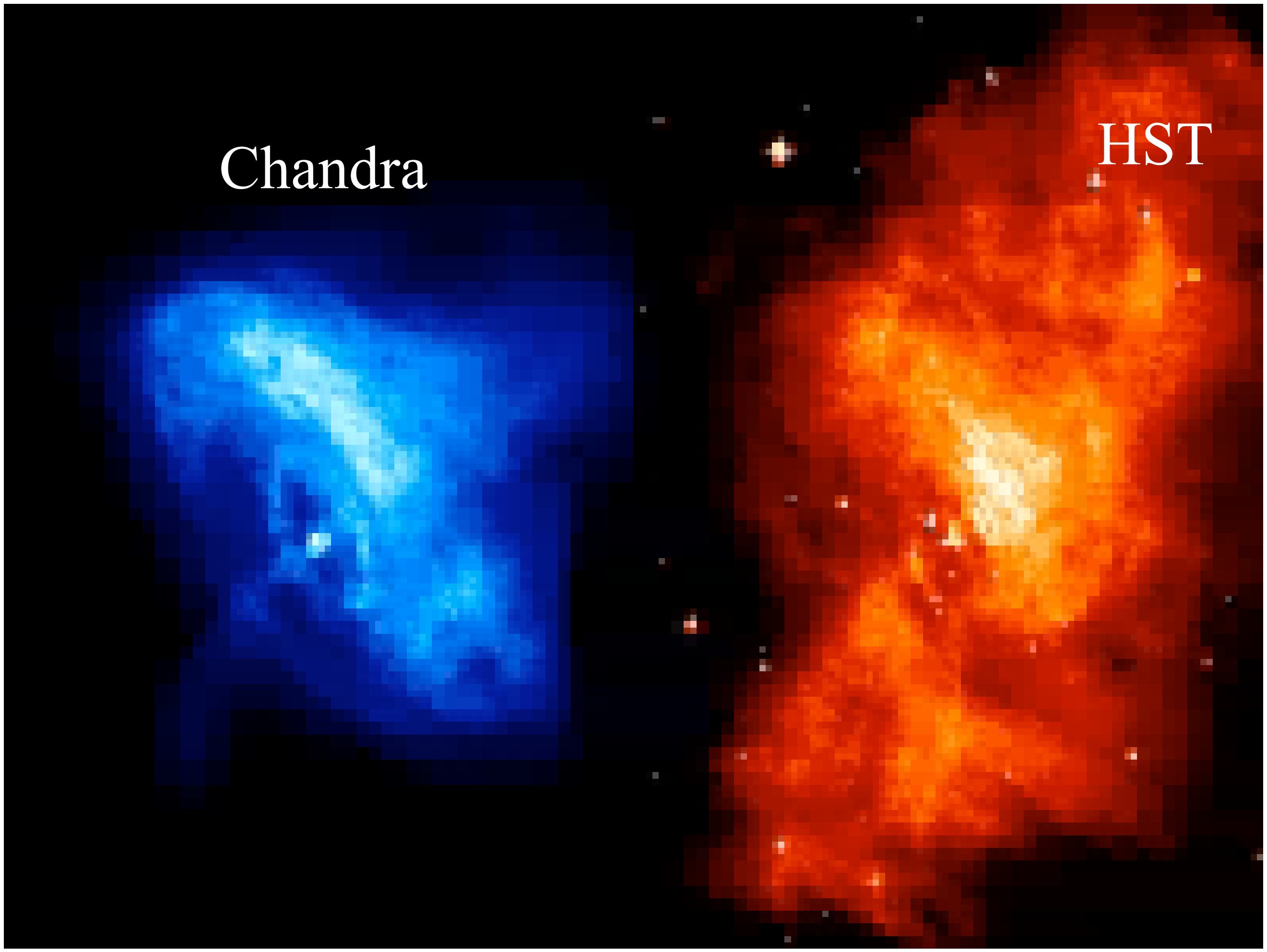


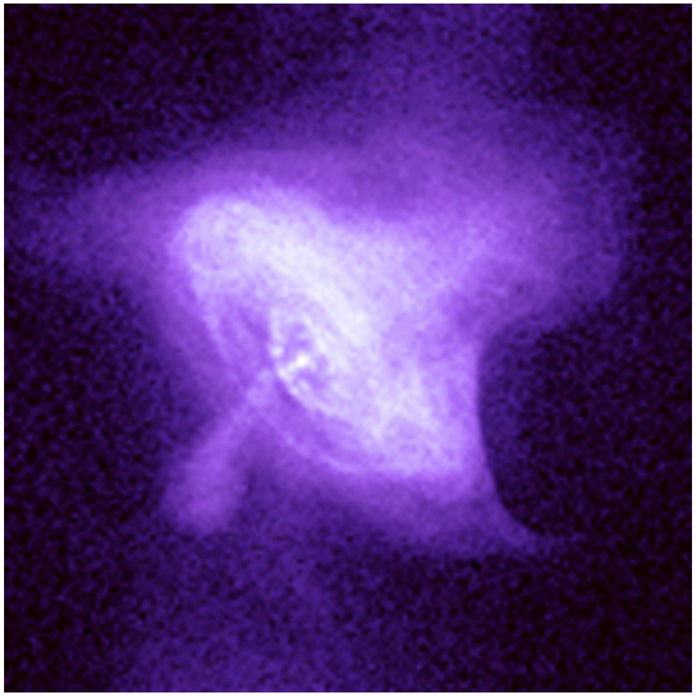
Credit: NASA/NCSSM/C. Olbert et al.

