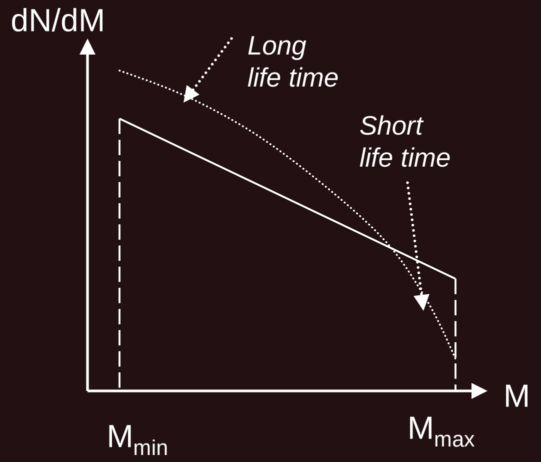
Young Isolated Neutron Stars: Observations and Evolution

Sergei Popov
SAI MSU

Stars in the Galaxy



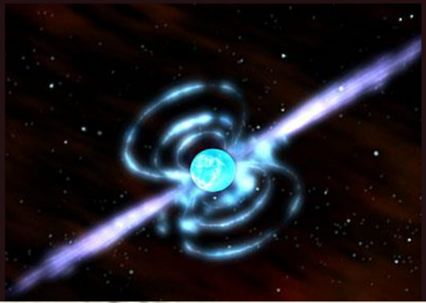
Salpeter (1955) mass function:
$dN/dM \sim M^{-2.35}$

There are many modification (Miller-Scalo, Kroupa etc.).
At high masses the slope is usually steeper.
Note: it is *initial* mass function, not the present day!

It is possible to estimate the number of NS and BH progenitors.
Then using there average lifetime we can estimate the birth rate
and total numbers (with a given age of the Galaxy and assuming constant rate)
taking into account SFR~3 solar mass per year.
[see also Ch.1 in Shapiro, Teukolsky]

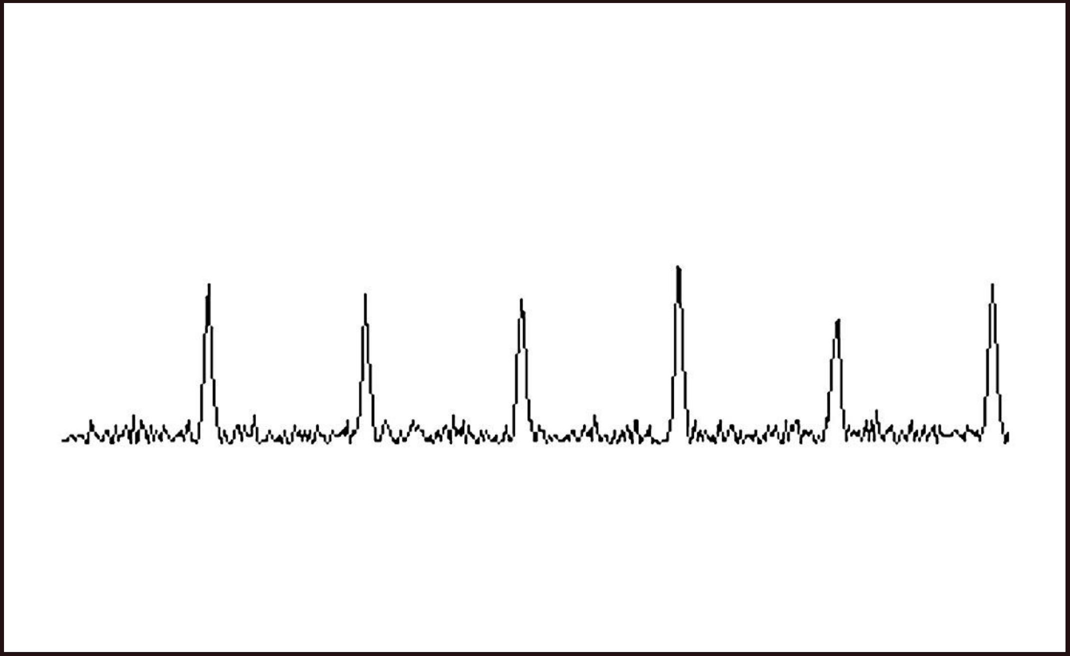
So, finally we have $(0.3\text{-}1)10^9$ NSs in the Galaxy.

Discovery !!!!



1967: Jocelyn Bell. Radio pulsars.

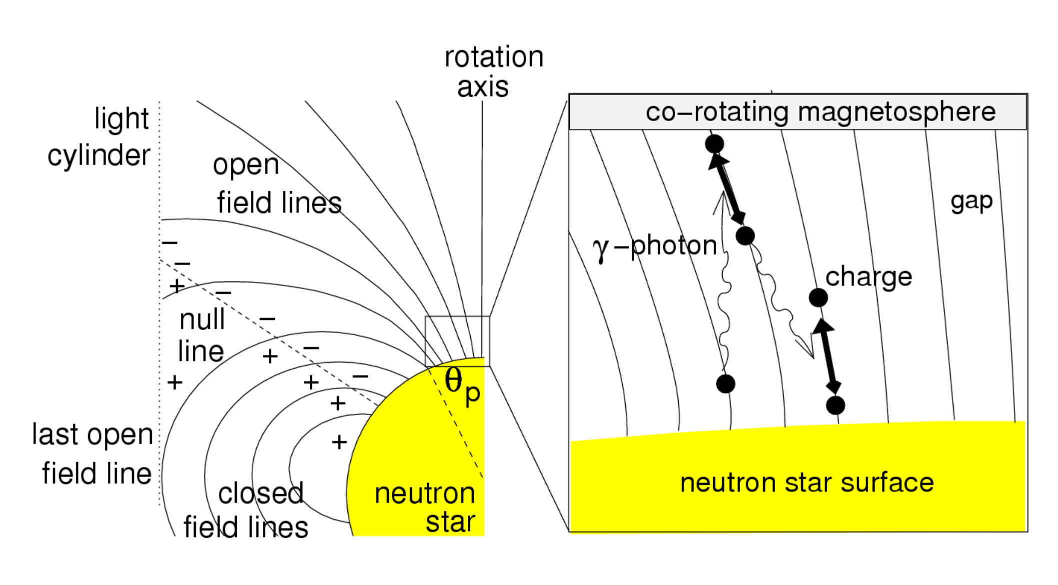
Seredipitous discovery.



The pulsar in the Crab nebula

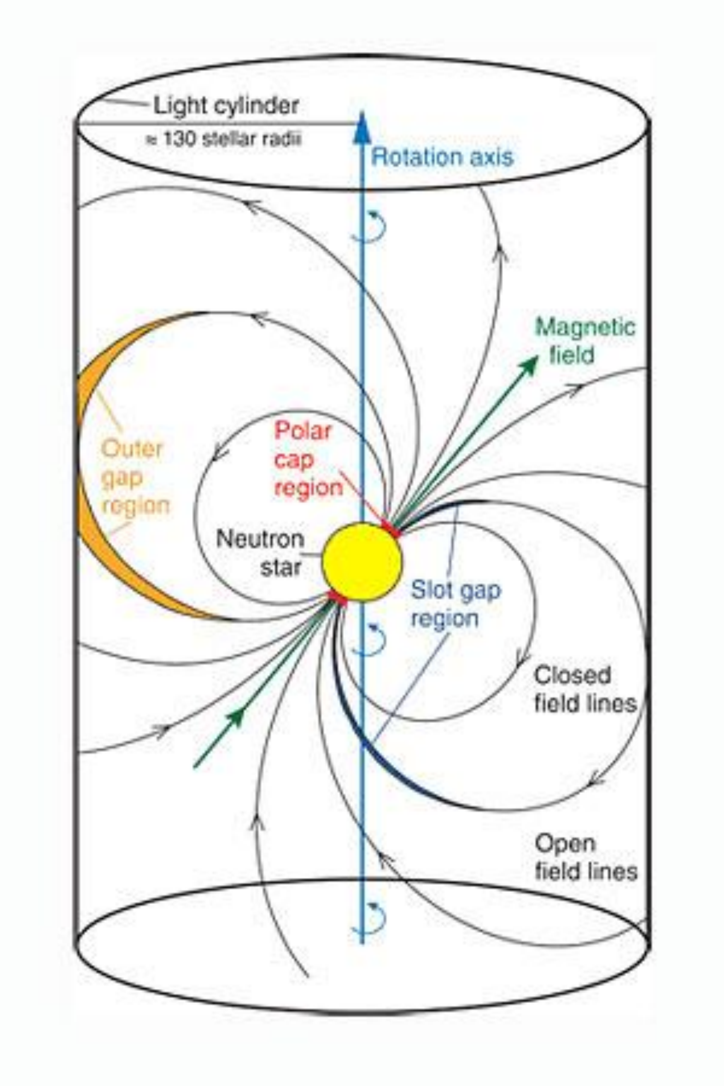
ANTF pulsar catalogue:
http://www.atnf.csiro.au/people/pulsar/psrcat/

How do pulsars work?



$$P_{\rm rad} = \frac{2}{3}\frac{m_\perp^2 \Omega^4}{c^3} = \frac{2m_\perp^2}{3c^3}\left(\frac{2\pi}{P}\right)^4 = \frac{2}{3c^3}(BR^3 \sin\alpha)^2\left(\frac{2\pi}{P}\right)^4,$$

Cascade of charged particles is formed in the magnetosphere. And then these particles move along curved field lines.



http://www.cv.nrao.edu/course/astr534/Pulsars.html

How do pulsar loose their energy?

$$E_{\text{rot}} = \frac{1}{2} I \Omega^2 = \frac{2\pi^2 I}{P^2} \, .$$

Rotation of PSRs is slowed.
Rotational ebergy is the main source of pulsar's energy.

$$I = \frac{2}{5} M R^2 \approx \frac{2 \cdot 1.4 \cdot 2.0 \times 10^{33} \text{ g} \cdot (10^6 \text{ cm})^2}{5} \approx 10^{45} \text{ gm cm}^2$$

$$E_{\text{rot}} = \frac{2\pi^2 I}{P^2} \approx \frac{2\pi^2 \cdot 10^{45} \text{ g cm}^2}{(0.033 \text{ s})^2} \approx 1.8 \times 10^{49} \text{ ergs}$$

$$\frac{dE_{\text{rot}}}{dt} = \frac{d}{dt}\left(\frac{1}{2} I \Omega^2\right) = I \Omega \dot{\Omega}$$

http://www.cv.nrao.edu/course/astr534/Pulsars.html

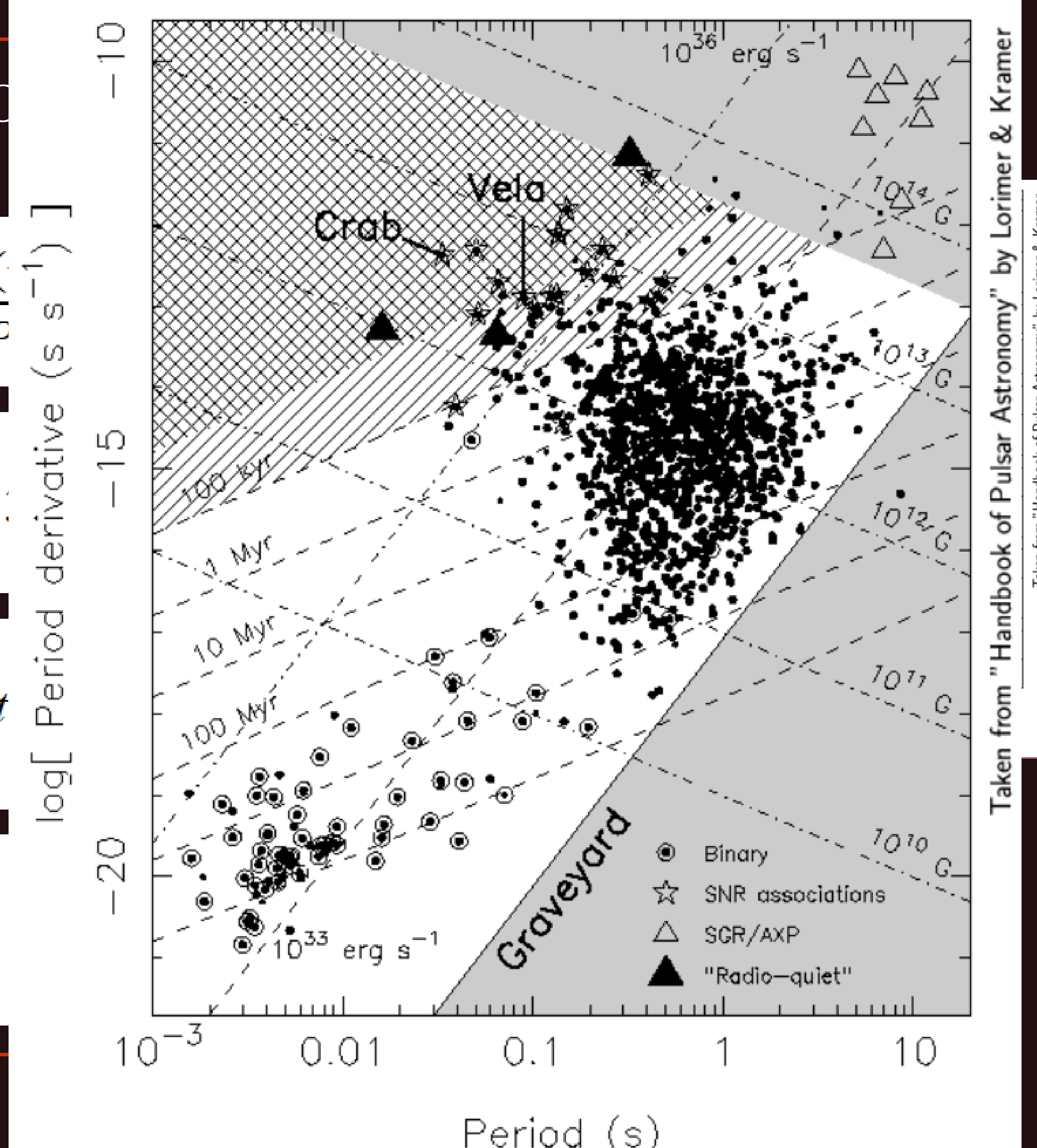
Evolution o

$$\frac{dE_{rot}}{dt} = I\Omega\dot{\Omega} = I\frac{2\pi}{P}\frac{2\pi(}{P}$$

$$\left(\frac{B}{\text{Gauss}}\right) >$$

$$\int_{P_0}^{P} P\,dP = \int_0^{\tau} (P\dot{P})\,dt$$

$$\frac{P^2 - P_0^2}{2} = P\dot{P}\tau$$



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

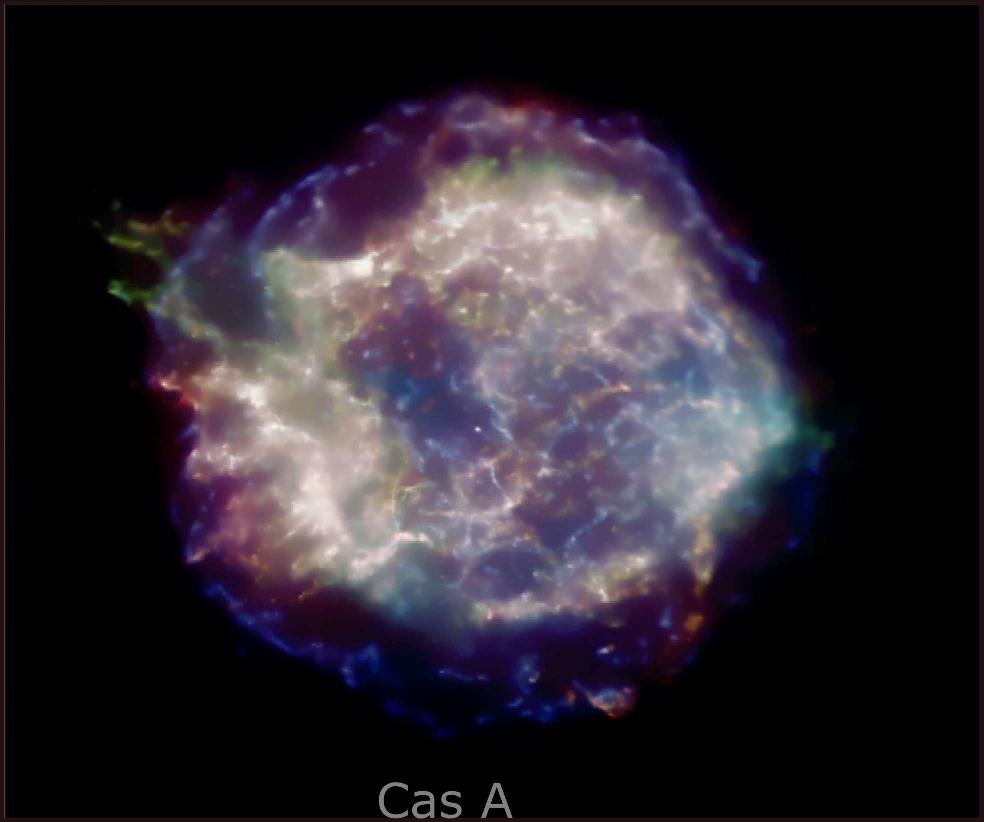
The new zoo of young neutron stars

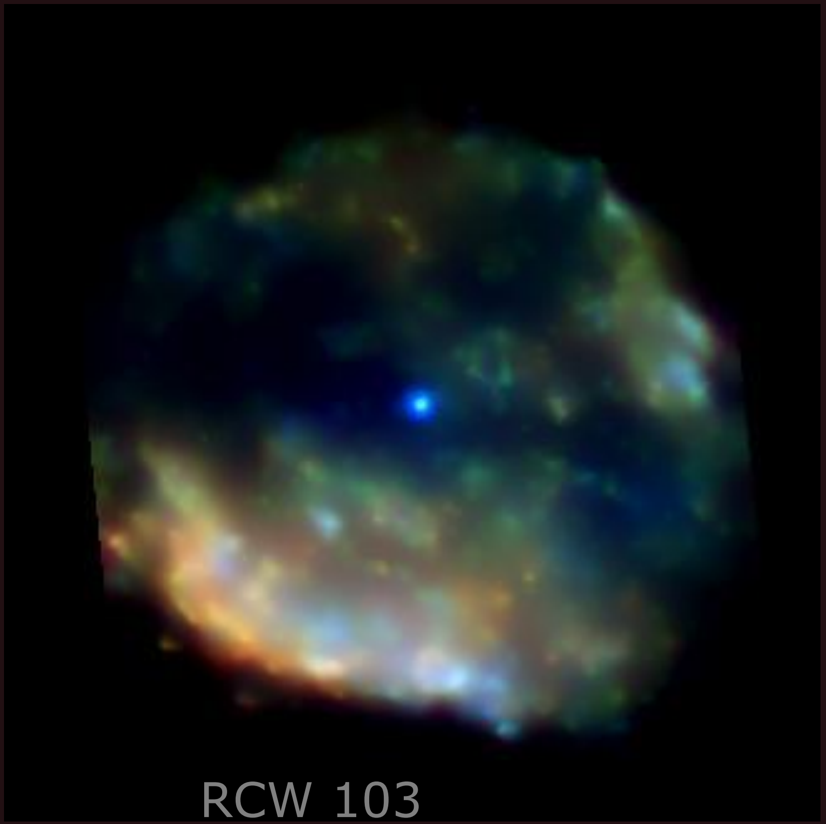
During last ~20 years
it became clear that neutron stars
can be born very different.
In particular, absolutely
non-similar to the Crab pulsar.

o High-B PSRs
o Compact central X-ray sources
in supernova remnants.
o Anomalous X-ray pulsars
o Soft gamma repeaters
o The Magnificent Seven
o Transient radio sources (RRATs)

Old and new zoos: Harding arXiv:1302.0869

Compact central X-ray sources in supernova remnants



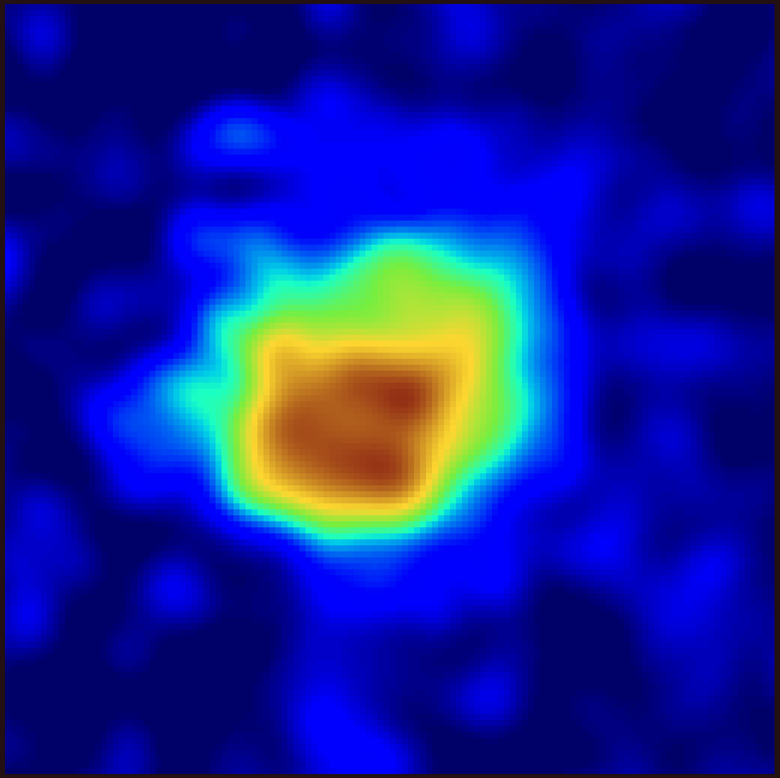


Rapid cooling
(Heinke et al. 1007.4719)

6.7 hour period
(de Luca et al. 2006)

CCOs in SNRs

		Age	Distance
J232327.9+584843	Cas A	0.32	3.3–3.7
J085201.4−461753	G266.1−1.2	1–3	1–2
J082157.5−430017	Pup A	1–3	1.6–3.3
J121000.8−522628	G296.5+10.0	3–20	1.3–3.9
J185238.6+004020	Kes 79	~9	~10
J171328.4−394955	G347.3−0.5	~10	~6



[Pavlov, Sanwal, Teter: astro-ph/0311526,
de Luca: arxiv:0712.2209]

For three sources there are strong indications for large (>~100 msec) initial spin periods and low magnetic fields:

1E 1207.4-5209 in PKS 1209-51/52

PSR J1852+0040 in Kesteven 79

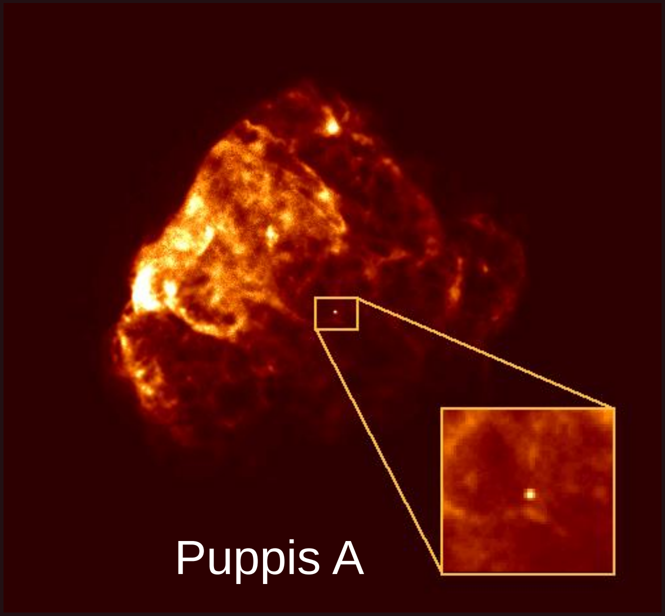
PSR J0821-4300 in Puppis A

[see Halpern et al. arxiv:0705.0978 and 1301.2717]

CCOs

High proper motion of CCO in Pup A.
Velocity 672 +/- 115 km/s

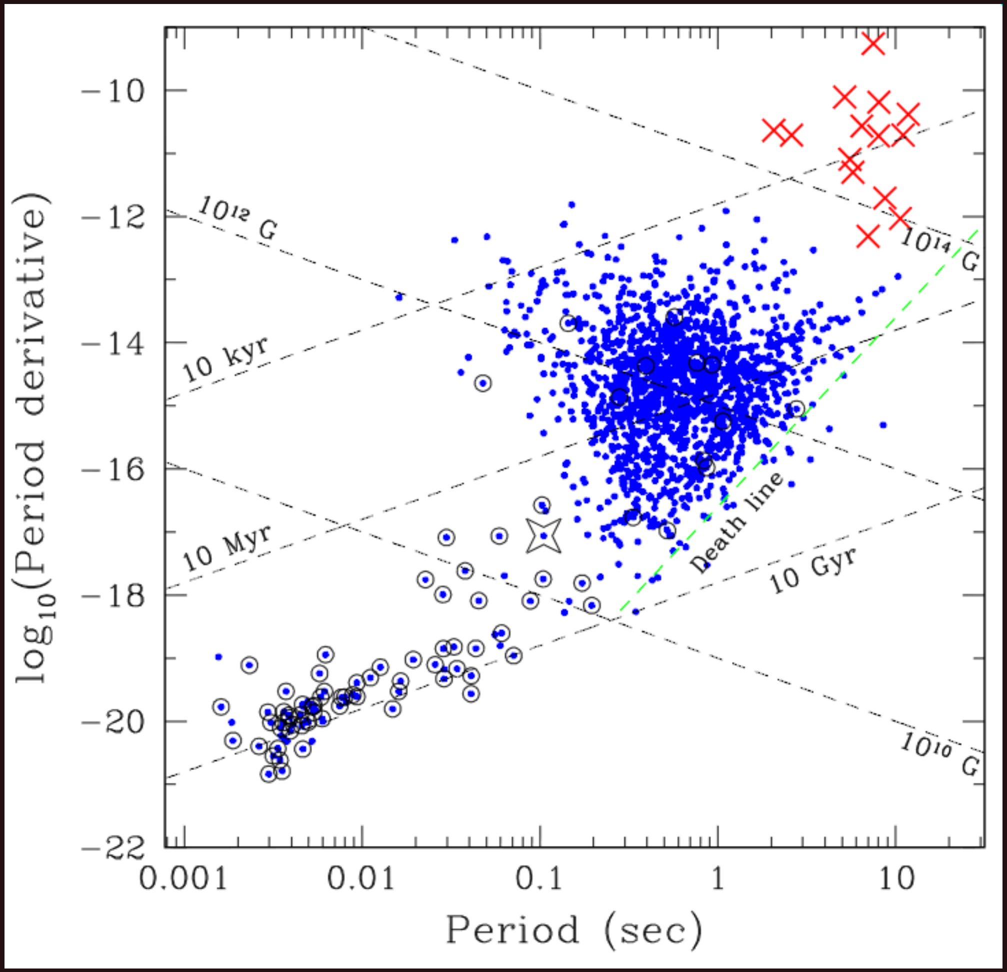
1204.3510



CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})	References
RX J0822.0−4300	Puppis A	3.7	2.2	0.112	11	< 9.8	6.5×10^{33}	1,2
CXOU J085201.4−461753	G266.1−1.2	1	1	...	< 7	...	2.5×10^{32}	3,4,5,6,7
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	< 3.3	2.5×10^{33}	8,9,10,11,12
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	...	< 40	...	1.5×10^{33}	13,14
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	...	< 7	...	$\sim 1 \times 10^{33}$	7,15,16
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	0.31	5.3×10^{33}	17,18,19,20
CXOU J232327.9+584842	Cas A	0.33	3.4	...	< 12	...	4.7×10^{33}	20,21,22,23,24
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	...	...	...	3.4×10^{33}	25
XMMU J173203.3−344518	G353.6−0.7	~ 27	3.2	...	...	...	1.0×10^{34}	26,27,28
CXOU J181852.0−150213	G15.9+0.2	$1 - 3$	(8.5)	...	...	...	$\sim 1 \times 10^{33}$	29

