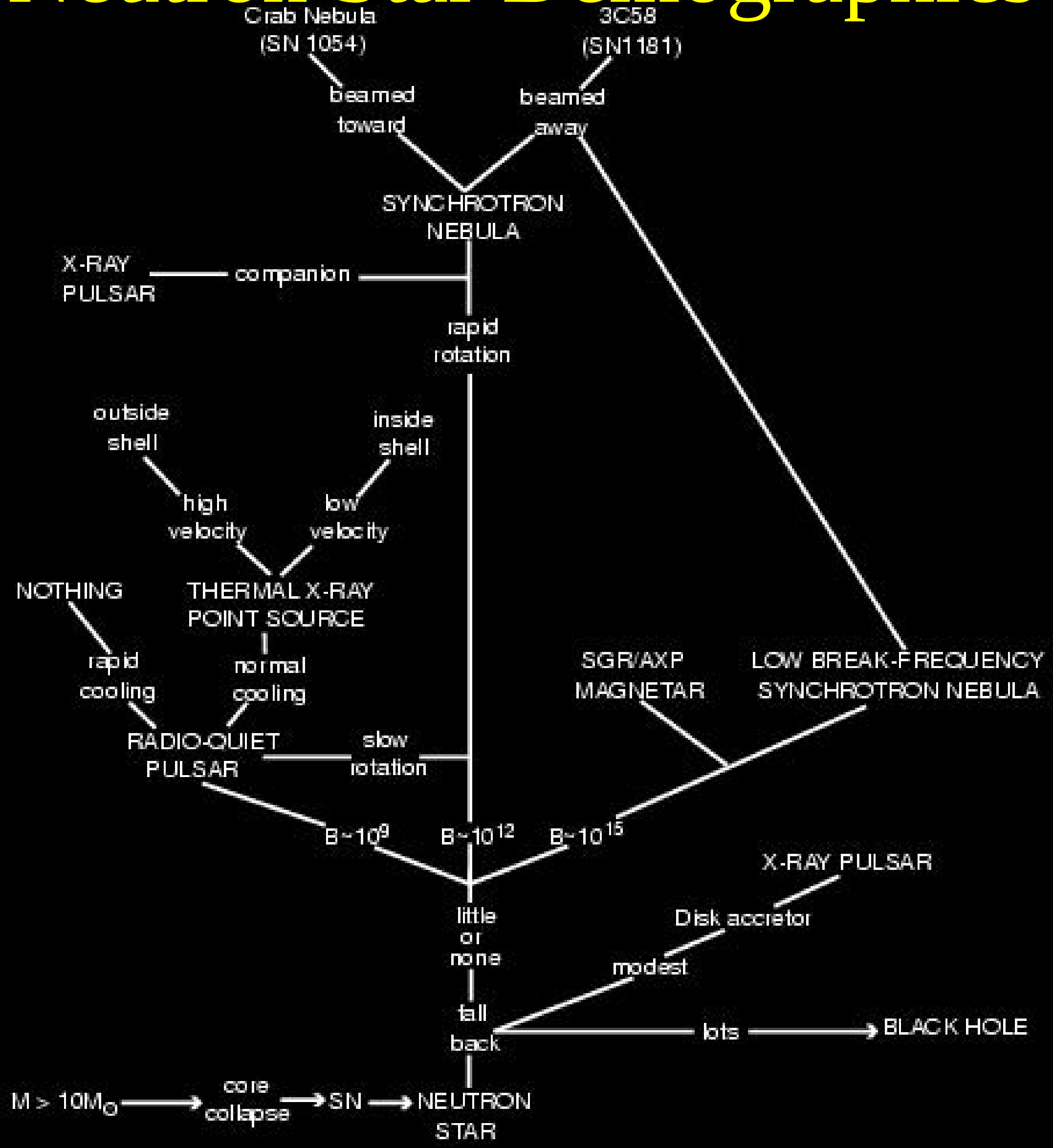
Neutron Star Demographics



Crab Nebula (SN 1054)

3C58 (SN1181)

beamed toward

beamed away

SYNCHROTRON NEBULA

X-RAY PULSAR

companion

rapid rotation

outside shell

inside shell

high velocity

low velocity

NOTHING

THERMAL X-RAY POINT SOURCE

rapid cooling

normal cooling

SGR/AXP MAGNETAR

LOW BREAK-FREQUENCY SYNCHROTRON NEBULA

RADIO-QUIET PULSAR

slow rotation

$B \sim 10^9$

$B \sim 10^{12}$

$B \sim 10^{15}$

X-RAY PULSAR

Disk accretor

little or none

modest

fall back

lots

BLACK HOLE

$M > 10M_{\odot}$ → core collapse → SN → NEUTRON STAR

Spin-down and Magnetic Dipole Model

- Pulsars are observed to spin w/ periods of ms to seconds: $\Omega = 2\pi / P$
  - for non-accreting systems, P increases with time; pulsars spin down:

$$\dot{P} = \frac{dP}{dt}$$

- Spin-down power is rate at which rotational energy is lost:

$$\dot{E} = -\frac{dE_{rot}}{dt} = 4\pi^2 I \frac{\dot{P}}{P^3}$$

where $I = \text{moment of inertia} \approx 10^{45}\,\text{g cm}^{-2}$

- values range from 3×10^{28} to 5×10^{38} ergs/s

- Typically a power-law spin-down is assumed

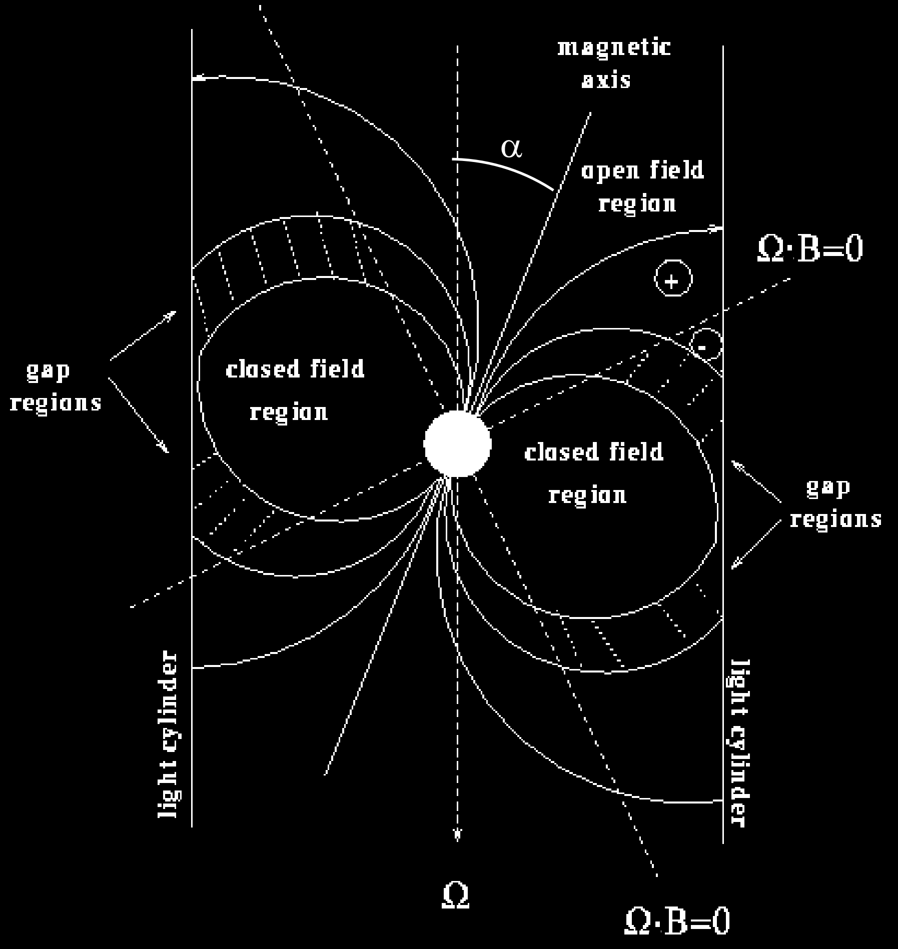
$$\dot{\Omega} = -k\Omega^n \qquad n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

