Being different isn't always a bad thing

The stories of the "other" Neutron Stars

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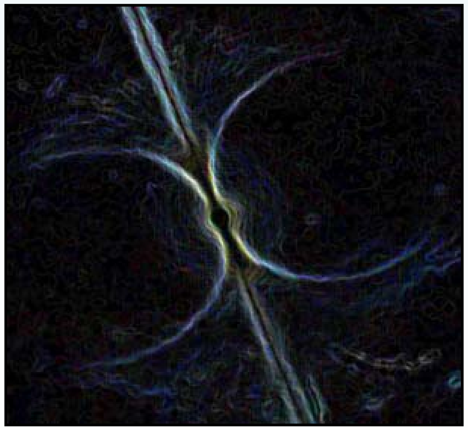
ESO, Vitacura, March 11th 2008

Talk Layout

- The common Neutron Star picture
- Neutron Stars not detected as Radio Pulsars
- Neutron Star Phenomenology
- Neutron Stars similarities & diversities
- Future Prospects

Radio Pulsars



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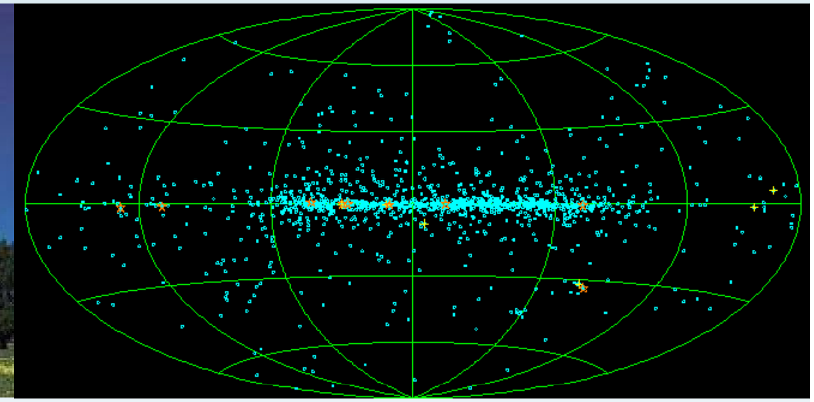
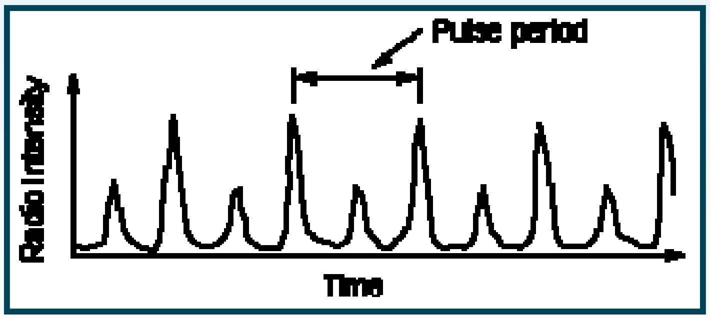
Overview

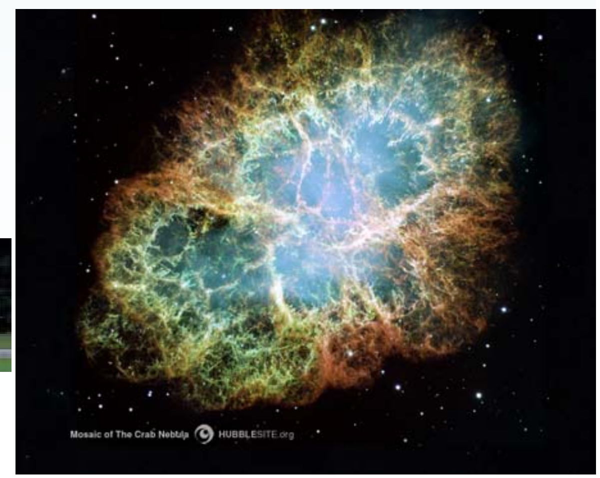


- After their discovery in 1967, ~2000 pulsars have been identified in radio.



$P = 1.5\text{ms} - 10\text{ s}$

$dP/dt = 10^{-20} - 10^{-11}\text{ s s}^{-1} > 0$ → spin down



- Associated with fast spinning Isolated Neutron Stars (INSs) born in SN explosions (Pacini 1968, Gold 1968)
- Progenitors of 8-20 M_{Sun}
- $R_{NS} \approx 10$ km, $M_{NS} \approx 1.4\ M_{sun}$, $\rho_{NS} \approx 10^{14}$ g cm^{-3}

20+mil/cm^3=1/10 ρ_{NS}

The Magnetic Dipole Model

Magnetic dipole loss

$$\dot{E} = -\frac{2}{3c^3}|\ddot{\mathbf{m}}|^2 = -\frac{B_p^2 R^6 \Omega^4 \sin^2\alpha}{6c^3}$$

Rotational energy loss

$$\dot{E} = I\Omega\dot{\Omega}$$ where: $$E = \frac{1}{2}I\Omega^2$$

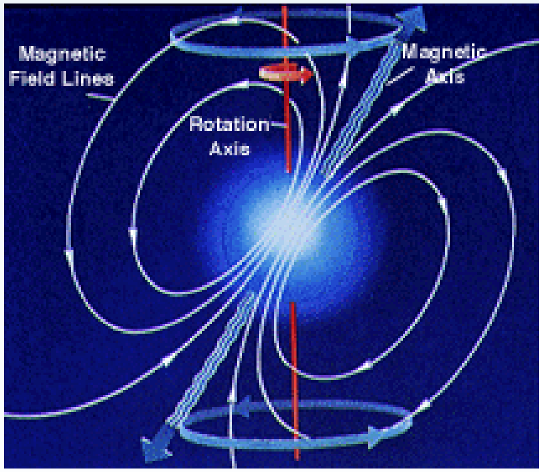
I= 10^{45} g cm^2
R = 10 km
M = 1.44 M_s

If $d\Omega/dt = k\,\Omega^n$ and n=3

Braking Index

$$B_p \sin\alpha(\mathrm{G}) = 3\times10^{19}\sqrt{P\dot{P}}$$

Dipole Magnetic field



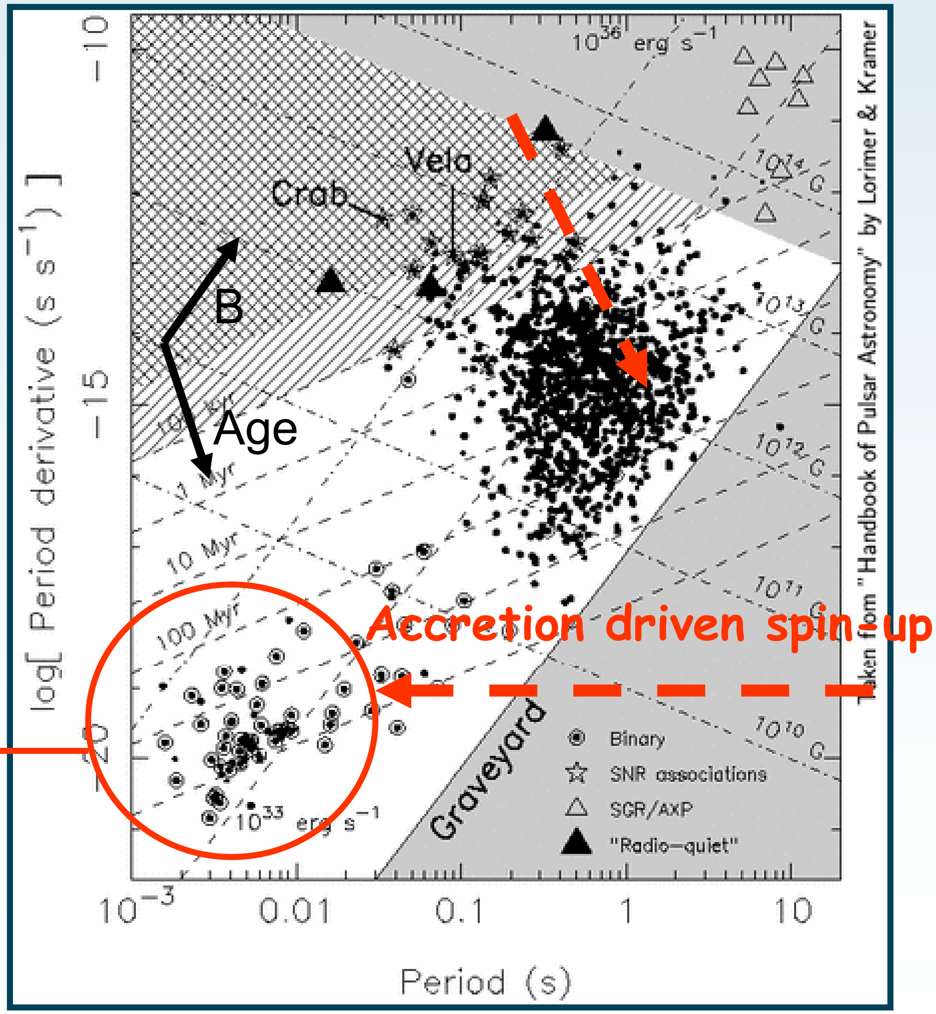
If $\Omega_o << \Omega_i$

$$T = -\Omega/\dot{\Omega} = P/\dot{P}$$

Characteristic Age

The "HR diagram" of Radio Pulsars ("PPdot")

"recycled" ms-pulsars



If a pulsar is alone in the graveyard is lost!

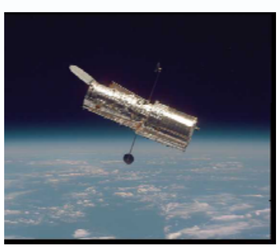
.... but, if it has a companion it can escape!

The common Neutron Star picture (so far)

- Radio sources
- Powered by rotation
- Persistent and stable emitters
- Crab is a prototype of young NSs
- Old NSs have low magnetic fields

Multi-λ Observations of Pulsars

- Multi-λ observations opened new ways to search for INSs
- Some radio pulsars were first detected at high energies and only later in radio
- ⇒ An INS can manifest **ONLY** at λλ different than radio
- ⇒ Identification of peculiar INSs, unnoticed otherwise
- The case of Geminga, *the first radio-quiet INS*, identified in γ-rays


The "other" INSs

- Other radio-quiet INSs were then discovered in X/γ-rays
- However, different INS flavours were unrecognized yet

Radio Pulsars

Radio Active ←

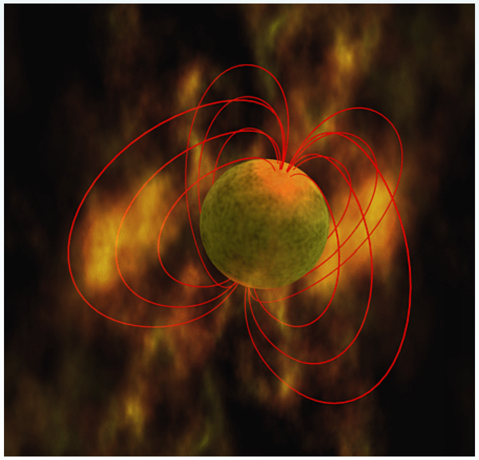
Radio Quiet →

Radio Quiet INSs

Why Radio Quiet?