0911.0093

Anti-magnetars



Star marks the CCO from 0911.0093

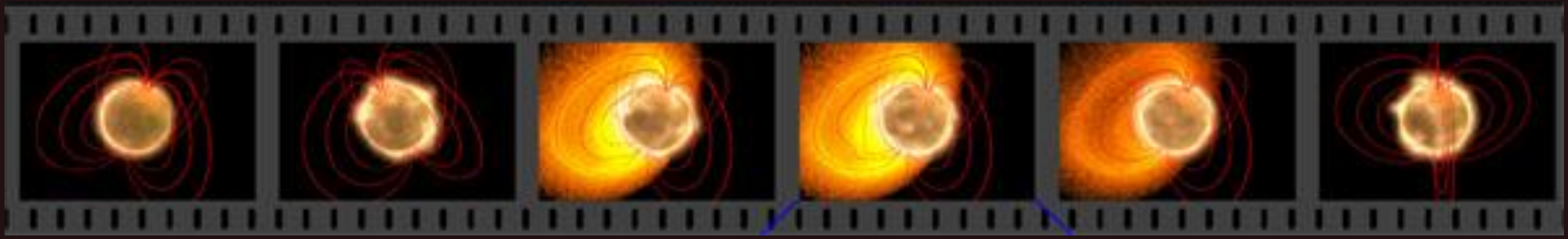
New results 1301.2717
Spins and derivative are measured for
PSR J0821-4300 and
PSR J1210-5226

0911.0093

Magnetars

- $dE/dt > dE_{rot}/dt$
- By definition: The energy of the magnetic field is released

Magnetic fields 10^{14}–10^{15} G

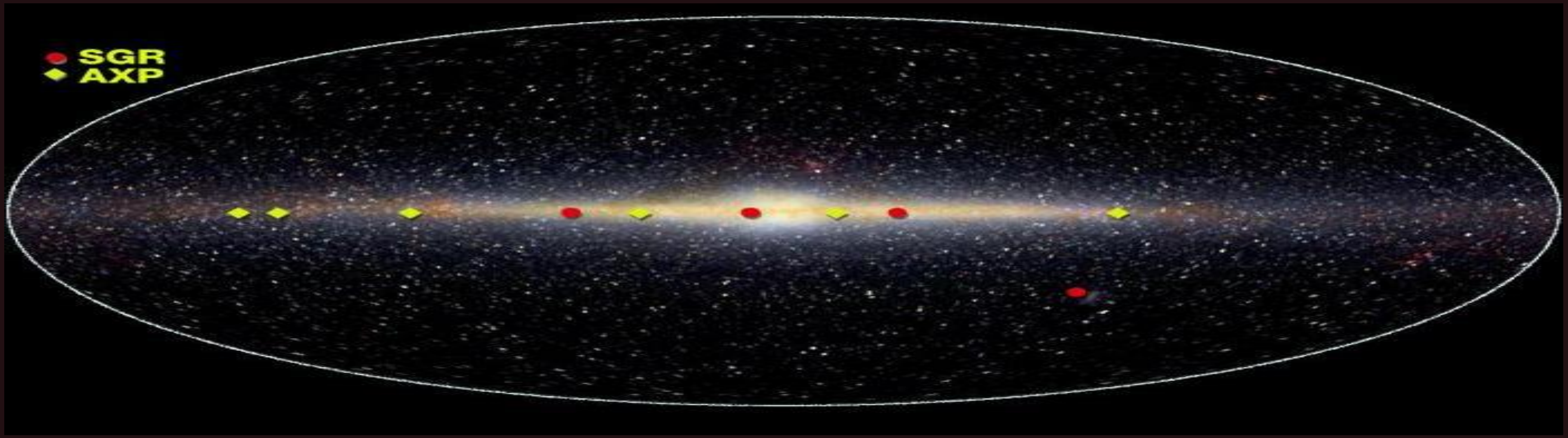


See a review in 1507.02924

Magnetars in the Galaxy

- ~15 SGRs, ~14 AXPs, plus 5 candidates, plus radio pulsars with high magnetic fields
- Young objects (about 10^4 year).
- About 10% of all NSs

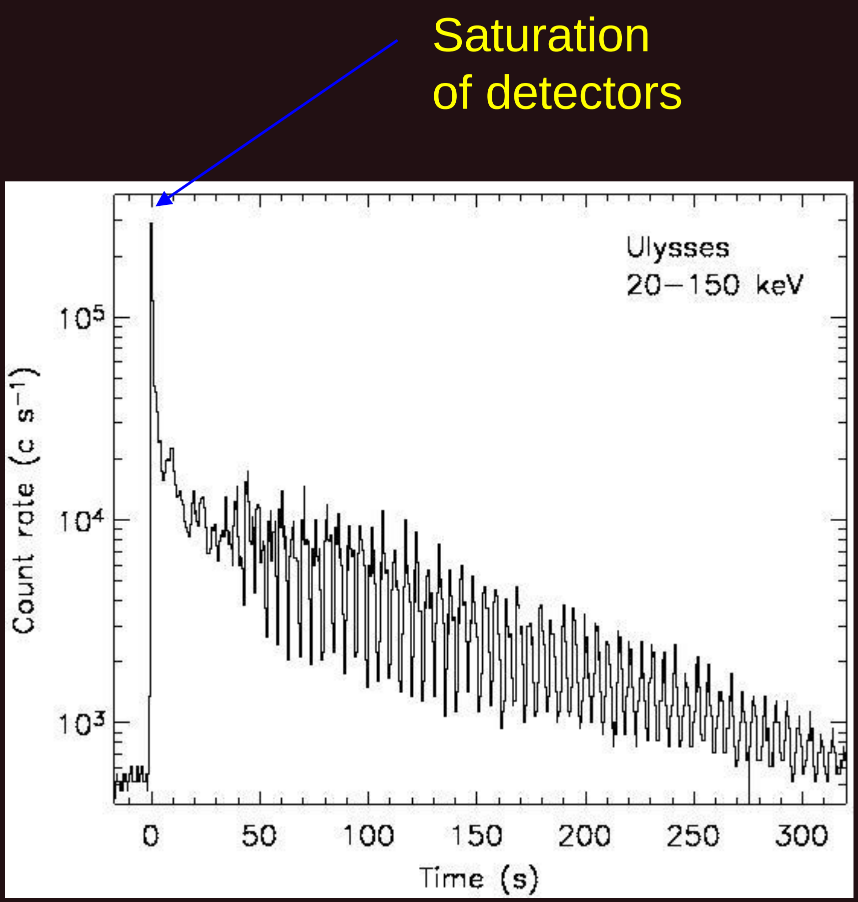
Catalogue: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html



(see a review in arXiv:0804.0250 and catalogue description in 1309.4167)

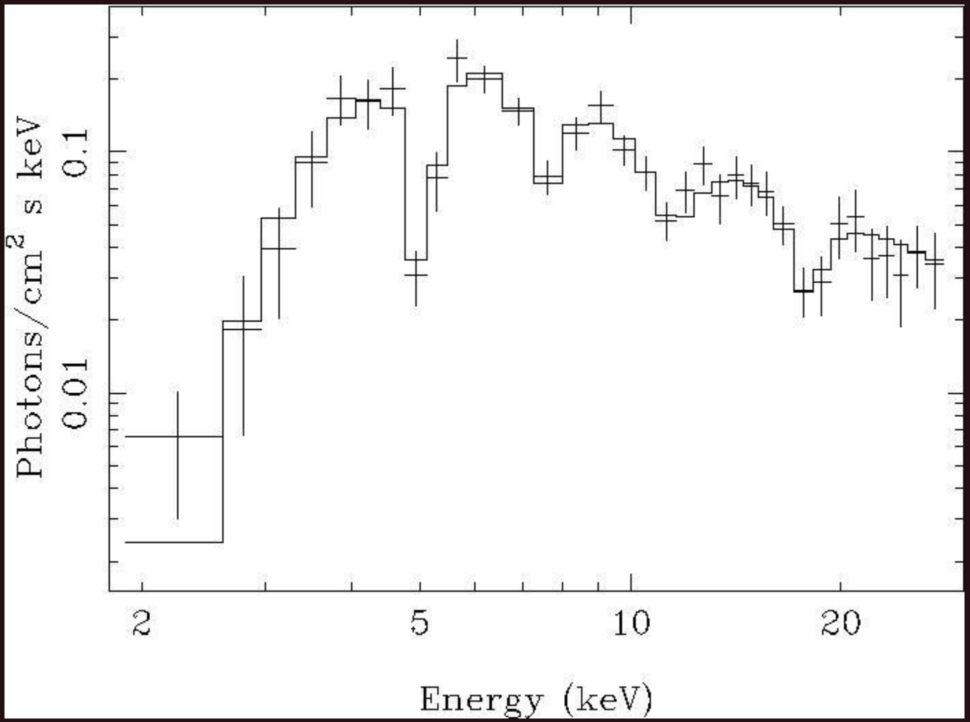
Soft Gamma Repeaters: main properties

- Energetic “Giant Flares” (GFs, L ≈ 10^{45}-10^{47} erg/s) detected from 3 (4?) sources
- No evidence for a binary companion, association with a SNR at least in one case
- Persistent X-ray emitters, L ≈ 10^{35} - 10^{36} erg/s
- Pulsations discovered both in GFs tails and persistent emission, P ≈ 5 -10 s
- Huge spindown rates, $\dot{P}/P \approx 10^{-10}\ s^{-1}$



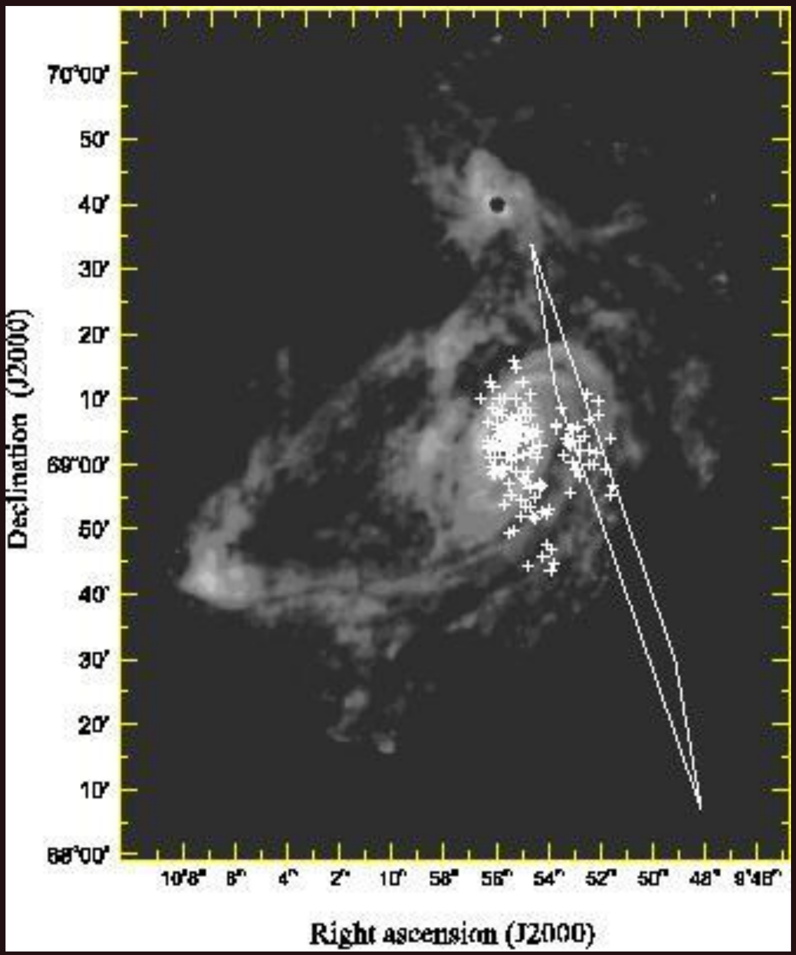
Magnetic field estimates

- Spin down
- Long spin periods
- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)
- Direct measurements of magnetic field (cyclotron lines)



Ibrahim et al. 2002

Extragalactic SGRs



It was suggested long ago (Mazets et al. 1982) that present-day detectors could already detect giant flares from extragalactic magnetars.

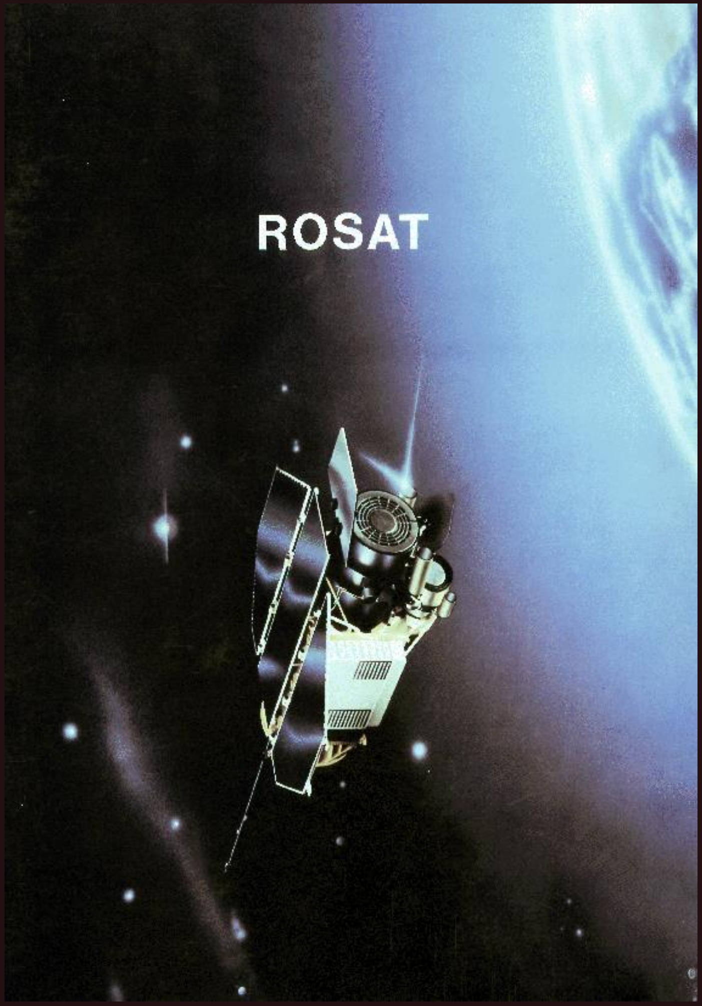
However, all searches in, for example, BATSE database did not provide god candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

Finally, recently several good candidates have been proposed by different groups (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider ...., see arxiv:0712.1502 and references therein, for example).

Burst from M31

[D. Frederiks et al. astro-ph/0609544]

ROSAT

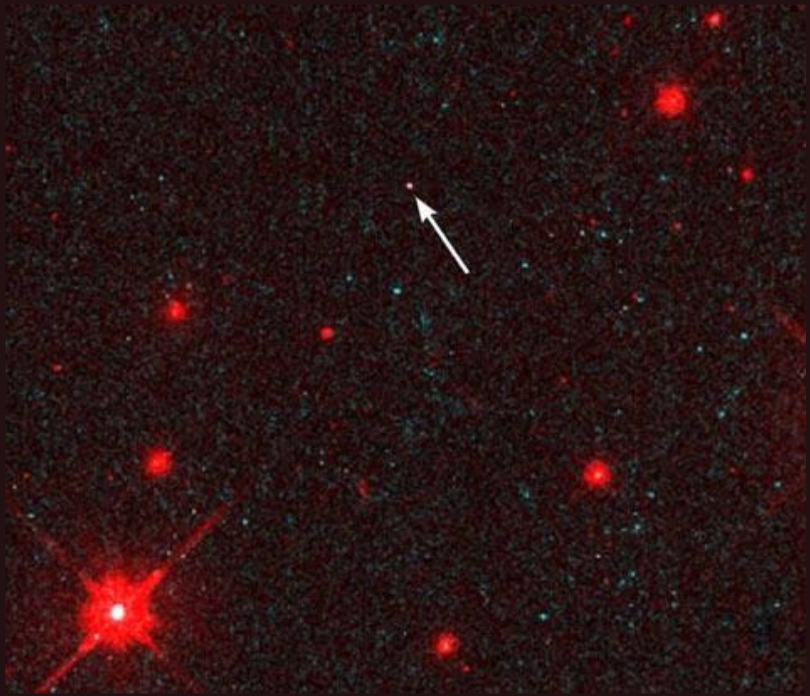


ROentgen SATellite

German satellite
(with participation of US and UK).

Launched 01 June 1990.
The program was successfully ended on 12 Feb 1999.

Close-by radioquiet NSs



RX J1856.5-3754

- Discovery: Walter et al. (1996)
- Proper motion and distance: Kaplan et al.
- No pulsations
- Thermal spectrum
- Later on: six brothers

Magnificent Seven

Name	Period, s
RX 1856	7.05
RX 0720	8.39
RBS 1223	10.31
RBS 1556	3.39
RX 0806	11.37
RX 0420	3.45
RBS 1774	9.44

Radioquiet
Close-by
Thermal emission
Absorption features
Long periods

See a review in Turolla (2009)

Spin properties and other parameters

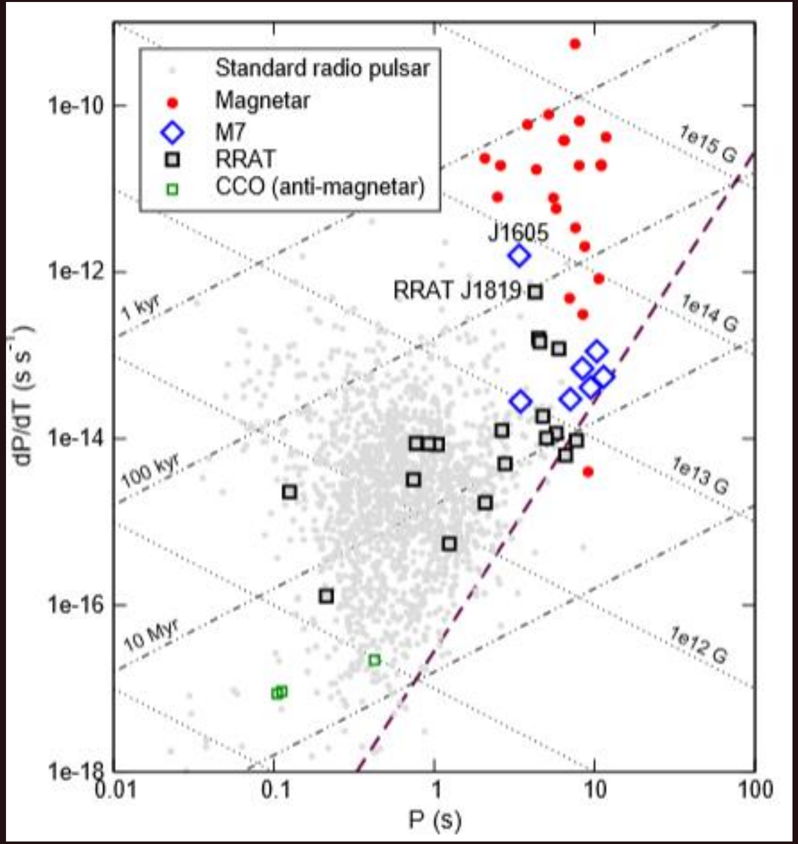
RX J	Spin[*]			Spectrum[†]					Astrometry[**]		References
	P (s)	$\dot{P}$ (10^{-14})	PF (%)	$N_{H,20}$ (cm^{-2})	kT (l eV)	PN (s^{-1})	E_{abs} (keV)	m_B (mag)	μ (mas yr^{-1})	d (pc)	
1856.5−3754	7.06	. . .	1	0.8	62	8.3	. . .	25.2	333	160	14, 15, 18–20
0720.4−3125[‡]	8.39	7	11	1.0	87	7.6	0.3	26.6	97	360	21–26
1605.3+3249	. . .	. . .	< 3	0.8	93	5.6	0.5(0.6,0.8)	27.2	155	390	27–31
1308.6+2127	10.31	11	18	1.8	102	2.5	0.2(0.4)	28.4[§]	200[¶]	. . .	32–36
2143.0+0654	9.44	. . .	4	3.6	102	2.0	0.7	> 26[‖]	. . .	430	37–39
0806.4−4123	11.37	. . .	6	1.1	92	1.8	0.3(0.6)	> 24	. . .	250	29, 40
0420.0−5022	3.45	. . .	17	2.1	45	0.2	0.3	26.6	. . .	345	29, 40

Kaplan arXiv: 0801.1143

Updates:

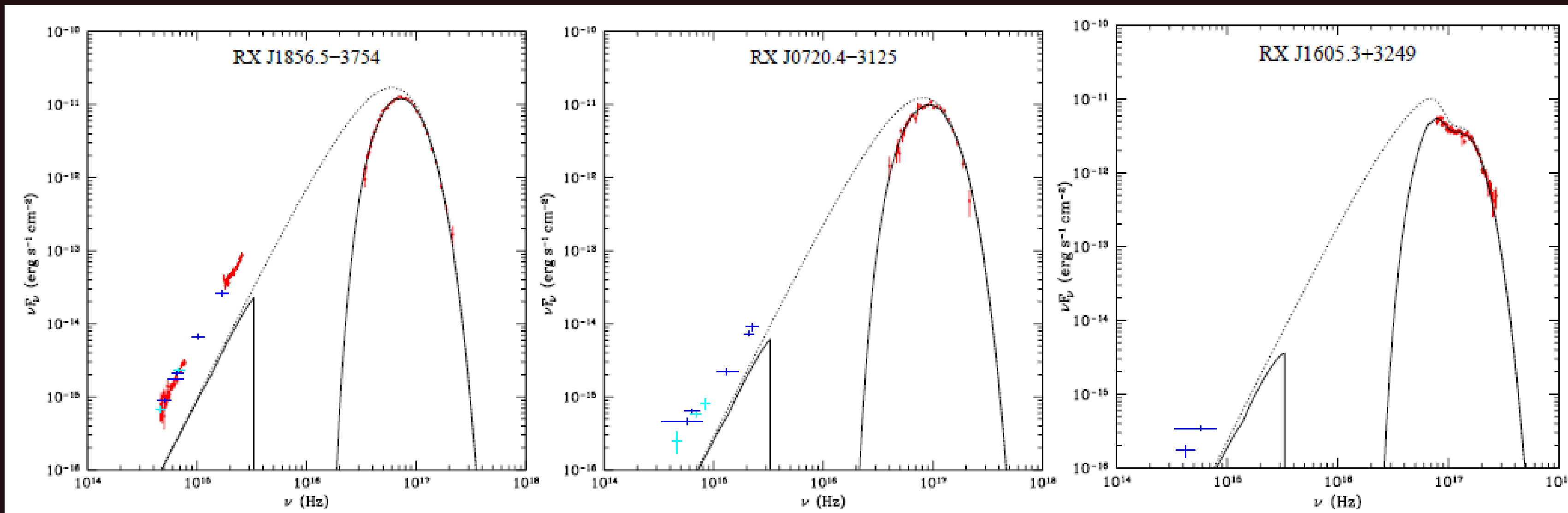
- 1856. vdot=-6 10^{-16} (| vdot|<1.3 10^{-14}) van Kerkwijk & Kaplan arXiv: 0712.3212
- 2143. vdot=-4.6 10^{-16} Kaplan & van Kerkwijk arXiv: 0901.4133
- 0806. |vdot|<4.3 10^{-16} Kaplan and van Kerkwijk arXiv: 0909.5218

Object	kT_∞ (eV)	P (s)	p_f (%)	$\log(\dot{P})$ (s s^{-1})	$\log(\dot{E})$ (erg s^{-1})	$\log(\tau_{ch})$ (yr)	$\log(t_{kin})$ (yr)	$\log(B_{dip})$ (10^{13} G)	$\log(B_{cyc})$ (10^{13} G)	Reference
RX J1856.5-3754	61	7.06	1	−13.527	30.580	6.58	5.62	13.17	–	[1]
RX J0720.4-3125	84 – 93	8.39	11	−13.156	30.726	6.28	5.93	13.39	13.75	[2]
RX J1605.3+3249	100	3.39	4	−11.796	33.267	4.53	5.65	13.87	13.92	[3]
RX J1308.6+2127	100	10.31	18	−12.951	30.663	6.16	5.95	13.54	13.60	[4]
RX J2143.0+0654	104	9.43	4	−13.398	30.332	6.57	–	13.29	14.15	[5]
RX J0806.4-4123	95	11.37	6	−13.260	30.227	6.51	–	13.40	13.96	[6]
RX J0420.0-5022	48	3.45	17	−13.553	31.487	6.29	–	13.00	–	[7]

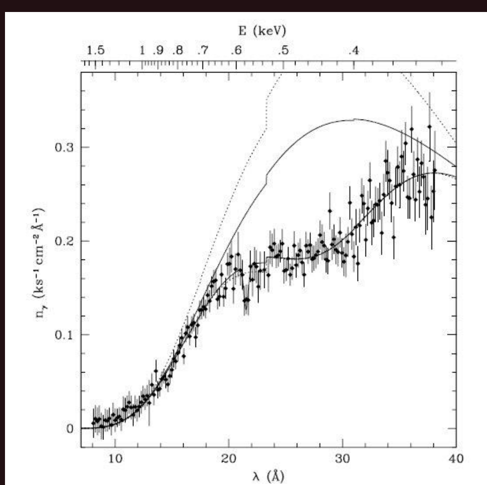


1401.7147

Spectral properties



Kaplan arXiv: 0801.1143



Van Kerkwijk et al. (2004)

Spectra are blackbody plus one or several wide absorption features.
The origin of features is not understood, yet.

New data: Kaplan et al. 1105.4178

Radio observations

Up to now the M7 are not detected for sure at radio wavelengths, however, there was a paper by Malofeev et al., in which the authors claim that they had detect two of the M7 at very low wavelength (<~100 MHz).

At the moment the most strict limits are given by Kondratiev et al. Non-detection is still consistent with narrow beams.