High School Confidential: Stellar Corpse Found

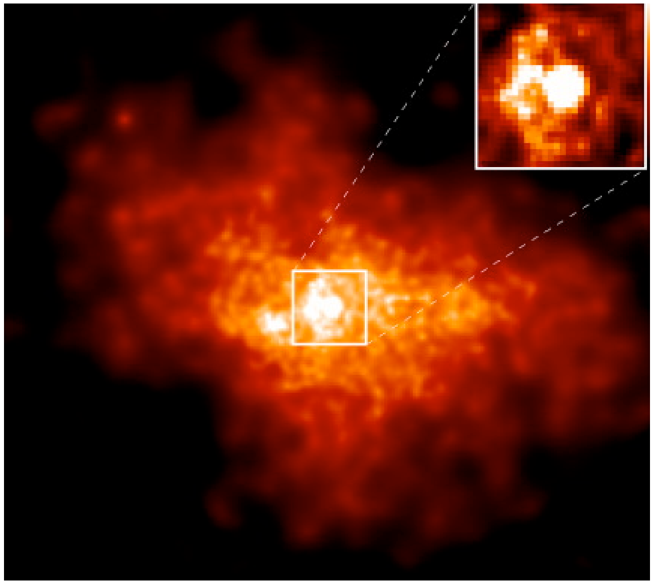
Olbert, Clearfield, Williams, and Keohane 2001

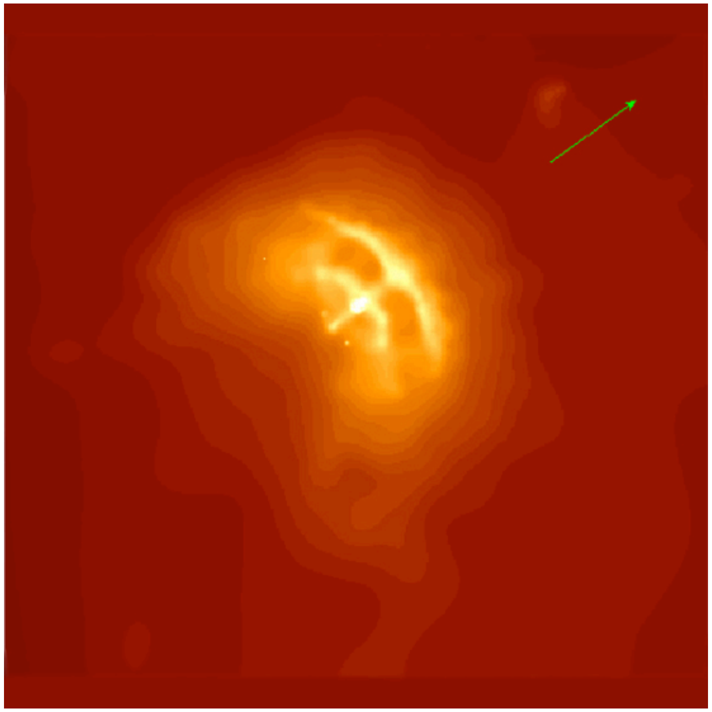
The Dynamic Crab



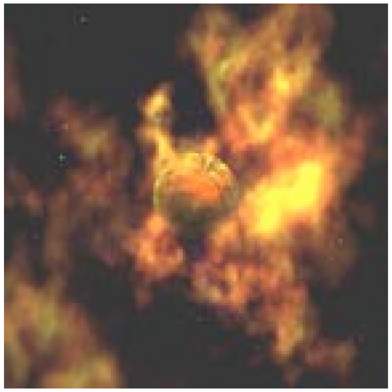


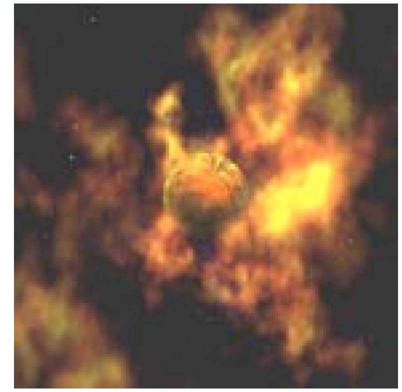
Crabs with Chandra





SSH





Magnetars

Anomalous X-ray Pulsars (AXPs)

Soft Gamma-ray Repeaters (SGRs)

Central Compact Objects (CCOs)??

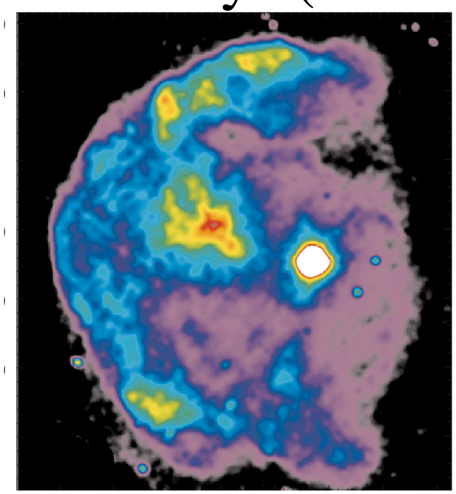
The Anomalous X-ray pulsars (AXPs)

"Anomalous" : source of energy was not understood

- –Unlike the Crab, they can not be powered by rotation!
- –They can not be powered by accretion from a companion star.
- –Period ~ 5-12 seconds (slow..)

➢ **Magnetars? (B~$10^{14\text{-}15}$ G)**

X-rays (XMM)



A 7sec pulsar (1E2259+586) in a supernova remnant (CTB 109)

AXP	P(s)	Pdot (10^{-12})	Age (kyr)	**B (10^{14} G)**	SNR
4U 0142+615	8.7	2	609	**1.3**	--
1E 1048-5937	6.4	33	3.0	**4.7**	--
RX 1708-4009	11.0	19	9.2	**4.6**	--
1E 1841-045	11.8	41	4.6	**7.0**	kes73
AX 1845-0258	6.97	--	--	**--**	G29.6+0.1
1E 2259+586	**6.98**	**0.48**	**210**	**0.6**	**CTB109**
CXOU0110043.1-721134	8.0	?	?	**?**	--
XTE 1810-197*	5.5	11?	7.6?	**2.5?**	--