where n is the braking index

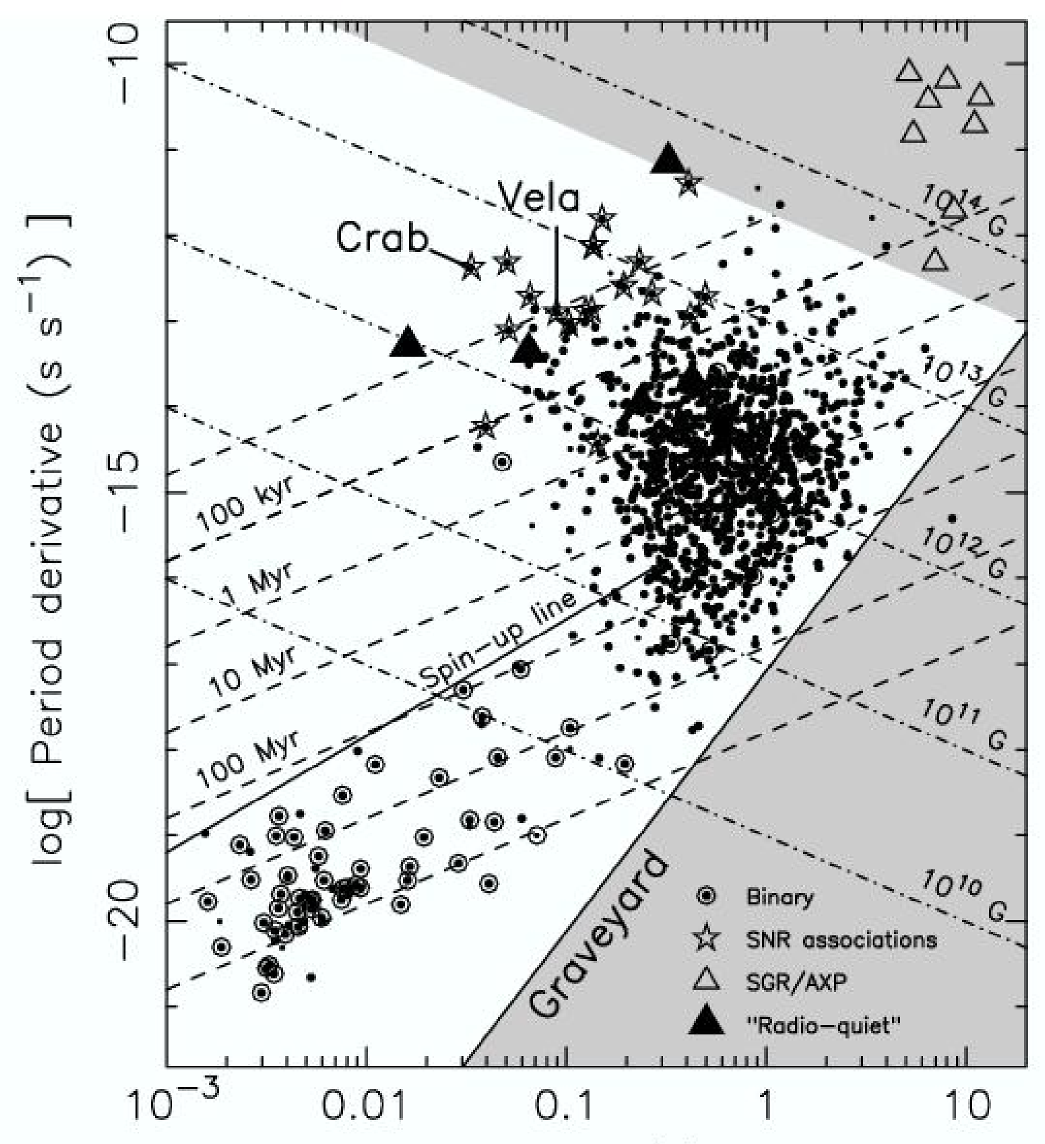
- For magnetic dipole spin-down,

$$\left.\dot{E} = \frac{B_0^2 \sin\alpha\, \Omega^4 R^6}{6c^3} \longrightarrow n = 3 \text{ for dipole}\right\} \quad B_0 = \left[\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6}\right]^{1/2}$$

magnetic field at equator



The P-Pdot Diagram



Cordes et al. 2005

- Integrating the spin-down law,

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

- if the age is known, we can determine the initial spin period

- For $P >> P_0$, and $n = 3$

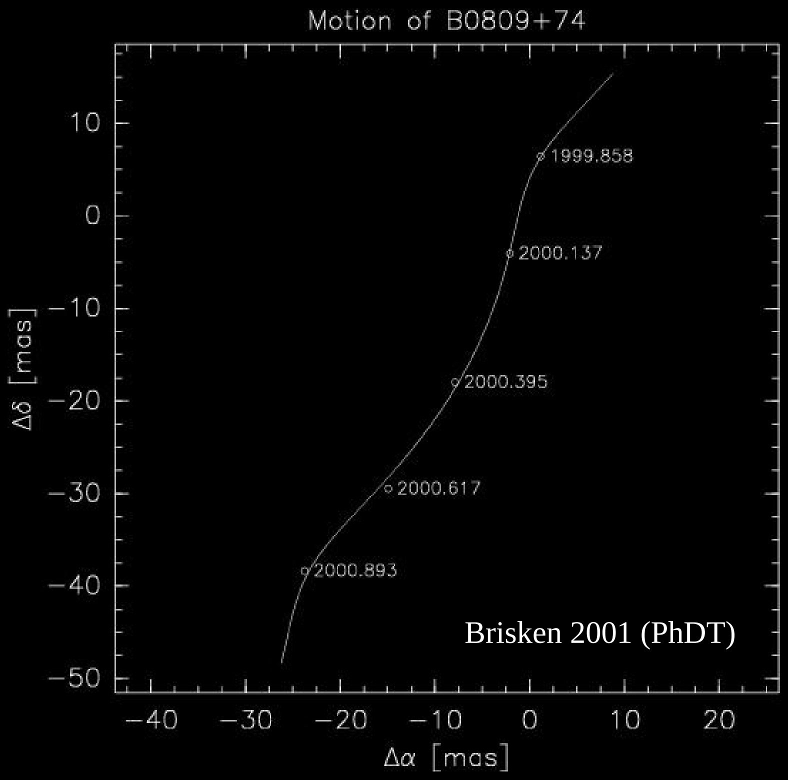
$$\tau_c \equiv \frac{P}{2\dot{P}}$$

"characteristic age"

- note: some pulsars appear to have slow birth periods

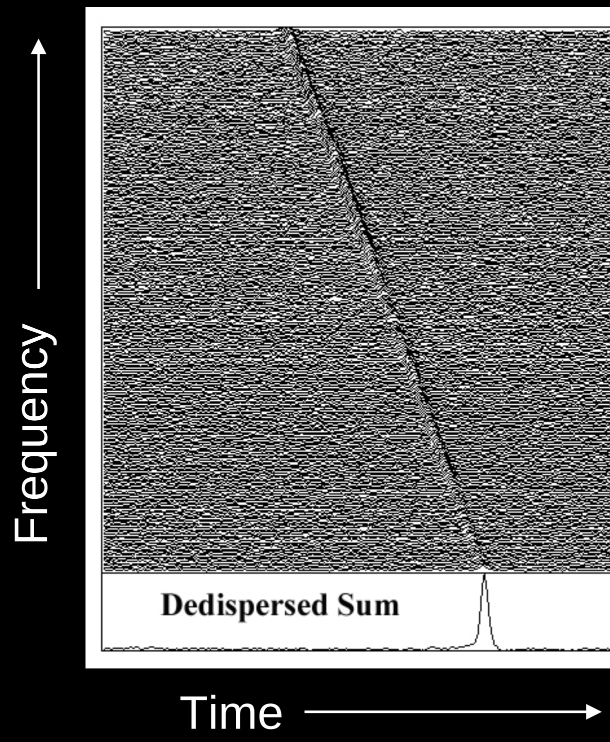
- P-Pdot diagram is the H-R diagram for pulsars (though evolutionary sequence is not completely clear)
  - obvious groups include young pulsars in SNRs, rapidly-spinning low-B pulsars in binaries, and high field magnetars

Neutron Star Distances



Brisken 2001 (PhDT)

- **Parallax**
  - only possible for very nearby pulsars
  - currently about 25 pulsar parallax measurements exist