XDINS	Pulsed emission $S_{\rm lim}$ (μJy)	Pulsed emission $L_{1400}^{\rm p,max}$ (mJy kpc^2)	Pulsed emission $L_{820}^{\rm p,max}$ (mJy kpc^2)	Bursty emission rate upper limit (hr^{-1})	Bursty emission $S_{\rm lim}^{\rm sp}$ (mJy)	Bursty emission $L_{1400}^{\rm b,max}$ (mJy kpc^2)
RX J0720.4−3125	8	4×10^{-4}	10^{-3}	0.25	21	1
RX J0806.4−4123	10	4×10^{-3}	10^{-2}	0.32	18	6.9
RX J1308.6+2127	10	4×10^{-3}	10^{-2}	0.24	17	6.5
RX J1605.3+3249	8	3×10^{-3}	8×10^{-3}	0.25	22	8.4
RX J1856.5−3754	14	1.4×10^{-4}	3.6×10^{-4}	0.32	24	0.2
RX J2143.0+0654	13	5×10^{-3}	1.3×10^{-2}	0.36	20	7.6

Kondratiev et al. arXiv: 0907.0054

The isolated neutron star candidate 2XMM J104608.7-594306

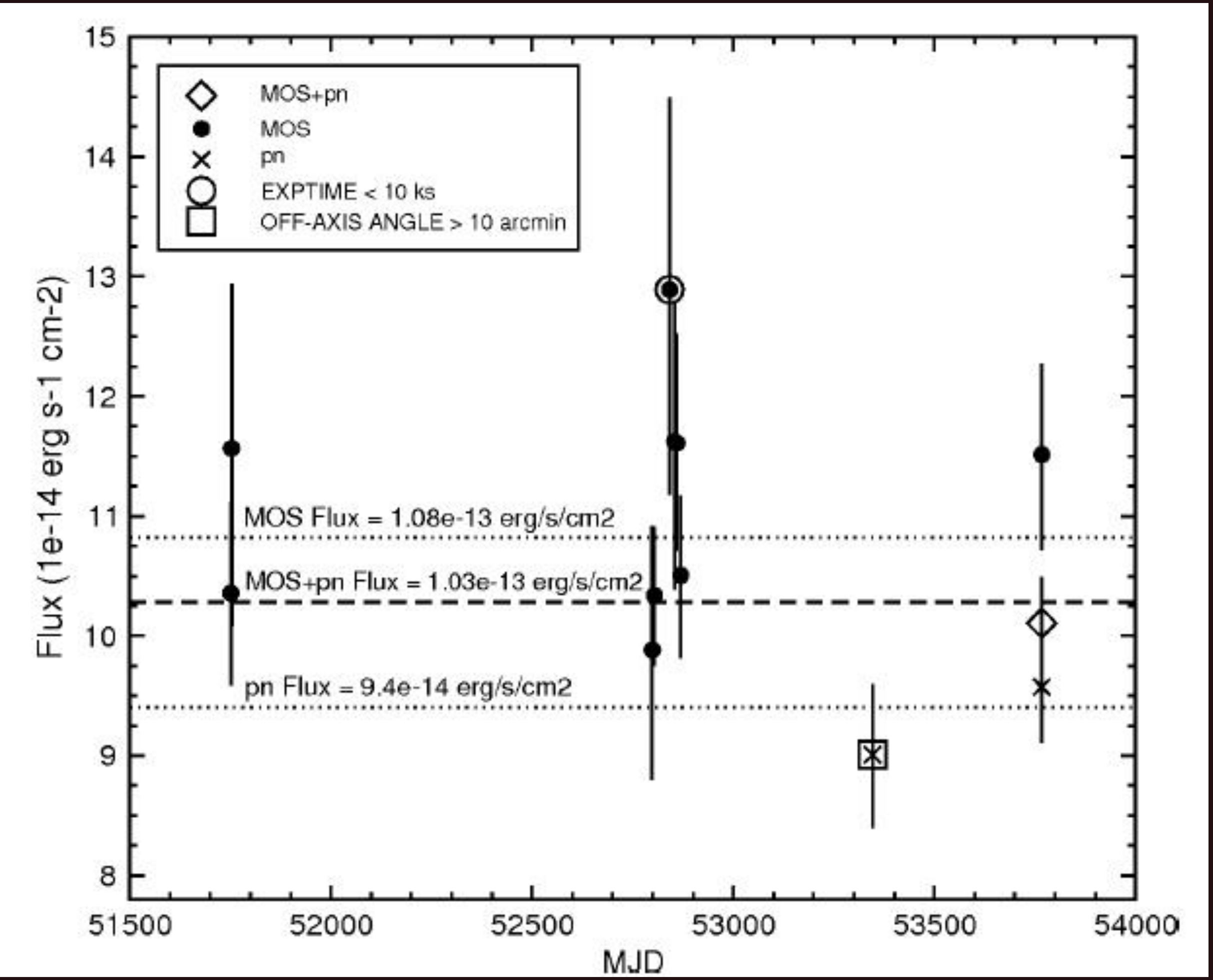
A new INS candidate.

$B > 26$, $V > 25.5$, $R > 25$
(at 2.5σ confidence level)

$\log(F_X/F_V) > 3.1$
$kT = 118$ +/-15 eV

unabsorbed X-ray flux:
$F_x \sim 1.3\ 10^{-12}$ erg s^{-1} cm^{-2}
in the 0.1–12 keV band.

At 2.3 kpc (Eta Carina)
the luminosity is
$L_X \sim 8.2\ 10^{32}$ erg s^{-1}
$R_\infty \sim 5.7$ km

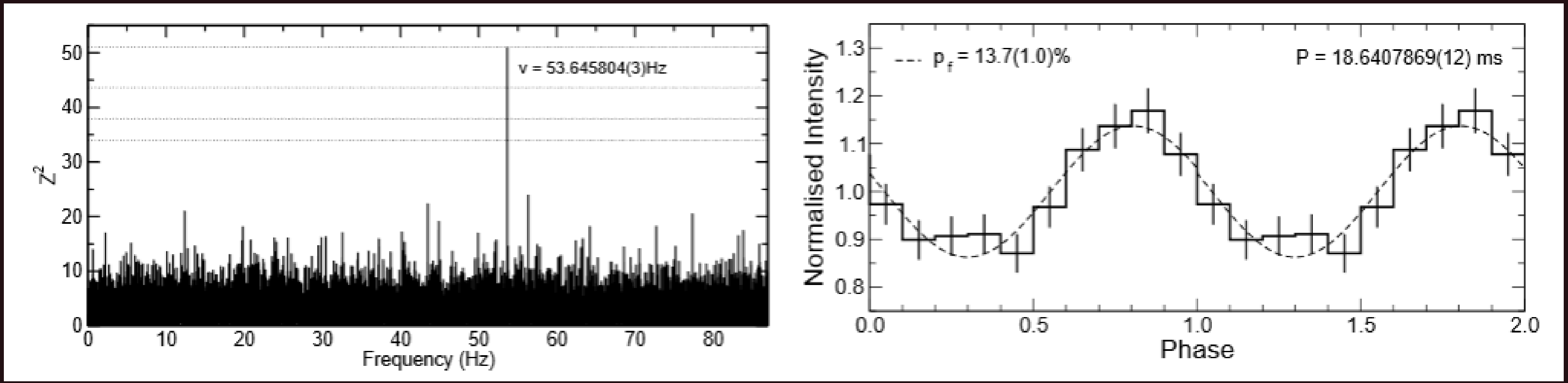


M7-like? Yes!
But P=19 msec

[Pires & Motch arXiv: 0710.5192 and Pires et al. arXiv: 0812.4151]

Spin period of 2XMM J1046-5943

Spin period of this candidate is very short: 18.6 msec
This makes it different from the Seven objects.

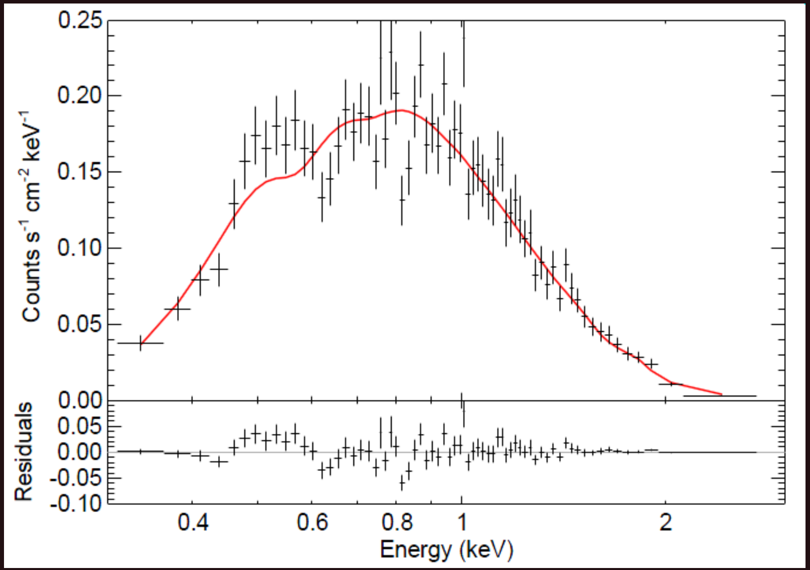


1508.05246

Calvera et al.

In 2008 Rutledge et al. reported the discovery of an enigmatic NS candidated dubbed *Calvera*. It is high above the galactic plane.

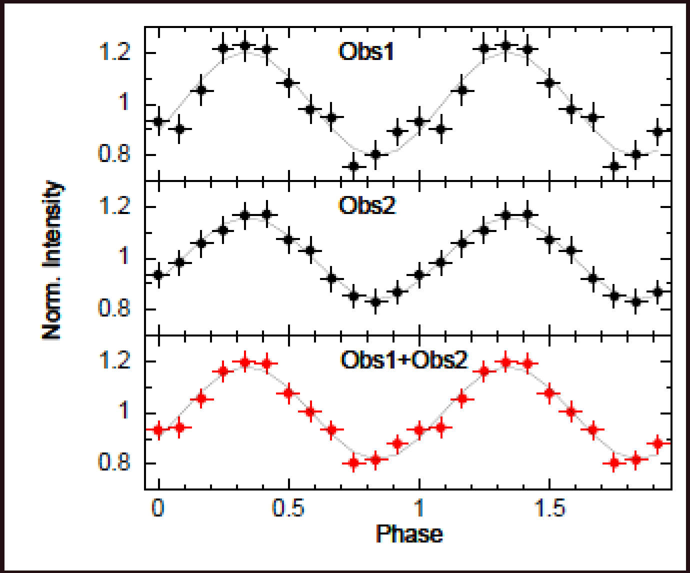
Characteristic	Value
Right Ascension (J2000)	$14^{h}\ 12^{m}\ 55\overset{s}{.}759$
Declination (J2000)	$+79°\ 22'\ 03\overset{''}{.}41$
Uncertainty Ellipse	$0.31''$ (R.A.) $\times$ $0.25''$ (Dec.)
Absorbed Blackbody[a]	
$N_{\rm H}$	0 (limit)
$kT_{\rm eff}$	229 eV
$(R_{\rm km}/D_{10\,\rm kpc})^2$	26.6
Observed X-ray Flux (0.3–9.5 keV)	7.1×10^{-13} erg cm^{-2} s^{-1}
χ^2_ν (ν)	2.04 (67 dof)
NS Hydrogen Atmosphere (NSA)[b]	
$N_{\rm H}$	$3.1^{+0.9}_{-0.9}\times10^{20}$ cm^{-2}
$kT_{\rm eff}$	109^{+1}_{-1} eV
$D^{-2}_{\rm kpc}$	$7.71^{+0.41}_{-0.38}\times10^{-2}$
Observed X-ray Flux (0.3–9.5 keV)	7.62×10^{-13} erg cm^{-2} s^{-1}
χ^2_ν (ν)	1.31 (67 dof)

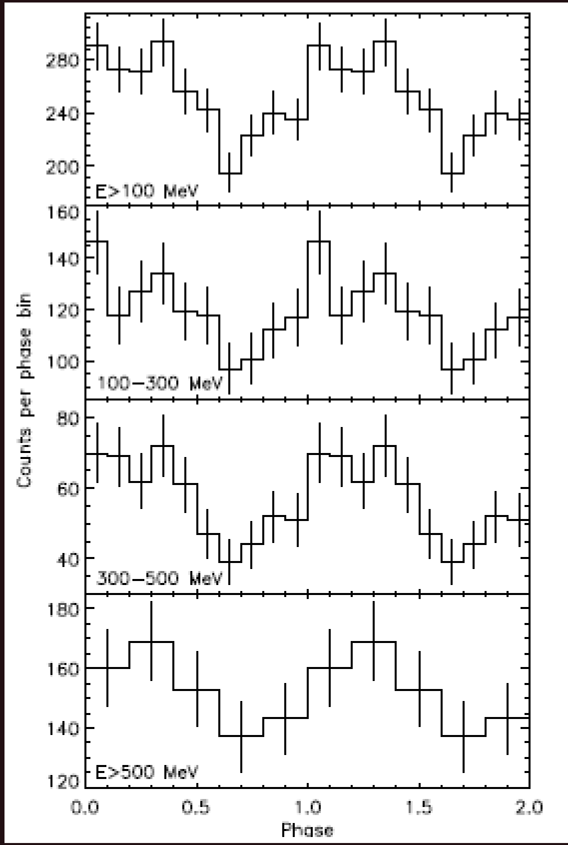


Shevchuk et al. arXiv: 0907.4352

More data on Calvera

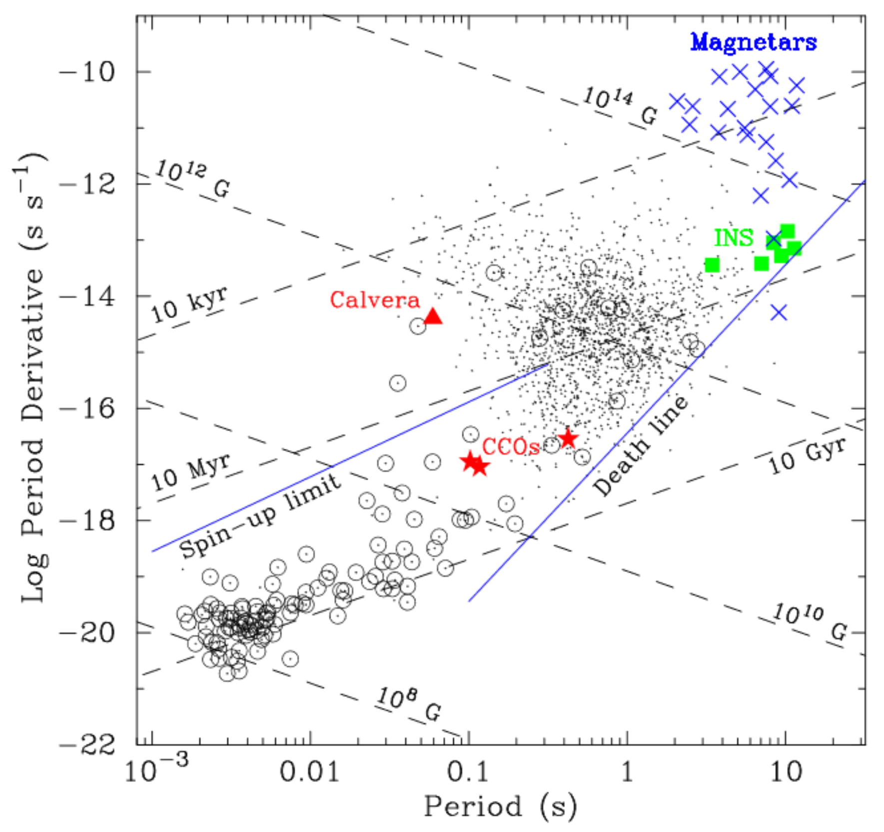
XMM-Newton observations. Zane et al. arXiv: 1009.0209
Thermal emission (two blackbody or two atmospheric: ~55/150 eV and ~80/250 eV
P=0.06 sec – now doubt
Pdot <5 10^{-18} (B<5 10^{10} G) – wrong!
No radio emission
Probably detected also by Fermi
(or not? 1106.2140)





New data 1310.6789 Pdot = 3.2 10^{-15} (B=4.4 10^{11} G)

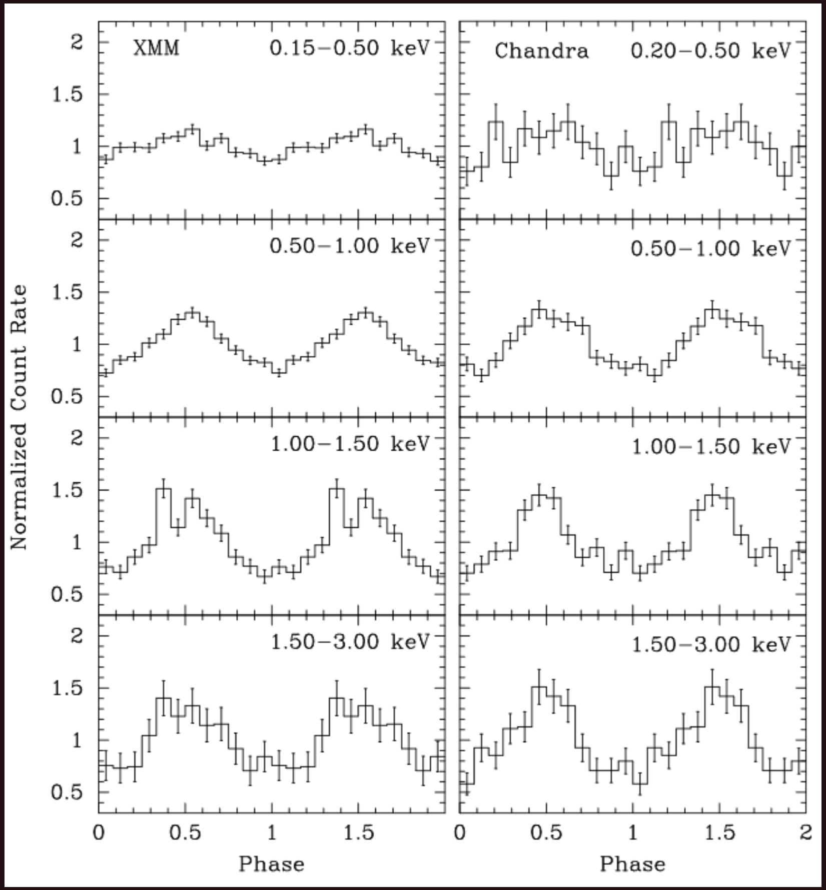
Calvera properties



P=0.059 s

Pdot = 3.2 10^{-15}

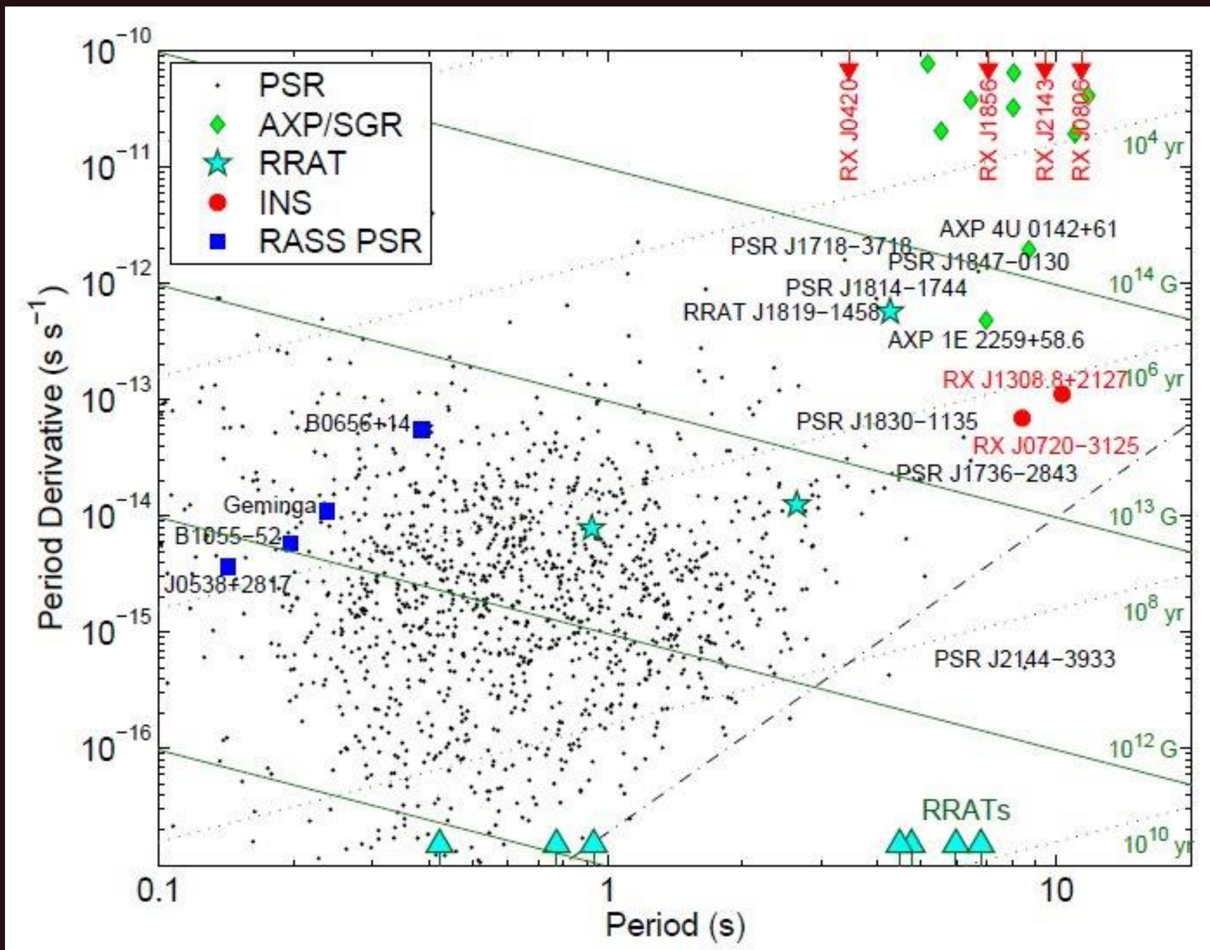
B=4.4 10^{11} G



No gamma-rays

1310.6789

M7 among other NSs



Evolutionary links of M7 with other NSs are not clear, yet.

M7-like NSs can be numerous.

They can be descendants of magnetars.

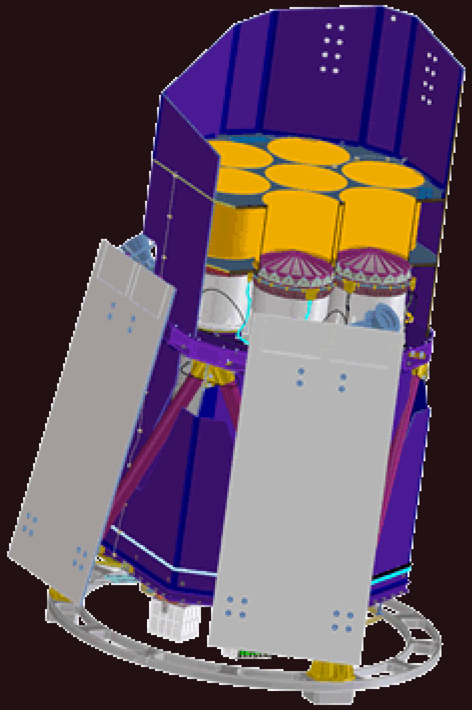
Can be related to RRATs.

Or, can be a different population.

How to find new candidates?

1. <u>Digging the data</u>
   Many attempts failed. One of the latest used SDSS optical data together with ROSAT X-ray. Candidates have been observed by Chandra. Nothing was found (Agueros et al. arXiv: 1103.2132).

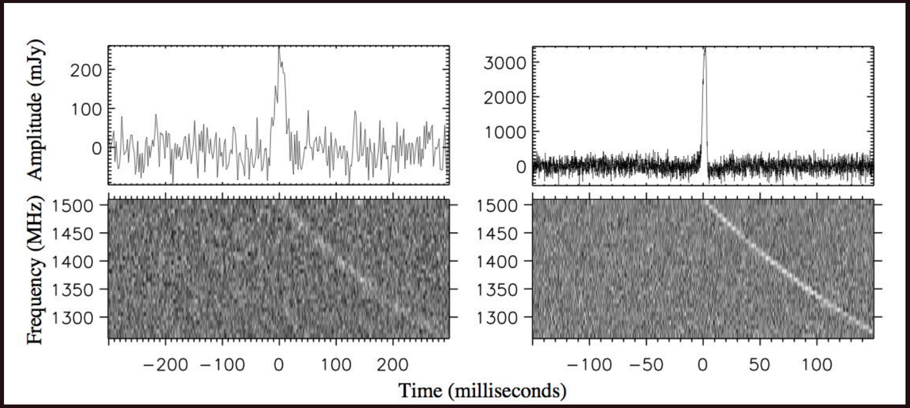
2. <u>eROSITA is coming!</u>
   In 2014 spectrum-RG with eROSITA will be launched.
   It is expected that with this telescope tens of
   new M7-like NSs can be found (Boldin et al., Pires et al.)



Discovery of radio transients

McLaughlin et al. (2006) discovered a new type of sources– RRATs (Rotating Radio Transients).
For most of the sources periods about few seconds were discovered.
The result was obtained during the Parkes survey of the Galactic plane.

Burst duration 2-30 ms, interval 4 min-3 hr
Periods in the range 0.4-7 s

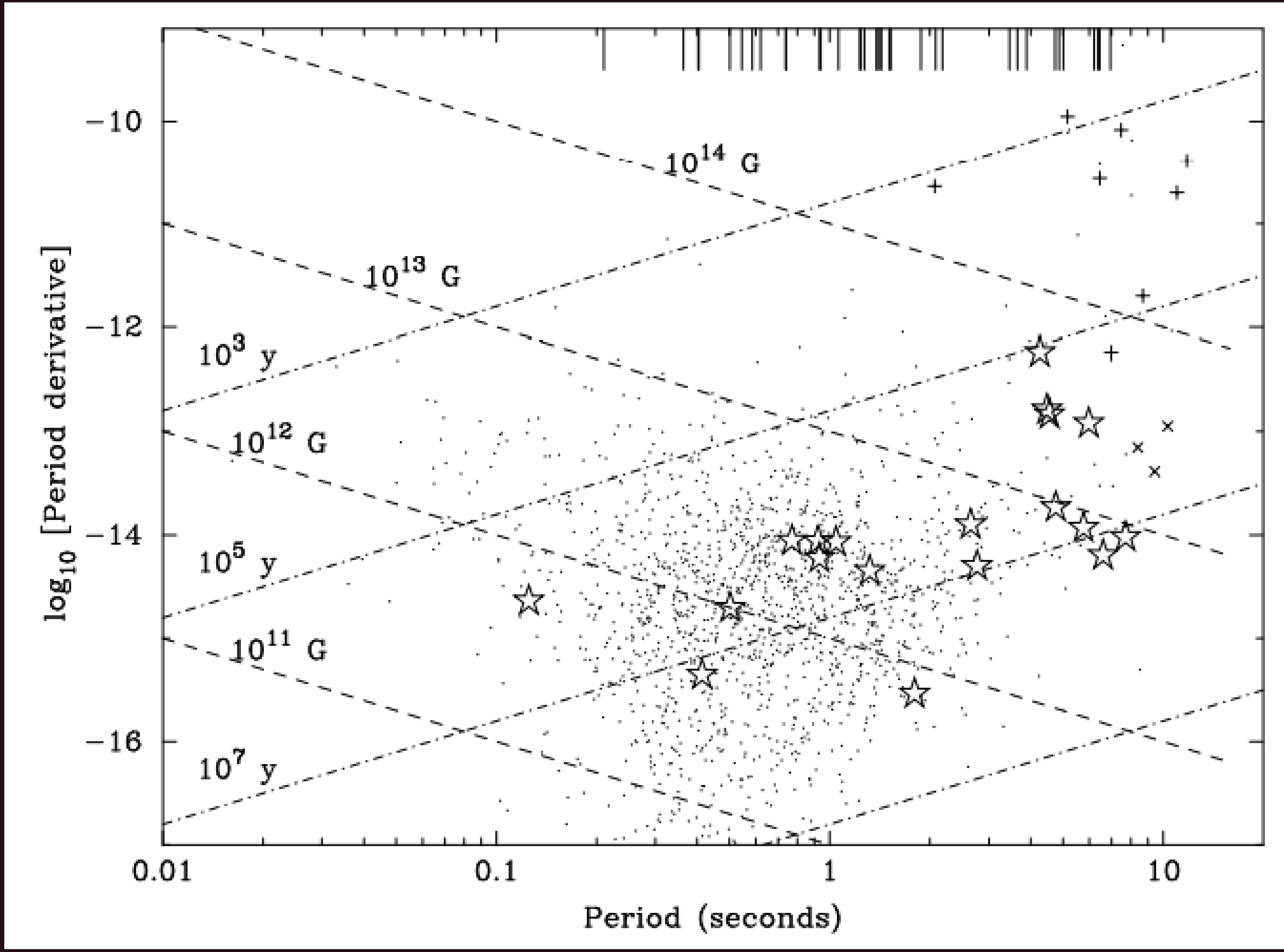


Thermal X-rays were observed from one of the RRATs (Reynolds et al. 2006). This one seems to me the youngest.