- Unfavorable radio beam geometry (To Beam or not To Beam ?)
- Radio Emission has decayed because the NS has moved to the Graveyard
- Radio Emission is suppressed (e.g. by accretion from ISM or a debris disk)
- NS born in the graveyard, as a very slow rotator with a very low spin-down rate
- May be indeed radio active but intrinsically very faint
- May be radio active but not persistent

Hyper-Magnetic Neutron Stars
(a.k.a. Magnetars)



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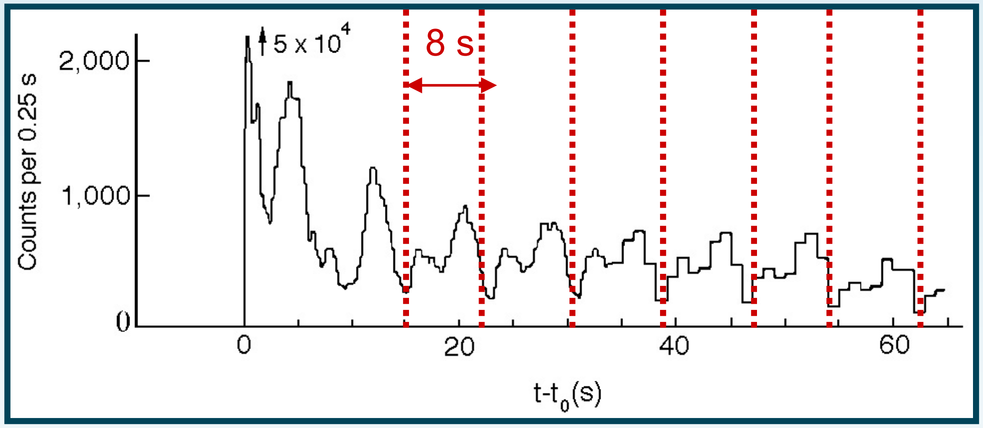
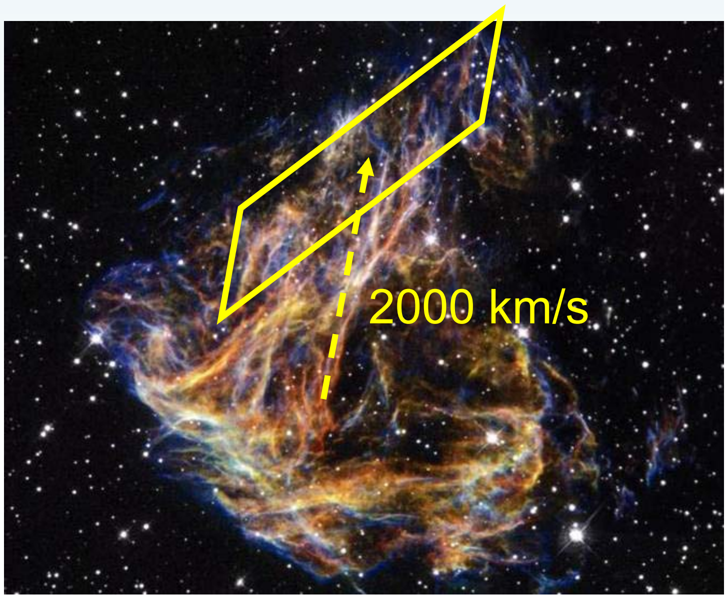
The Soft Gamma Ray Repeaters (SGRs)

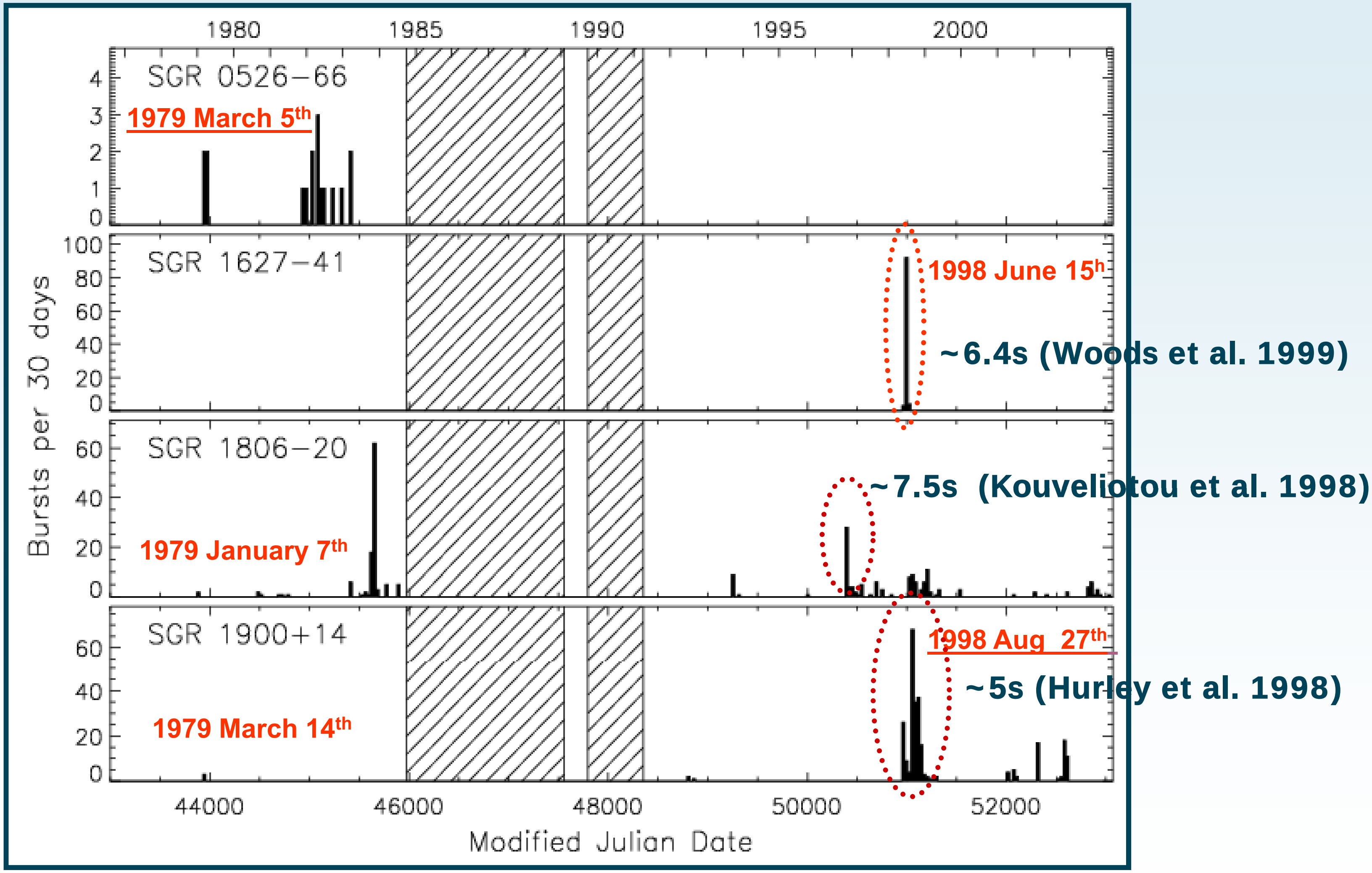
- March 5th 1979: γ-ray burst from the LMC direction ($L_\gamma \sim 10^{45}$ ergs s^{-1})



- Recurrent → NOT like the known GRBs
- Discovery of 8s period in the light curve decay
- Associated to the N49 SNR
- Pulsations + SNR → Neutron Stars
- Slow pulsar + young SNR →very fast spin down

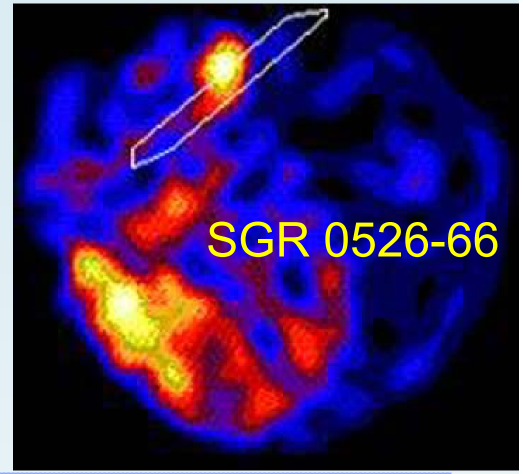


The Discovery of New SGRs



All known SGRs are found to pulsate → The Neutron Star hypothesis settles!

Timing Parameters

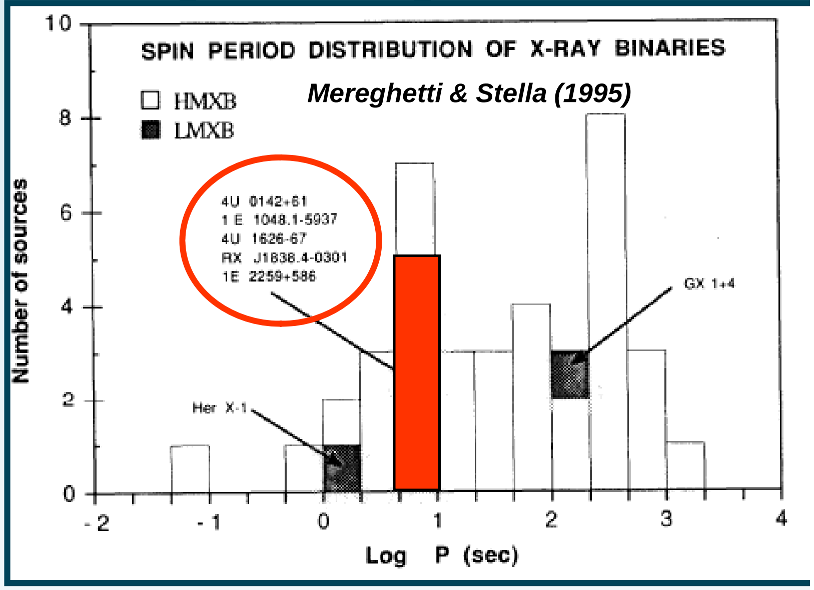


- Pulsating X-ray counterparts detected. Steady.
- X-ray timing yielded the period derivative, hence: (i) the age , (ii) the B-field and (iii) the rotational energy loss
- $L_X \sim 10^{35}$ ergs/s >> dE/dt → X-ray emission not powered by the NS rotation
- X-ray spectra: BB + PL
- What kind of NS ??

NAME	P (s)	dP/dt (10^{-11} s s^{-1})	dE/dt (10^{34} ergs s^{-1})	B (10^{14} G)	Age (kyrs)	SNR
SGR 0526-66	8.0	6.6	0.5	7.4	1.9	N49
SGR1627-41	*6.4*	-	-	-	-	
SGR1806-20	7.5	8.3	0.77	7.8	1.4	
SGR1900+14	5.2	6.1	1.7	5.7	1.3	

The Anomalous X-ray Pulsars (AXPs)

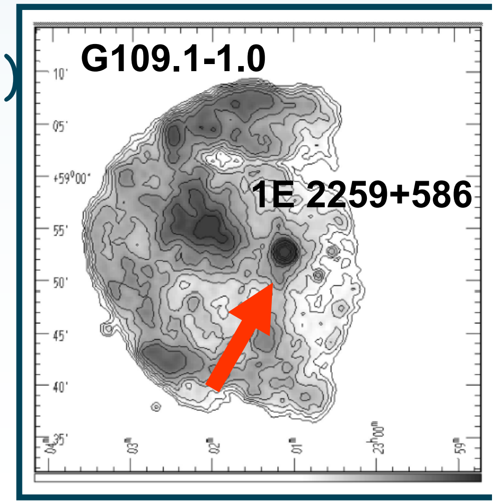
- Why "Anomalous"?
- Narrow P distribution



- Long P wrt isolated XRPs → Binary
- Lx ~ dM/dt → Binary

However,

- No optical counterparts → very low mass companions (if any)
- No evidence for a companion (X-ray eclipses, Doppler shifts)
- Steady spin down, not spin up as expected in XRB pulsars
- Coincident with SNRs, uncommon for XRBs (only SS433)