***XTE1810 is a newly discovered "transient" AXP!**

To put such high B into prespective…

Earth's B	North Pole	0.6 Gauss
Iron magnet	On refrigerator	100 Gauss
Strong sunspots	Within dark, magnetized areas on the solar surface	5000 Gauss
The strongest (steady) B so far achieved in the lab	Generated by hulking huge electromagnets	4.5×10^5 Gauss
The strongest man-made field ever achieved (briefly)	Made using explosive charges; last 4-8 microsec.	10^7 Gauss
The strongest fields on non neutron stars	Strongly magnetized white dwarfs	10^8 Gauss
Typical B of a neutron star	e.g. Crab pulsar	10^{12}-10^{13} Gauss
Magnetars	Soft Gamma-Ray Repeaters and Anomalous X-ray Pulsars	**10^{14}-10^{15} Gauss**

The Soft Gamma-Ray Repeaters

- US department of defense:

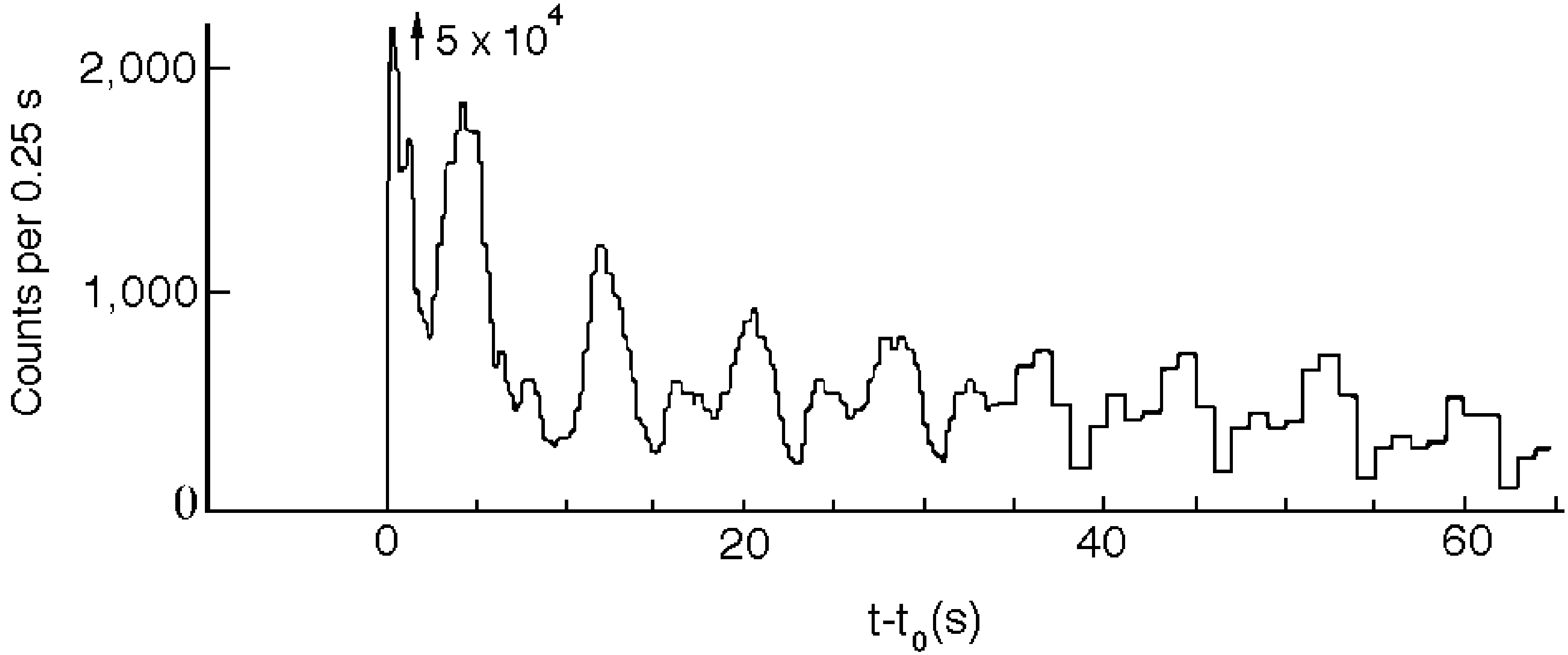
--> Vela satellites to look for *nuclear* weapons

- To everyone's surprise: bursts of gamma-rays
- 1974: Gamma-ray bursts (GRBs)
- 1979: Soft Gamma-Ray Repeaters (SGRs)

➢ low energy (soft) gamma-rays, high-energy (hard) x-rays

➢ The bursting activity repeats from the same location.

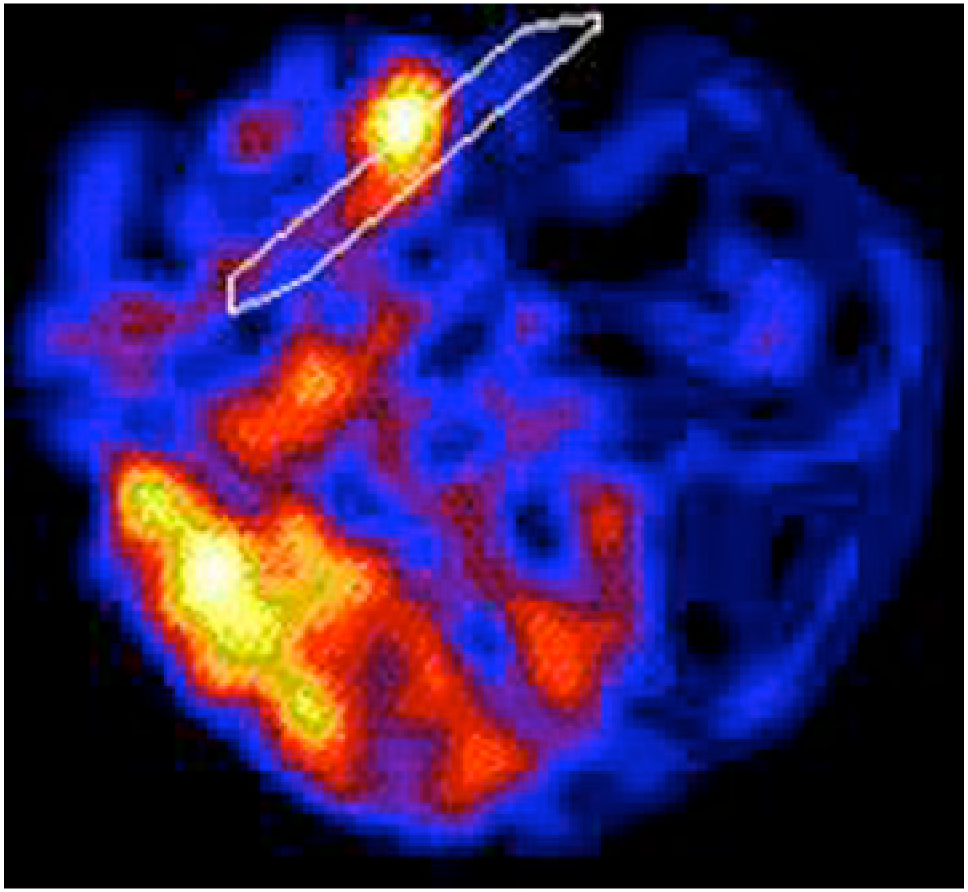
The 'famous' March 5th (1979) event!