See a review in: 1109.6896

Catalogue: http://www.as.wvu.edu/~pulsar/rratalog/

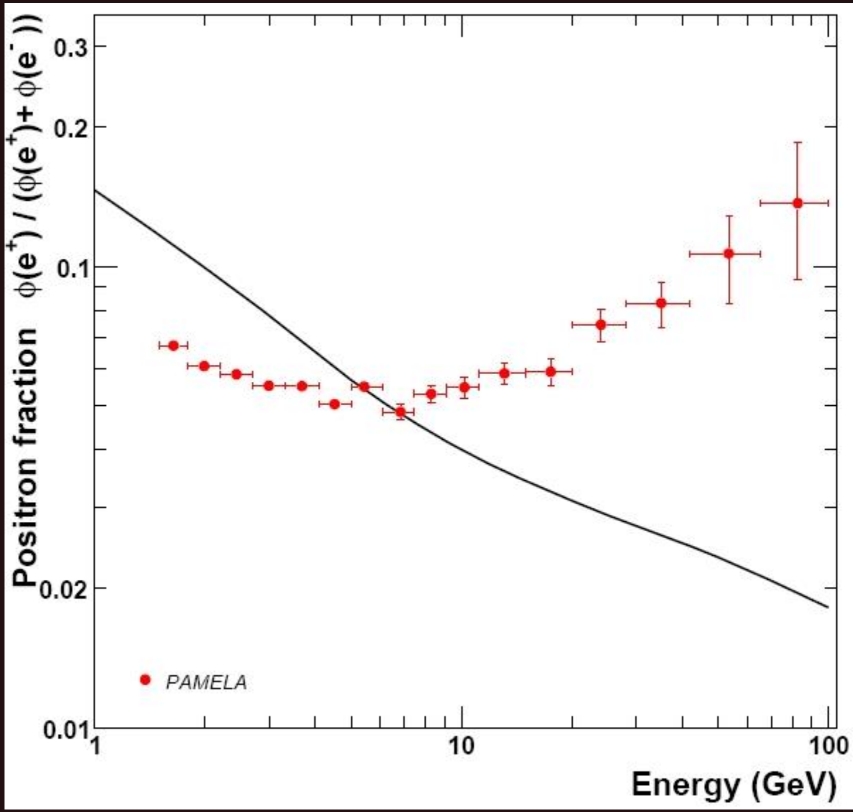
RRATs properties

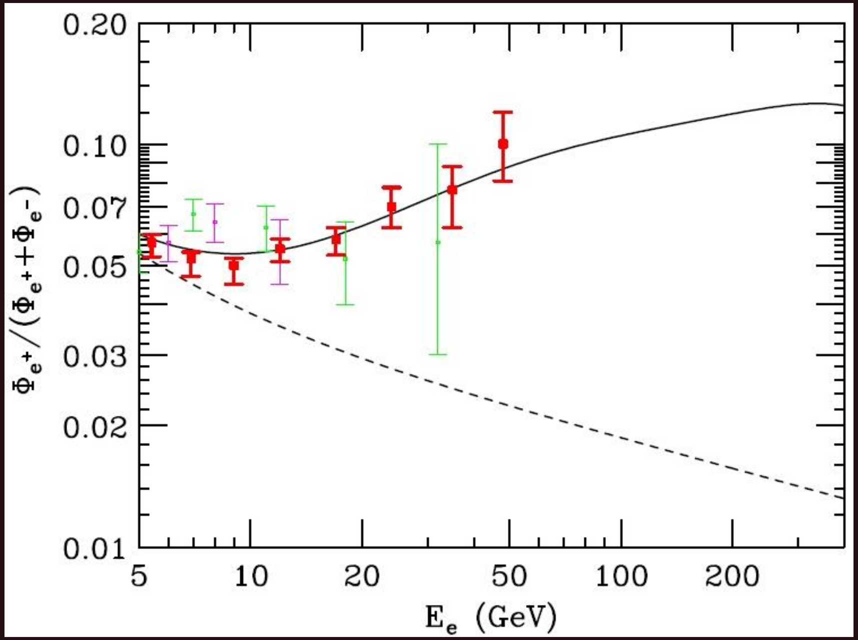


19 with P-Pdot RRATs seem to be similar to PSRs

1109.6896

Pulsars, positrons, PAMELA



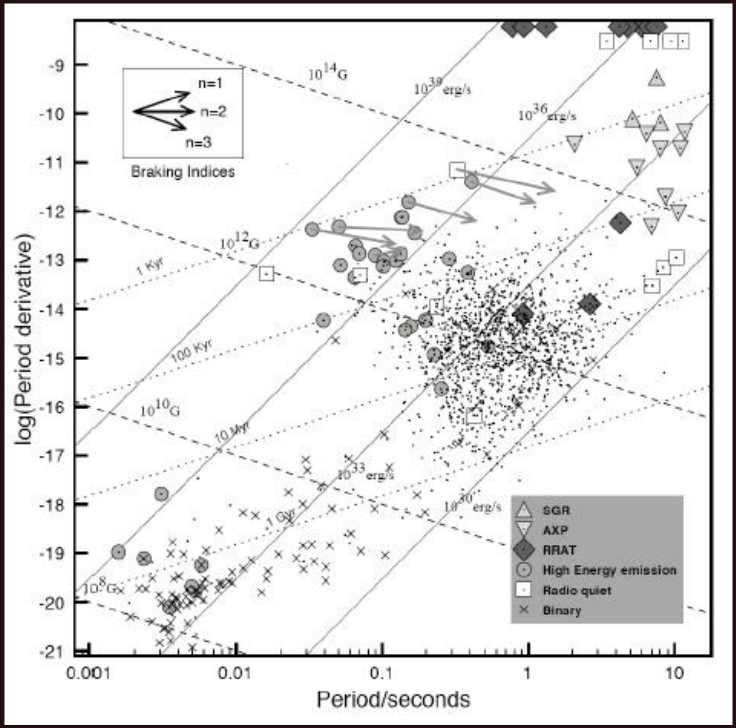


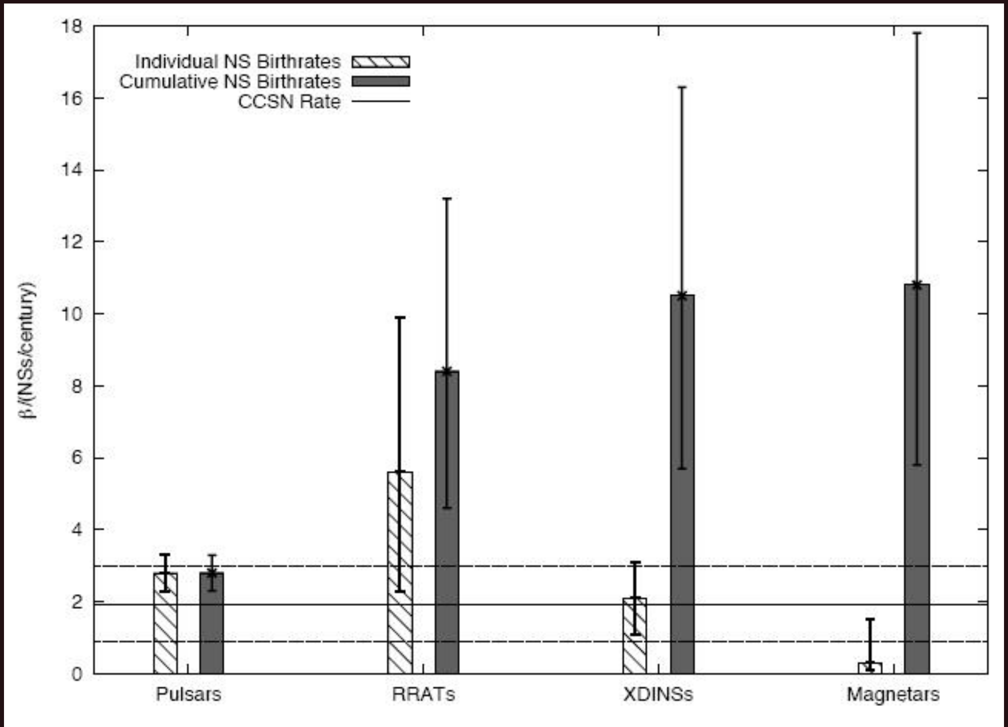
Geminga, PSR B0656+14, and all PSRs

[O. Adriani et al.] arXiv:0810.4995

[Dan Hooper et al. 2008
arXiv: 0810.1527]

NS birth rate





[Keane, Kramer 2008, arXiv: 0810.1512]

Too many NSs???

β_{PSR}, n_e	PSRs	RRATs	XDINSs	Magnetars	Total	CCSN rate
FK06, NE2001	2.8 ± 0.5	$5.6^{+4.3}_{-3.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$10.8^{+7.0}_{-5.0}$	1.9 ± 1.1
L+06, NE2001	1.4 ± 0.2	$2.8^{+1.6}_{-1.6}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$6.6^{+4.0}_{-3.0}$	1.9 ± 1.1
L+06, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1
V+04, NE2001	1.6 ± 0.3	$3.2^{+2.5}_{-1.9}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$7.2^{+5.0}_{-3.4}$	1.9 ± 1.1
V+04, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1

It seems, that the total birth rate is larger than the rate of CCSN.
e^- - capture SN cannot save the situation, as they are <~20%.

Note, that the authors do not include CCOs.

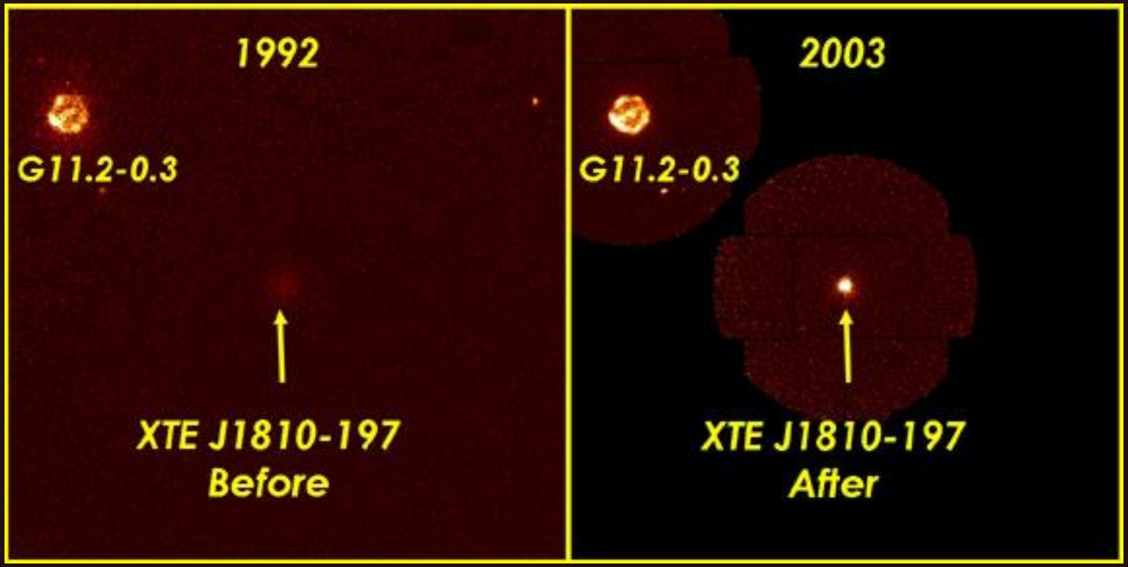
So, some estimates are wrong, or some sources evolve into others.

See also astro-ph/0603258.

GRAND UNIFICATION: 1005.0876

[Keane, Kramer 2008, arXiv: 0810.1512]

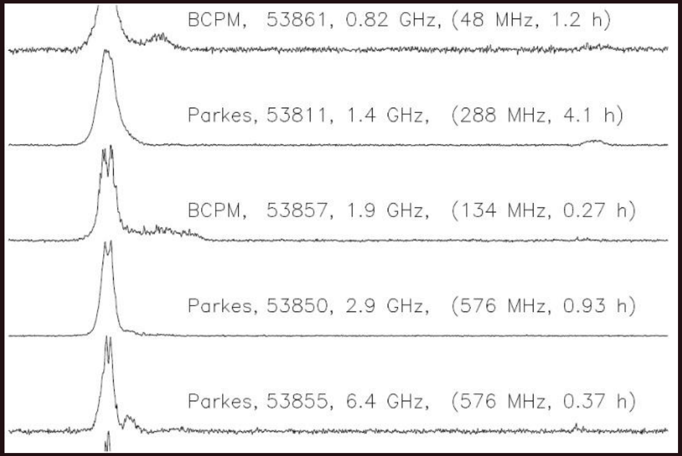
Transient radio emission from AXP



ROSAT and XMM images an X-ray outburst happened in 2003.

AXP has spin period 5.54 s

Radio emission was detected from XTE J1810-197 during its active state.
Clear pulsations have been detected.
Large radio luminosity.
Strong polarization.
Precise Pdot measurement.
Important to constrain models, for better distance and coordinates determinations, etc.



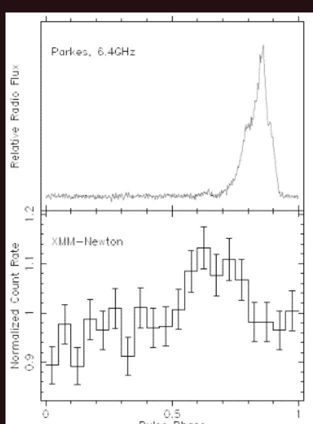
(Camilo et al. astro-ph/0605429)

Another AXP detected in radio

1E 1547.0-5408
P= 2 sec
SNR G327.24-0.13

Pdot changed significantly on the scale of just ~few months
Rotation and magnetic axis seem to be aligned

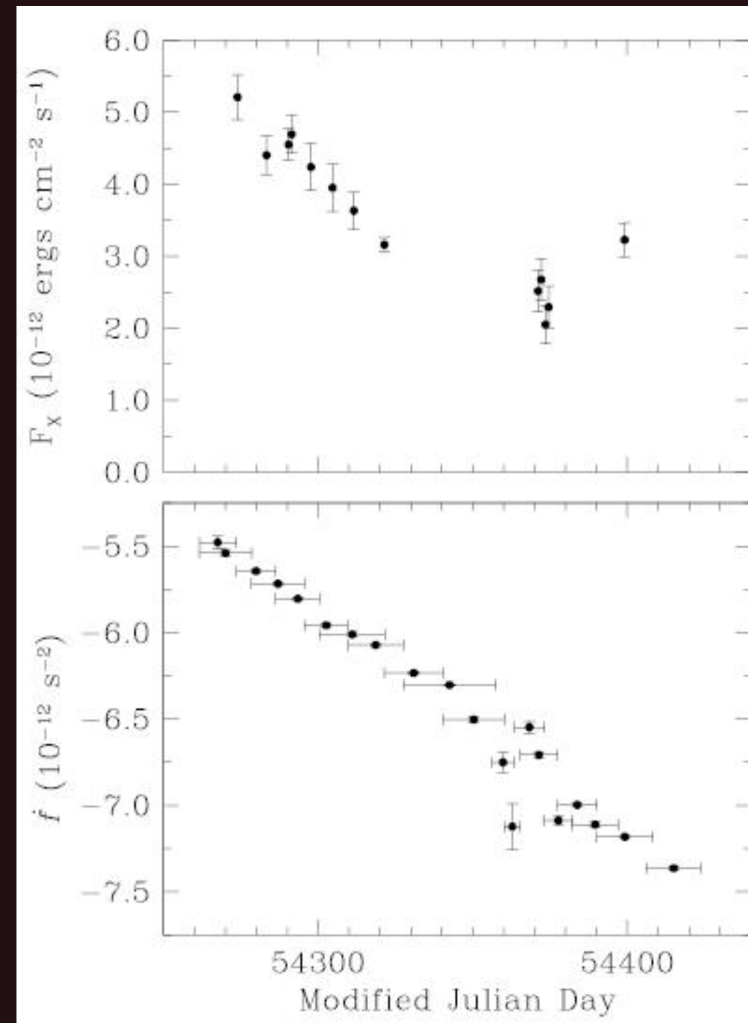
Also this AXP demonstrated weak SGR-like bursts (Rea et al. 2008, GCN 8313)



Radio

[simultaneous]

X-rays



0802.0494 (see also arxiv:0711.3780)

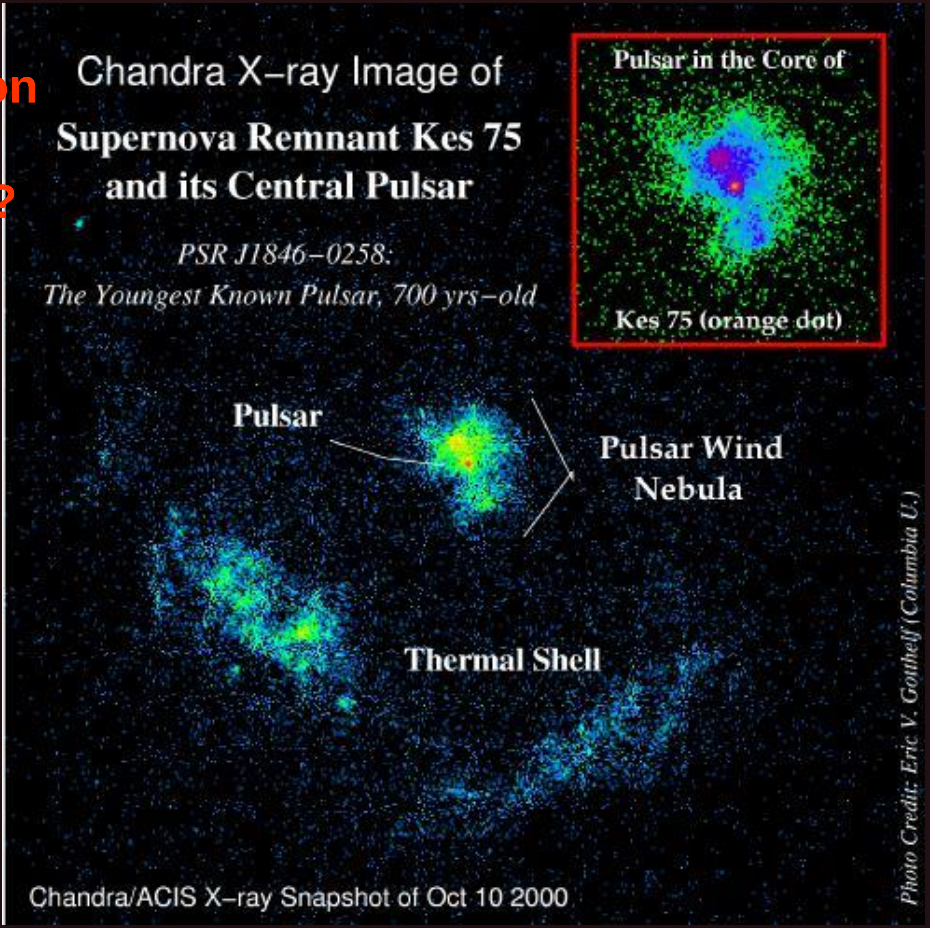
Transient radiopulsar

PSR J1846-0258
P=0.326 sec
B=5 10^{13} G

However,
no radio emission detected.
Due to beaming?

Among all rotation powered PSRs it has the largest Edot.
Smallest spindown age (884 yrs).

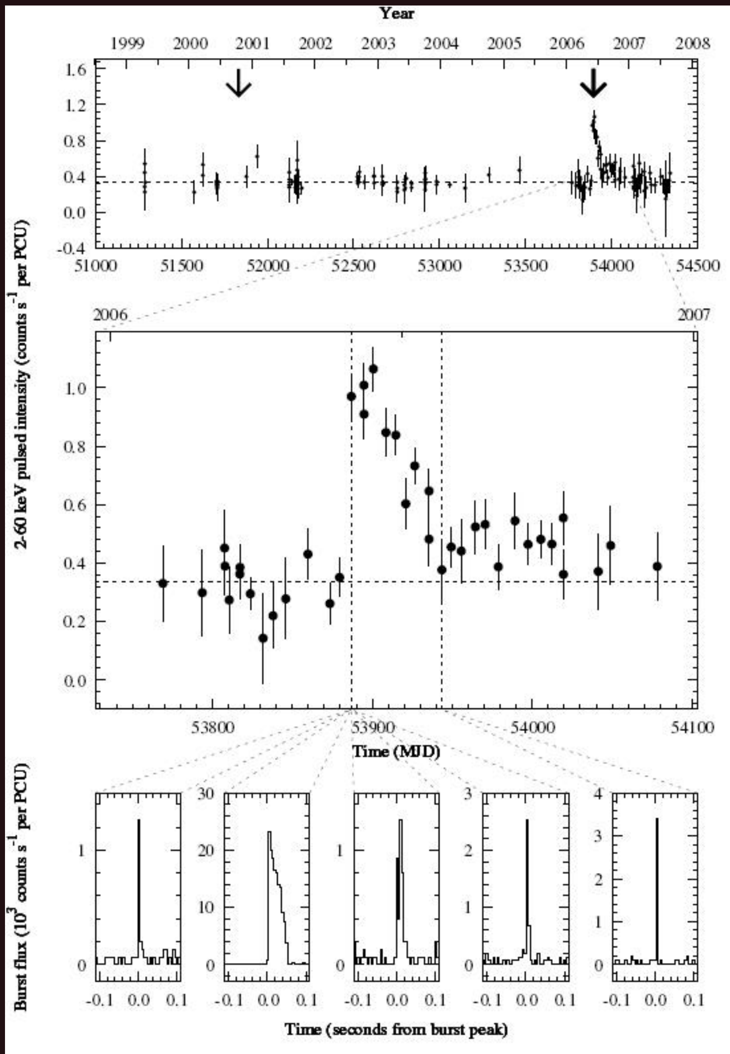
The pulsar increased its luminosity in X-rays.
Increase of pulsed X-ray flux.
Magnetar-like X-ray bursts (RXTE).
Timing noise.



See additional info about this pulsar at the web-site http://hera.ph1.uni-koeln.de/~heintzma/SNR/SNR1_IV.htm

0802.1242, 0802.1704

Bursts from the transient PSR



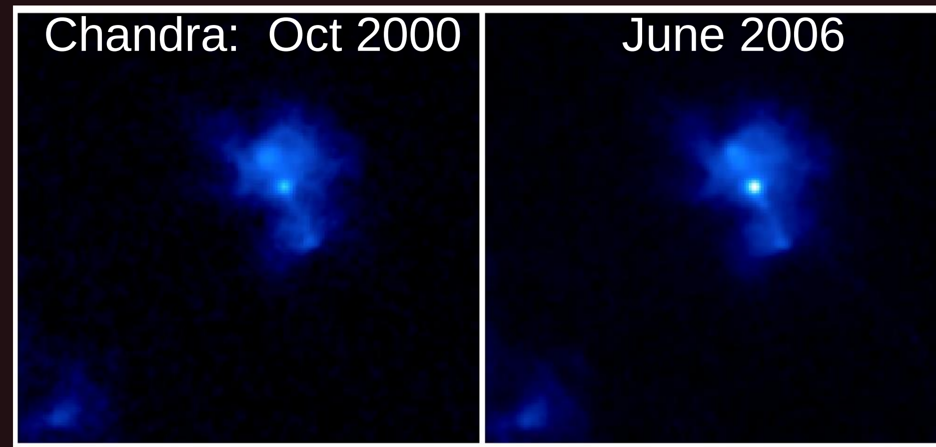
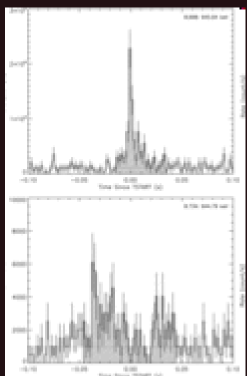


Table 1	PSR J1846−0258 Burst Temporal and Spectral Properties				
	Burst 1	Burst 2	Burst 3	Burst 4	Burst 5
Temporal properties					
Burst day (MJD)	53886	53886	53886	53886	53943
Burst start time (fraction of day)	0.92113966(5)	0.93247134(1)	0.93908845(2)	0.94248467(5)	0.45543551(1)
Rise time, t_r (ms)	$4.2^{+3.5}_{-2.0}$	$1.1^{+0.9}_{-0.5}$	$1.90^{+1.7}_{-0.9}$	$4.1^{+3.1}_{-1.9}$	$0.9^{+2.2}_{-0.7}$
T_{90} (ms)	$71.8^{+38.0}_{-5.5}$	$42.9^{+0.3}_{-0.2}$	$137.0^{+11.4}_{-36.2}$	$33.4^{+29.1}_{-23.1}$	$65.3^{+0.7}_{-0.5}$
Phase (cycles)	-0.49(1)	-0.04(1)	-0.20(1)	-0.05(1)	-0.08(1)
Fluences and fluxes					
T_{90} Fluence (counts/PCU)	8.9±0.7	712.8±2.5	18.3±0.7	18.4±0.7	18.4±1.1
T_{90} Fluence (10^{-10} erg/cm^2)	4.1±2.4	289.9±13.1	6.6±2.5	5.8±1.7	5.3±2.0
Flux for 64 ms (10^{-10} erg/s/cm^2)	57±36	4533±227	99±41	97±31	79±32
Flux for t_r (10^{-10} erg/s/cm^2)	678±427	5783±885	810±385	828±284	2698±1193
Spectral properties					
Power-law index	0.89±0.58	1.05±.04	1.14±0.34	1.36±0.25	1.41±0.31
χ^2/DoF (DoF)	0.42 (1)	1.16 (55)	0.97 (3)	0.35 (2)	1.18 (2)

Gavriil et al. 0802.1704

Weak dipole field magnetar



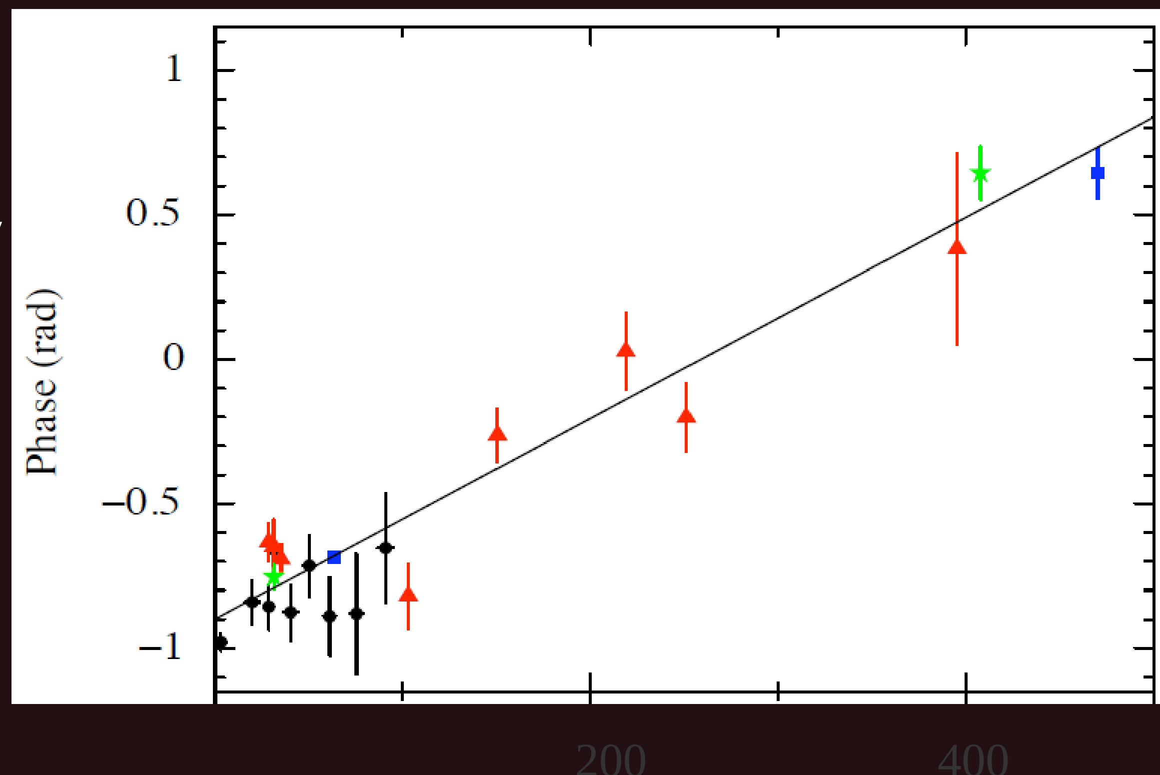
Spin period of a neutron star grows.
The rate of deceleration is related to the dipole magnetic field.
Measuring the spin-down rate we measure the field.