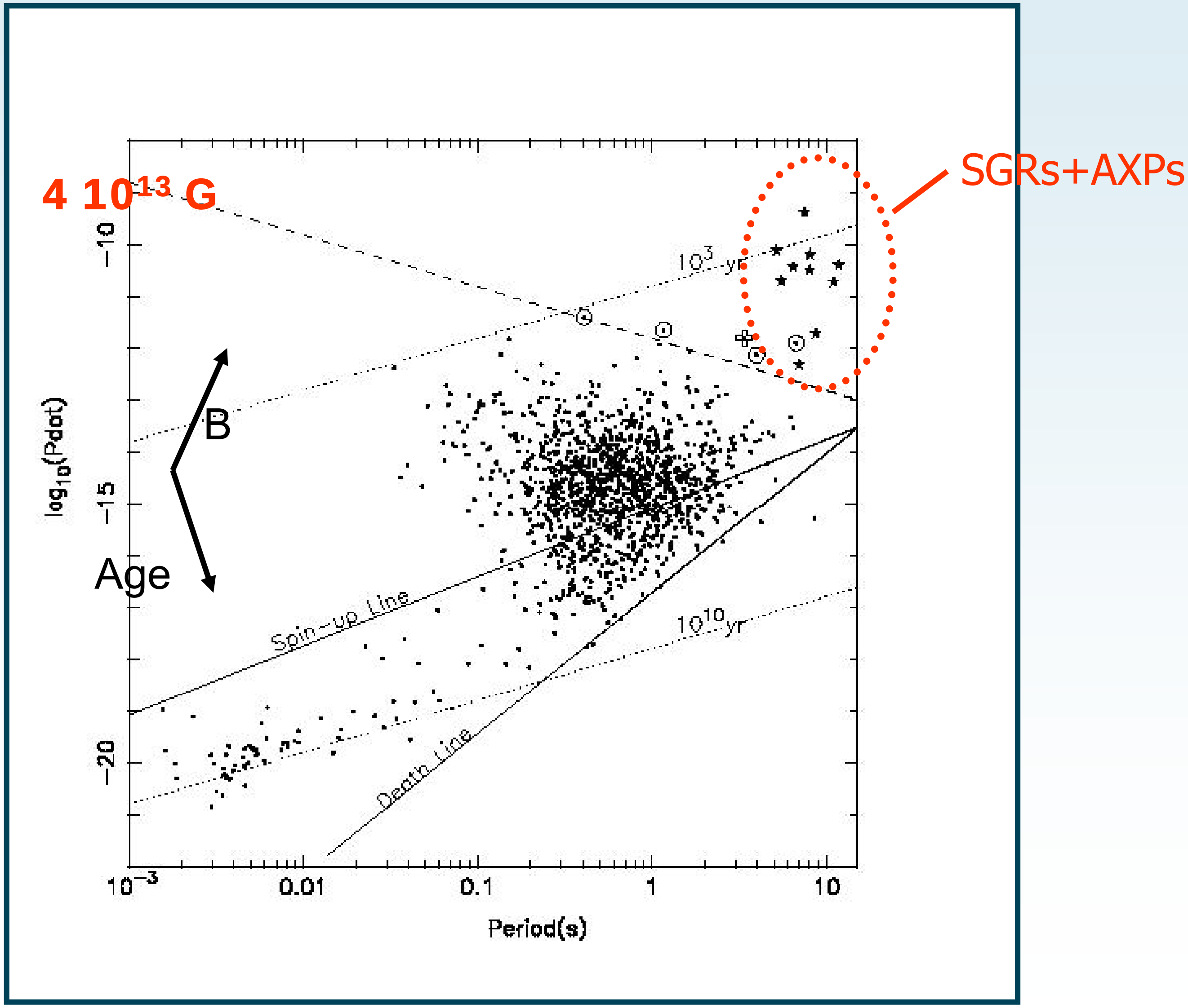


Timing Parameters

- Periods, spin down, age, magnetic fields, all make them similar to SGRs
- $L_X \sim 10^{35}$ ergs/s >> dE/dt → X-ray emission not powered by the NS rotation
- X-ray spectra: BB + PL
- However, bursting is very rare (in X-rays only). No γ-ray activity (quiescent?)

NAME	P (s)	dP/dt (10^{-11} s s^{-1})	dE/dt (10^{34} ergs s^{-1})	B (10^{14} G)	Age (kyrs)	SNR	Notes
CXOU J010043.1-721134	8.0	1.88	0.14	3.9	7		
4U 0142+61	8.7	0.20	0.012	1.3	70		
1E 1048.1-5937	6.4	1.3	0.19	3.9	4.3		*bursting*
CXOU J164710.2-455216	*10.6*	*<20*	*<0.3*	*<15*	*>0.8*		*transient*
RX J170849-400910	11.0	1.9	0.056	4.7	9.0		
XTE J1810-197	5.5	1.5	0.35	2.9	5.7		*transient*
1E 1841-045	11.8	4.2	0.1	7.1	4.5	G27.4+0.0	
AX J1844-0258	*7.0*	-	-	-	-	*G29.6+0.1*	
1E 1547.0-5408	2.0	2.3	10	2.2	1.4		*transient*
1E 2259+586	7.0	0.05	0.0057	0.60	220	G109.1-1.0	*bursting*

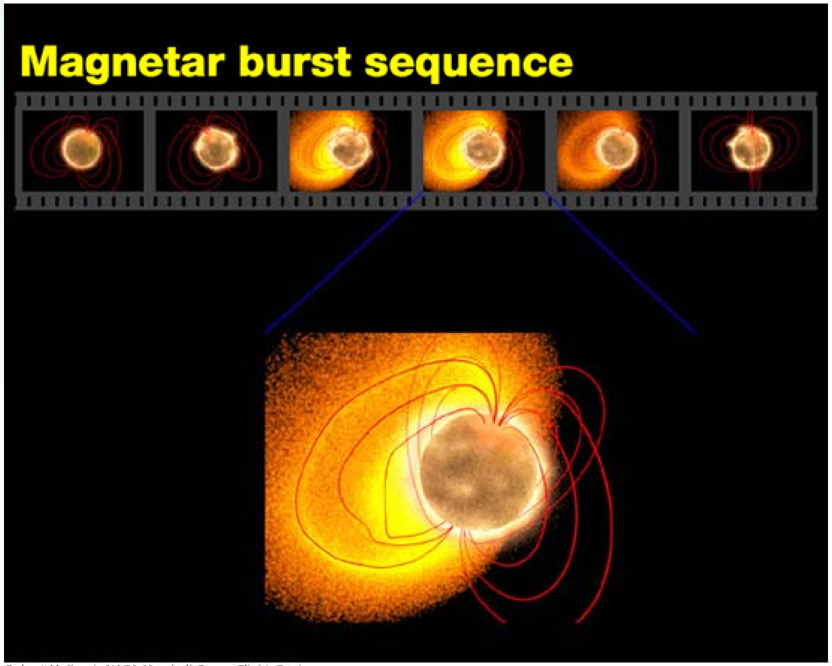
Both AXPs and SGRs have high inferred magnetic fields



The Magnetar Model

(Duncan & Thompson 1992; Thompson & Duncan 1995)

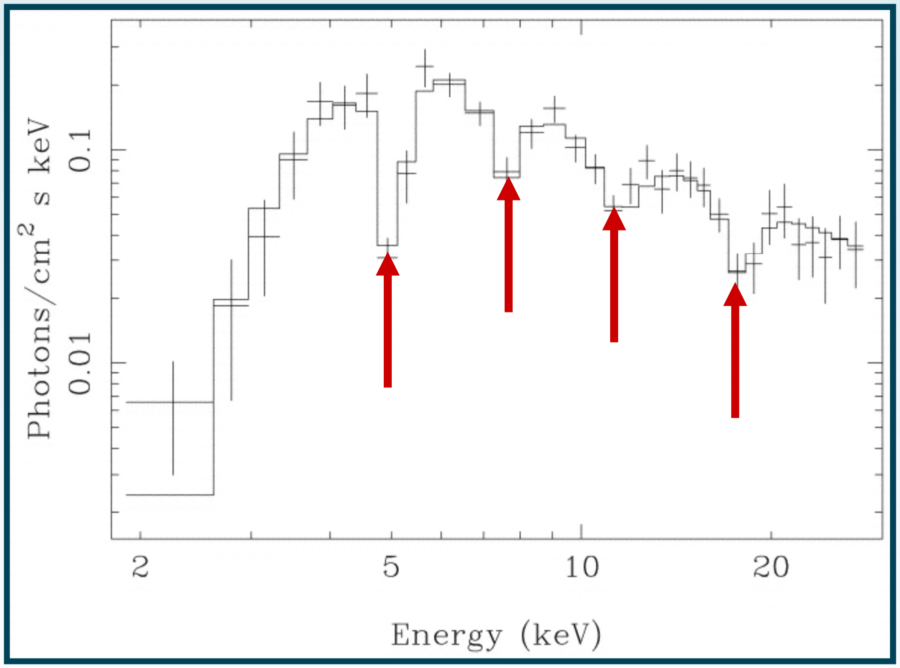
- Magnetar = Magne(tic s)tar
- Radio emission inhibited by the high magnetic field (> 4.33 10^{13} Gauss)
- The magnetic braking slows down rapidly the neutron star rotation
- X-ray emission powered by the magnetic field decay
- Star quakes in the crust produce twists of the magnetic field which energize particles in the external magnetosphere → bursts



Robert Mallozzi, NASA Marshall Space Flight Center

A Direct Measure of the Magnetic Field

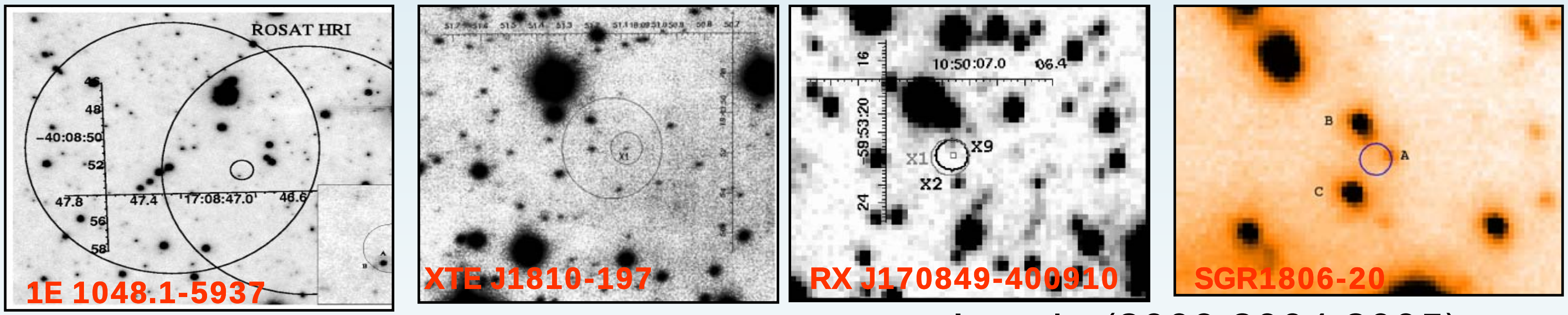
- In the meantime, X-ray cyclotron absorption lines have been detected in SGR 1806-20 (Ibrahim et al. 2002; 2003)



- B ~ 10^{15} G (proton cyclotron), vs B ~ 8 10^{14} G from the spin-down
- Features detected in outburst ONLY → difficult to monitor
- Tracers of some kind of change in the magnetic activity during the outburst

Accretion models

- Accretion from a very low mass companion or from a fallback disk
- Optical/IR observations are important to test different models

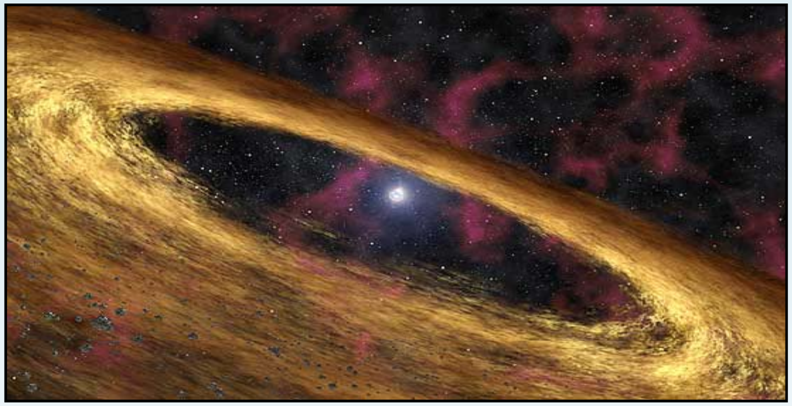


Israel+ (2003,2004,2005)