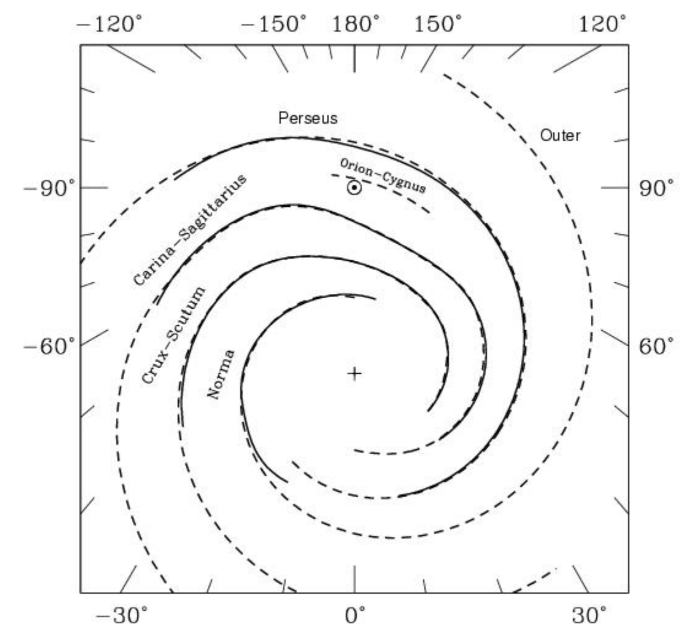


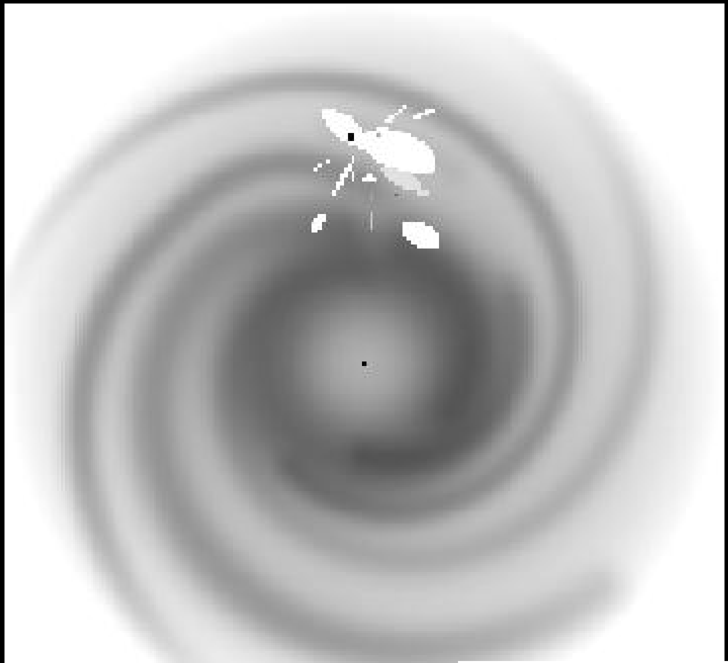
- **Dispersion Measure**
  - propagation of radio signals through ionized ISM yields frequency-dependent delay in pulse arrival times

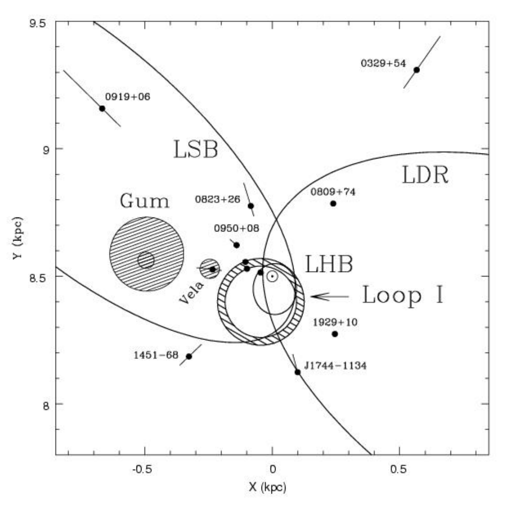
$$\mathrm{DM} = \int n_e \, dl$$

- Use model for electron density to get D

Neutron Star Distances (cont.)

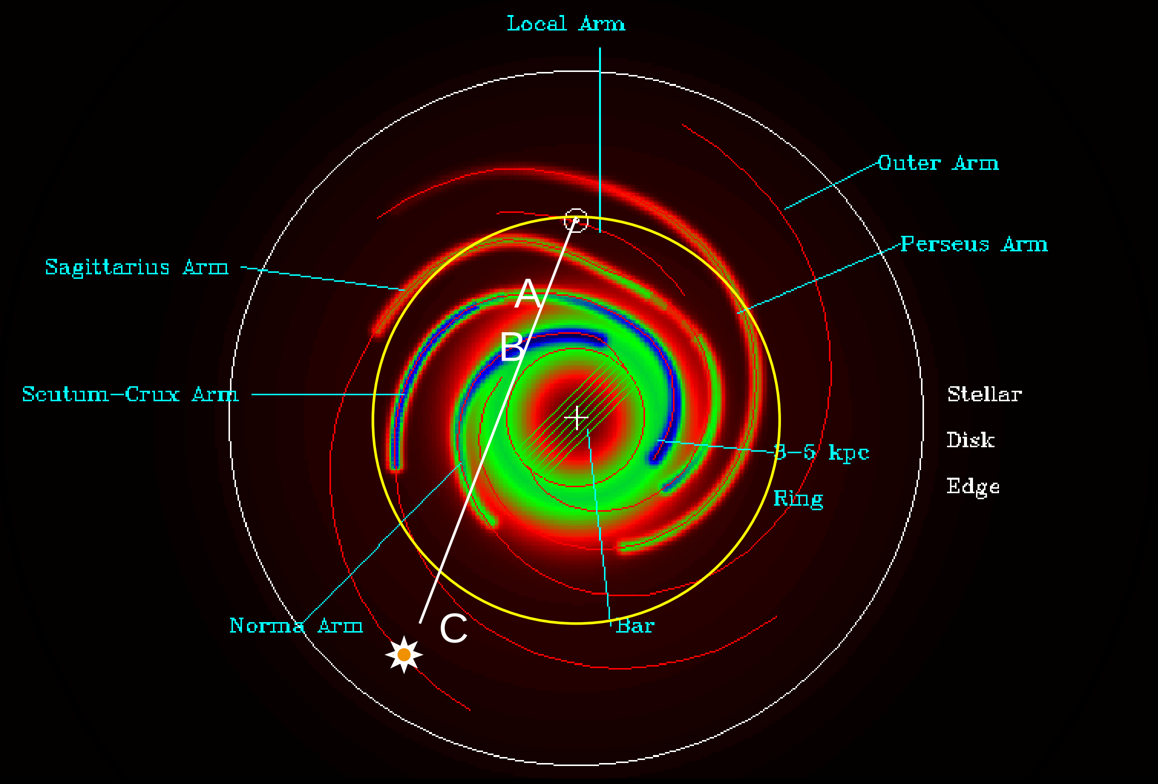


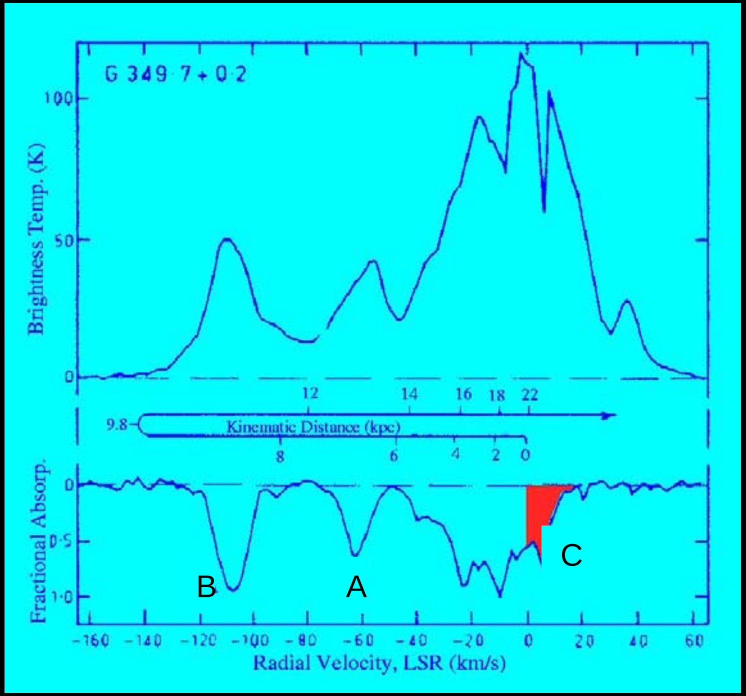




- **Electron Density Model** (Cordes & Lazio 2003)
  - use pulsars w/ known distance along w/ models for Galactic structure to build up electron density model; include spiral structure, local bubble, thin/thick disk, GC, individual clumps
  - DM measurements for individual pulsars then yield distances
  - accurate to ~10-25% on average, though (much) larger errors can exist for particular directions

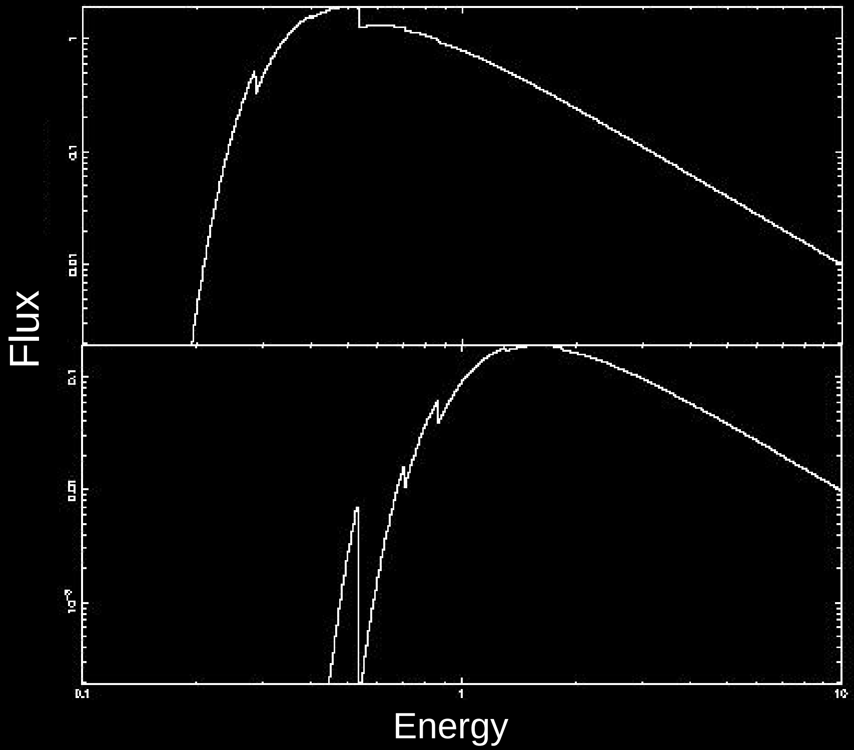
Neutron Star Distances (cont.)