The source is a soft gamma-ray repeater: SGR 0418+5729
P=9.1 s

The straight line in the plot corresponds to a constant spin periods: i.e. no spin-down

$B<7.5\ 10^{12}$ G (arXiv:1010.2781)

Old magnetar ? (1107.5488)



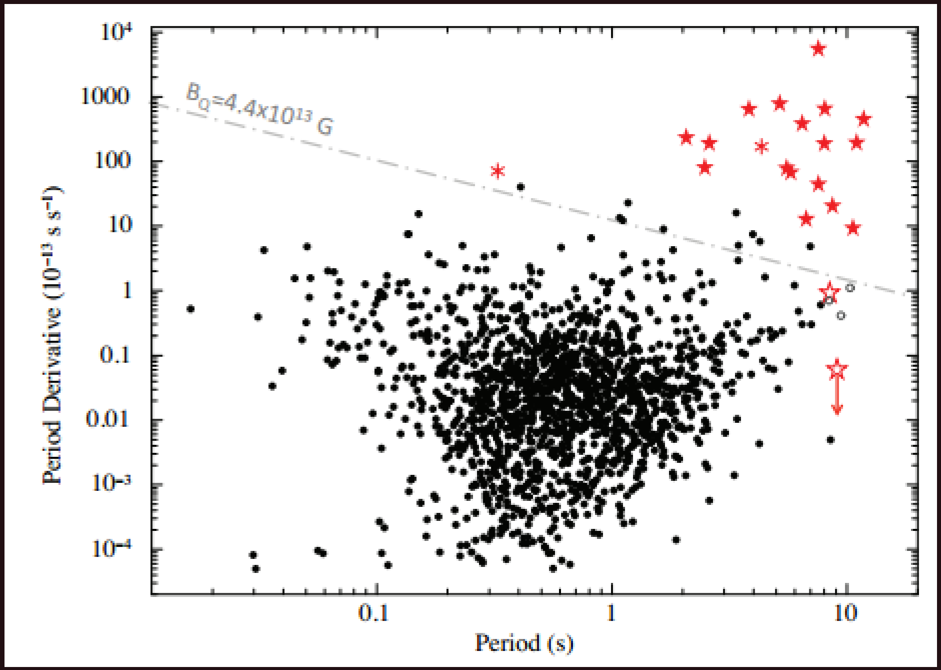
Spectral data suggests high field on the surface: 1103.3024

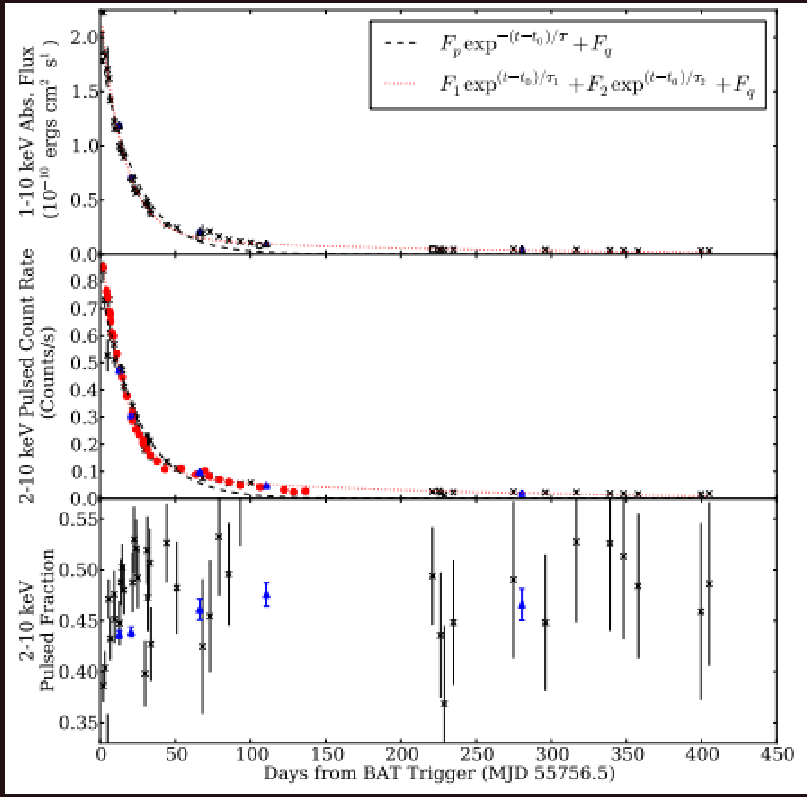
Another low field magnetar

Swift J1822.3-1606 (SGR 1822-1606)

P=8.44 s

B=3-5 10^{13} G



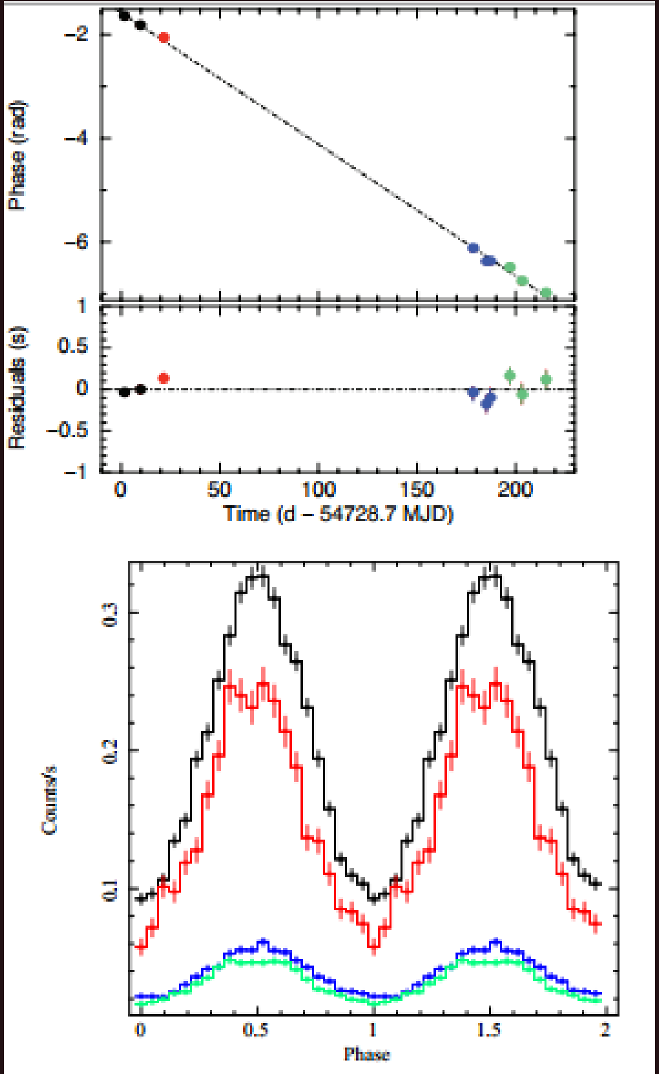


1204.1034

1203.6449

New data: 1211.7347

One more low-field magnetar

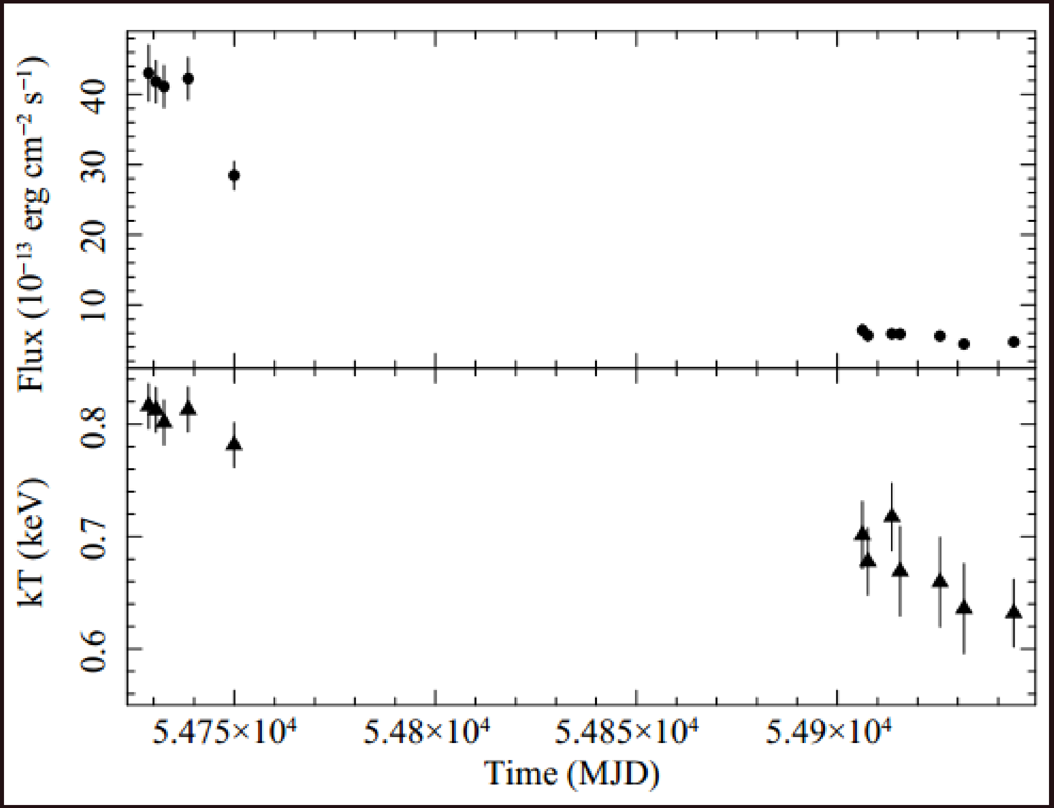


3XMM J185246.6+003317

P=11.5 s No spin-down detected after 7 months

$B<4\ 10^{13}$ G

Transient magnetar



1311.3091

Quiescent magnetar

Normally magnetars are detected via their strong activity: gamma-ray bursts or enhanced X-ray luminosity.

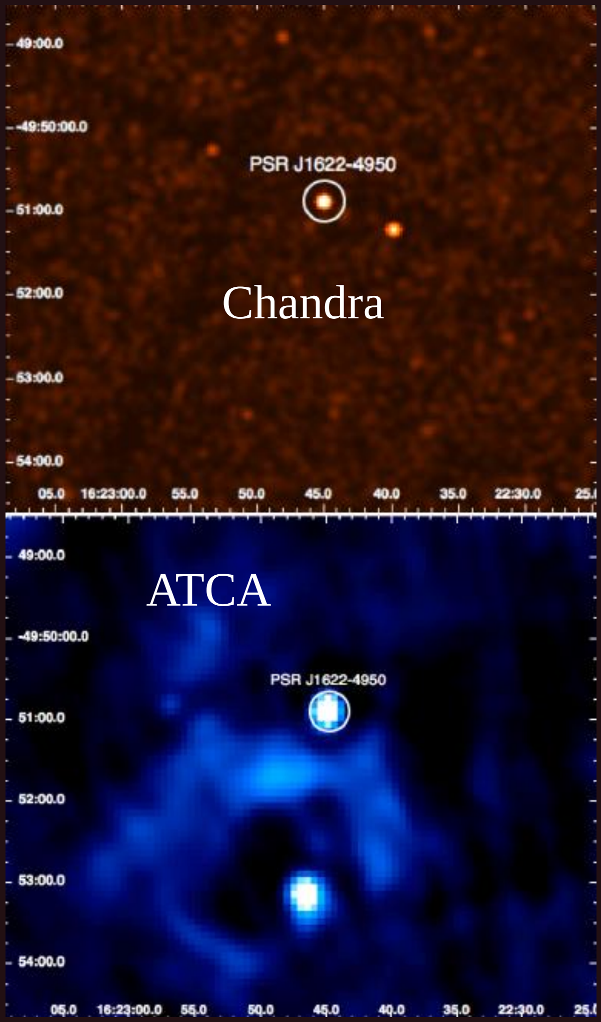
This one was detected in radio observations
The field is estimated to be $B \sim 3\ 10^{14}$ G

It seems to be the first magnetar to be
Detected in a quiescent state.

PSR J1622–4950 was detected in a radio survey
As a pulsar with P=4.3 s.

Noisy behavior in radio

(see a review on high-B PSRs in 1010.4592

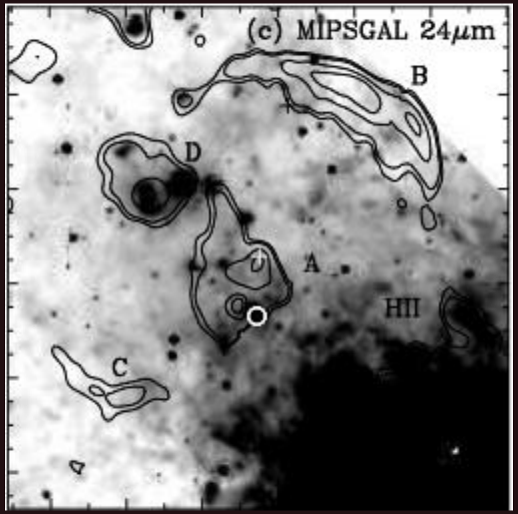


arXiv: 1007.1052

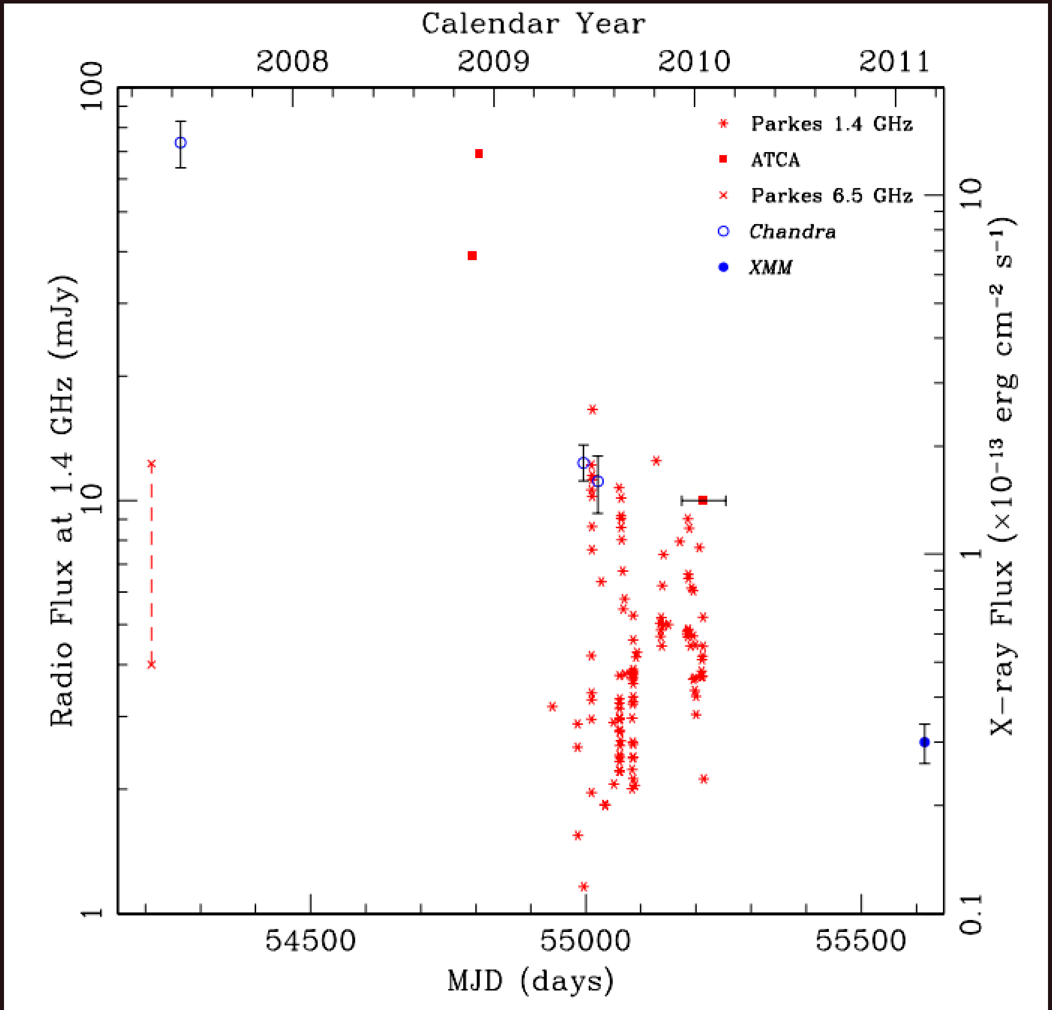
A transient magnetar?

PSR J1622–4950

X-ray flux is decaying
for several years.
Probably, the source
was active years before.



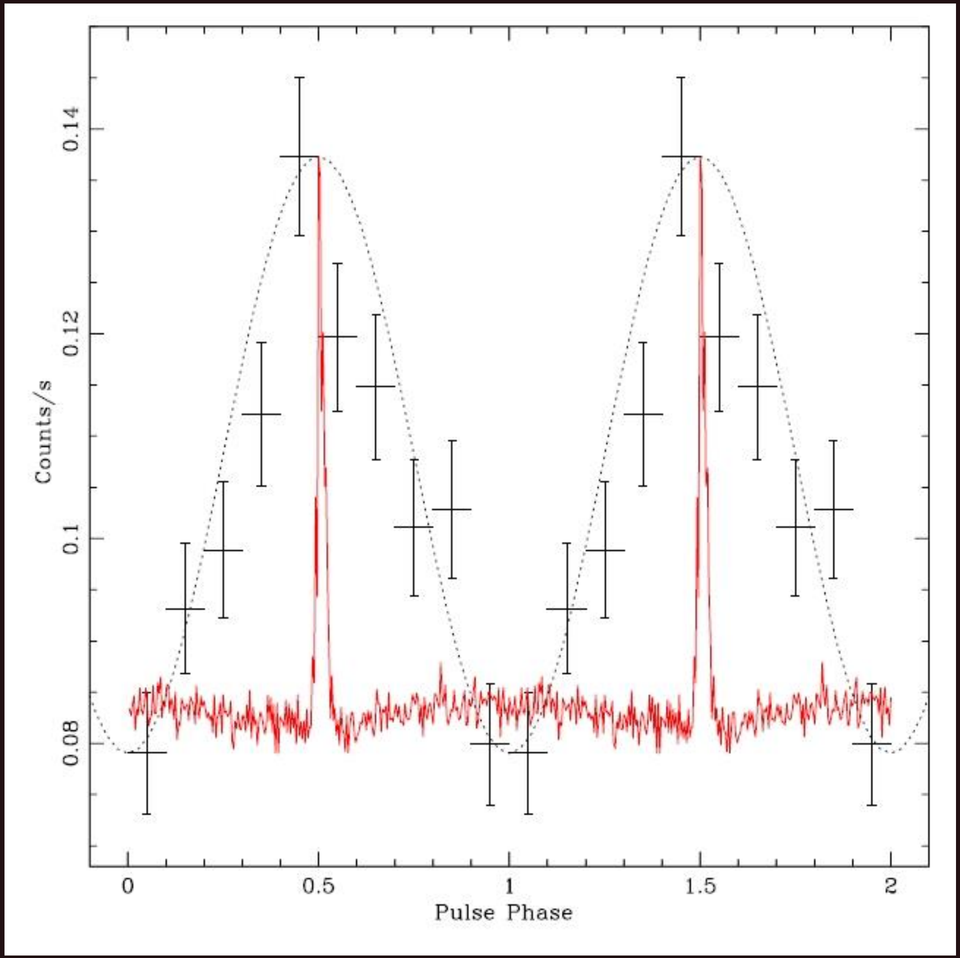
G333.9+0.0 SNR ?



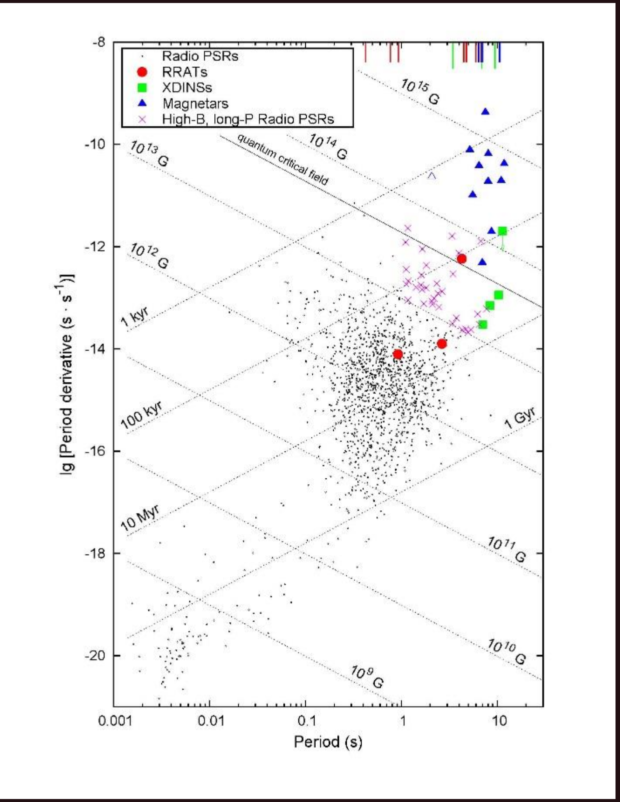
1203.2719

See also 1204.2045

RRATs. X-ray + radio data

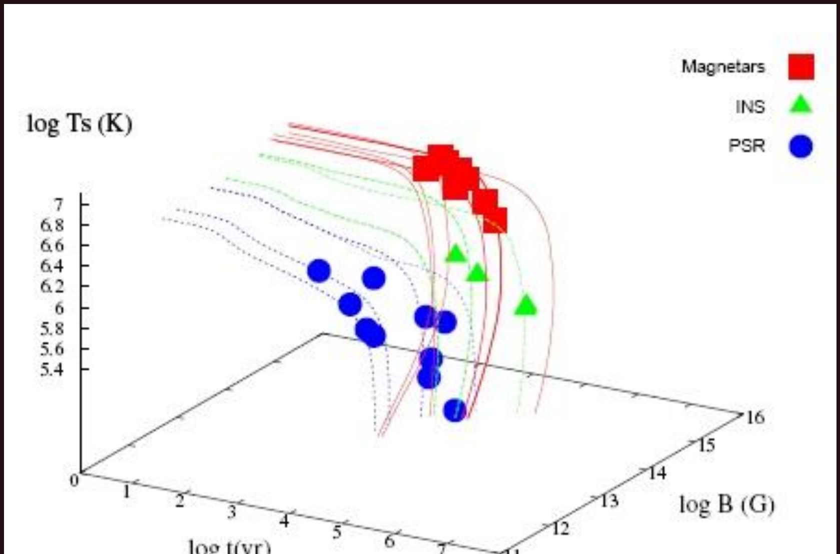


X-ray pulses overlaped on radio data of RRAT J1819-1458.

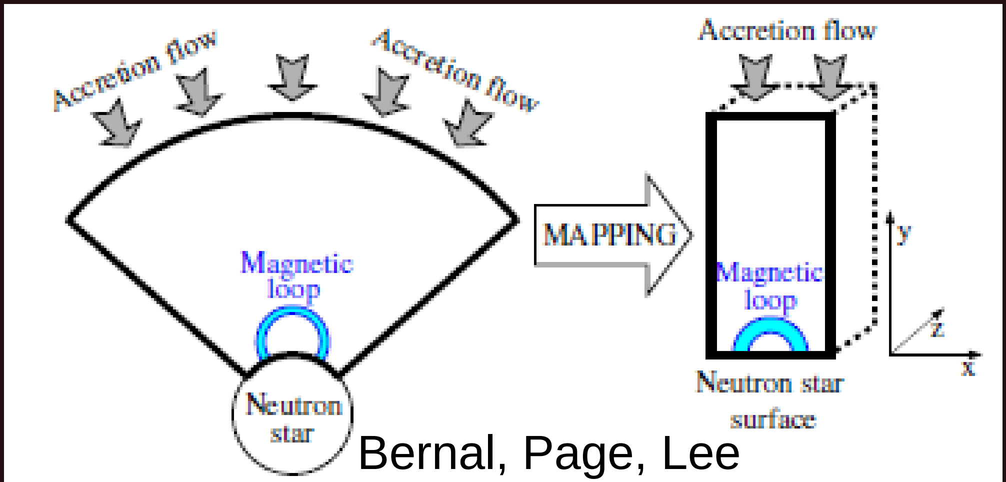


(arXiv: 0710.2056)

Three main ingredients:

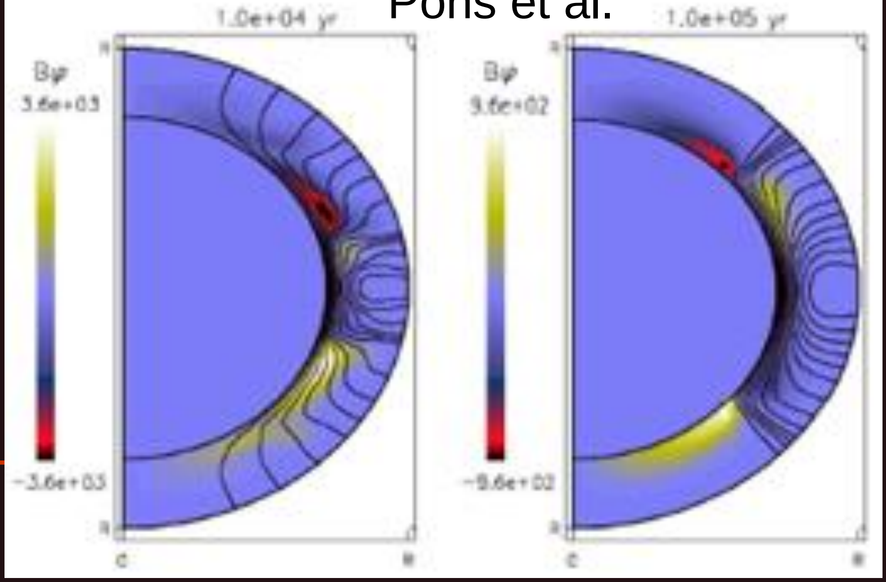


Aguilera et al.