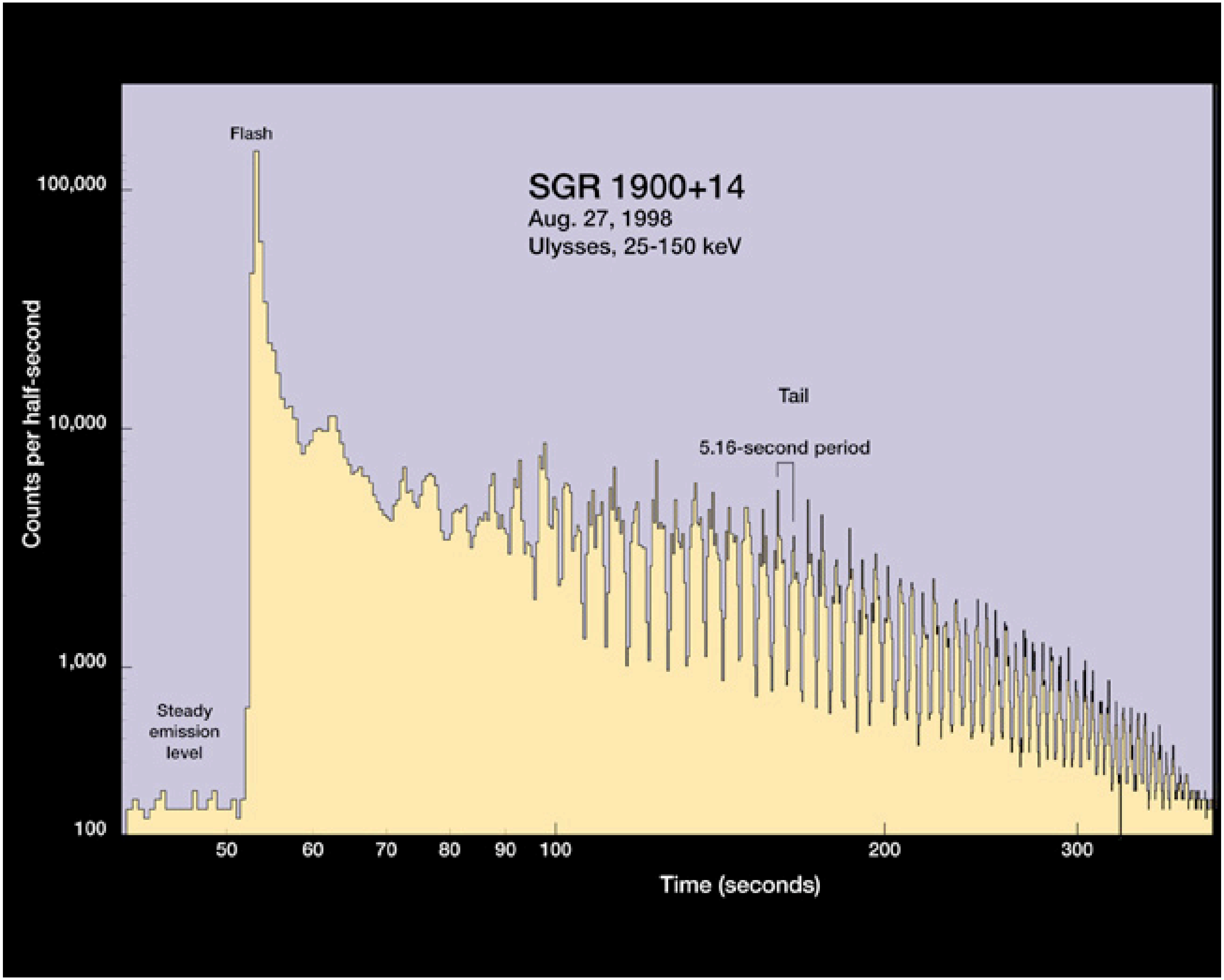
SGR 0526-66, LMC, P=8 SEC

During 0.2 sec, the energy released is as much as the Sun releases in 10,000 years

The burst was located in a supernova (N49) in LMC



N49 in X-rays



Flash
SGR 1900+14
Aug. 27, 1998
Ulysses, 25-150 keV
Tail
5.16-second period
Steady
emission
level
100,000
10,000
1,000
100
Counts per half-second
50
60
70
80
90
100
200
300
Time (seconds)

Measuring the magnetic field?