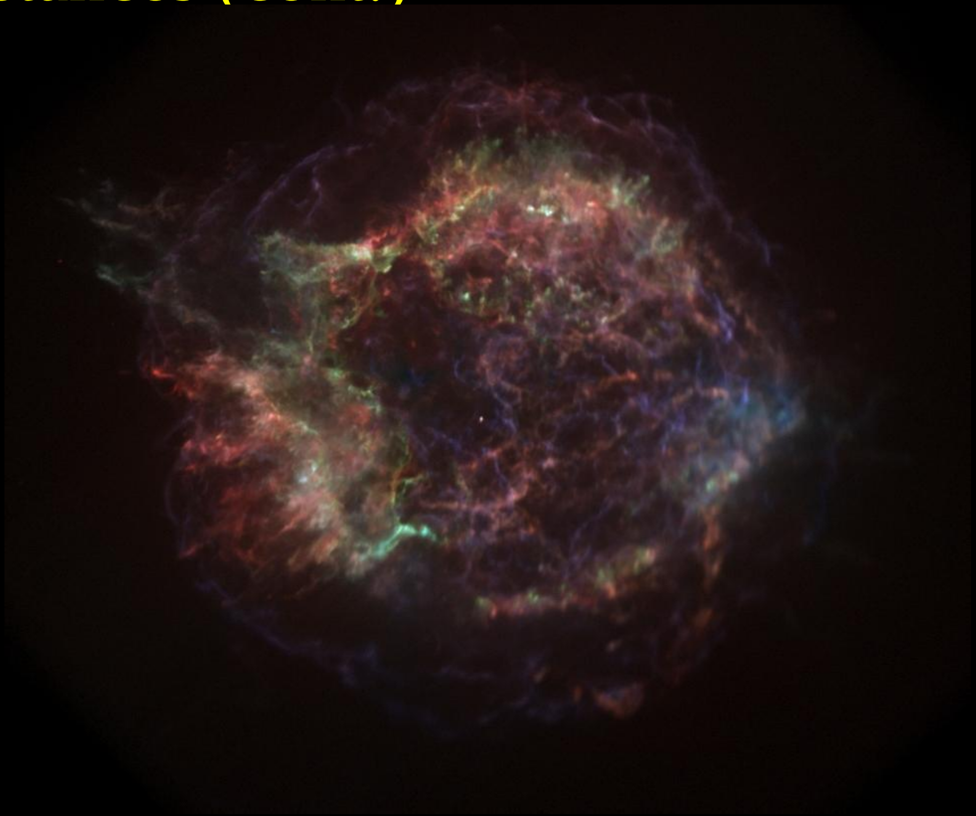




- **Kinematic distances**
  - rotation curve of Galaxy can be used to identify positions based on relative velocities
  - pulsars (or SNRs) provide beacon against which foreground HI absorption can be detected
  - only boundaries or upper limits obtained for distances
  - two-fold amibiguity in inner galaxy

Neutron Star Distances (cont.)





- **Absorption/Reddening**
  - X-ray or optical spectrum shows effects of absorption
  - can be correlated with distance
  - this is a very approximate technique

- **Associations w/ SNRs; ISM Interactions**
  - distances to SNRs provide that for associated pulsars
  - SNR distances can be estimated as above, and also through kinematic distances for molecular clouds with which they interact

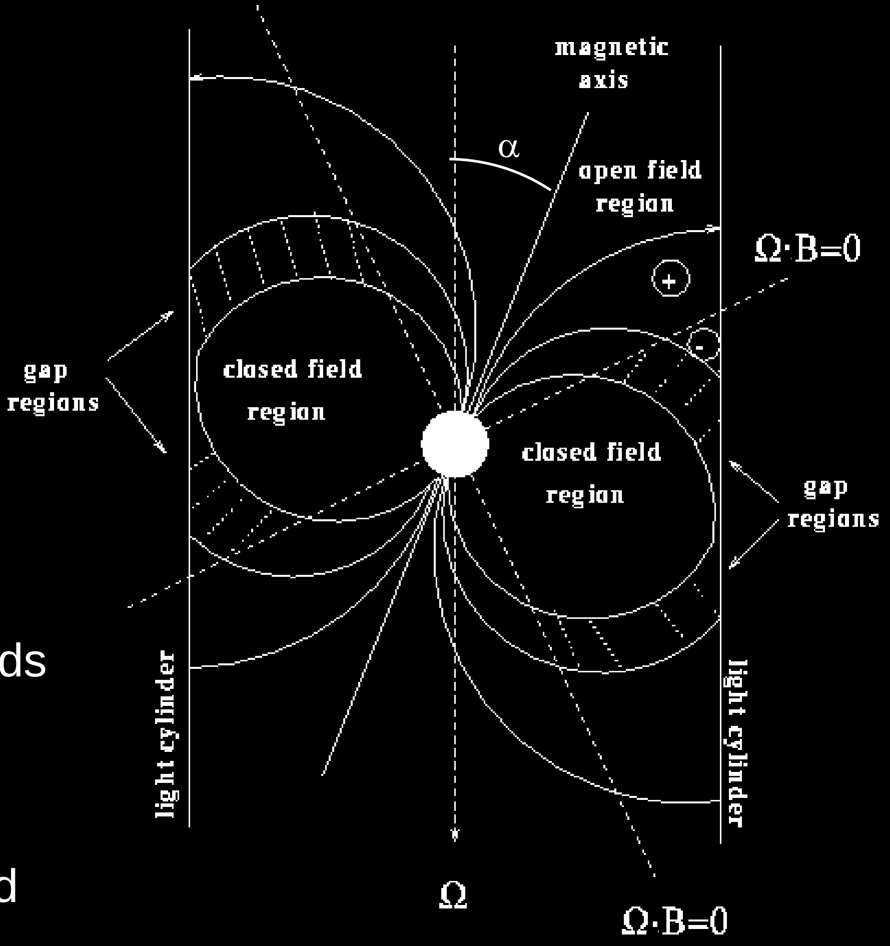
NS Demographics: Canonical Isolated Pulsars

- Present-day periods from ~15 ms - 8 s
  - born with periods of ~10 ms, though evidence for some born with periods >100 ms

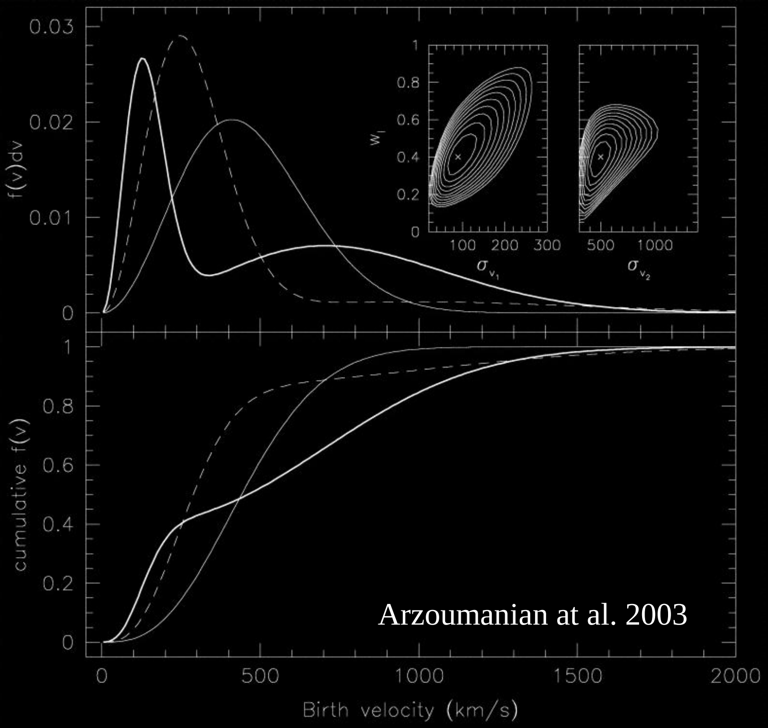
- Surface magnetic fields log B ~ 12 +/- 1
  - strong field effects in atmosphere/magnetosphere

- Luminosity derived from spin-down
  - large B coupled with fast rotation generates electric fields sufficient to pull charges from surface
  - teravolt potential differences across magnetosphere accelerate particles that radiate across EM spectrum
  - acceleration in polar and/or outer gaps; relativistic winds

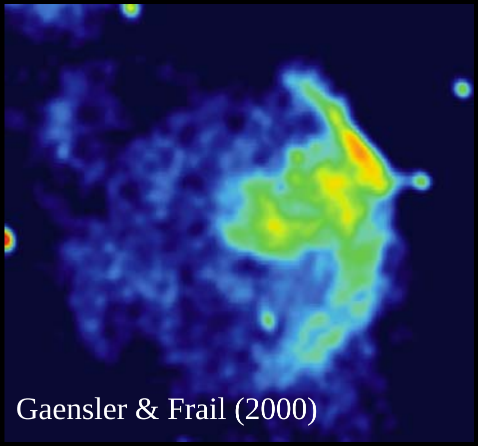
- Over 1000 known; youngest still in associated SNRs
  - youngest undergo considerable glitching, associated with unpinning/repinning of vortices between superfluid interior and crust
  - glitches, cooling, and measurements of mass and radius provide picture of physics at ultrahigh densities