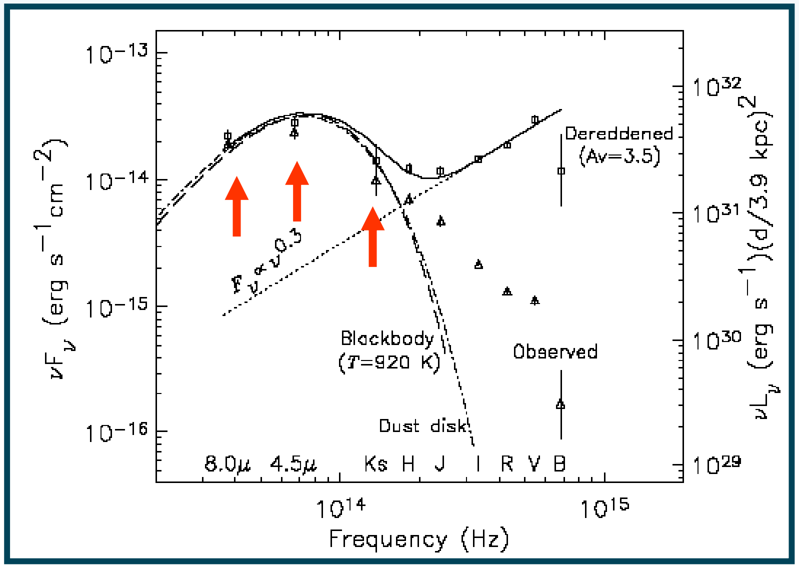
- IR emission most likely from the Magnetar itself or from a fossil disk
- From disk models → $r_{disk} \gg r_{corotation}$
- No disk-magnetar interaction

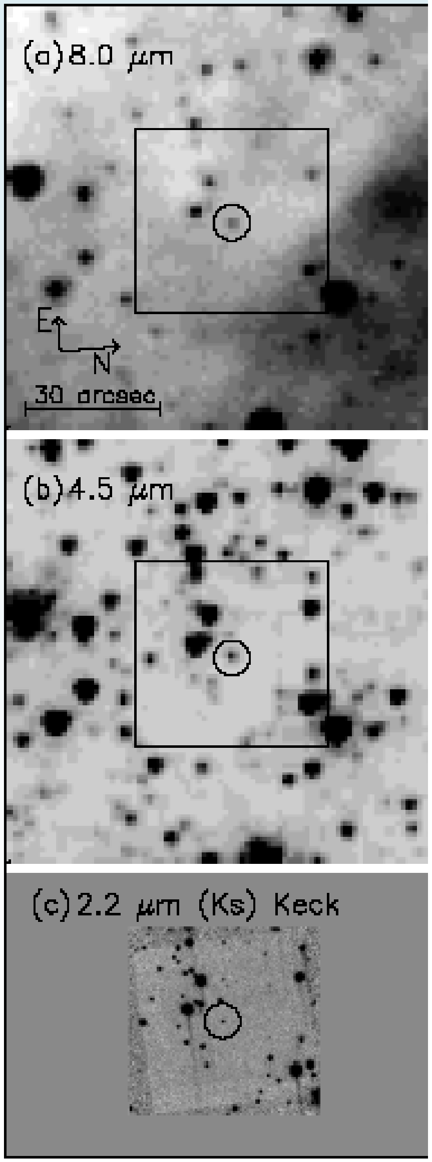
→ disk does not power the X-ray emission
→ does not affect the spin-down → measured B-field genuine

Evidence of a Fossil Disk (?)

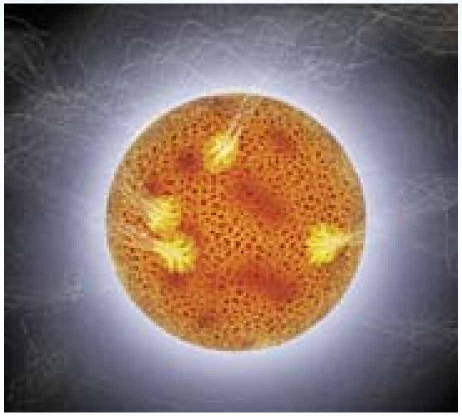


- The existence of disks around a NS has been supported by recent Keck and Spitzer observations of the AXP 4U0142+61 (Wang+ 2006)





Old Neutron Stars
with
Surface Thermal Emission
(a.k.a. X-ray Thermal INSs)



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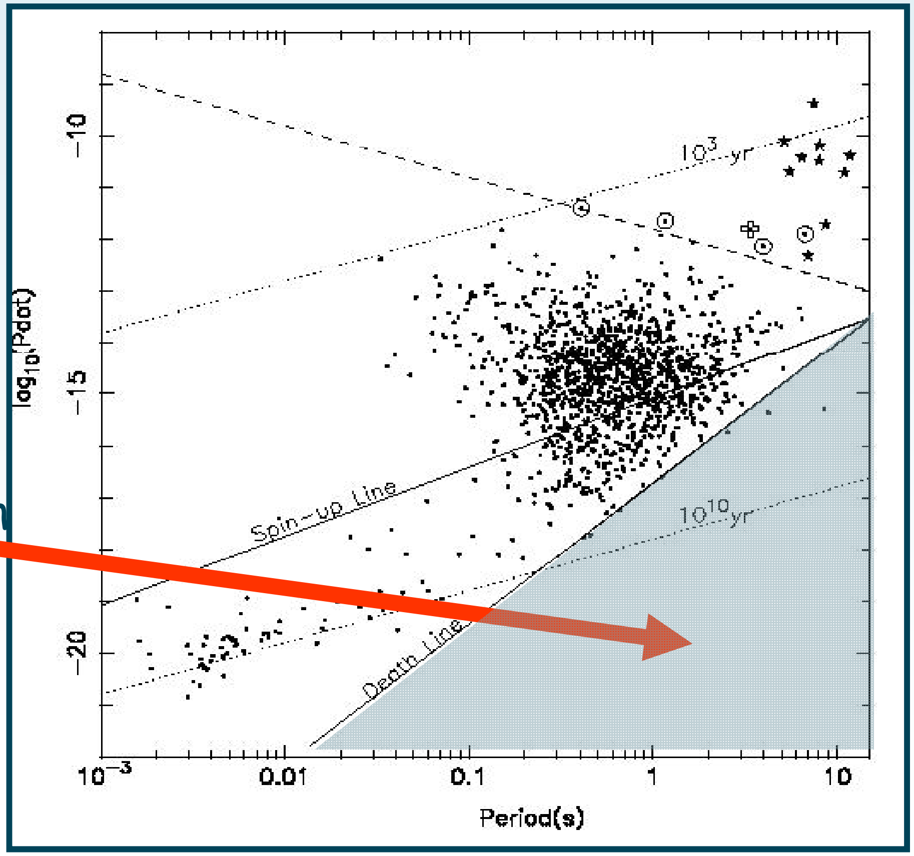
Overview

- 7 nearby INSs with purely thermal X-ray emission discovered by ROSAT
- $L_X \sim 10^{30-31}$ ergs/s
- INS identification certified by extreme F_X/F_{opt}

- Age > 10^6 years
- No SNR association → old
- No magnetospheric emission → old
- Old → No longer radio active

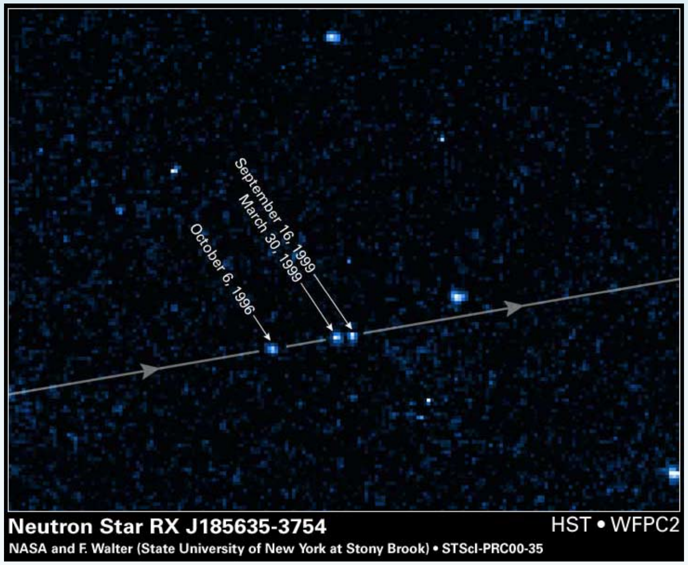
- Originally thought to be the tip of the iceberg of the radio-dead pulsar population

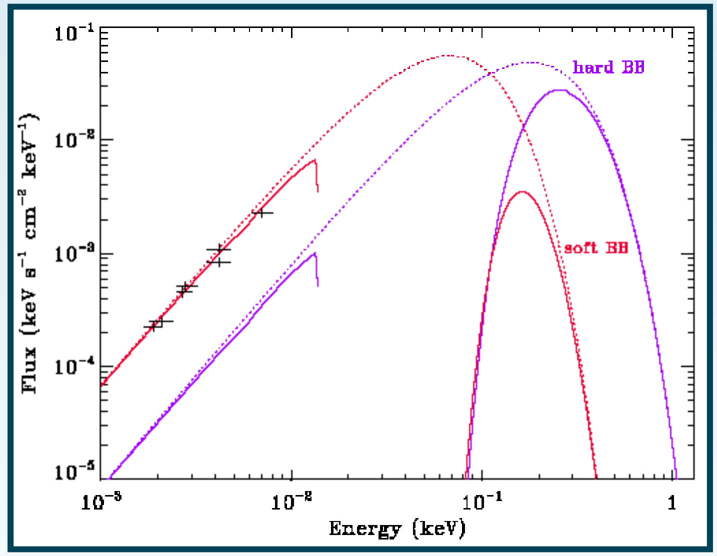
- X-rays from ISM accretion



Cooling Neutron Stars ?