- Period, time-derivative of the period
  $B \sim \sqrt{P\, dP/dt}$: indirect measurement (assumes dipole braking)

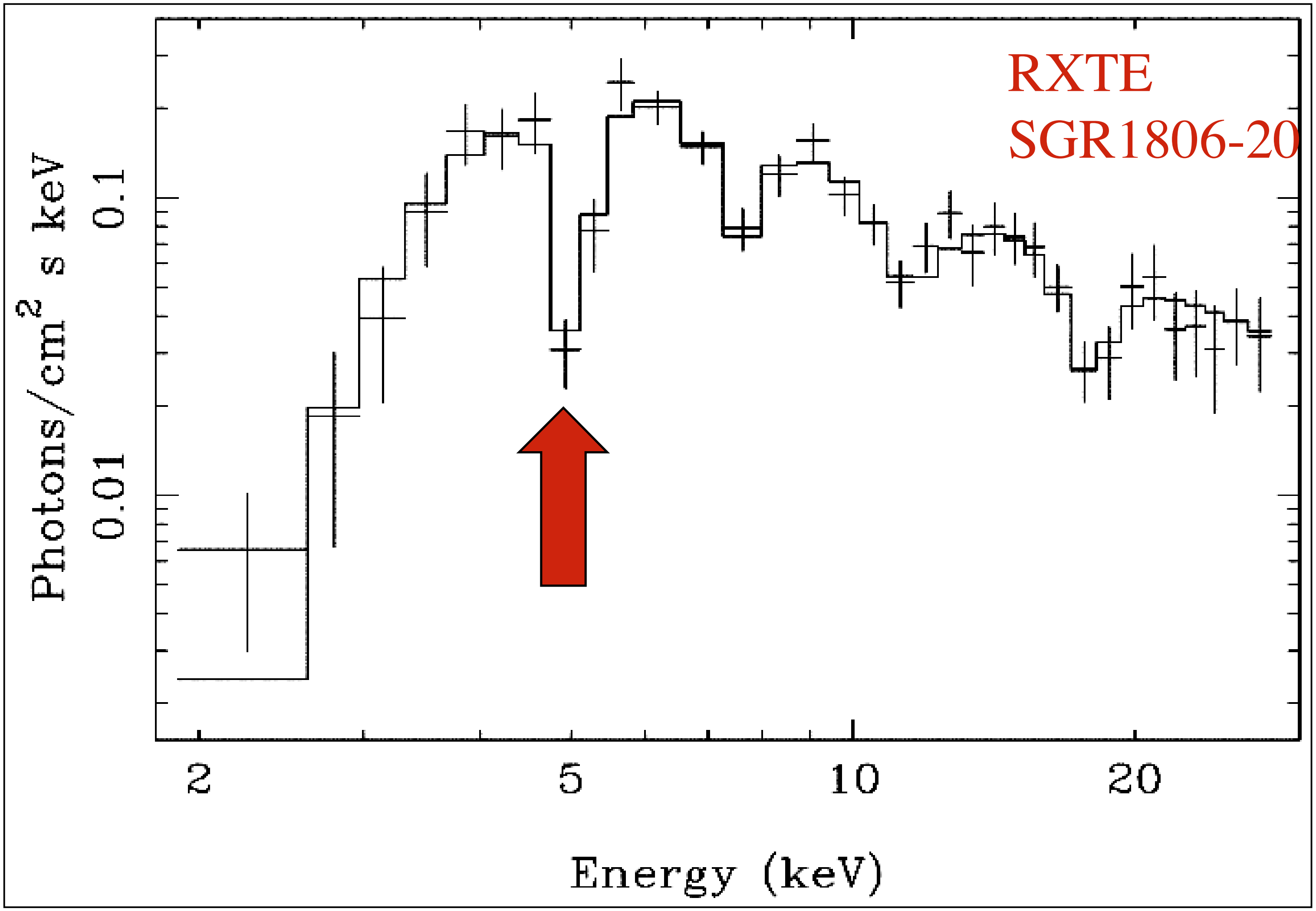
From observations of a few SGRs, observers inferred a field $B \sim 10^{14}$-10^{15} Gauss!

(i.e. ~ 100-1000 times larger than the Crab's magnetic field).

- Observations of cyclotron lines

--> a direct measurement of B

$$E_p = 6.3(1+z)^{-1} B/(10^{15}\ \mathrm{G})\ \mathrm{keV}$$



5keV Absorption cyclotron line B=10^{15} G
(the 1st evidence of cyclotron lines from SGRs)

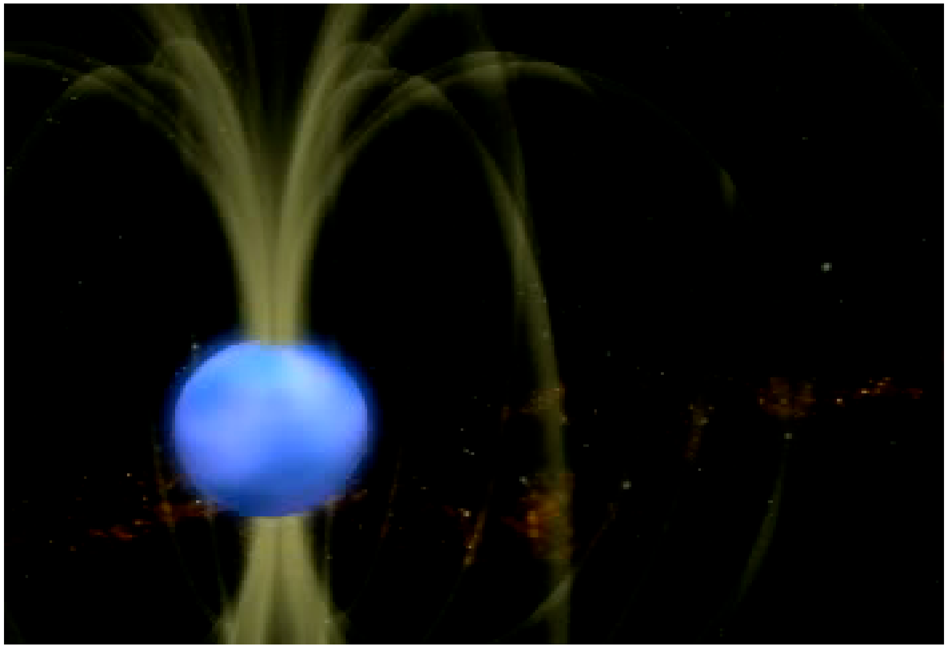
Ibrahim, Safi-Harb, Swank, Parke, Zane, Turolla, ApJL (2002)