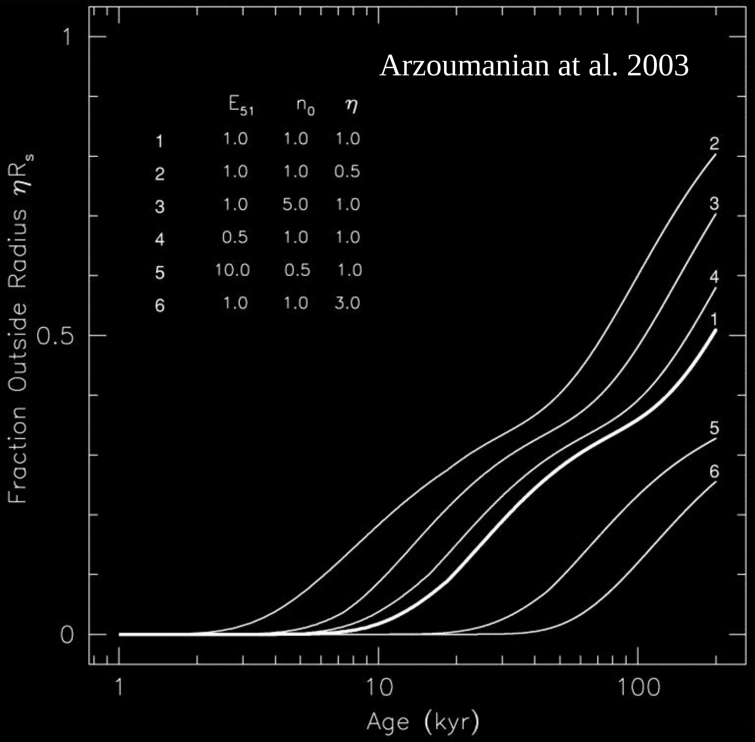
Pulsar Velocities



Arzoumanian at al. 2003



Gaensler & Frail (2000)



Arzoumanian at al. 2003

- Pulsars are born with high velocities
  - bimodal distribution with:

σ_1~ 90 km/s, σ_2~ 500 km/s (40%)

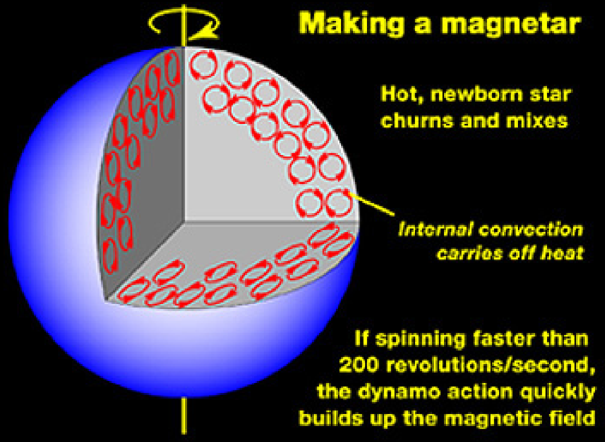
- Mechanism by which this is imparted not well-understood (Lai et al. 2001)
  - convective instabilities in core; asymmetric matter ejection?
  - asymmetric neutrino emission induced by strong B fields?
  - electromagnetic rocket effect?
  - how do these relate to spin-kick alignment (if real)?

- Even with high velocities, most young pulsars should be found within their SNRs

- As they approach SNR shell, or break through into ISM, a bowshock will form
  - the shape of the bowshock can yield the velocity (more on this later)

NS Demographics: Magnetars

see Duncan & Thompson 1992

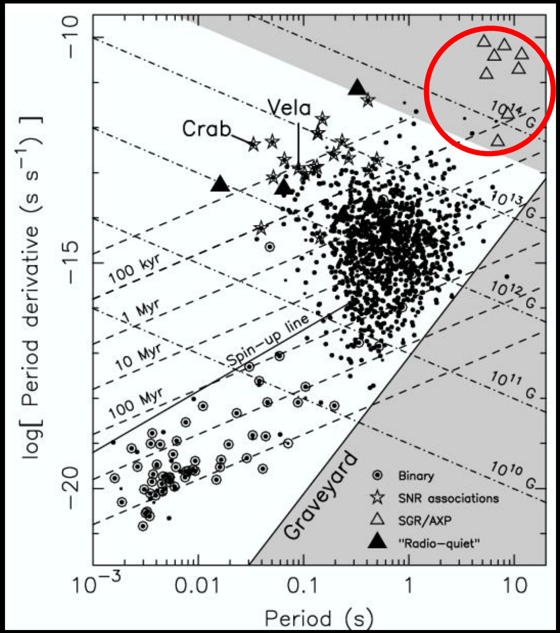


- During initial formation of neutron stars, rapid spin of core can produce magnetic fields as high as 10^{15-16} G
  - most NSs do not spin this fast upon formation, prohibiting this dynamo from operating; more “typical” pulsar fields result

- Ultra-strong NS fields will decay, causing extreme heating heating of crust → high X-ray luminosity (“magnetar”)
  - occasionally, stress on crust causes fracture, leading to rapid readjustment of external field and release of large amounts of energy accompanied by burst of γ-rays

- Trapped fireball of relativistic plasma is confined by magnetic field
  - rotation produces fading pulsations

- In quiescence, emission from hot crust yields X-rays, but pulsations are not always evident



Anomalous X-Ray Pulsars

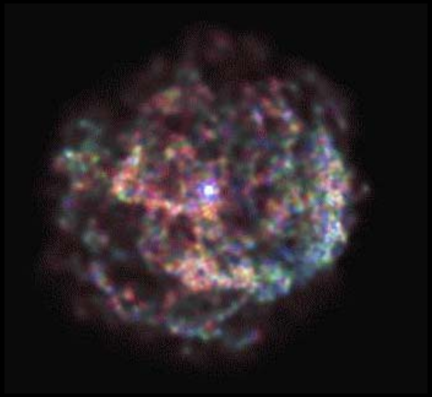
Source Name	Period s	Age kyr	log B G	SNR Name
1E 2259+586	6.98	210	13.8	CTB 109
1E 1841-045	11.76	4.0	14.9	Kes 73
1E 1048-5937	6.45	4.6	14.6	---------
4U 0142+615	8.69	60	14.5	---------
AX J1845-0258	6.97	----		G29.6+0.1
RX J170849.0-400910	11.00	9.2	14.7	---------
CXOU J010043.1-721134	8.02	6.8	14.6	---------

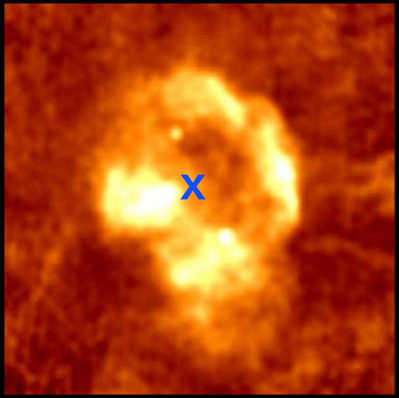
- Slow rotation period (P ~ 6 - 10 s)
  - rapid spin-down ⟹ huge B-field (B ~ 0.6 - 7 x10^{14} G)

- $L_x \sim 10^{34-36}$ ergs/s >> $\dot{E}$ - What is the energy source?
  - accretion? no direct evidence for binary
  - magnetic field decay (“magnetars”)

- 3 of 7 associated with SNRs
  - located near SNR centers; ages are ~10 kyr

- X-rays show blackbody with power law tail (PL dominates energy)





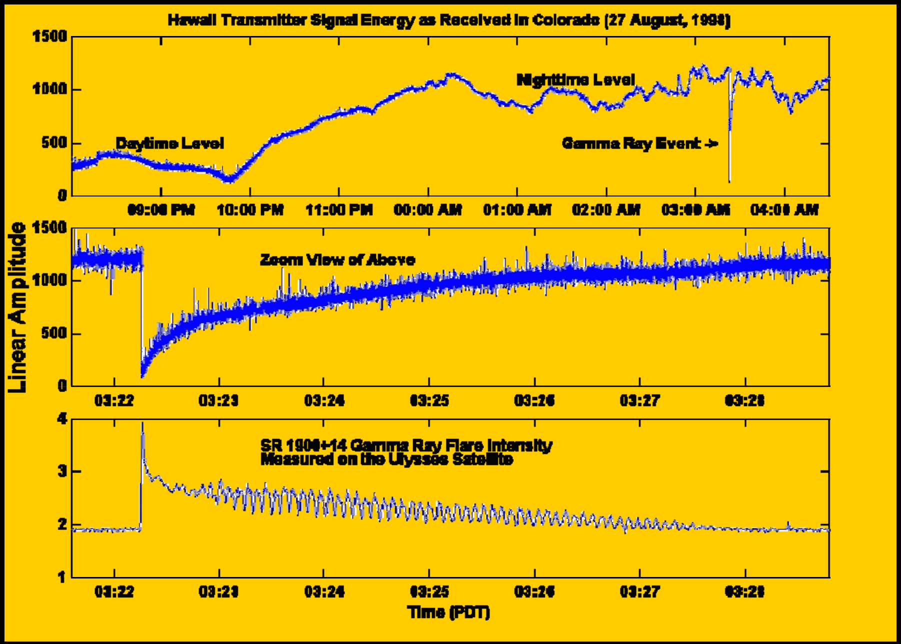
Soft Gamma-Ray Repeaters

- Sources produce brief but luminous outbursts of γ-rays and X-rays
  - five sources currently known

- Three of the sources have undergone giant outbursts (SGR 0526-66, 1900+14, and 1806-20)
  - these outbursts can be energetic enough to affect the Earth's ionosphere!