- Optical identifications → proper motions & parallaxes → velocity wrt ISM



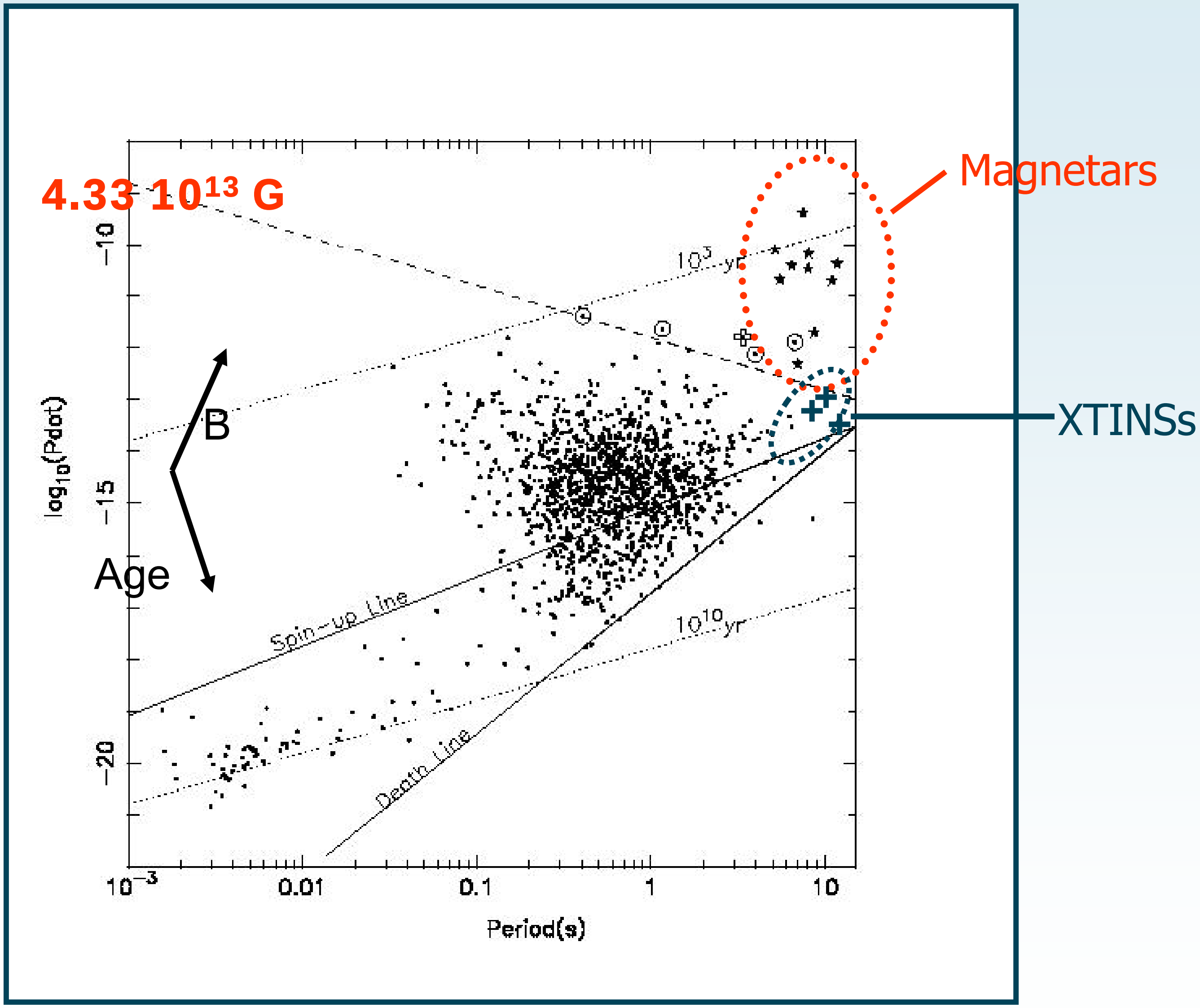


- Cooling favored vs ISM accretion
- Optical SED is thermal with BB_{opt} cooler than BB_X (Mignani+ 2004)
- NS thermal map → heat transfer in the NS interior → composition
- Distance + T → NS radius → M/R → EOS

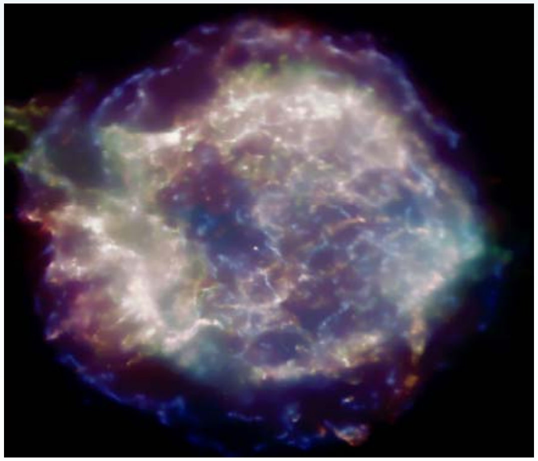
Or Evolved Magnetars ?

- Pulsed X-ray emission
- Periods ~ magnetars + $L_X \approx dE/dt$ + B ≈ magnetars
- Much less energetic wrt the Magnetars
- No magnetar-like behavior
- No γ-ray emission. X-ray emission is steady

NAME	P (s)	dP/dt (10^{-11} s s^{-1})	dE/dt (10^{34} ergs s^{-1})	B (10^{14} G)	Age (kyrs)	Notes
RXJ 1856.5-3754	10.0	0.003	0.0003	0.15	4000	$L_X >> dE/dt$
RXJ 0720.4-3125	8.4	0.007	0.00047	0.56	1900	$L_X >> dE/dt$
RXJ 1308.6+2127	10.3	0.011	0.00039	0.46	1500	$L_X \approx dE/dt$
RXJ 1605.3+3249	6.88 (?)	-	-	0.8	-	-
RXJ 0420.0-5022	3.45	-	-	0.66	-	-
RXJ 0806.4-4123	11.4	-	-	0.86	-	-
RXJ 214303.7+065419	9.43	-	-	~1	-	-


4.33 10^{13} G
Magnetars
XTINSs
B
Age
10^3 yr
10^{10} yr
Spin-up Line
Death Line
$\log_{10}$(Pdot)
−10
−15
−20
10^{-3}
0.01
0.1
1
10
Period(s)

Enigmatic Neutron Stars in Supernova Remnants
(a.k.a. Compact Central Objects – CCO)



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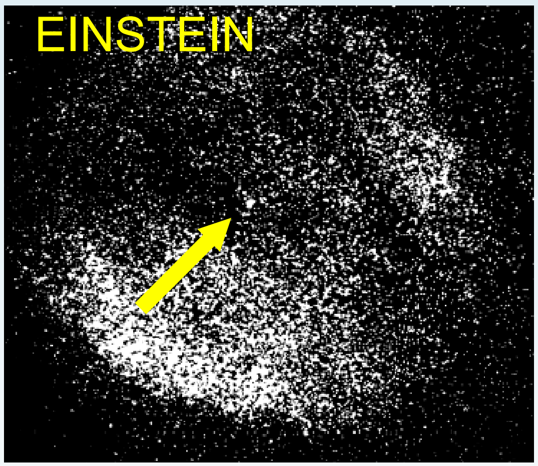
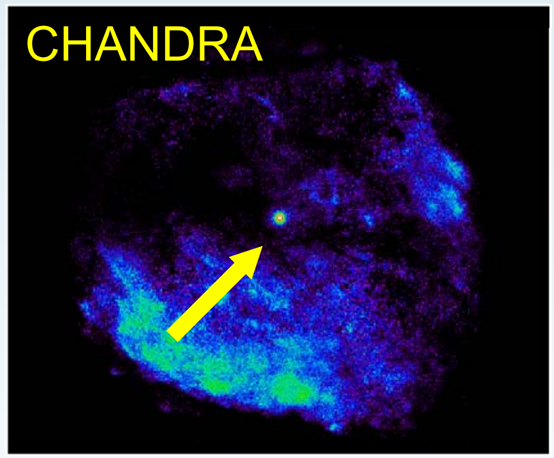
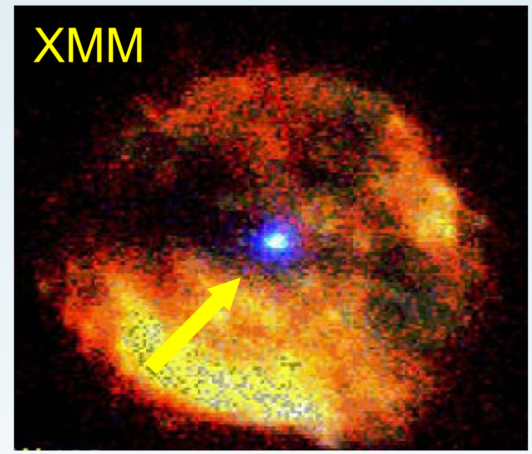
Overview

- 8 X-ray sources detected at the center of SNRs. Pinpointed by EINSTEIN, then by ROSAT, got the limelight with CHANDRA and XMM







- Not yet detected in radio. Unfavorable Beaming ??
- X-ray spectra: 2 BBs ($\approx 10^6$ K). NO magnetospheric activity
- Young (~ kyrs) from SNR ages, but not from X-ray spectra. No γ-ray emission.
- Nature of CCOs is unclear

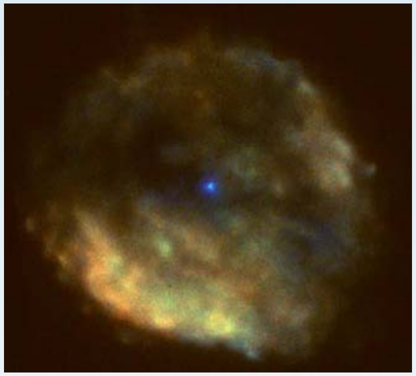
Timing Parameters

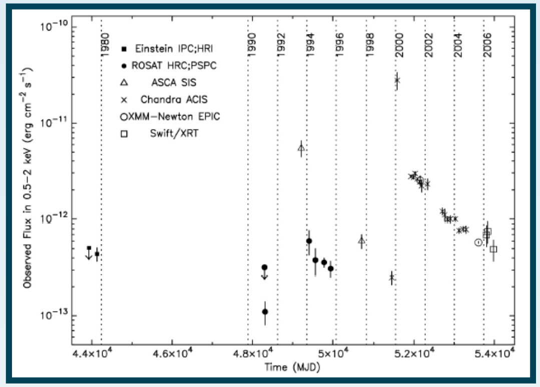
- Not pulsating in X-rays, apart from two (possibly four)
- Periods might look somehow longer than expected for young pulsars
- For only one case period derivative measures have been obtained (uncertain)

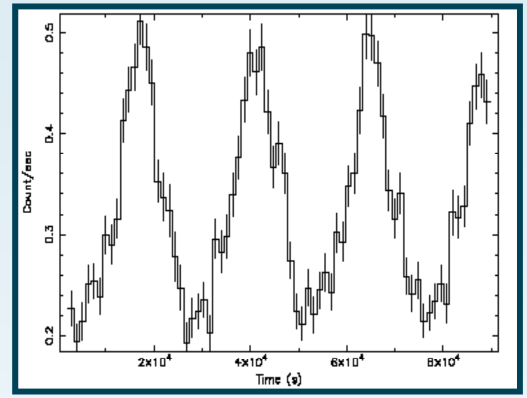
NAME	P (s)	dP/dt (10^{-11} s s^{-1})	dE/dt (10^{34} ergs s^{-1})	B (10^{14} G)	Age (kyrs)	Notes
RX J082157.5-430017	0.22(?)	-	-	-	3	Puppis A
RX J085201.4-461753	-	-	-	-	2	Vela Jr.
1E 1207-5209	0.424	<0.000016	*<0.013*	*<0.0033*	*700*	G296.5+10.0
CXOU J16013.1-513353	7.5 (?)	-	-	-	-	G330.2+1.0
1E 16148-5051	-	-	-	-	2	RCW103
CXOU J171328.4-394955	-	-	-	-	10	G347.3-0.5
CXOU J171801.0-372617	-	-	-	-	*2*	*G349.7+0.2*
CXOU J185238.6+004020	0.105	<0.00002	<0.7	<0.0015	7	Kes 79
CXOU J232327.9+584843	-	-	-	-	0.3	Cas A

- Slowly born, low-magnetic, neutron stars (Gotthelf & Halpern 2007)