Common Characteristics (AXPs and SGRs)

- Both AXPs and SGRs "burst"
- Unpredictable
- Inferred B ~10^{14} - 10^{15} Gauss.
- During one (big) burst, an SGR can emit as much energy per second as the sun emits in 1000s years!
- Similar spectra when "quiescent"
- Observed only at high-energies (and perhaps in the infrared), but NOT at radio wavelengths: *radio-quiet sources*

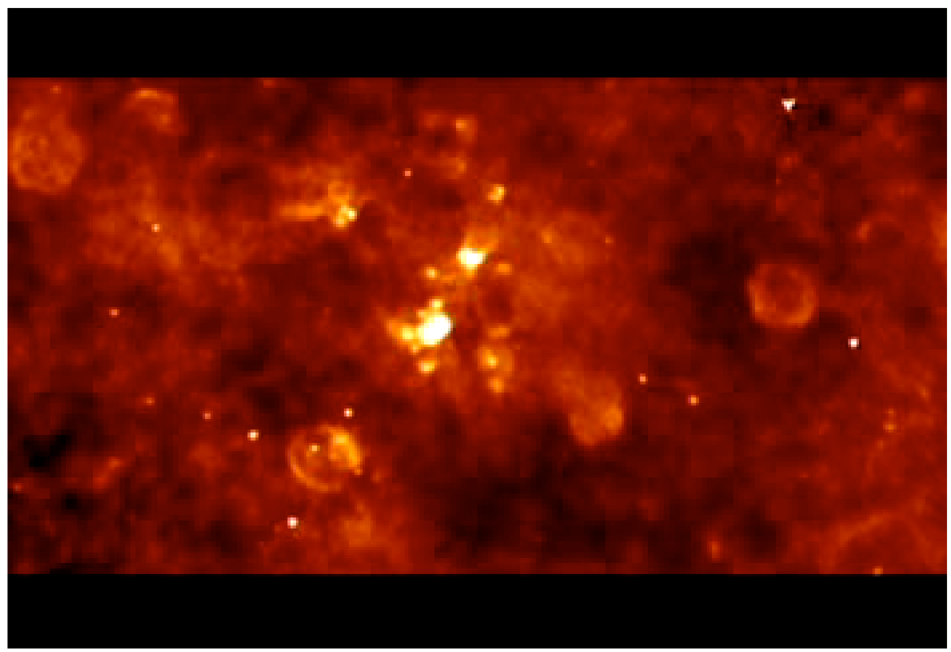
SGR1806-20: The most energetic explosion ever!

- Dec 27, 2004: a huge burst was detected with Integral, and 4 other missions including Swift
- Luminosity (peak) ~1.8 10^{47} ergs/s
- 100 times more energetic than any previously detected burst!
- Radio afterglow was detected with the VLA (*no other magnetar has been detected in the radio band, except for an after flare from SGR1900+14 and which was 500 times fainter*).
- Believed to be caused by a magnetar flare caused by a magnetic instability



Artist's conception of the SGR 1806-20 flare on Dec 27, 2004

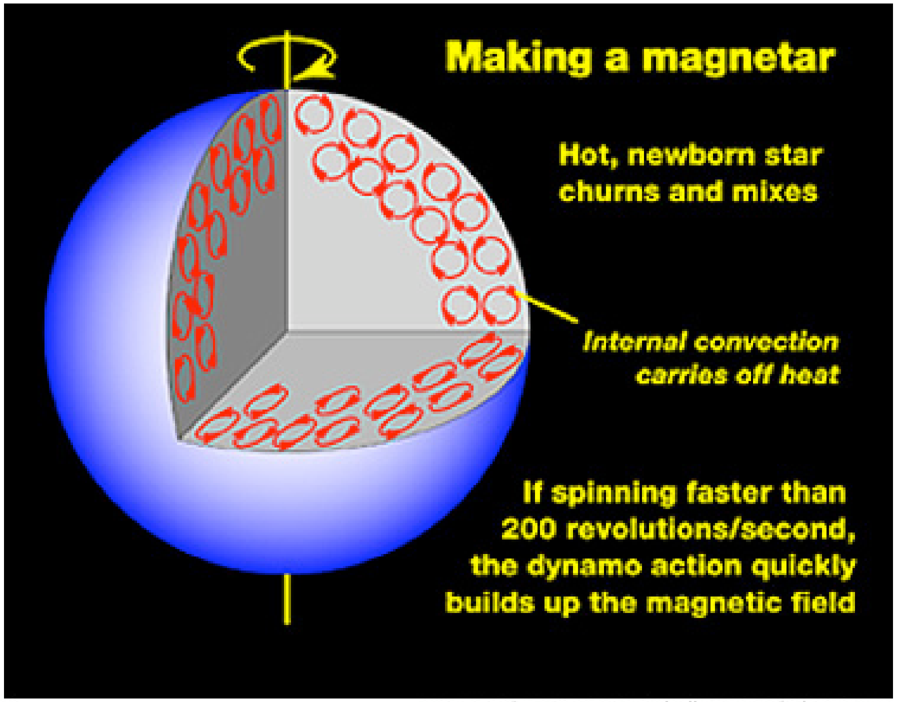
Evolution of the size and shape of the radio emission as detected by VLA



http://www.nasa.gov/vision/universe/watchtheskies/swift_nsu_0205.html

AXPs and SGRs are now believed to be MAGNETARS!

So how do magnetars form?