- Small bursts much more common, with active periods of several weeks, and recurrence times of order several years
  - typical durations are ~100 ms

- Several SGRs are observed to pulse, with periods of 5 - 8 s.
  - inferred magnetic fields strengths approach 10^{15} G
  - well-explained by magnetar model
  - strong B confines energy in tails of bursts; need large B to power bursts; also powers in quiescence



Soft Gamma-Ray Repeaters

Source Name	Period s	Age kyr	log B G	SNR Name	Associated? (Chance Prob)
SGR 1806-20	7.5	1.4	14.9	G10.0-0.3	N
SGR 1900+14	5.2	0.7	14.8	G42.8+0.6	4%
SGR 0526-66	8.0	----	-----	N49	0.5%
SGR 1627-41	-----	----	-----	G337.0-0.1	5%
SGR 1801-23	-----	----	------	--------------	

- In quiescence these appear to have properties similar to AXPs
  - slow rotation; $L_x > \dot{E}$ (where measured)

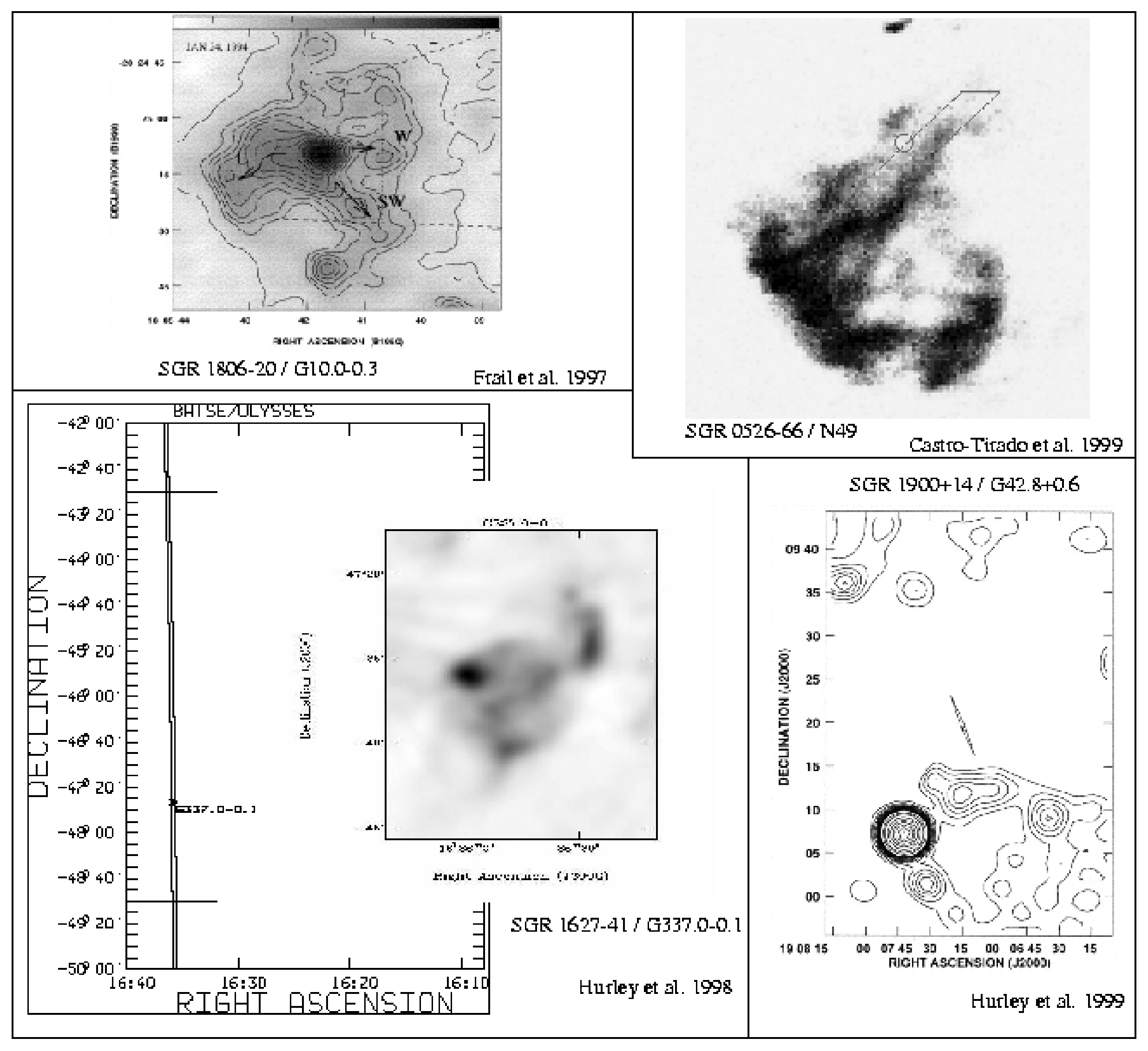
- Many found in the vicinity of SNRs, suggesting associations
  - offsets are large, suggesting a high-velocity population
  - but are these *real*?

- Chance probability for random overlap of fields not small (Gaensler et al. 2001)
  - quite likely that SNRs in vicinity just means SGRs come from same star-forming region (and thus are a young population)

SGRs: Do They Live in SNRs?

Poorly defined SNR

Anything is possible...



SGR 1806-20 / G10.0-0.3

Frail et al. 1997

SGR 0526-66 / N49

Castro-Tirado et al. 1999

SGR 1627-41 / G337.0-0.1

Hurley et al. 1998

SGR 1900+14 / G42.8+0.6

Hurley et al. 1999

v = 1200 km/s

using Sedov age of 10 kyr

v > 50000 km/s

for τ ~ 750 yr

SGRs & AXPs: How Are They Related?

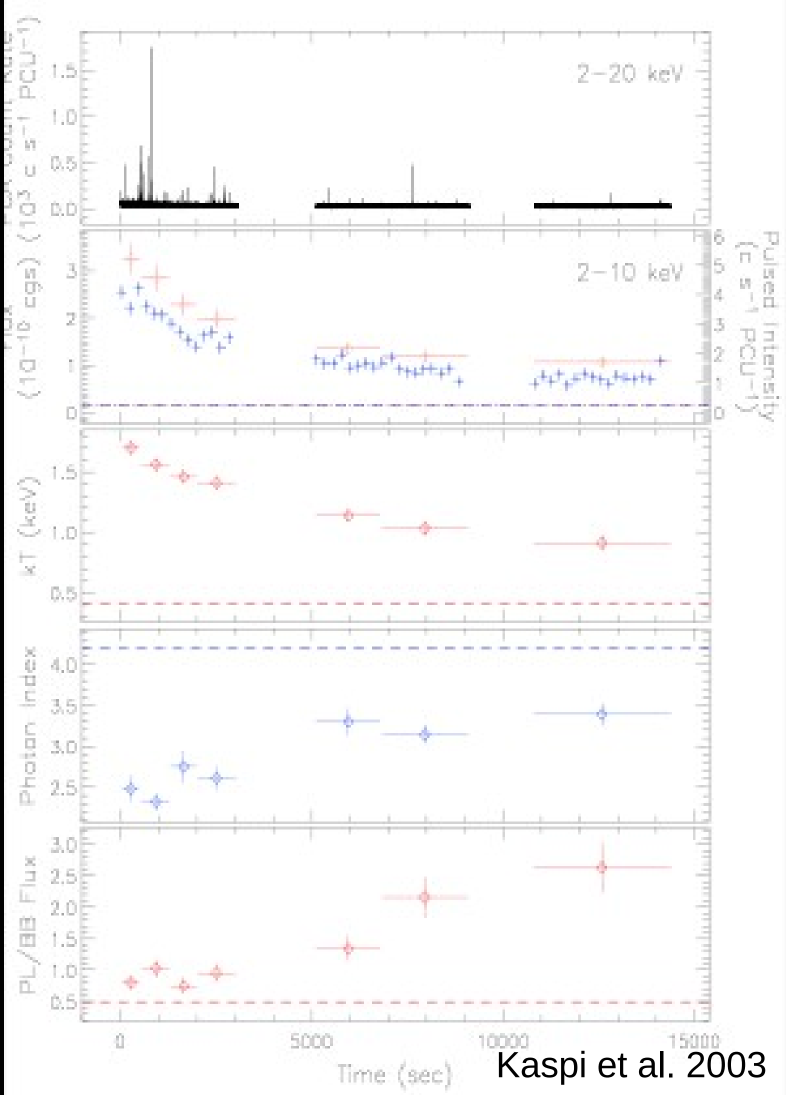
- **Populations appear very similar**
  - similar inferred magnetic field strengths
  - similar spin-down periods and spin-down rates
  - similar quiescent emission

- **Why don't AXPs show bursts? They do!**
  - 1E 1048-5937 and 1E 2259+586 have recently both shown to undergo burst episodes
  - burst properties similar to SGRs

- **What about radio pulsars with high fields?**
  - there are now several high-B radio pulsars that, in principle, should be similar to magnetars
  - radio pulsar PSR J1718-3718:
    - P=3.4 s, B= $7.4\times10^{13}G$
    - blackbody model: (for R=10 km, d=4kpc)

$$T=1.5\times10^{6}K \qquad L_{2-10keV}=10^{30}erg/s$$

    - much fainter than AXPs; do magnetar properties develop suddenly? Are the field structures fundamentally different (e.g. multipoles)?