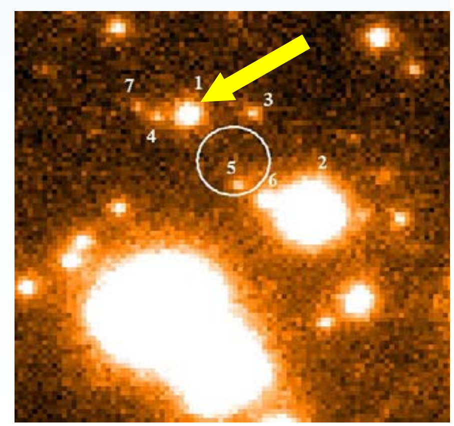
The peculiar CCO in RCW103



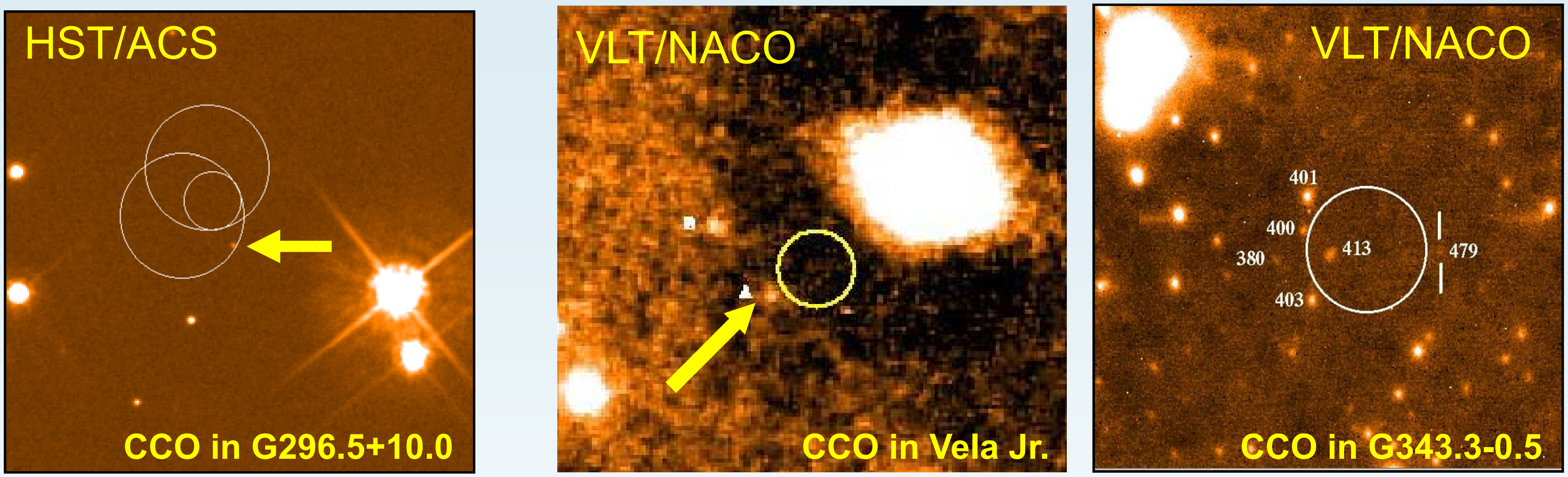




- Long term X-ray variability measured with all X-ray satellites since ROSAT
- 6 hrs period clearly detected by XMM (De Luca+ 2006)
- Accreting NS? Or ultra slowly spinning NS (De Luca+ 2006)?
- Candidate low-mass (~ 0.1 M_{sun}) M dwarf companion star (Mignani+ 2004)
- Not confirmed by NACO observations (Mignani+ 2007; De Luca+ 2008). Only very late companion (or disk) allowed



Optical/IR Observations



- Candidate optical counterpart for the G296.5+10 CCO, ruled out (Mignani+ 2007a)
- Candidate IR counterpart identified for the Vela Jr CCO, compatible with a low-mass star (>M) or a debris disk (Mignani+ 2007b)
- No obvious counterpart for the G343.3-0.5 CCO. Best candidates also compatible with disks (Mignani+ 2008).

Radio Loud
vs.
Radio Quiet

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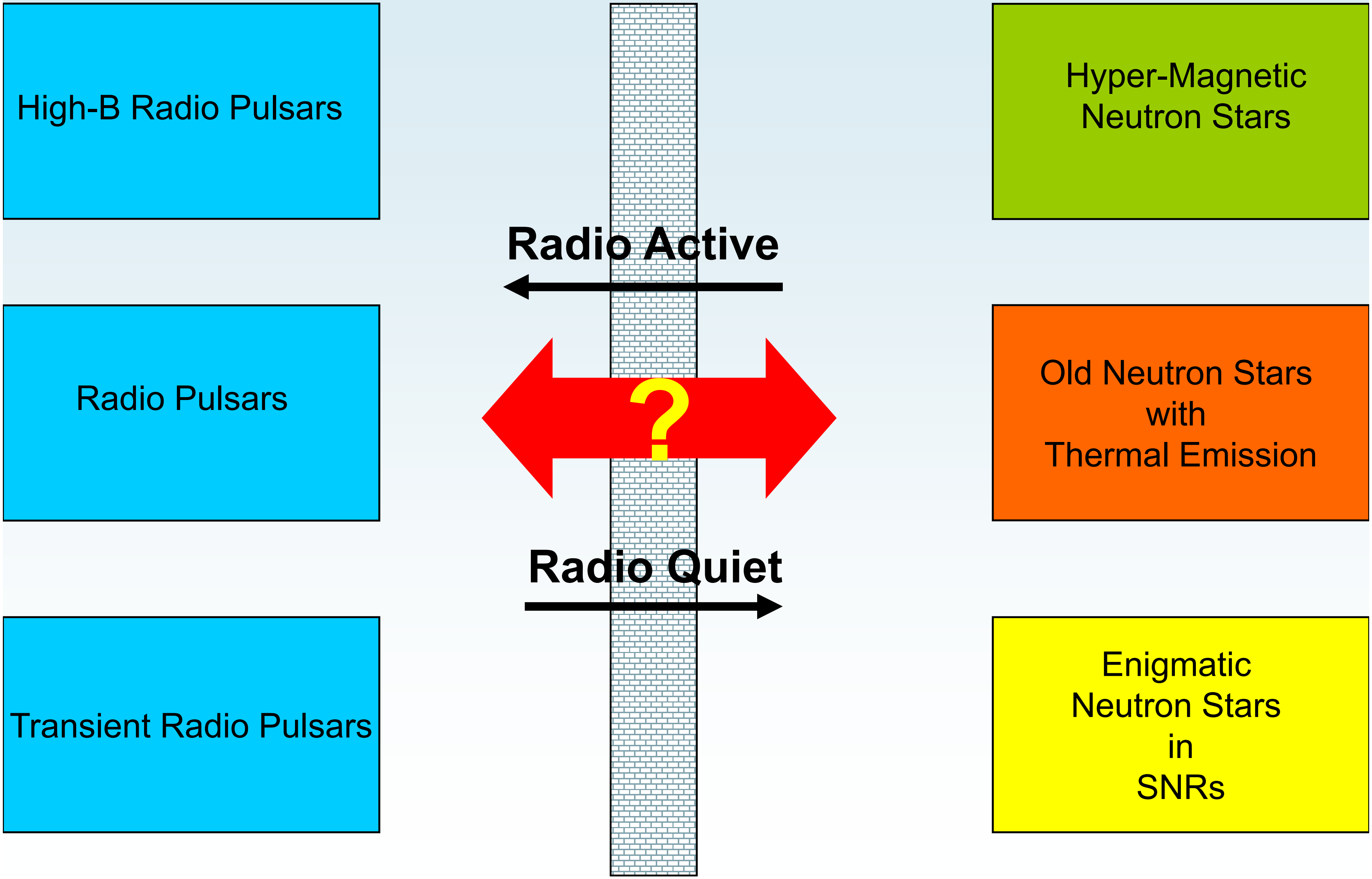
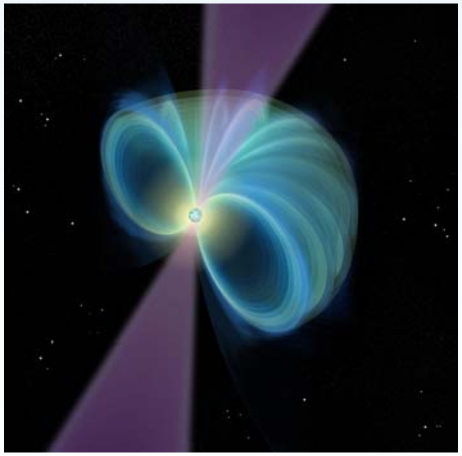

High-B Radio Pulsars
Radio Pulsars
Transient Radio Pulsars
Radio Active
?
Radio Quiet
Hyper-Magnetic Neutron Stars
Old Neutron Stars with Thermal Emission
Enigmatic Neutron Stars in SNRs

High-B Radio Pulsars (HBRPs)



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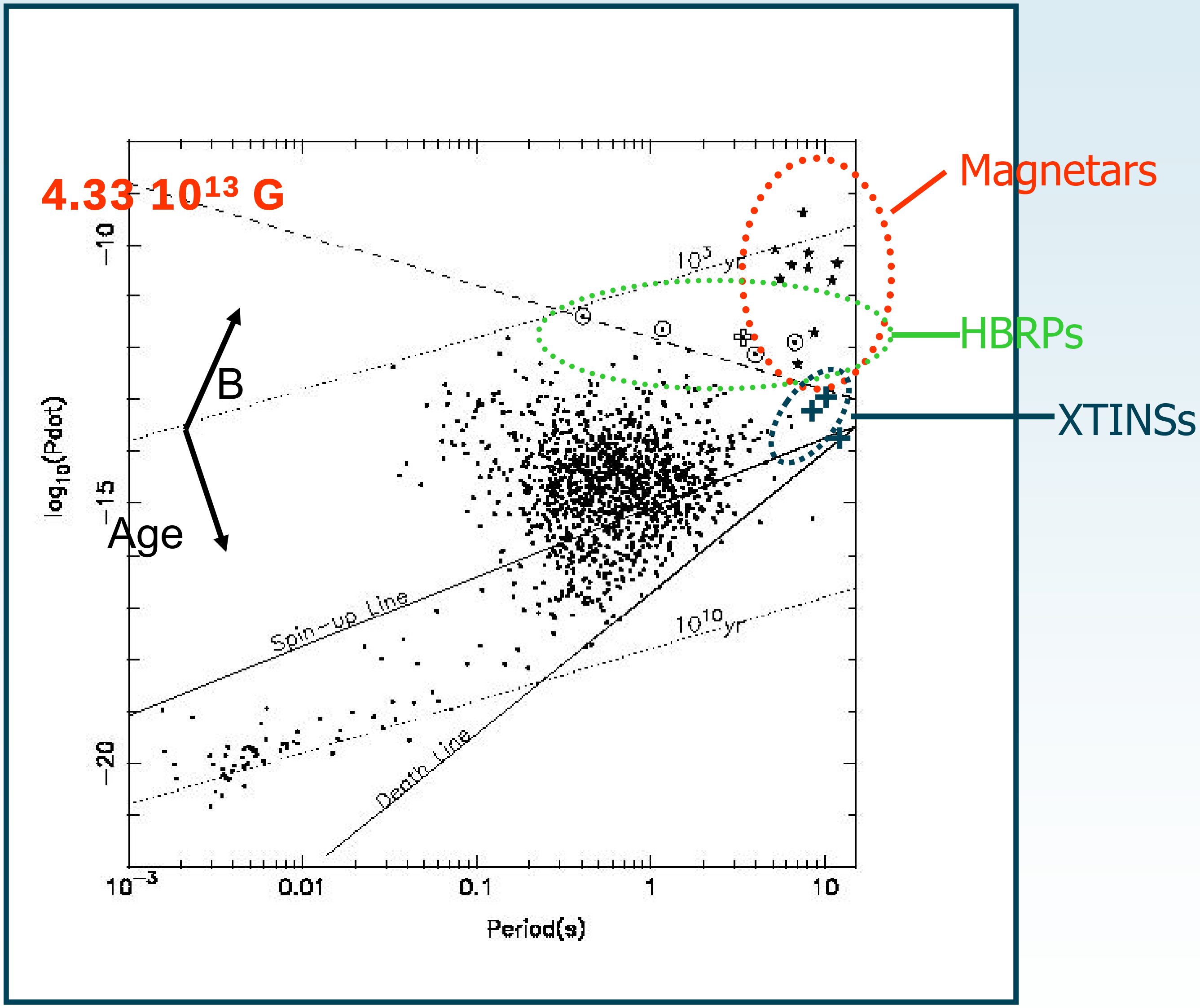
Overview

- A few (~40) **ordinary** radio pulsars identified with $B>10^{13}$ G
- 5 with $B>4.33\ 10^{13}$ G, i.e., the critical quantum field value above which radio emission should be suppressed
- These High-B radio pulsars should NOT expected to be radio pulsars at all !