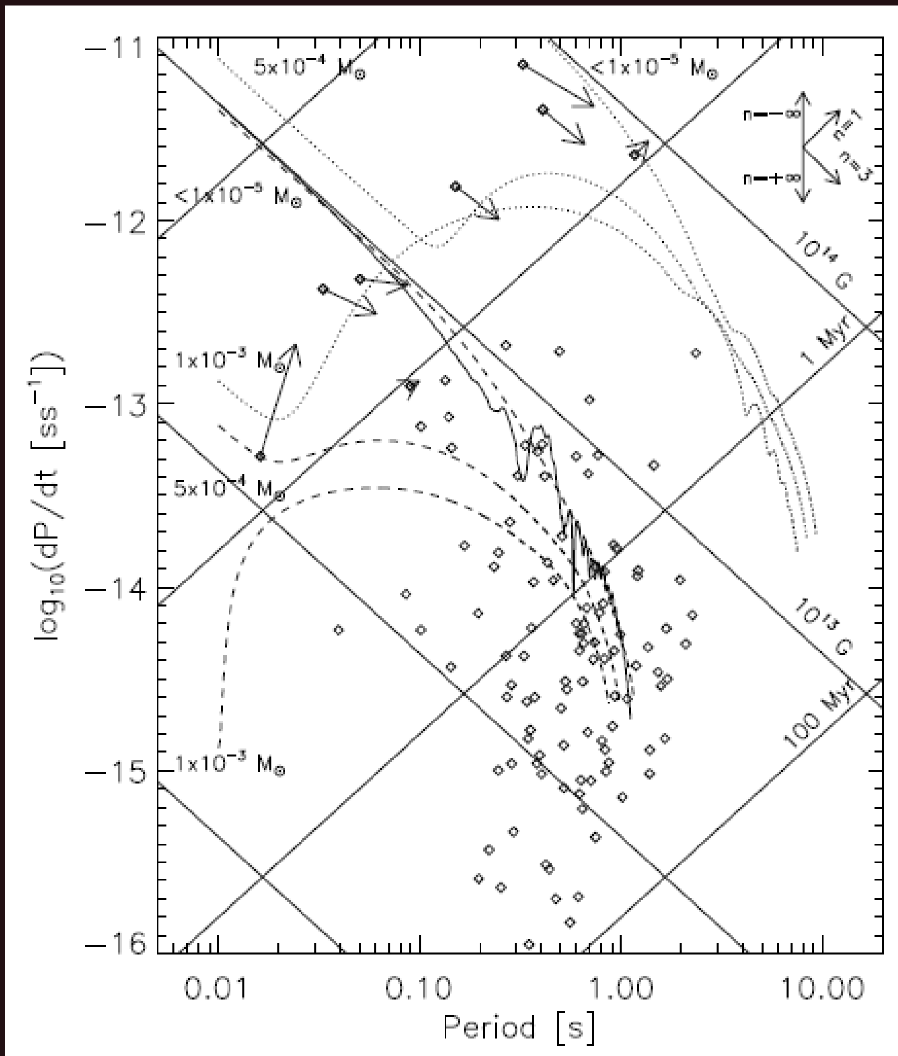
Bernal, Page, Lee

Pons et al.



- Field decay
- Emerging magnetic field
- Toroidal magentic field

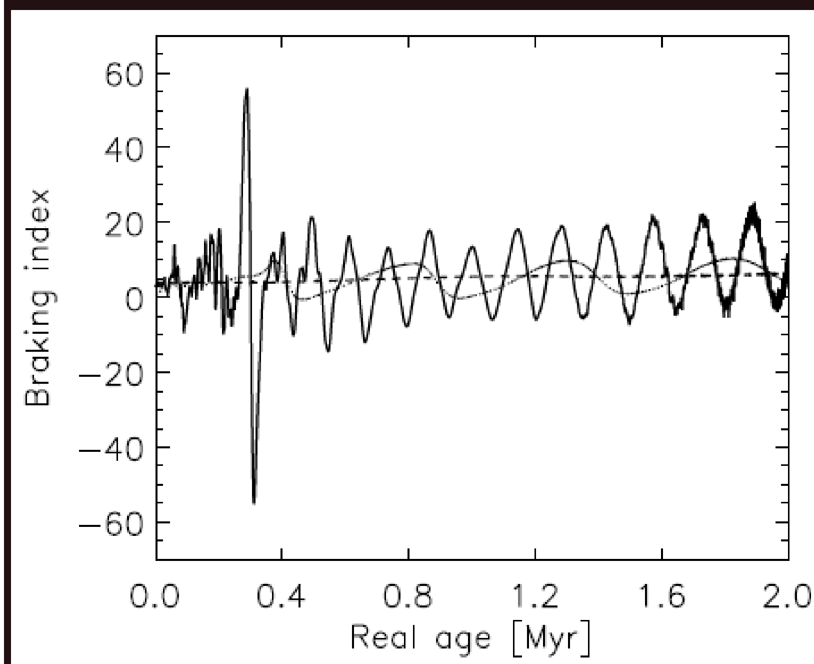
Evolution of PSRs with evolving field



Three stages:

1. n<=3 Standard + emerging field
2. n>3 Ohmic field decay
3. Oscillating and large n – Hall drift

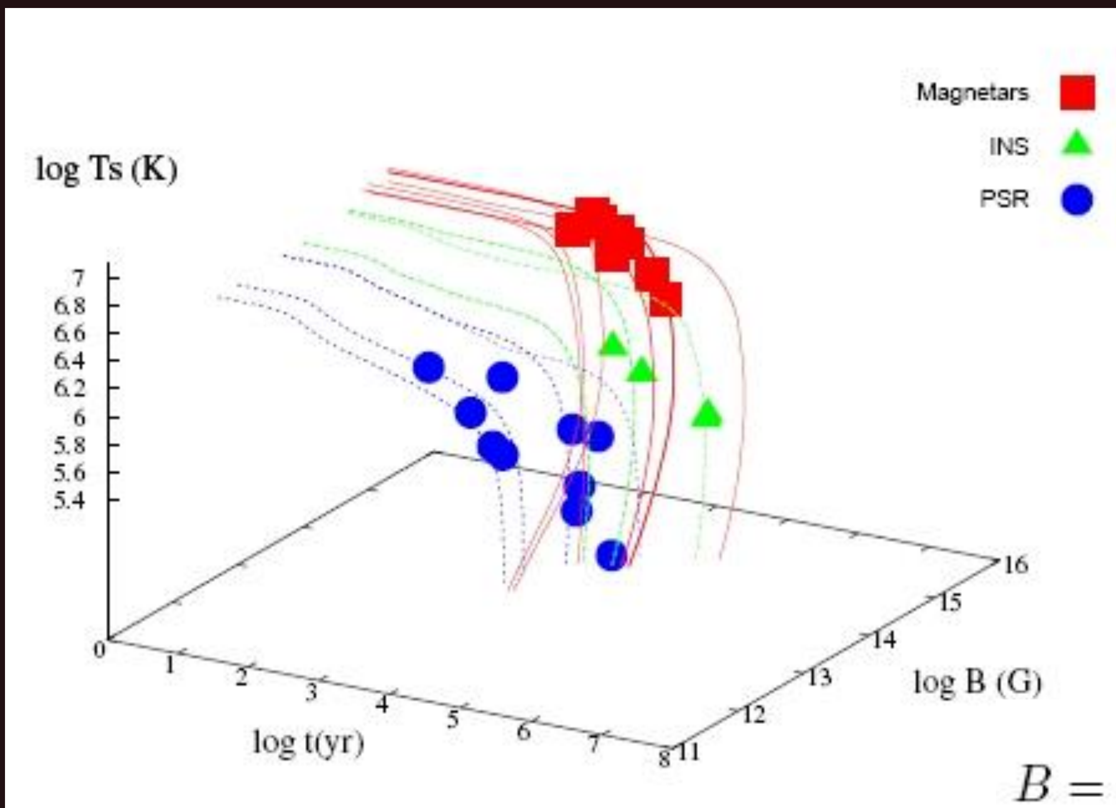
$$n = 3 - 4\frac{\dot{B}_0}{B_0}\tau_c \equiv 3 - 4\frac{\tau_c}{\tau_B} ,$$



Pons, Vigano, Geppert 2012

Magnetic field decay

A model based on the initial field-dependent decay
can provide an evolutionary link between different populations (Pons et al.).

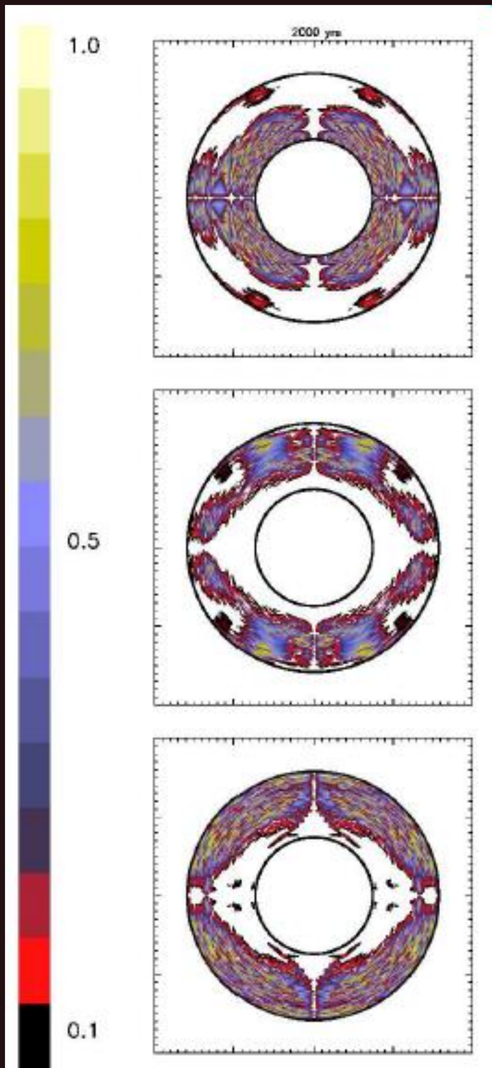


Toroidal field is very important for magnetar activity!

$$B = B_0 \frac{\exp\left(-t/\tau_{\rm Ohm}\right)}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}\left(1 - \exp\left(-t/\tau_{\rm Ohm}\right)\right)}$$

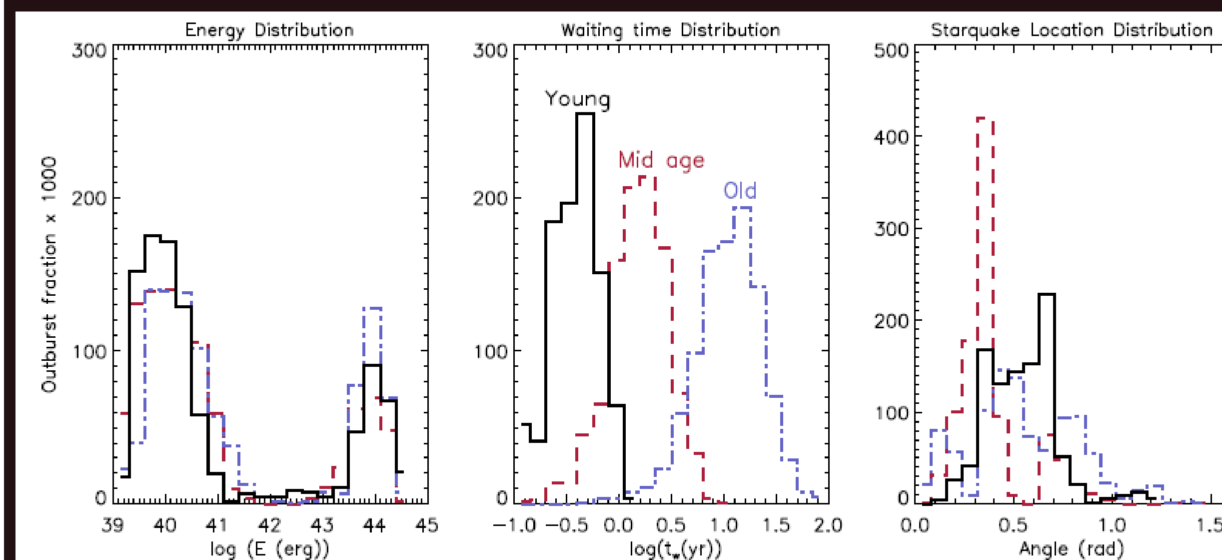
arXiv: 0710.4914 (Aguilera et al.)

Magnetars bursting activity due to decay



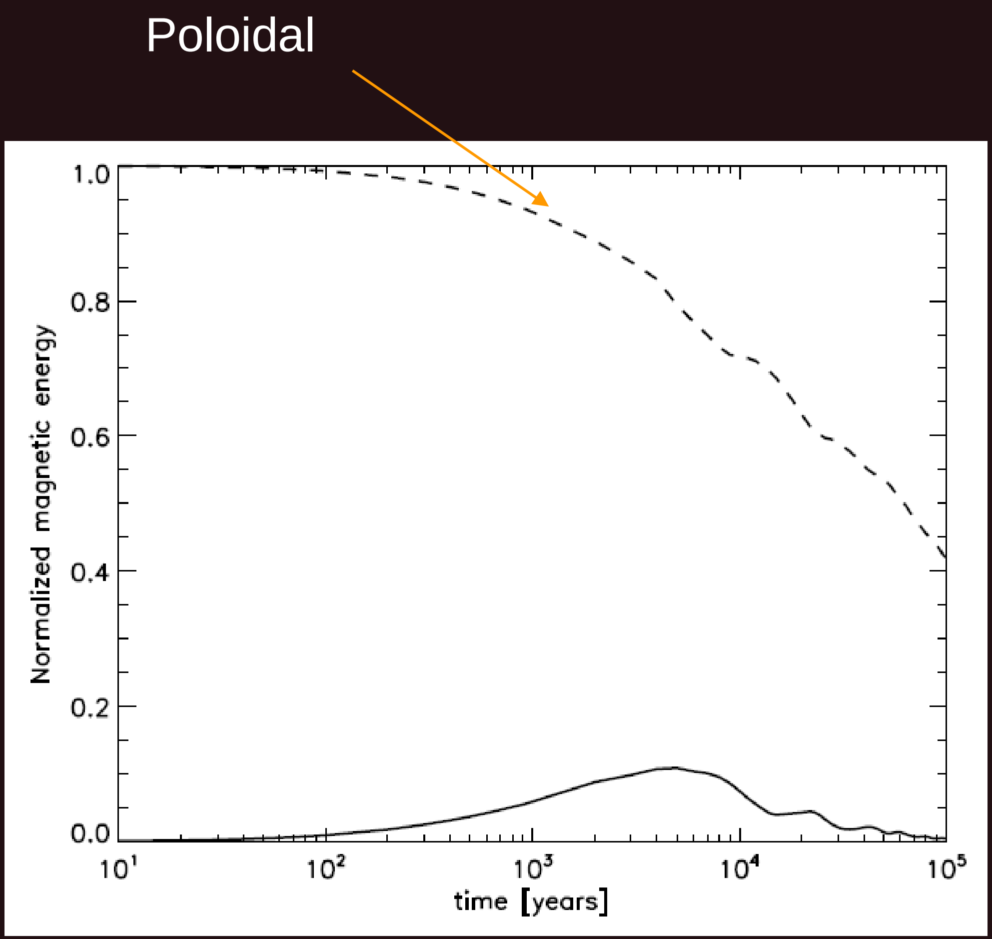
In the field decay model it is possible to study burst activity. Bursts occur due to crust cracking. The decaying field produce stresses in the crust that are not compensated by plastic deformations. When the stress level reaches a critical value the crust cracks, and energy can be released.

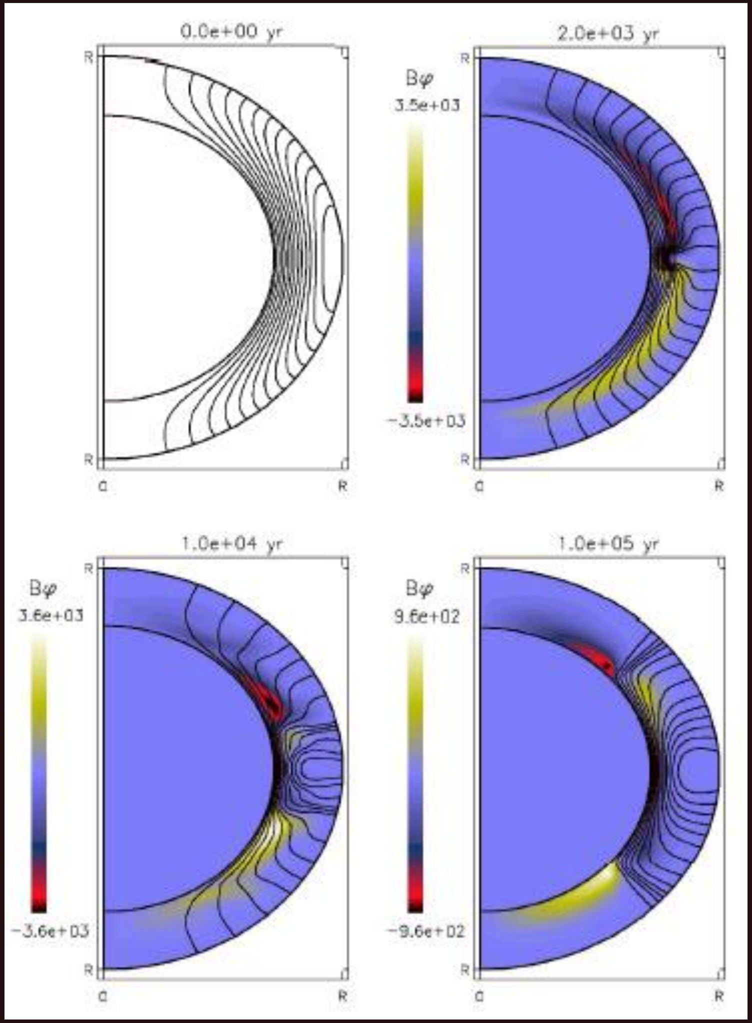
At the moment the model is very simple, but this just the first step.



1101.1098

A recent model



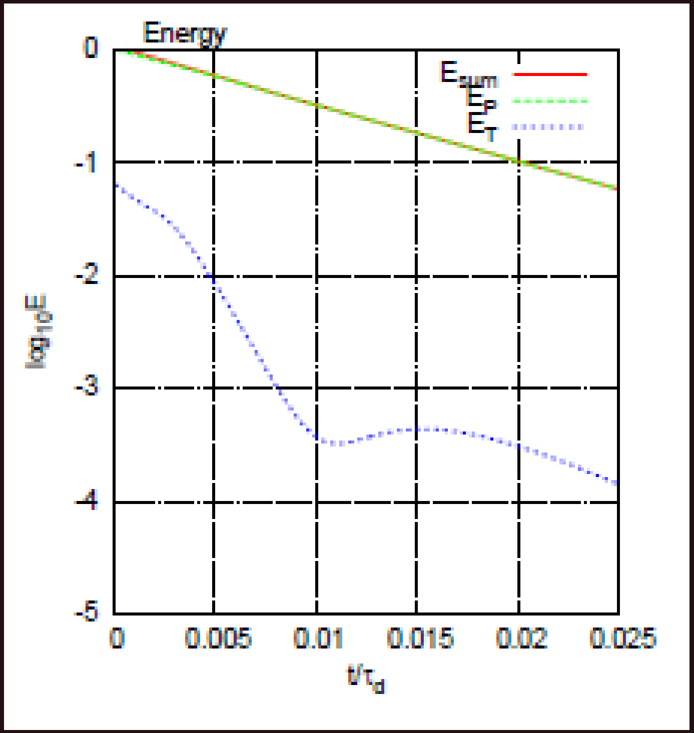


Test illustrates the evolution of initially purely poloidal field

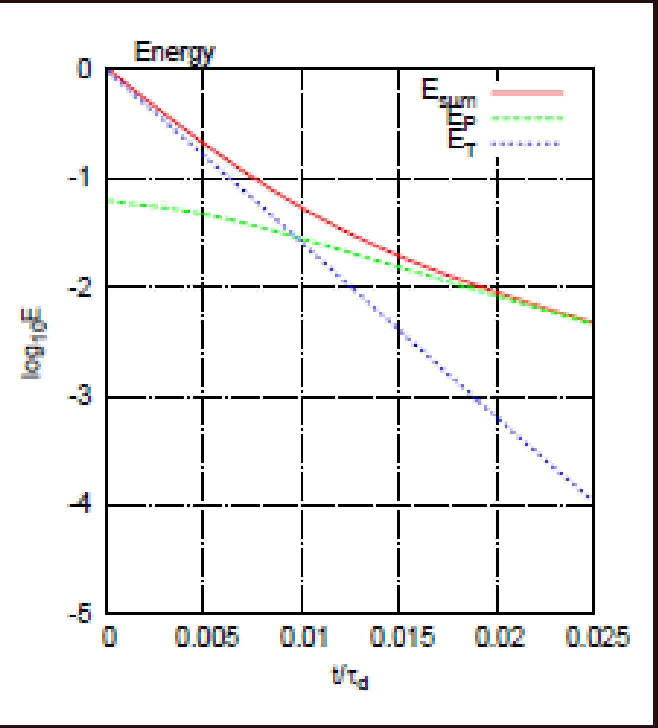
1204.4707

Another new model

Initially the poloidal field is large.



Initially the toroidal field is large.

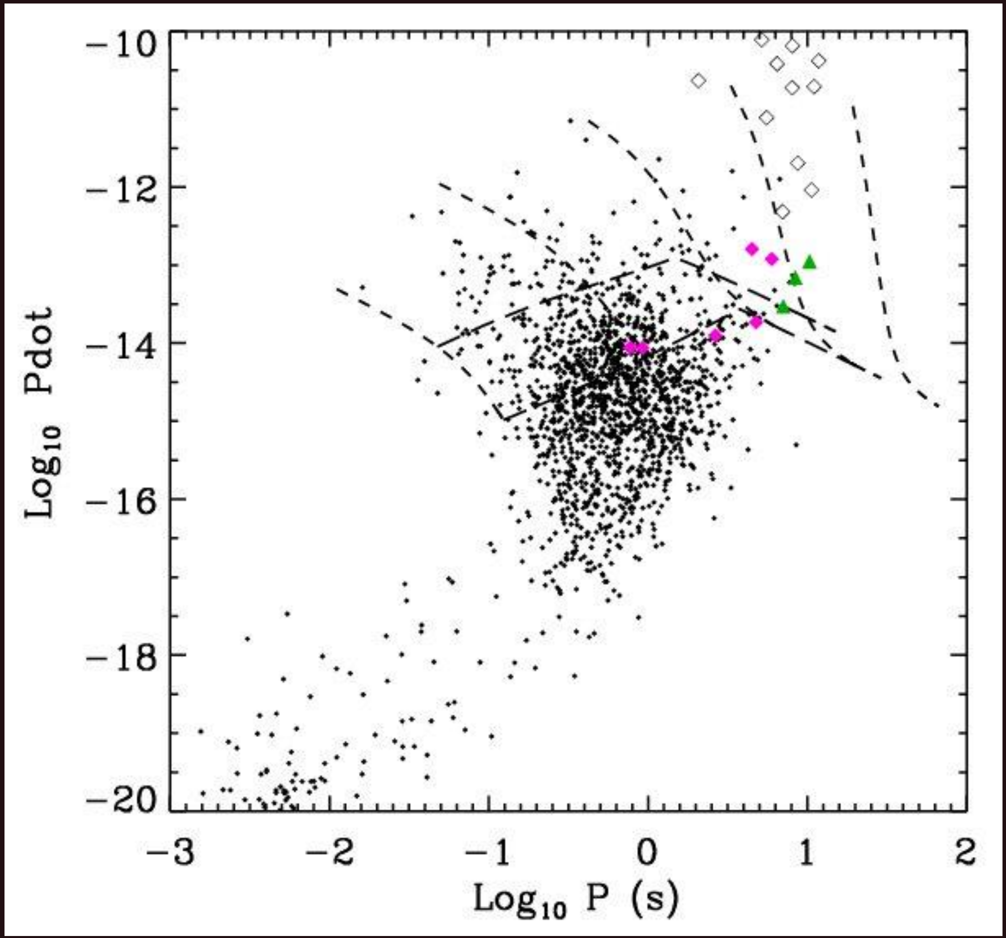


If the toroidal field dominates initially then significant energy is transferred to the poloidal component during evolution.

In the opposite case, when the poloidal component initially dominates, energy is not transferred. The toroidal component decouples.

1201.1346

Magnetic field decay and links



$$B = B_0 \frac{\exp(-t/\tau_{\rm Ohm})}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}(1 - \exp(-t/\tau_{\rm Ohm}))}$$

arXiv: 0710.4914 (Aguilera et al.)

It is possible to use HMXBs to test models of field decay on time scale >1 Myr (Chashkina, Popov 2012)

Recently, another important concept was proposed:
A Hall attractor
(Gourgouliatos, Cumming 2014)

1112.1123

Extensive population synthesis

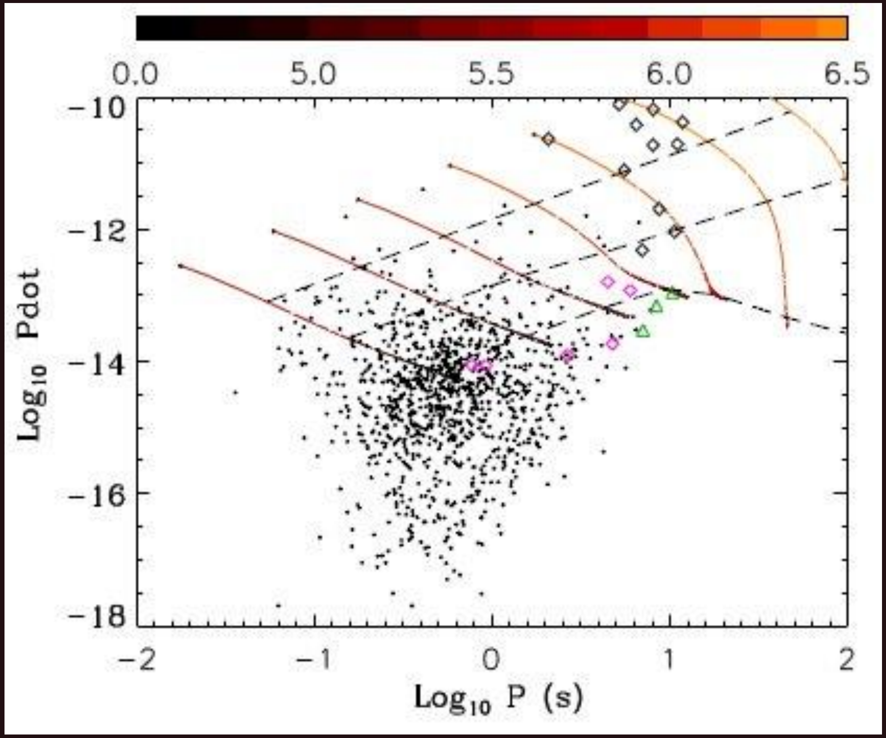
We want to make extensive population synthesis studies using as many approaches as we can to confront theoretical models with different observational data

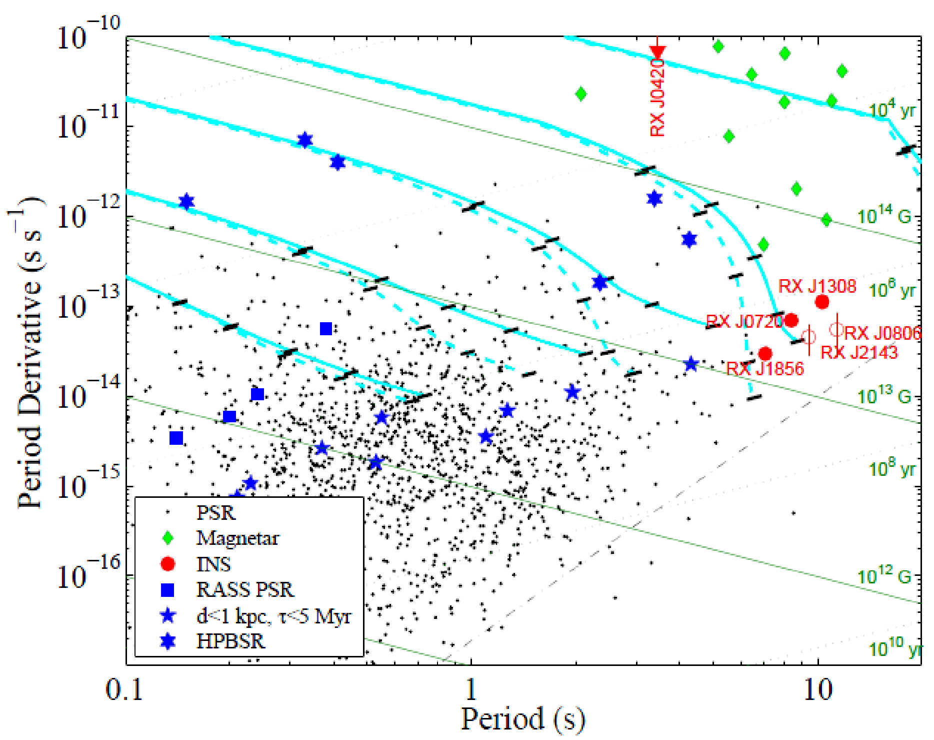
- Log N – Log S for close-by young cooling isolated neutron stars
- Log N – Log L distribution for galactic magnetars
- P-Pdot distribution etc. for normal radio pulsars

MNRAS 401, 2675 (2010)
arXiv: 0910.2190

See a review of the population synthesis technique in
Popov, Prokhorov *Physics Uspekhi* vol. 50, 1123 (2007)

P-Pdot tracks





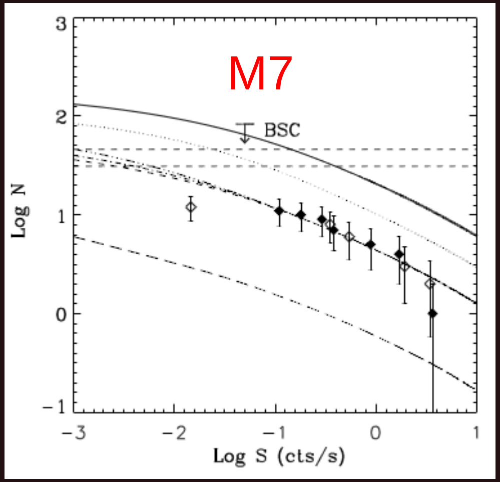
Color on the track encodes surface temperature.