Dave Dooling, NASA Marshall Space Flight Center

•Magnetars were predicted *theoretically* in 1992 (*Duncan and Thompson*)

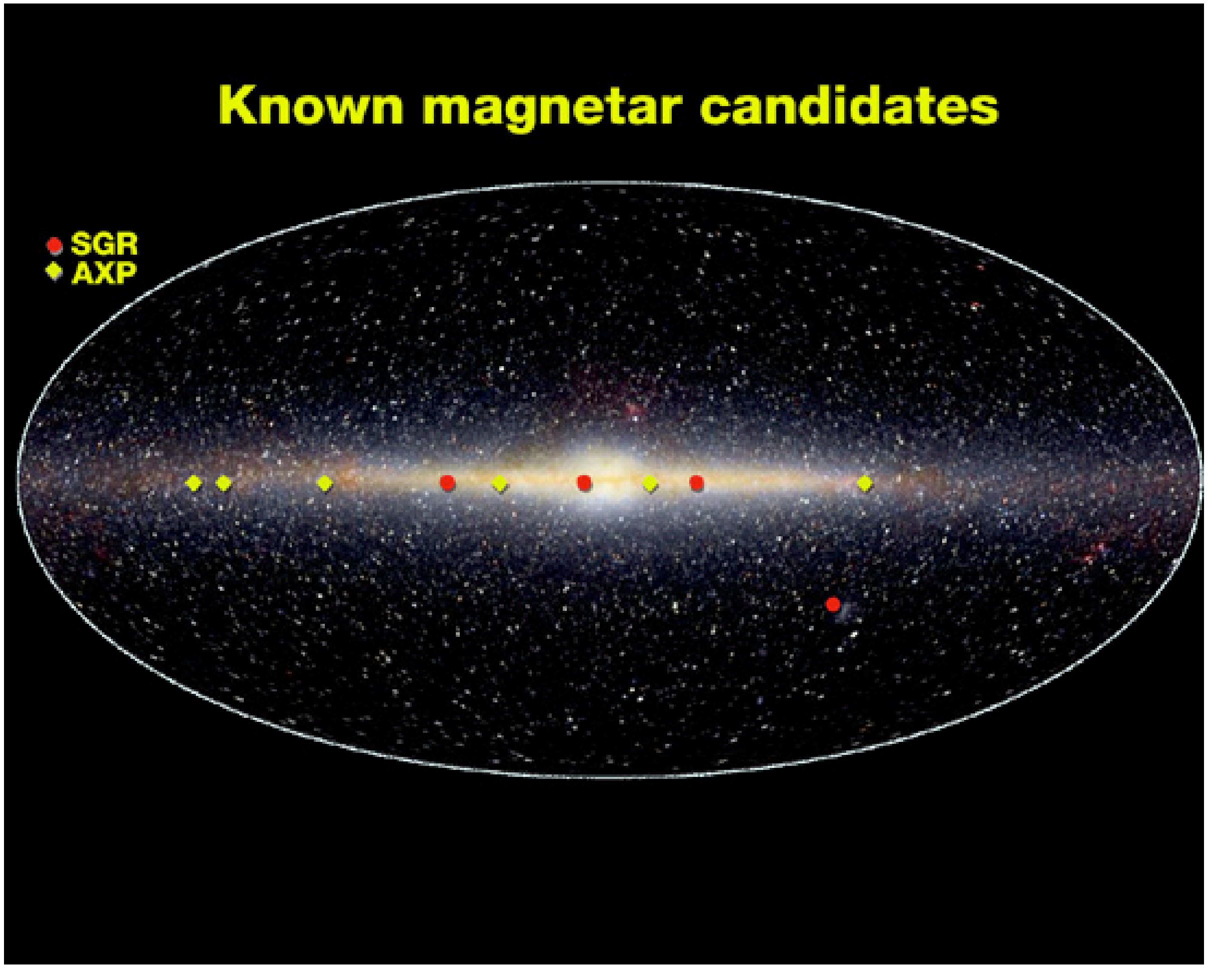
➢Surface Magnetic Field $B > B(QED) = m_e^2 c^3/e = 4.4 \times 10^{13}$ G

•To make a magnetar, need a <u>very fast spinning pulsar at birth</u> (>200 rev/s).

•The combination of fast rotation and convection --> Perfect dynamo at birth

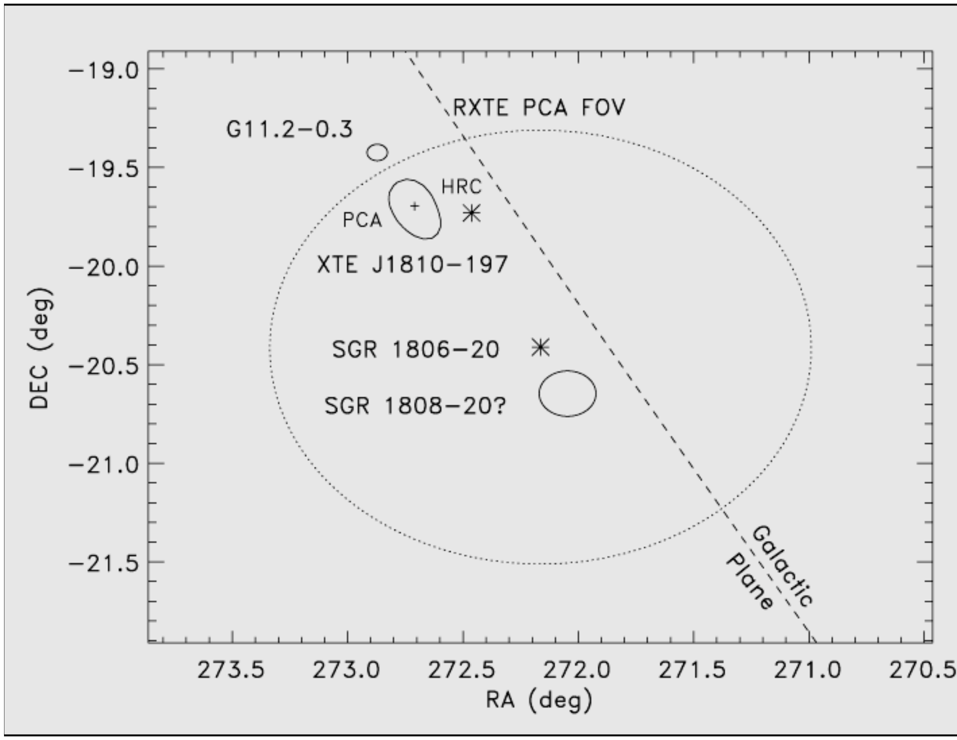
•The large B explains their slow periods and energetics