NAME	P (s)	dP/dt (10^{-11} s s^{-1})	dE/dt (10^{34} ergs s^{-1})	B (10^{14} G)	Age (kyrs)
PSR J1119-6127	0.4	0.41	250	0.41	1.7
PSR J1718-3718	3.3	0.15	0.16	0.74	34
PSR J1734-3333	1.17	0.22	5.6	0.52	8.1
PSR J1814-1744	3.97	0.074	0.047	0.55	84.8
PSR J1847-0130	6.70	0.127	0.017	0.93	83.3

- Only two detected in X-rays. $L_X \sim 10^{32-33}$ ergs/s
- X-ray spectra: BB !!



4.33 10¹³ G
Magnetars
HBRPs
XTINSs
B
Age
Spin-up Line
Death Line
10³ yr
10¹⁰ yr
log₁₀(Pdot)
Period(s)

HBRPs vs Magnetars

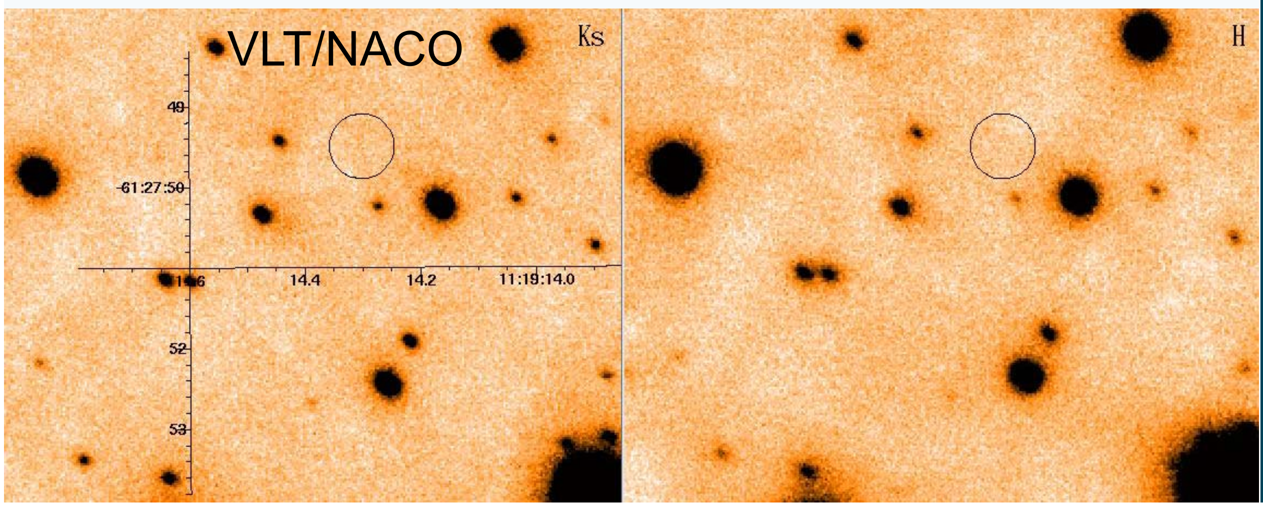
- HBRPs do not show magnetar-like behavior
  → Not transient. Not bursting. No γ-ray emission. **L_X < dE/dt**

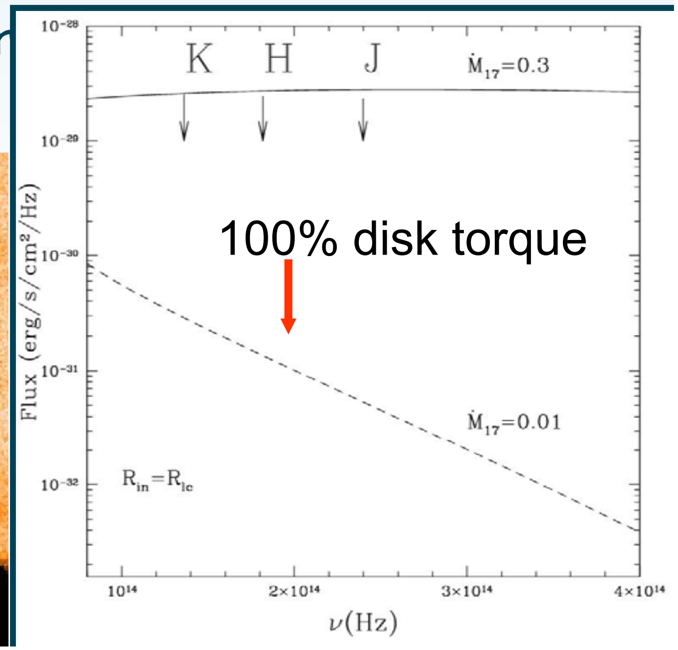
- HBRPs could be a different magnetar manifestation, or magnetars in a different evolutionary stage

-OR-

- Magnetic fields from spin down might be affected by torques from a disk

- A disk should be detectable in the IR but only upper limits so far (Mignani+ 2006,2007c)





Transient Radio Pulsars
(a.k.a. Rotating RAdio Transients -RRATs)

ESO, Vitacura, March 11th 2008

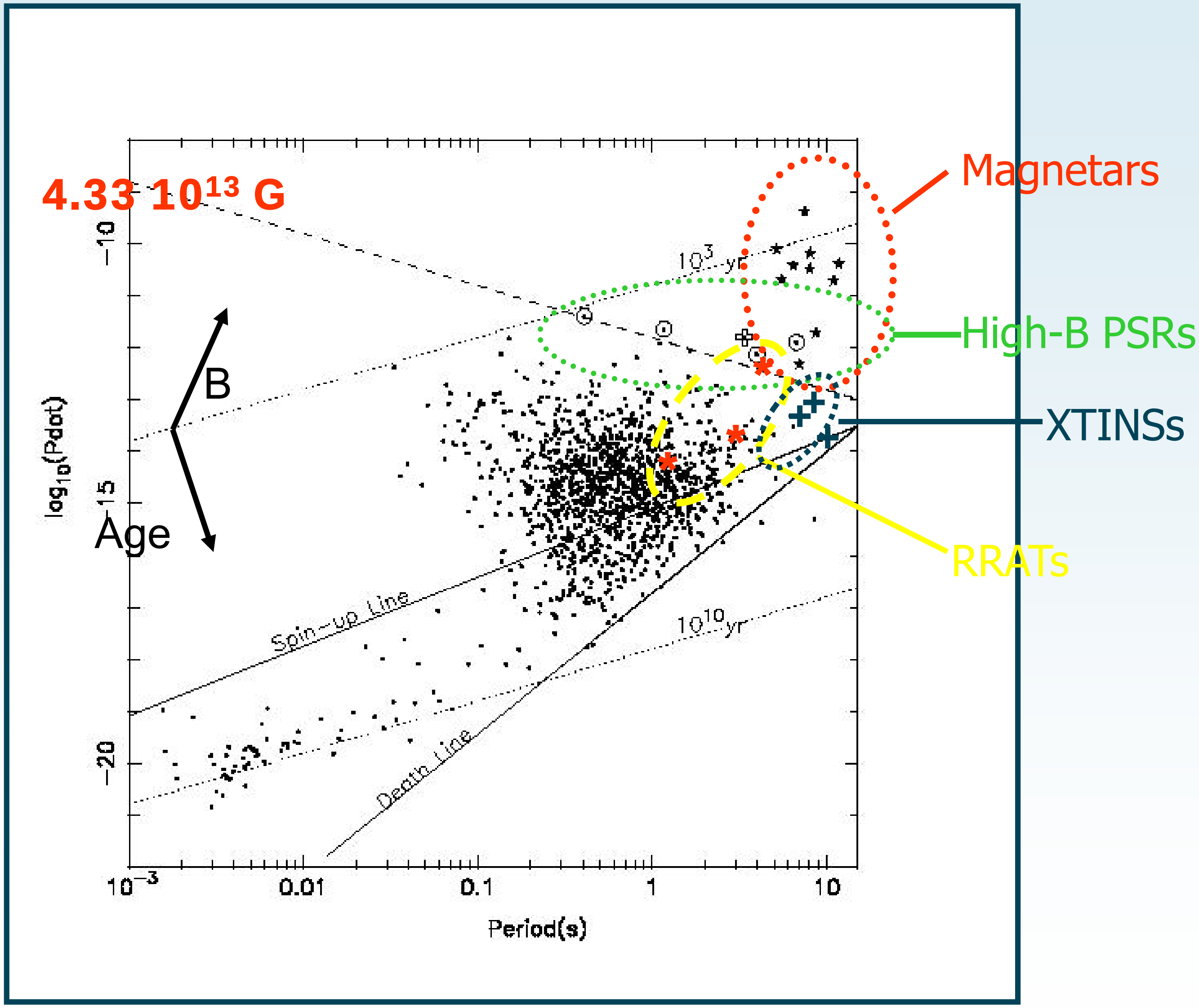
Overview

- 10 RRATs discovered (Mc Laughlin+ 2006), all in the Galactic Plane
- $F_{1400\ MHz} \sim 0.1\text{-}3.6$ Jy → among brightest radio sources in the sky
- Nature of RRATs is unclear (Binary ? Isolated ?)
- Proposed to be radio pulsars close to (or just beyond) the end of their life cycles (Zhang+ 2006)
- Only one RRAT detected in X-rays so far (Mc Laughlin+ 2007).
- $L_x \approx 3\ 10^{33}$ erg s^{-1}
- X-ray spectra: BB ($\approx 10^6$ K)

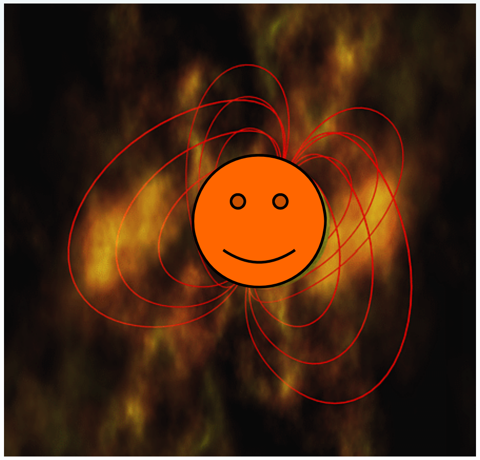
Timing Parameters

- $P = 0.4\text{-}7$ s , 3 with measured dP/dt
- Young and Old.
- $L_X > dE/dt + B \sim 0.5\ 10^{14}$ G → Candidate magnetar?

NAME	P (s)	dP/dt (10^{-11} s s^{-1})	dE/dt (10^{34} ergs s^{-1})	B (10^{14} G)	Age (kyrs)	Notes
J0848-43	5.97	-	-	-	-	
J1317-5759	2.64	0.0012	0.00269	0.058	3330	
J1443-60	4.75	-	-	-	-	
J1754-30	0.42	-	-	-	-	
J1819-1458	4.26	0.0576	0.0249	0.5	117	$L_X > dE/dt$
J1826-14	0.77	-	-	-	-	
J1839-01	0.93	-	-	-	-	
J1846-02	4.47	-	-	-	-	
J1848-12	6.79	-	-	-	-	
J1913+1333	0.92	0.000787	0.0394	0.0272	1860	


4.33 10^13 G
Magnetars
High-B PSRs
XTINSs
RRATs
B
Age
10^3 yr
10^10 yr
Spin-up Line
Death Line
log10(Pdot)
−10
−15
−20
10^−3
0.01
0.1
1
10
Period(s)

Radio Active – Radio Quiet INSs (?)