Tracks start at 10^3 years, and end at ~3 10^6 years.

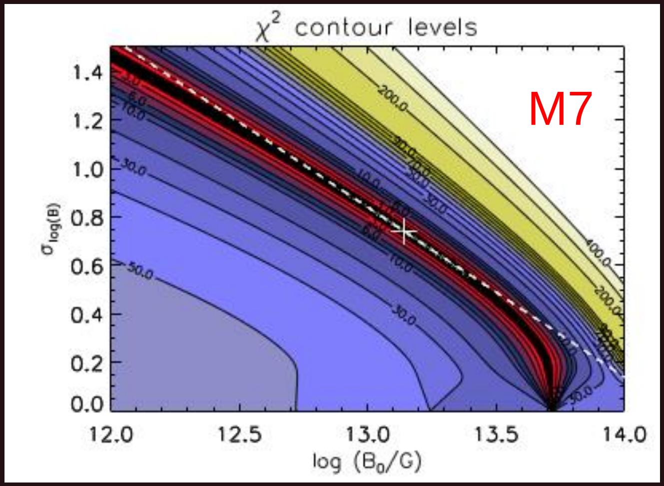
Kaplan & van Kerkwijk arXiv: 0909.5218

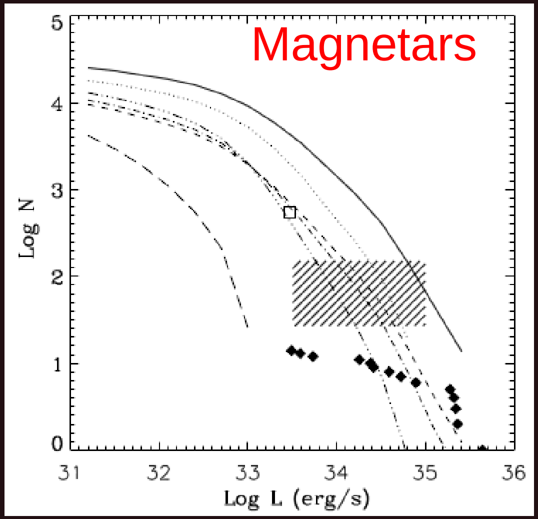
0910.2190

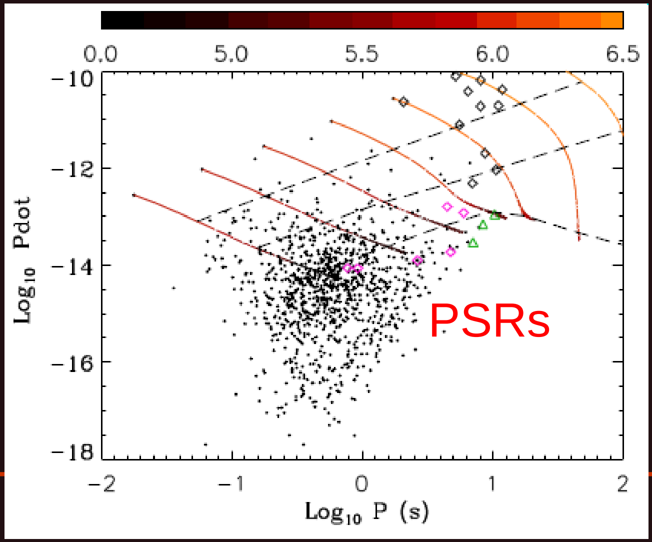
Extensive population synthesis: M7, magnetars, PSRs



Using one population
it is difficult or impossible
to find unique initial
distribution for the
magnetic field



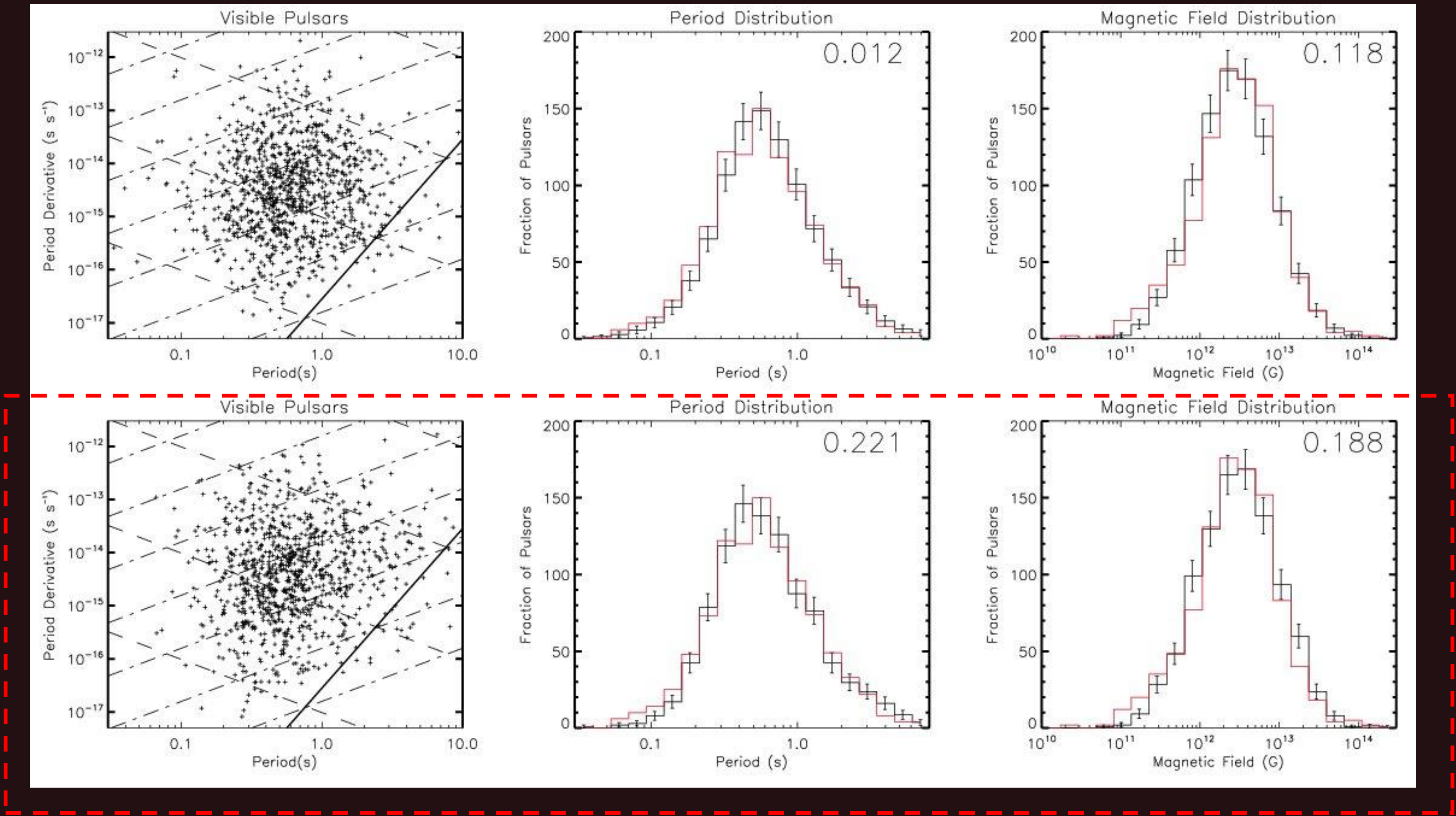




All three populations are compatible with a unique distribution.

Of course, the result is model dependent.

The best model: PSRs+magnetars+M7

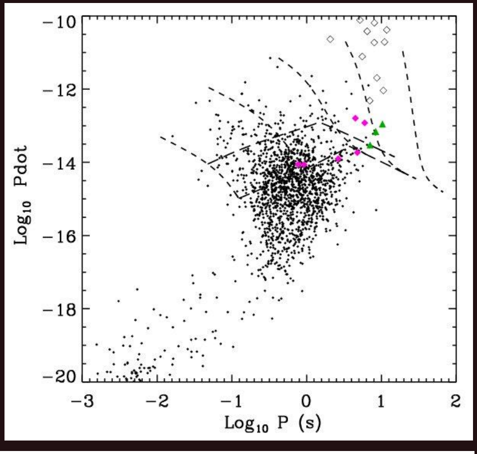


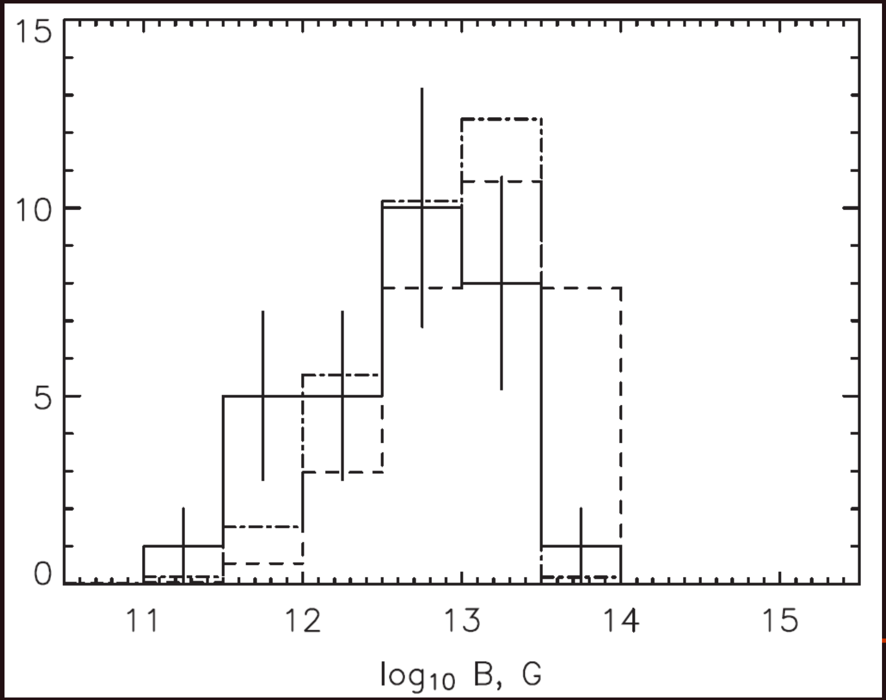
Best model: $\langle \log(B_0/[G]) \rangle = 13.25$, $\sigma_{\log B0} = 0.6$, $\langle P_0 \rangle = 0.25$ s, $\sigma_{P0} = 0.1$ s

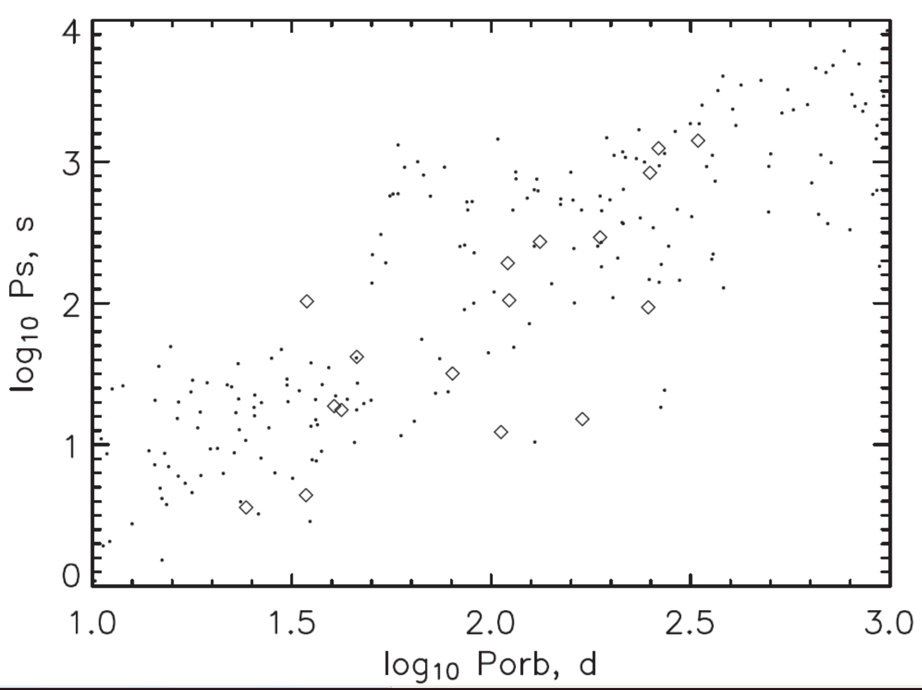
New calculations by Gullon et al. support these results.

Additional evidence for field decay

It is possible to use HMXBs to test models of field decay on time scale >1 Myr (Chashkina, Popov 2012).
We use observations of Be/X-ray binaries in SMC to derive magnetic field estimates, and compare them with prediction of the Pons et al. model.



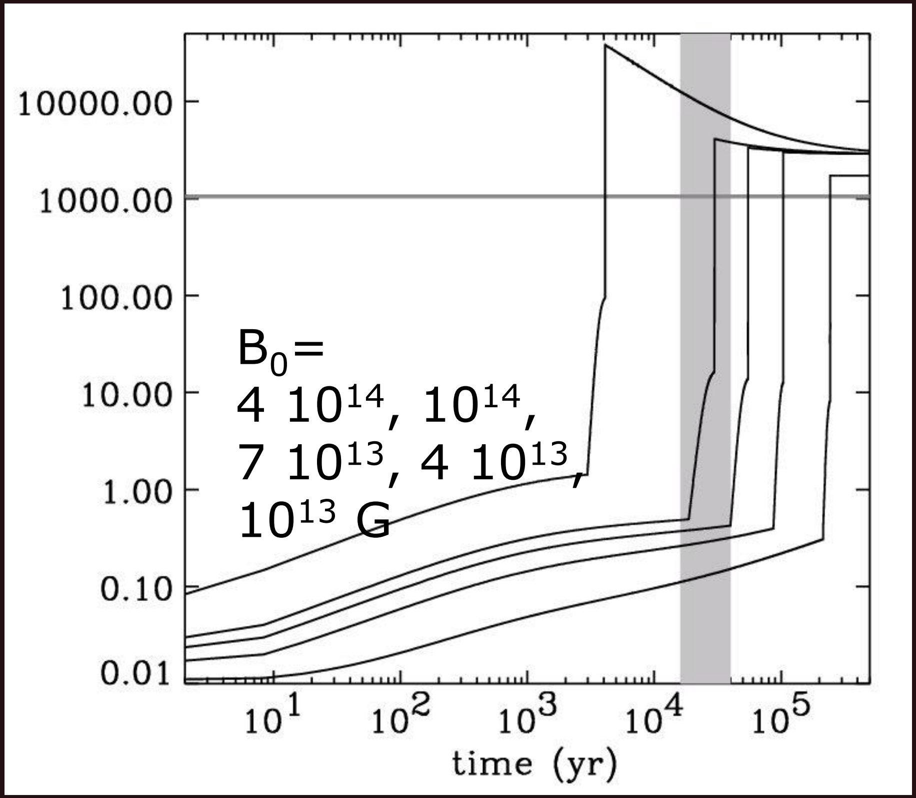




Chashkina, Popov (2012)

SXP 1062

A crucial thing for studying magneto-rotational evolution is to have an independent age estimate.
In the case of HMXBs a unique source with known age is SXP1062 (H´enault-Brunet et al. 2012, Haberl et al. 2012).



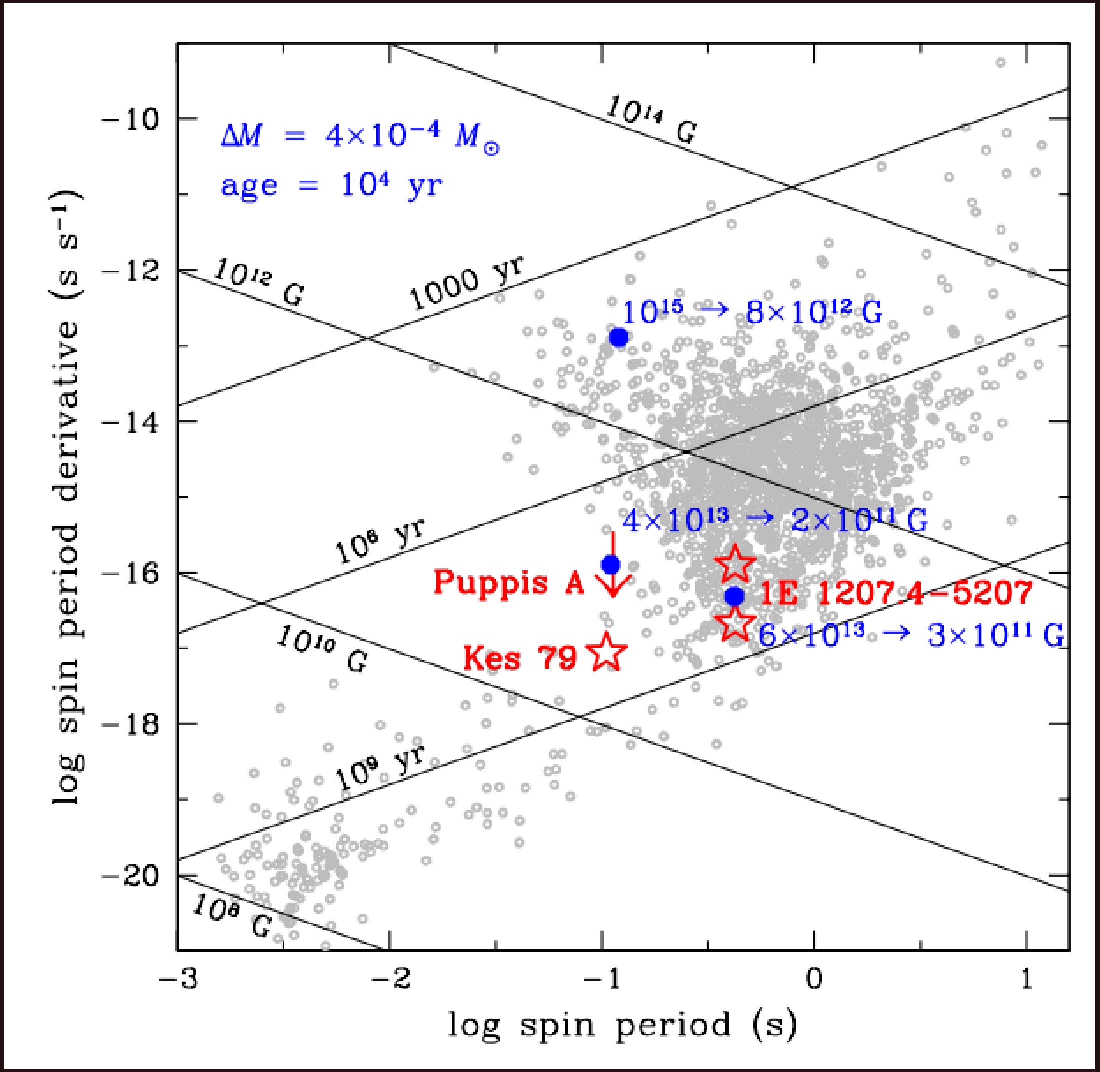
We were able to reproduce properties of SXP 1062 assuming a magnetic field decay.

I.e., initially the NS was a magnetar but now it has s standard magnetic field.
The crucial element of this model is the new accretion model by Shakura et al. (2013).

The main alternative:
long initial spin period ~1 sec

arXiv: 1112.2507

Anti-magnetars

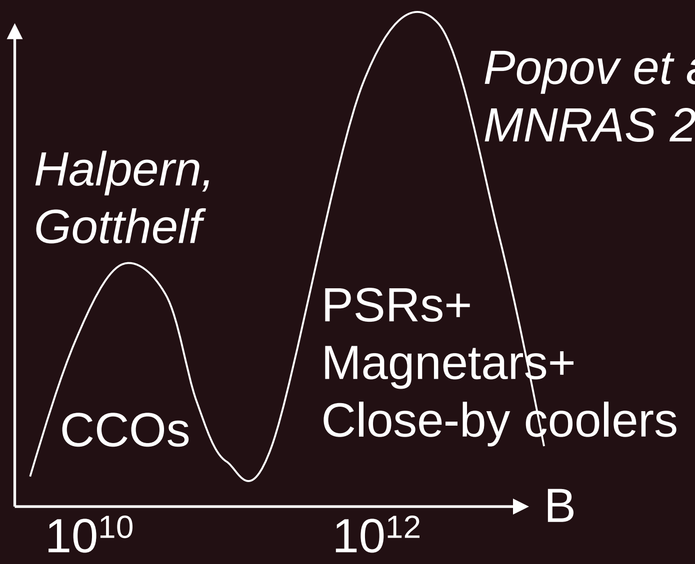


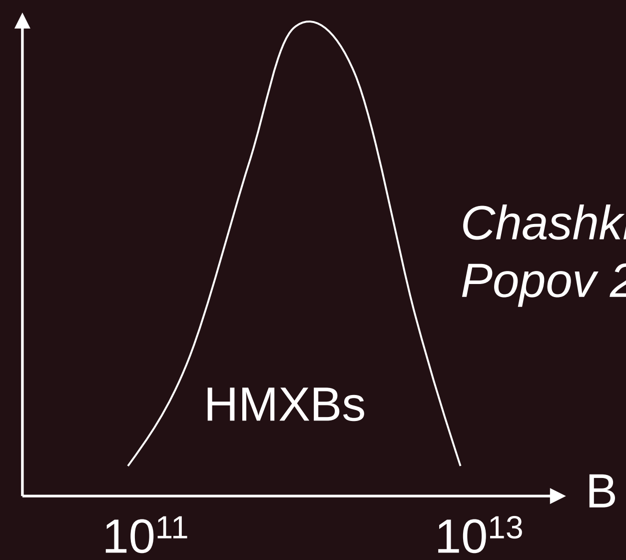
Note, that there is no room for antimagnetars from the point of view of birthrate in many studies of different NS populations.

New results 1301.2717
Spins and derivative are measured for
PSR J0821-4300 and
PSR J1210-5226

Ho 1210.7112

Evolution of CCOs

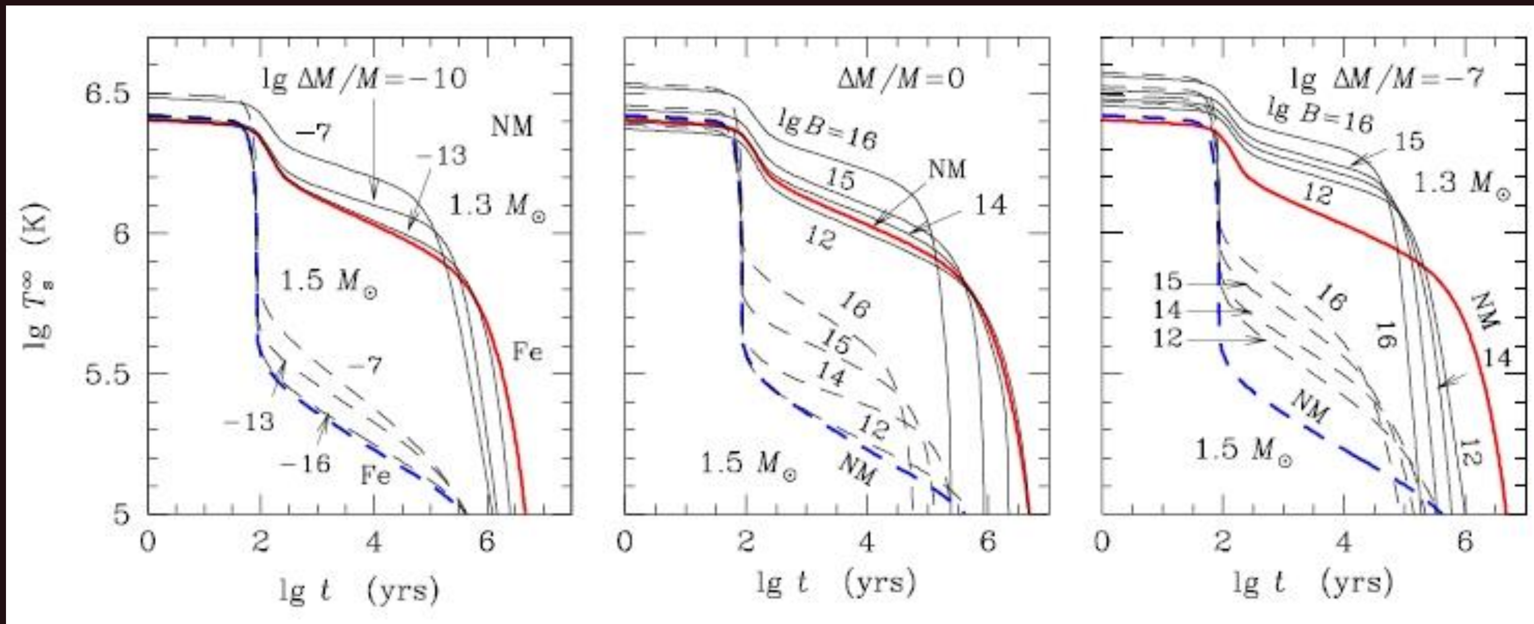




Among young isolated NSs about 1/3 can be related to CCOs.
If they are anti-magnetars, then we can expect that 1/3 of NSs in HMXBs are also low-magnetized objects.
They are expected to have short spin periods <1 sec.
However, there are no many sources with such properties.
The only good example - SAX J0635+0533. An old CCO?