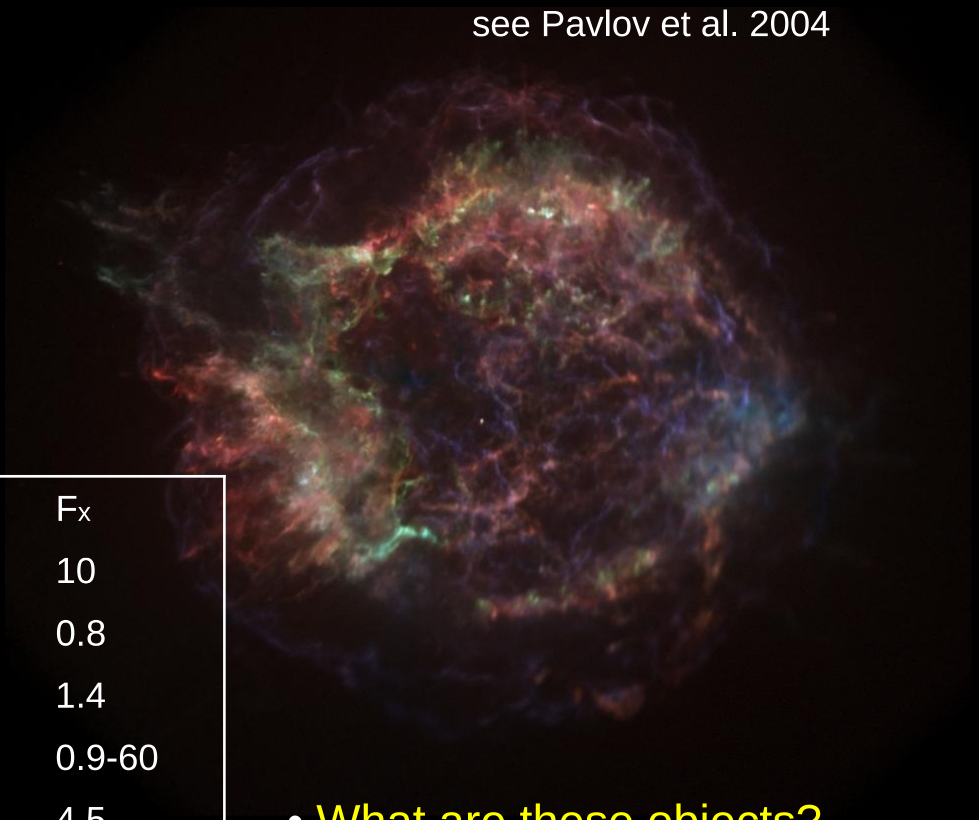


Kaspi et al. 2003

NS Demographics: Compact Central Objects

- Class of point-like X-ray sources found near centers of SNRs
  - no radio or γ-ray counterparts
  - no evidence of extended wind nebulae

- Soft thermal X-ray spectra
  - blackbody temperatures of 0.2 - 0.5 keV
  - typical luminosities are 10^{33-34} ergs/s



see Pavlov et al. 2004

Object	SNR	Age (kyr)	D (kpc)	P	F_x 10
J232327.9+584843	Cas A	0.32	3.3-3.7	-	0.8
J085201.4-461753	G266.1-1.2	1-3	1-2	-	1.4
J161736.3-510225	RCW 103	1-3	3-7	6.4 hr	0.9-60
J082157.5-430017	Pup A	1-3	1.6-3.3	-	4.5
J121000.8-522628	G296.5+10.0	3-20	1.3-3.9	424 ms	2.3
J185238.6+004020	Kes 79	~9	~10	105 ms	2.8
J171328.4-394955	G347.3-0.5	~10?	~6?	-	2.8
J000256+62465	G117.9+0.6?	?	~3?	-	0.1

may not belong to class

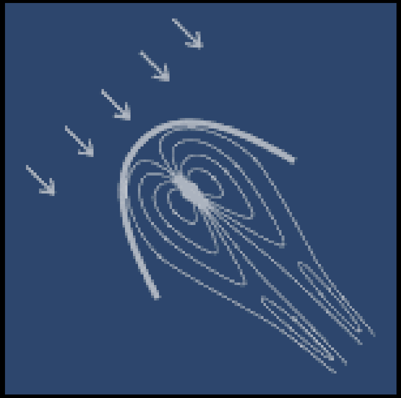
- What are these objects?
  - related to magnetars?
  - internal NS heat channeled to small emission regions?

NS Demographics: Isolated Old Neutron Stars

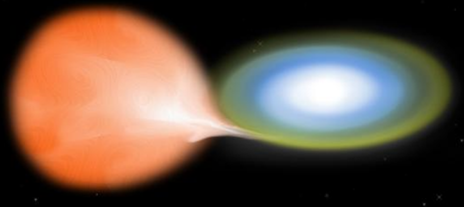
see Treves et al. 2000)

- There should be roughly a billion NSs in the Galaxy; we see less than 2000
  - beaming can limit number observed
  - pulsar lifetime is about 10^7 years, after which B/P is too low for pair-production
  - older pulsars are too old to be seen from their own thermal emission (Lecture 2)
  - Galaxy is basically a graveyard for bunches of cold, dead pulsars…

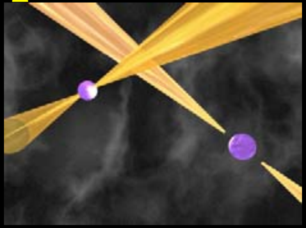
- But NSs typically have high velocities, and very strong gravitational fields
  - should accrete material as they move through ISM
  - these would be observable as soft X-ray sources



- Surveys with ROSAT don’t reveal much of this population. Why?
  - velocity distribution is faster than assumed? (Bondi accretion rate decreases with increasing velocity)
  - NSs do not spin down quickly enough (rapid rotation causes strong centrifugal barrier to accretion)
  - magnetic field decay is sufficient to prevent funneling of accretion flow onto small cap regions (resulting in high temperatures)
  - plenty of observational selection effects (low luminosity, absorption, low temperature)



NS Demographics: NSs in Binaries



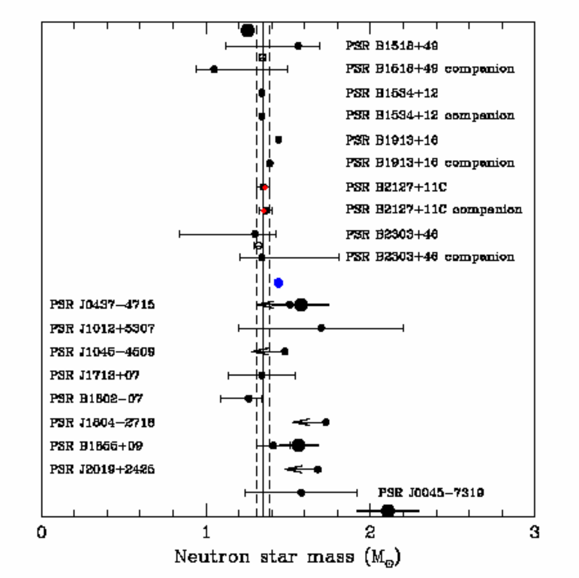
- X-ray binaries
  - powered by accretion
  - provide the most direct mass measurements

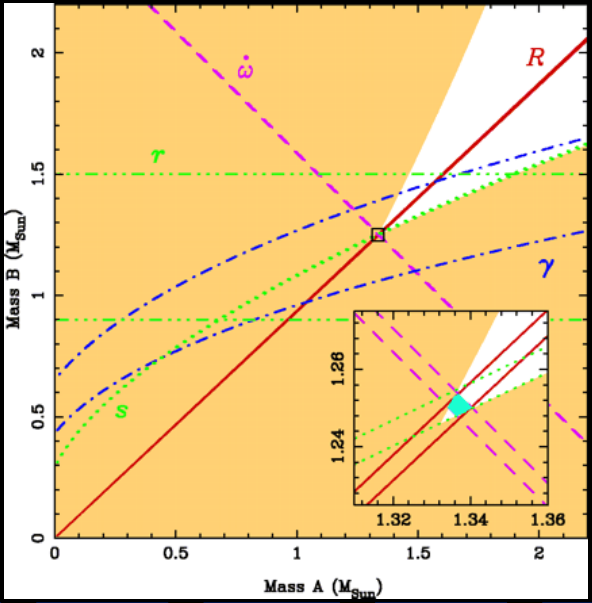
- Recycled pulsars
  - very rapid (P ~ several ms)
  - spin-down is low (log B ~8-10)
  - pulsars have been spun up by accretion from companion
  - subsequent X-ray emission can evaporate companion

Fastest pulsar (P = 1.3 ms) just discovered
- rotating nearly as fast as EOSs suggest is possible
- observed for only ~20% of orbit (bloated companion?)
-suggests there may be a lot of these that we don't see!