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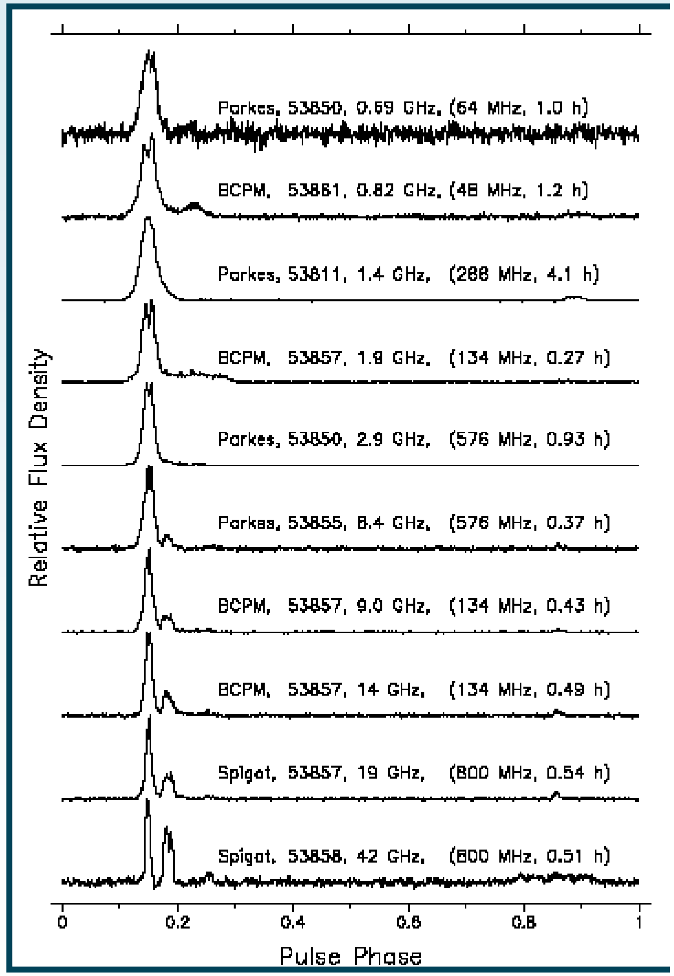
Transient Radio Emission from Magnetars

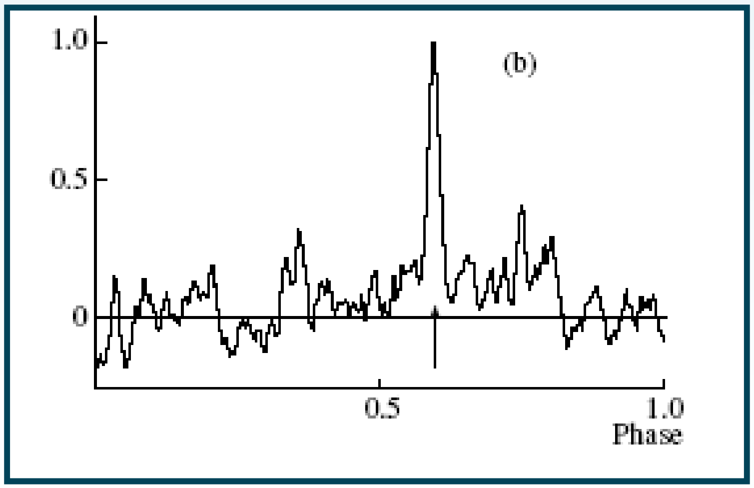
- Pulsed radio emission detected from two transient AXPs XTE J1810-197 (Camilo+ 2006) and 1E 1547.0-5408 (Camilo+ 2007)
- Radio emission from XTE J1810-197 80-95% polarized (Kramer+ 2007)
- In both cases radio emission observed after transition to high state (argues against accretion)
- Magnetic field rearrengement after X-ray brightening responsible for radio emission turn-on.



Steady Radio Emission from a Magnetar

- Radio pulsations detected for:

- 1E 2259+586 (Malofeev+ 2005)
- F_{111MHz} = 35 ± 25 mJy
- P = 6.97 s; dP/dt = 0.48 10^{-12} s s^{-1}

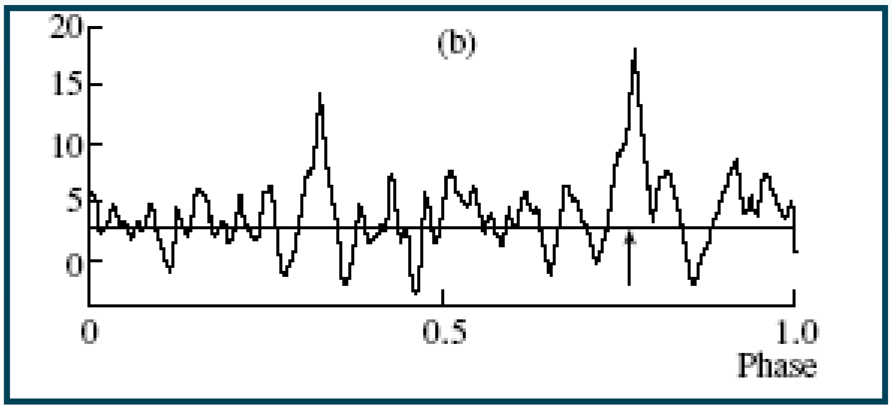


Steady Radio Emission from two XTINSs

- Radio pulsations detected for:

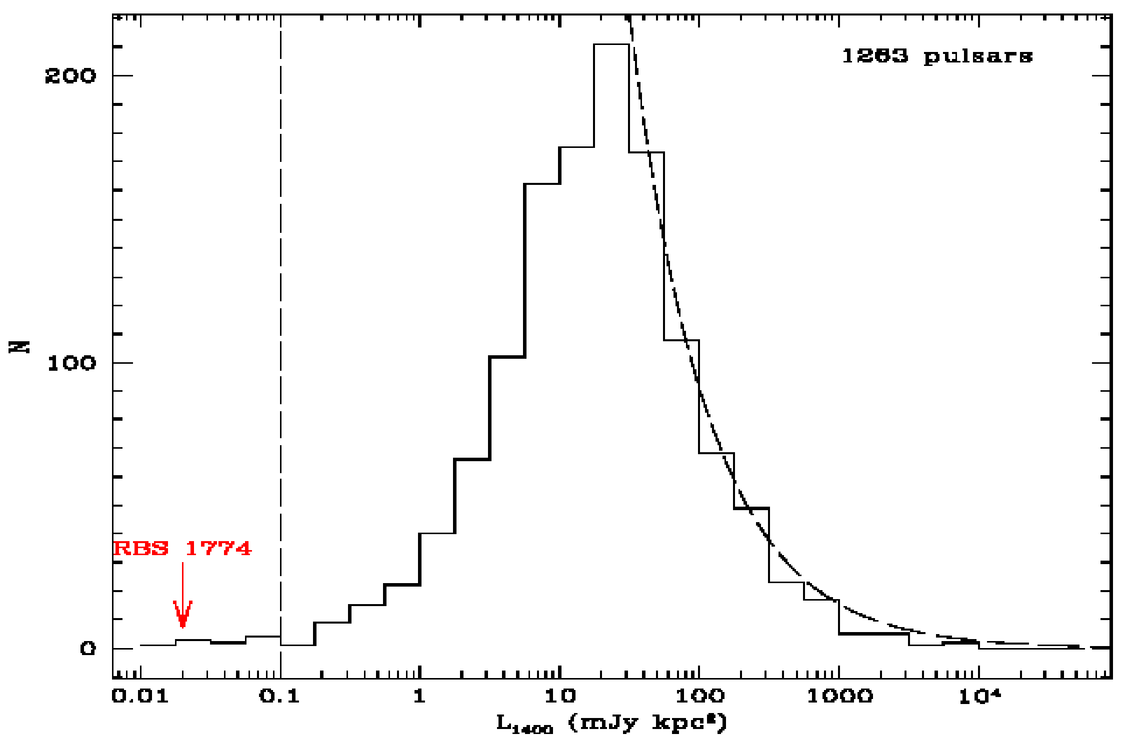
- 1RXS J214303.7+065419 (Malofeev+ 2007)
- F_{111MHz} = 60 ± 25 mJy
- P = 9.43 s; dP/dt = -1.5 ± 2.2 10^{-12} s s^{-1} (period evolution unconstrained !)

- 1RXS J130848.6+212708 (Malofeev+ 2007)
- F_{111MHz} = 50 ± 20 mJy
- P = 10.31 s; dP/dt = 12.9 10^{-12} s s^{-1} (consistent with the X-ray one)



However …

- We observed 1RXS J214303.7+065419 from Parkes @ 1.4 GHz but we did not detect radio emission down 0.02 mJy kpc^2 (Rea+ 2007)
- Very steep radio spectrum or false detection ?
- Difficult to check. Very few radio telescopes operate at very low frequencies



Conclusions and Perspectives

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Open Points

- High Energy observations have unveiled a variety of different INSs flavours, with a complex phenomenology

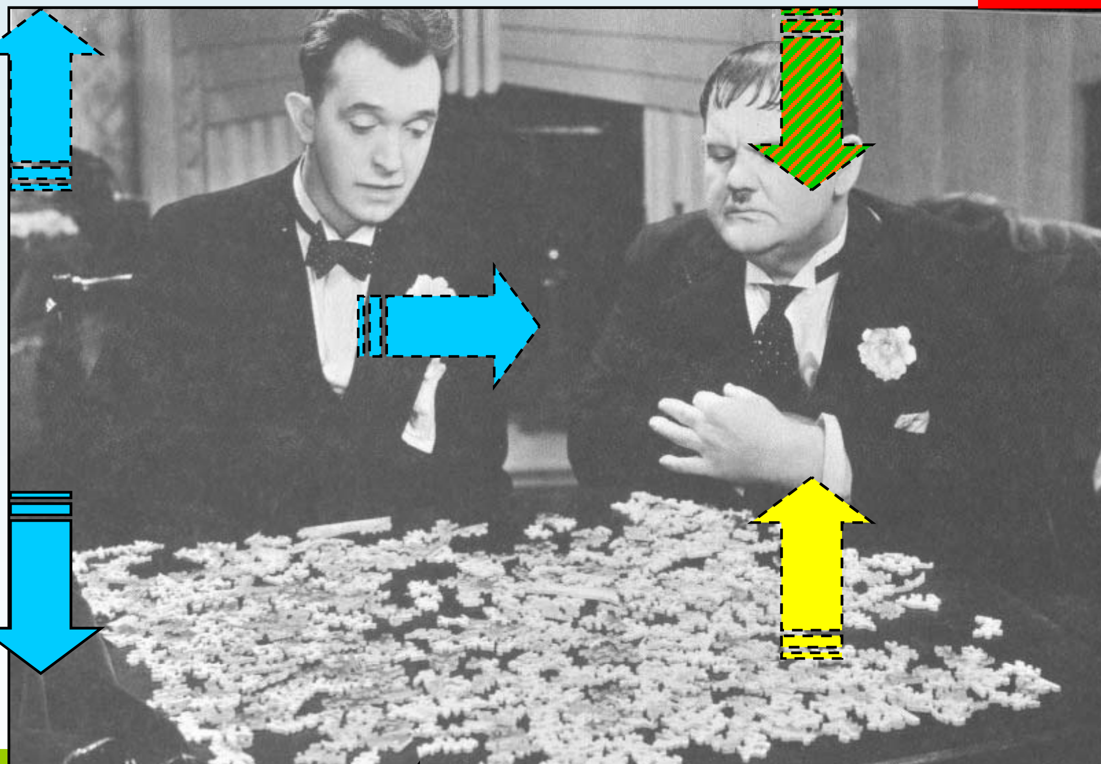
1. What makes all these INSs different ?
2. What determines these differences? The birth event? The parent star? The evolution? The environment?
3. How are different INSs classes related ?
4. Are they part of a common evolutionary scheme?

- Addressing these points is critical to understand the endpoints of massive stellar evolution

Compact Central Objects

Radio Pulsars

X-ray Binaries



High-B Radio Pulsars

Anomalous X-ray Pulsars

Soft γ-ray Repeaters

Rotating Radio Transients

Thermal INSs

The Road Map

- **Assess NS nature**:

  → To sort out the sample (isolated, binary, disk)

- **Multi-λ Phenomenology**:

  → To study the physics and find similarities/diversities

- **INS Archeology**:

  → To understand origin, formation, and evolution

- **Multi-λ Identifications**:

  → To enlarge the sample

Thank you !