Possible solution: emergence of magnetic field
(see physics in Ho 2011, Vigano, Pons 2012).

Where are old CCOs?



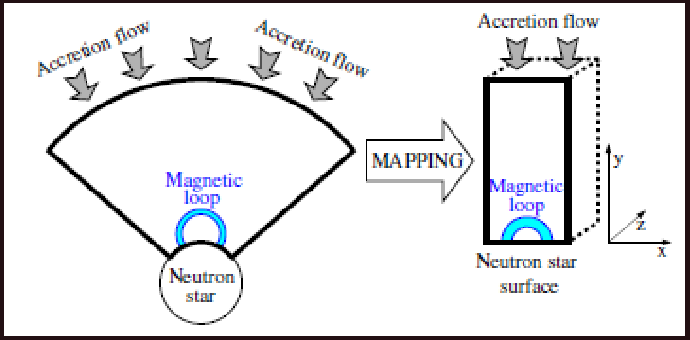
Yakovlev, Pethick 2004

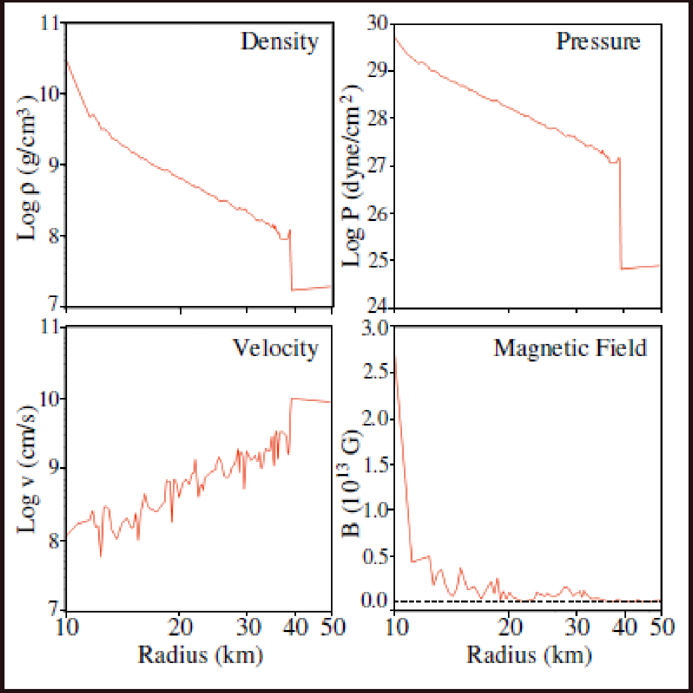
According to cooling studies they have to be bright till at least 10^5 years.
But only one candidate (2XMM J104608.7-594306 Pires et al.) to be a low-B cooling NS is known (Calvera is also a possible candidate).

We propose that a large set of data on HMXBs and cooling NSs is in favour of field emergence on the time scale $10^4 \leq \tau \leq 10^5$ years (arXiv:1206.2819).

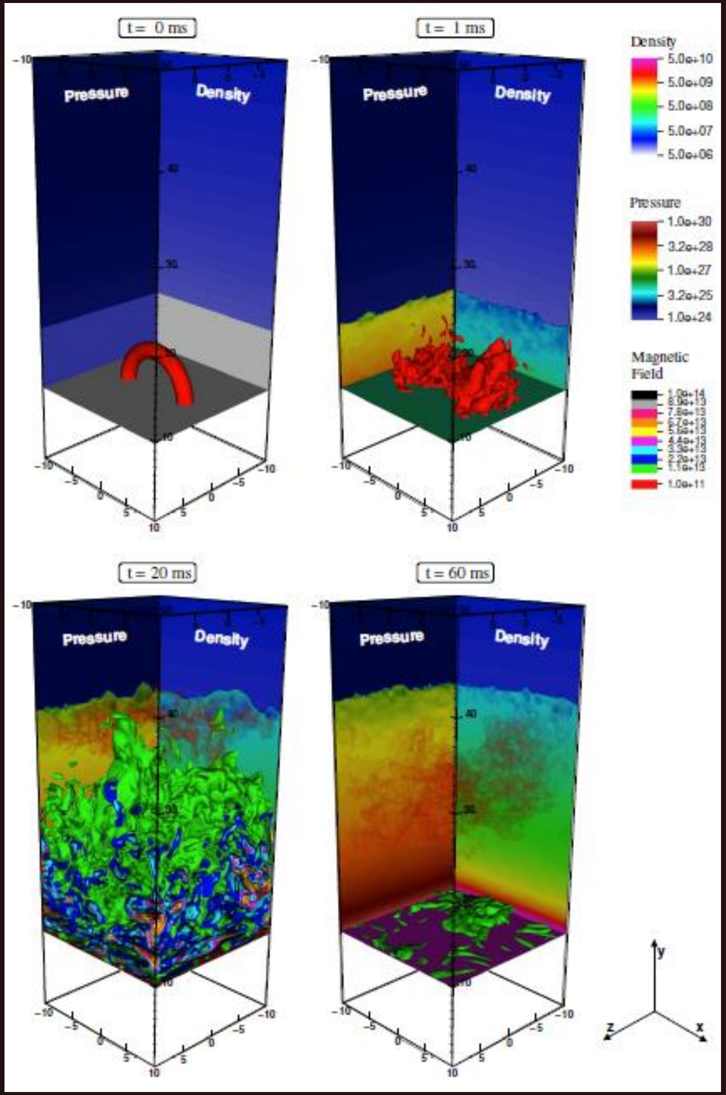
Some PSRs with thermal emission for which additional heating was proposed can be descendants of CCOs with emerged field.

How the field is buried





For t=60 msec



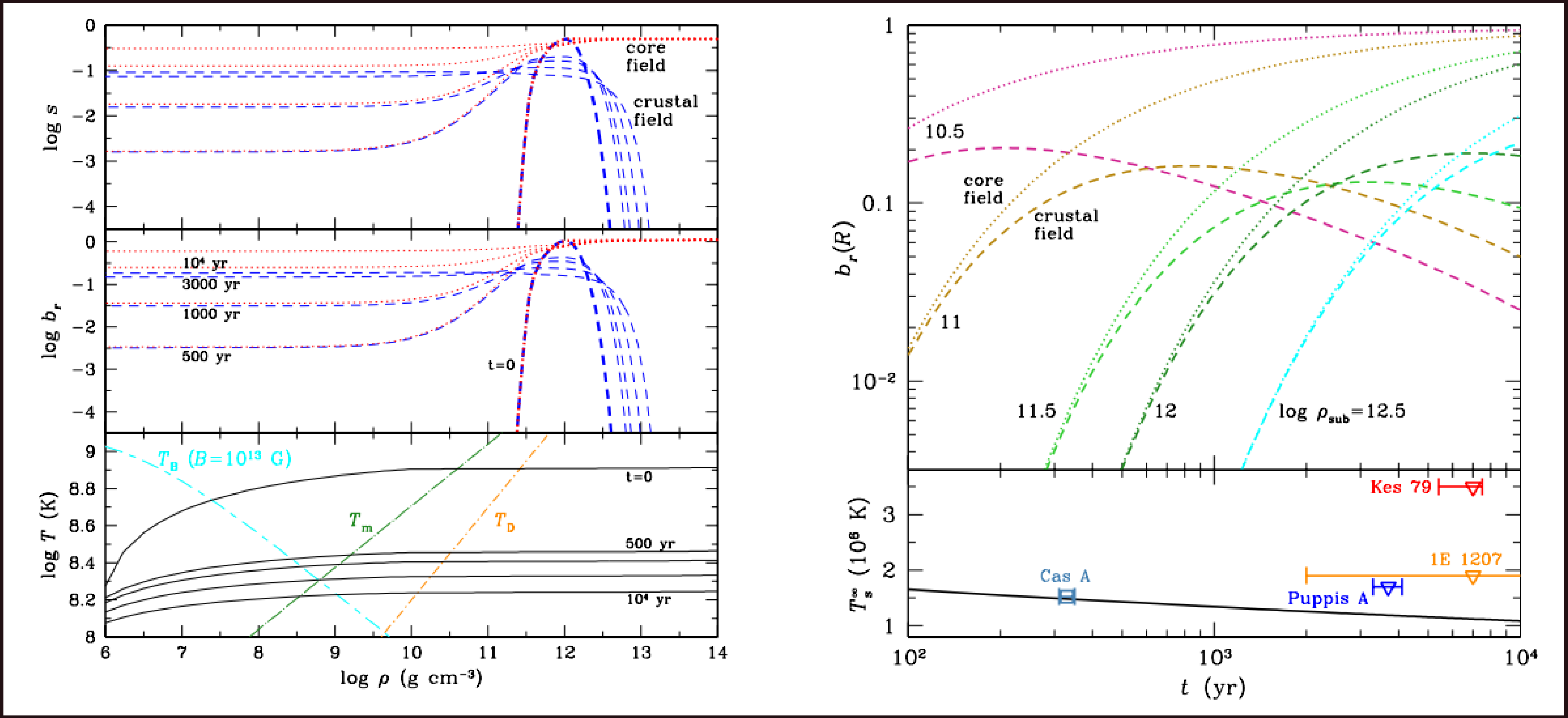
1212.0464

See 1210.7112 for a review of CCOs magnetic fields

Emerging field: modeling

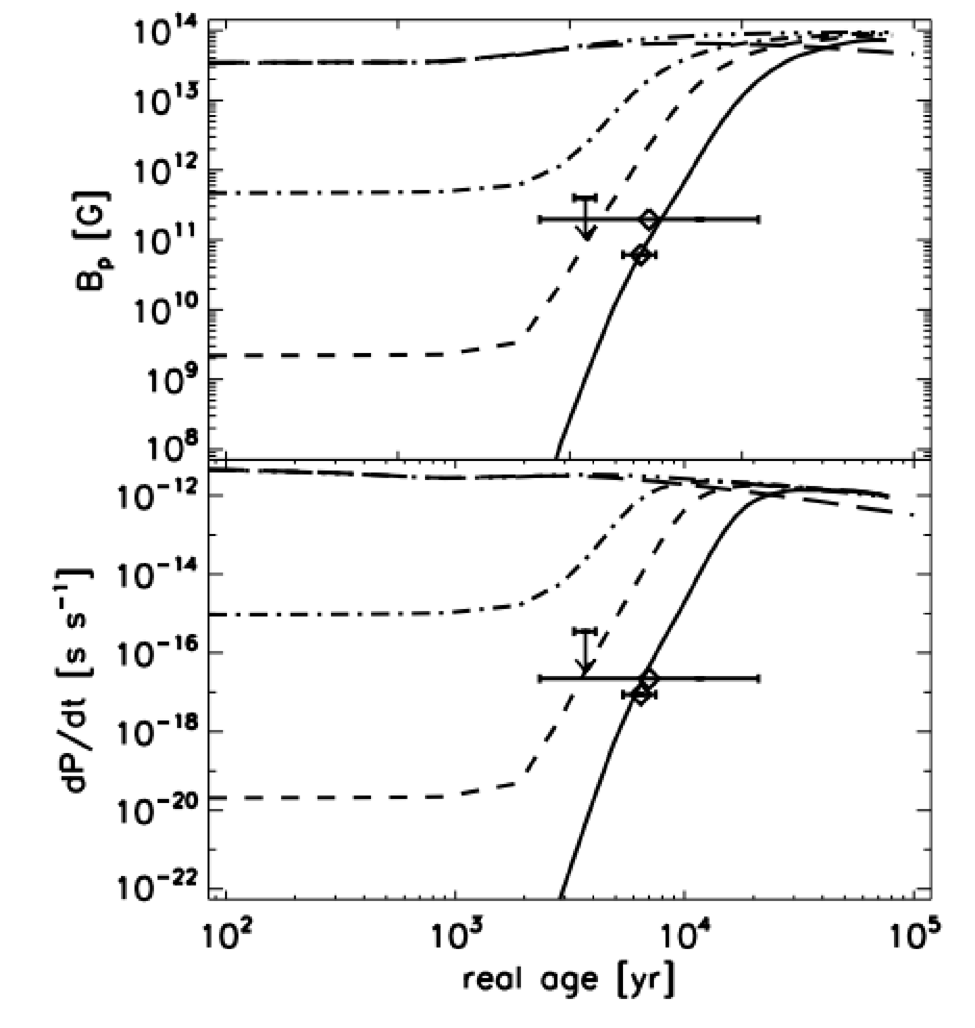
1D model of field emergence

Dashed – crustal, dotted – core field



Ho 2011

Another model



2D model with field decay

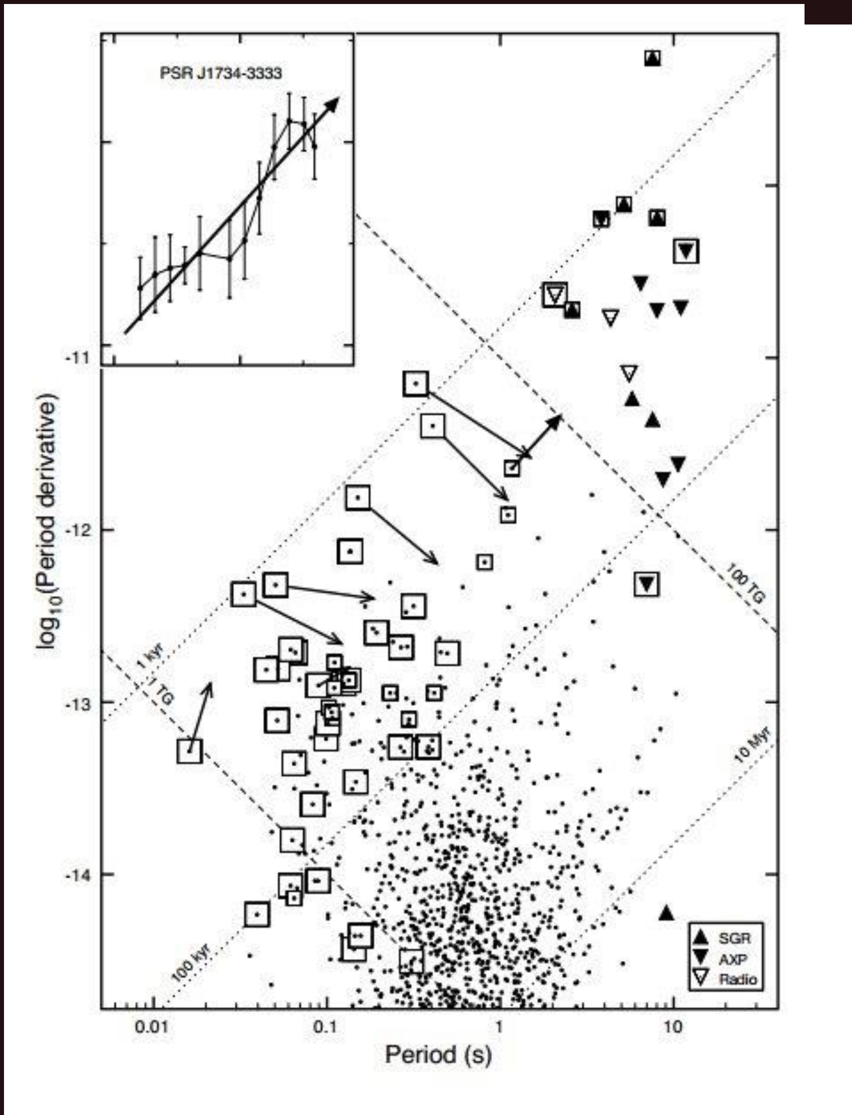
Ohmic diffusion dominates in field emergence, but Hall term also can be important.

Calculations confirm that emergence on the time scale 10^3-10^5 years is possible.

$B_{0p}=10^{14}$ G

Vigano, Pons 2012

Emerged pulsars in the P-Pdot diagram



Espinoza et al. arXiv: 1109.2740

Emerged pulsars are expected to have
P~0.1-0.5 sec
B~10^{11}-10^{12} G
Negative braking indices of at least n<2.
About 20-40 of such objects are known.

Parameters of emerged PSRs:
similar to “injected” PSRs
(Vivekanand, Narayan, Ostriker).

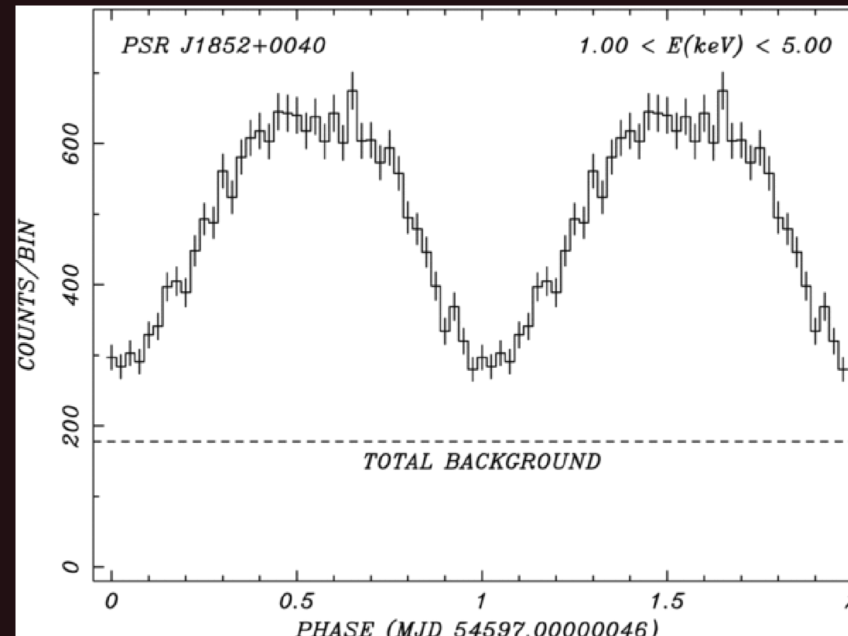
The existence of significant fraction
of “injected” pulsars formally
do not contradict recent pulsar current studies
(Vranesevic, Melrose 2011).

Part of PSRs supposed to be born with
long (0.1-0.5 s) spin periods can be
matured CCOs.

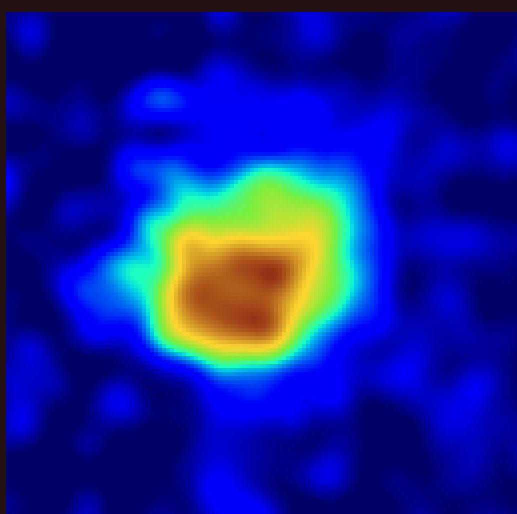
“Hidden” magnetars

Kes 79. PSR J1852+0040. P~0.1 s

Shabaltas & Lai (2012) show that large pulse fraction of the NS in Kes 79 can be explained if its magnetic field in the crust is very strong: few $\times 10^{14}$ G.



Halpern, Gotthelf 2010



- If submergence of the field happens rapidly, so the present day period represents the initial one
- Then, the field of PSR 1852 was not enhanced via a dynamo mechanism
- Detection of millisecond “hidden” magnetars will be a strong argument in favour of dynamo.

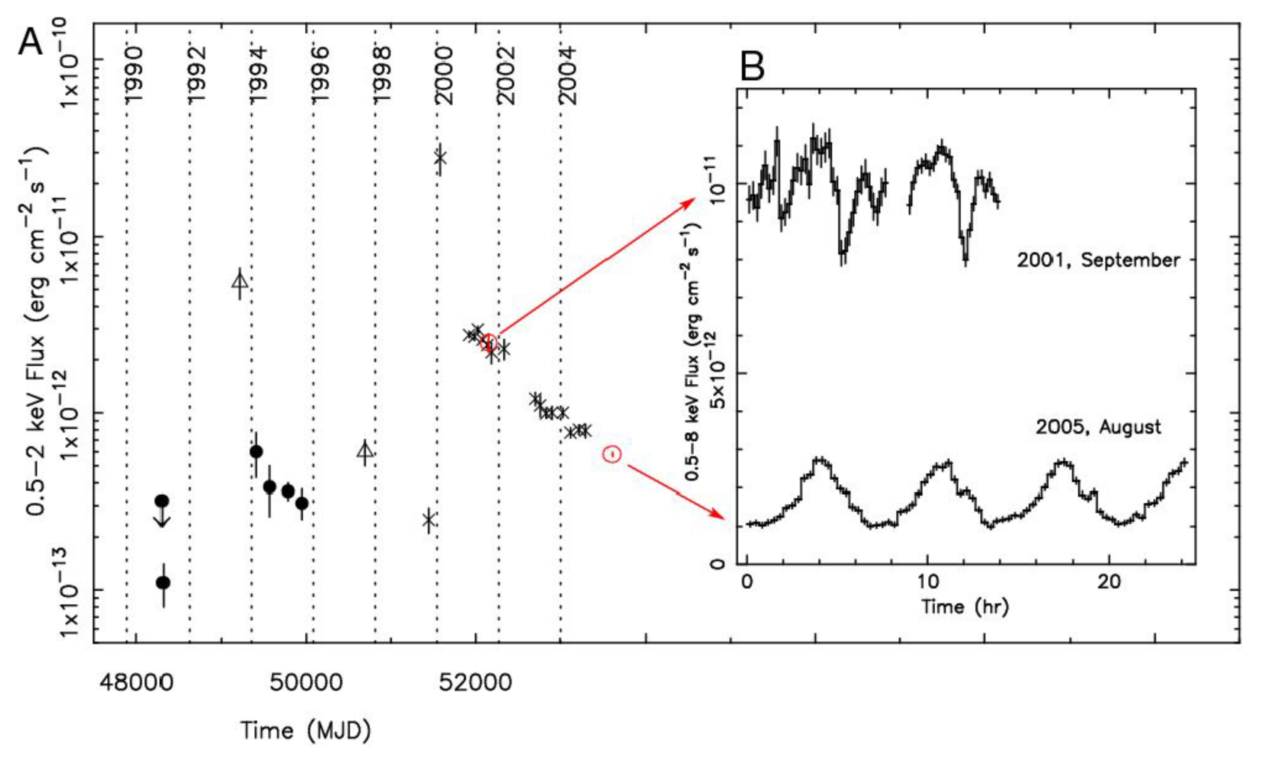
Kes 79

arXiv: 1307.3127

RCW 103 as a "hidden" magnetar with active crust. And Kes 79 as …. ?

Kes 79 looks very quiet, stable ....

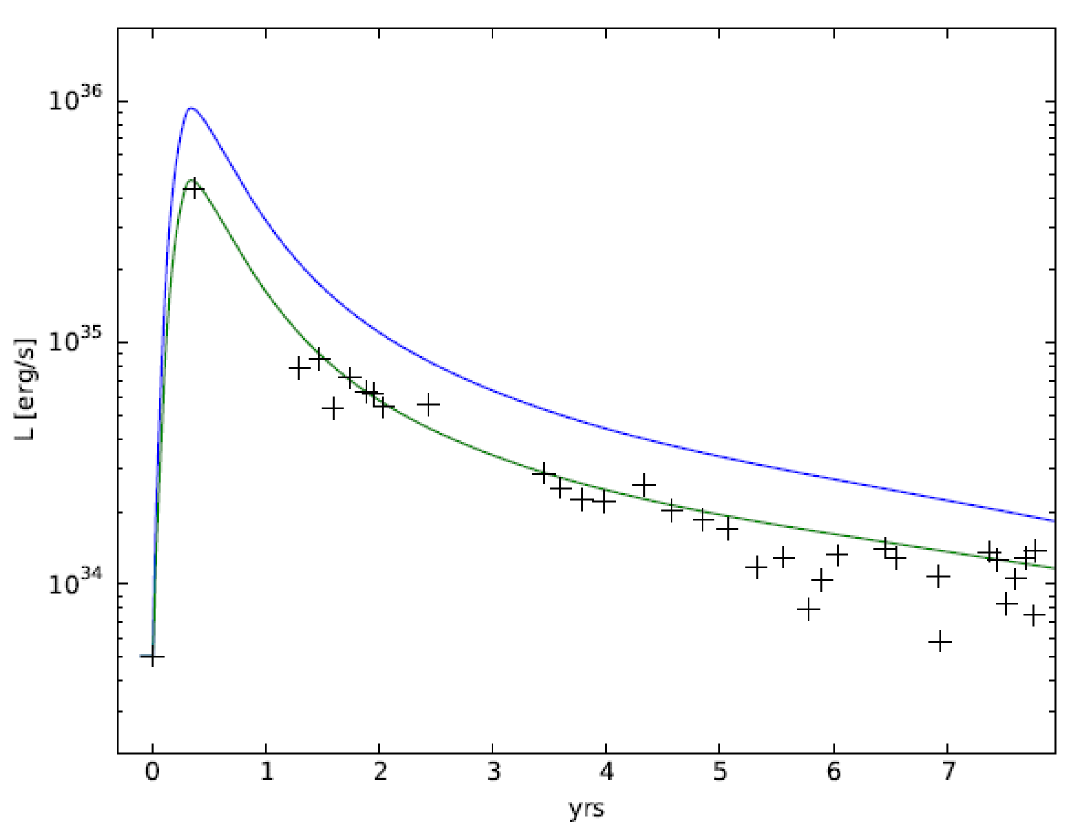
...but RCW 103 – not.



- Fluxes
- Temperatures
- Variability
- Pulse profile changes

De Luca et al. (2006)

Modeling a thermal burst



Parameters are chosen to reproduce data for RCW103 (calculated by A. Kaurov)

Calculated thermal X-ray luminosities versus time from the beginning of energy input $t_0 = 0$.
The observational data are indicated by crosses according to De Luca et al. (2008).

arXiv: 1504.03279

Conclusions

- Young isolated NSs appear as a very varied group of sources
- Main types are: radio pulsars, magnetars, CCOs, Magnificent seven, RRATs
- Observational appearances of NSs is significantly determined by their magnetic fields
- The field can have a complicated topology and evolution
- It is necessary to create a unified model of evolution of young NSs
- Magnetic field evolution is one of the main ingredient of such model
- Normally, magnetic field decays
- In some cases external field can increase, if initially it has been ‘’screened’’ due to a fall-back

Some reviews on isolated neutron stars

- NS basics: physics/0503245 astro-ph/0405262
- Thermal emission 1409.7666
- SGRs & AXPs: 1304.4825 arXiv: 1101.4472
- CCOs: astro-ph/0311526 arxiv:0712.2209
- Quark stars: arxiv:0809.4228
- The Magnificent Seven: astro-ph/0609066 arxiv:0801.1143
- RRATs: arXiv:1008.3693
- Cooling of NSs: arXiv: 0906.1621 astro-ph/0402143
- NS structure arXiv:0705.2708
- EoS arXiv: 1001.3294 arXiv: 1001.1272
- NS atmospheres 1403.0074
- NS magnetic fields arxiv:0711.3650 arxiv:0802.2227
- Different types arXiv:1005.0876 arXiv:1302.0869

- Internal structure and astrophysics 1312.0029
- X-rays from NS 1303.0317
- Low-field magnetars 1303.6052
- Magnetars 1507.02924

Read the OVERVIEW in the book by Haensel, Yakovlev, Potekhin