- Neutron star binaries
  - tight binary orbits; provide for measurements of post-Keplerian parameters of General Relativity
  - for recently-discovered double pulsar, can measure periastron advance, orbital decay (from gravitational radiation), gravitational redshift, and Shapiro delay

tight limits on masses of binary companions





Hot Off The Press: RRATs

- A new class of Rotating RAdio Transients (RRATS) has been discovered in the Parkes multibeam survey (McLaughlin et al. 2005)
  - 11 objects characterized by single radio bursts lasting 2-30 ms
  - burst intervals from 4 min - 3 hr

- Long-term monitoring leads to identification of P = 0.4 - 7 s
  - slightly long for normal pulsars, but not particularly unusual
  - slightly higher brightness temperature, but consistent with selection effects

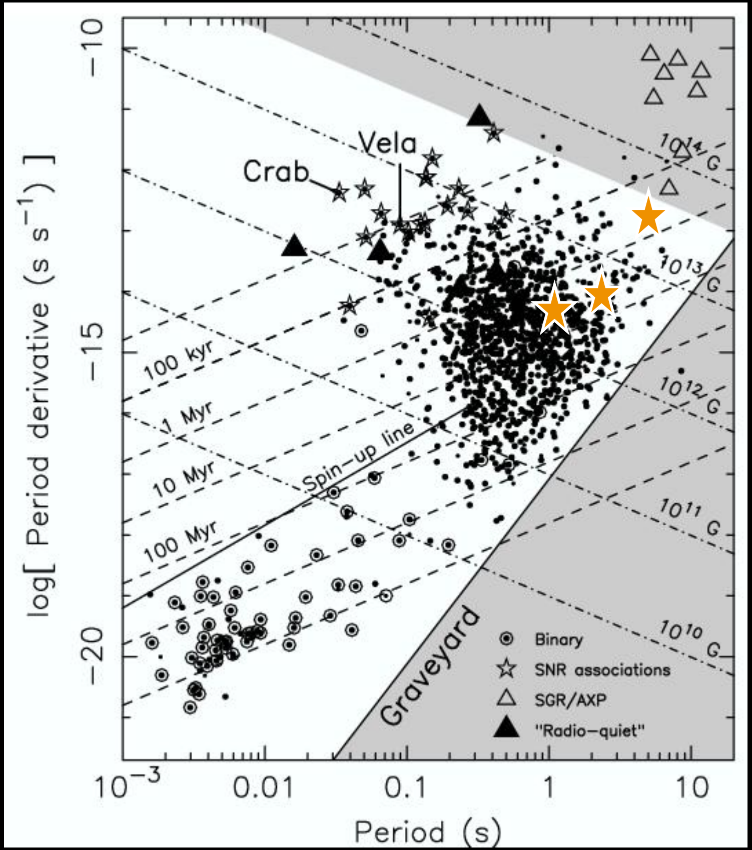
- For 3 of the pulsars, dP/dt measured; no binary motion detected
  - log $\dot{E}$ = 31.4 - 32.6, log B = 12.4 - 13.7, log t = 5.1 - 6.5
  - two of these are near the pulsar death line
  - for one (J 1819-1458), X-rays are detected (Gaensler et al. 2006); consistent with cooling from surface of old NS

Hot Off The Press: RRATs

What are RRATs?

- Reactivated dead pulsars?
  - need pair-production to generate radio emission
  - requires polar cap potentials of 10^{12} V ==> death line
  - if RRATs are pulsar below death line, appearance of strong sunspot-like B fields may occasionally emerge to activate pair production (Zhang et al. 2006); transient zombies?

- Pulsars with variable emission geometry?
  - perhaps some pulse structure flips to other pole (in some currently unkown way….)



How many RRATs are there?

- Current Monte Carlo estimates based on burst statistics of these 11 sources suggest there may be several hundred thousand such sources
  - more than current estimate for active radio pulsars!
  - future studies with wide-field telescopes (ultimately SKA!) may reveal huge new population

Crab Nebula (SN 1054)

3C58 (SN1181)

NO… we now see this pulsar

beamed toward

beamed away

SYNCHROTRON NEBULA

X-RAY PULSAR

companion

rapid rotation

bow shock

outside shell

inside shell

high velocity

low velocity

NOTHING

THERMAL X-RAY POINT SOURCE

NO… the pulsars we see in these have normal fields

rapid cooling

normal cooling

RRATs?

SGR/AXP MAGNETAR

LOW BREAK-FREQUENCY SYNCHROTRON NEBULA

RADIO-QUIET PULSAR

slow rotation

$B \sim 10^9$

$B \sim 10^{12}$

$B \sim 10^{15}$

X-RAY PULSAR

Disk accretor

little or none

modest

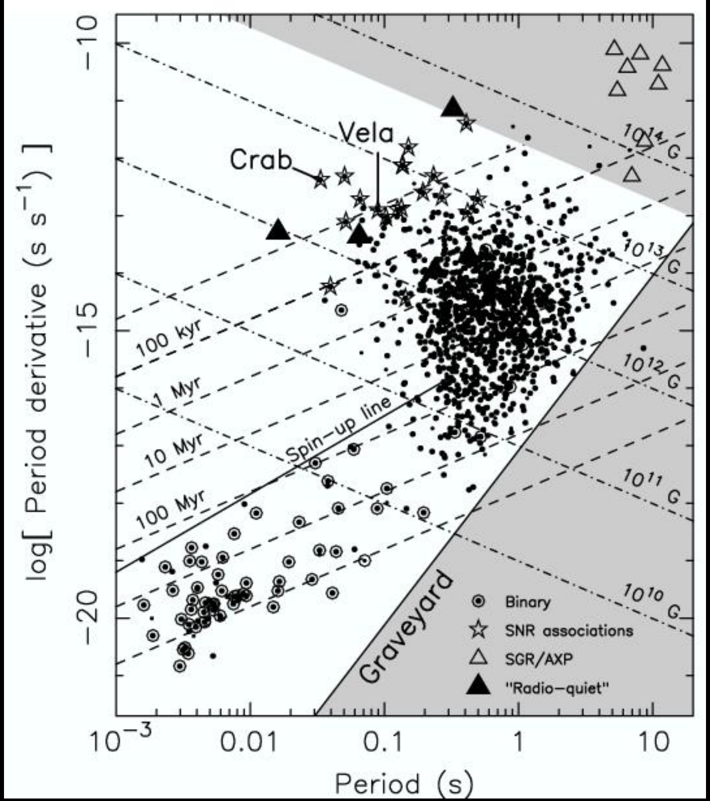
fall back

lots

BLACK HOLE

$M > 10M_\odot$ → core collapse → SN → NEUTRON STAR

Isolated Old Neutron Stars in the Galaxy



See Treves et al. 2000, PASP, 112, 297

Given a supernova rate of about 3 per century, there must be a lot of old neutron stars in the Galaxy. About how many?

As neutron stars move through the Galaxy, they encounter interstellar material. The emission from the accretion of this process could potentially be detected, giving us a way to identify many old neutron stars that are no longer active as pulsars (or cooling neutron stars). By requiring that the gravitational energy surpasses the kinetic energy associated with the relative motion of a neutron star and the ambient ISM, derive an expression for the accretion radius.

As the NS moves through the ISM of density ρ, at velocity v, it accretes material from a cylinder whose radius is the accretion radius. Calculate *dM/dt*, the rate at which matter is accreted by the NS, and the gravitational accretion luminosity. Assume a typical velocity for a NS, and a typical density for the ISM.

The polar cap of the neutron star can be considered to be a circular region centered on the magnetic axis and bounded by the last closed magnetic field line, which is located at

$$\sin\theta = \left(\frac{\Omega R_{NS}}{c}\right)^{1/2}$$

where $\Omega = 2\pi/P$ with P being the rotation period of the neutron star. Assuming that the magnetic field ultimately directs the accretion flow onto the polar cap, and that the accretion luminosity is in the form of blackbody radiation, estimate the temperature of the emission.

The emission from a NS accreting from the ISM is relatively faint, and also concentrated at low energies. It can be detected only for nearby NSs, for which absorption is not significant. Suppose a reasonable working estimate for the maximum distance at which such an object could be detected is 400 pc. About how many such old, accreting neutron stars might we expect to see?