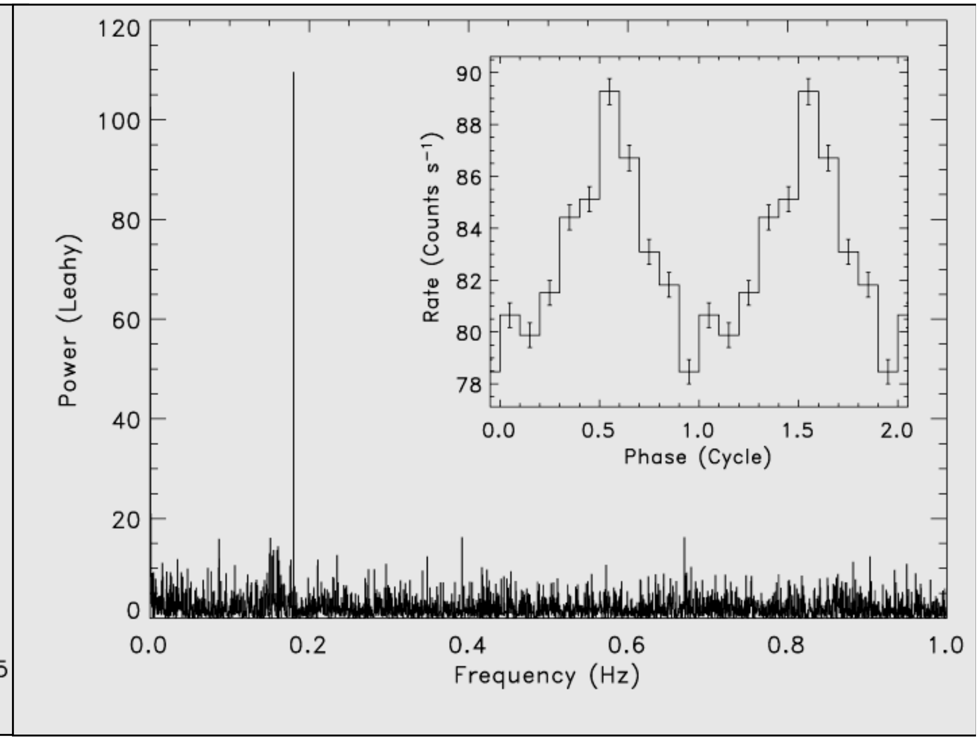
•The bursts are like **starquakes** on the surface of the magnetar! (similar to the solar flares, but on a much larger magnitude scale!)


Known magnetar candidates
SGR
AXP

Why do we know of only a dozen magnetars??

Transient Magnetars:
Link to CCOs?
XTE 1810-197





P=5.5s
B~3E14 (?) Gauss
Age~7,600 yrs

Transient magnetar (ctd)

•The discovery of a new magnetar candidate, which was *first observed as a dim X-ray star* without detectable pulsations as early as 1990.

•Around January 2003 this star got *brighter by more than a factor of 100*, revealing magnetar-like 5-second X-ray pulsations (due to a slowing stellar rotation)--Ibrahim et al. 2004

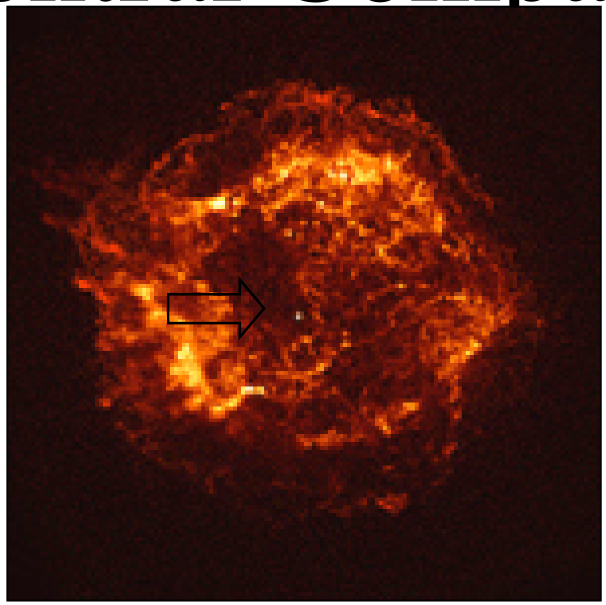
• It has since been gradually *dimming*.

•The star may have experienced an episode of plastic crust deformation in January 2003 which twisted the exterior field, driving currents outside the star and bright, transient X-ray emissions.

•This discovery indicates that `transient' magnetars exist and that we may have many other magnetars awaiting discovery!

Central Compact Objects (CCOs)

CCOs-Central Compact Objects



The first Chandra Image of Cas A

- Six confirmed central compact objects (x-rays)
- No counterparts at other wavelengths, radio-quiet
- No plerions (no pulsar activity)
- Spectra: soft, blackbody+power law (slightly cooler than AXPs and SGRs)
- No evidence of variability
- Periods (unknown, except for one: 424 ms)

 Young Magnetars????

Conclusions

- Since the discovery of the Crab pulsar, we've been assuming that all pulsars are Crab-like.. but we've been lately discovering many faces of neutron stars!
- Some neutron stars behave like the Crab nebula: they form Pulsar Wind Nebulae (Plerions)
- Some don't: these include the
  - the Anomalous X-ray Pulsars
  - the Soft Gamma-ray Repeaters
  - and Central Compact Objects (CasA-like)

  → **all discovered at high-energies!**
- AXPs and SGRs are now believed to be magnetars, with B~100 times B (Crab pulsar).

The many "faces" of neutron stars can be largely attributed to their properties at birth, in particular their magnetic fields, which span ~6 orders of magnitude scale.

Interested in:

- A neutron star or supernova project?
- A galaxy/AGN project?

Let us know!

Problem Set #5:

http://lheawww.gsfc.nasa.gov/docs/outreach/GWU_Space_Astrophysics/Spring05/problem_sets/ps5/ps5.html

Due next Thursday, March 10th.