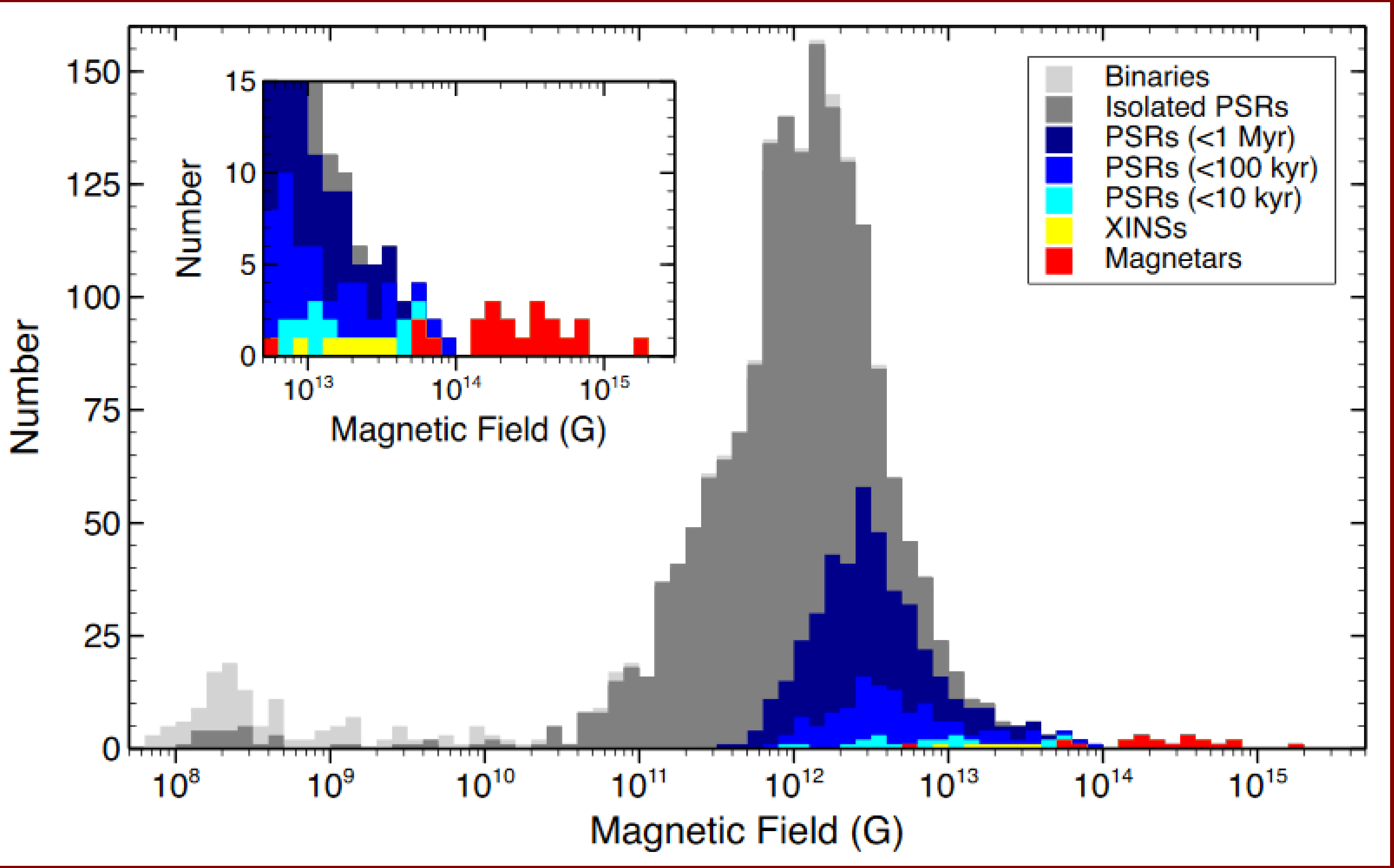
Magnetars: SGRs and AXPs

Magnetic field distribution



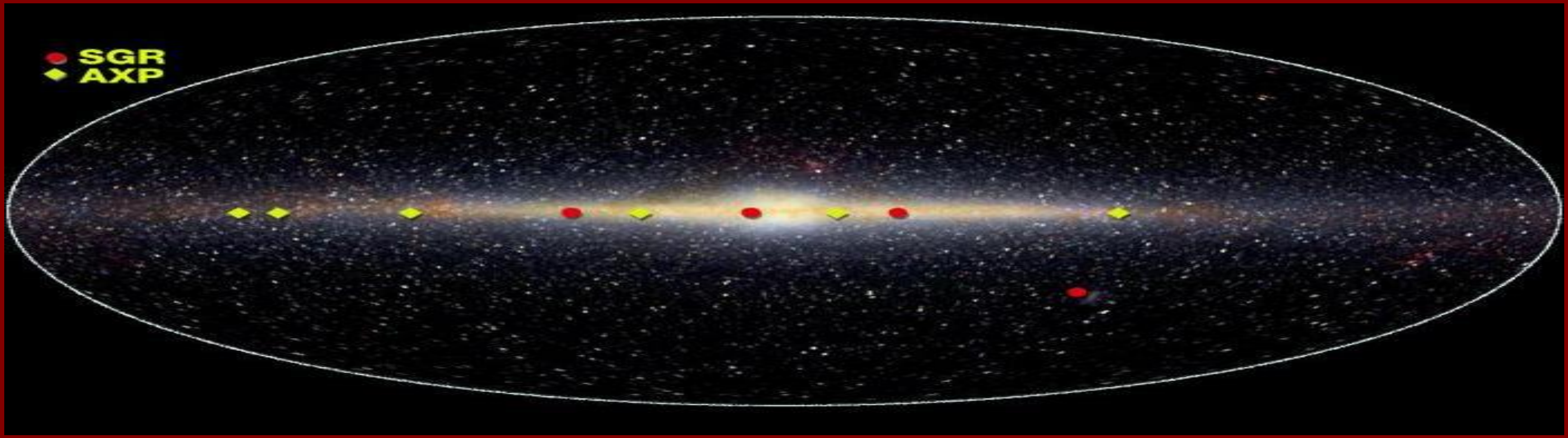
Fields from P-Pdot using magneto-dipole formula

1805.01680 (taken from Olausen, Kaspi 2014)

Magnetars in the Galaxy

- ~24 SGRs and AXPs, plus 6 candidates, plus radio pulsars with high magnetic fields (about them see arXiv: 1010.4592)…
- Young objects (about $10^{3\text{-}5}$ year).

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



(see a recent review in arXiv:1503.06313 and the catalogue description in 1309.4167)

Birth rate of magnetars

Fraction of magnetars among NSs is uncertain.

Typically, the value ~10% is quoted (e.g. 0910.2190).
This is supported observationally and theoretically.

Recent modeling favours somehow larger values: 1903.06718.
However, the result is model dependent.
In particular, it depends on the model of field decay.

Several of magnetars are related to SNRs.

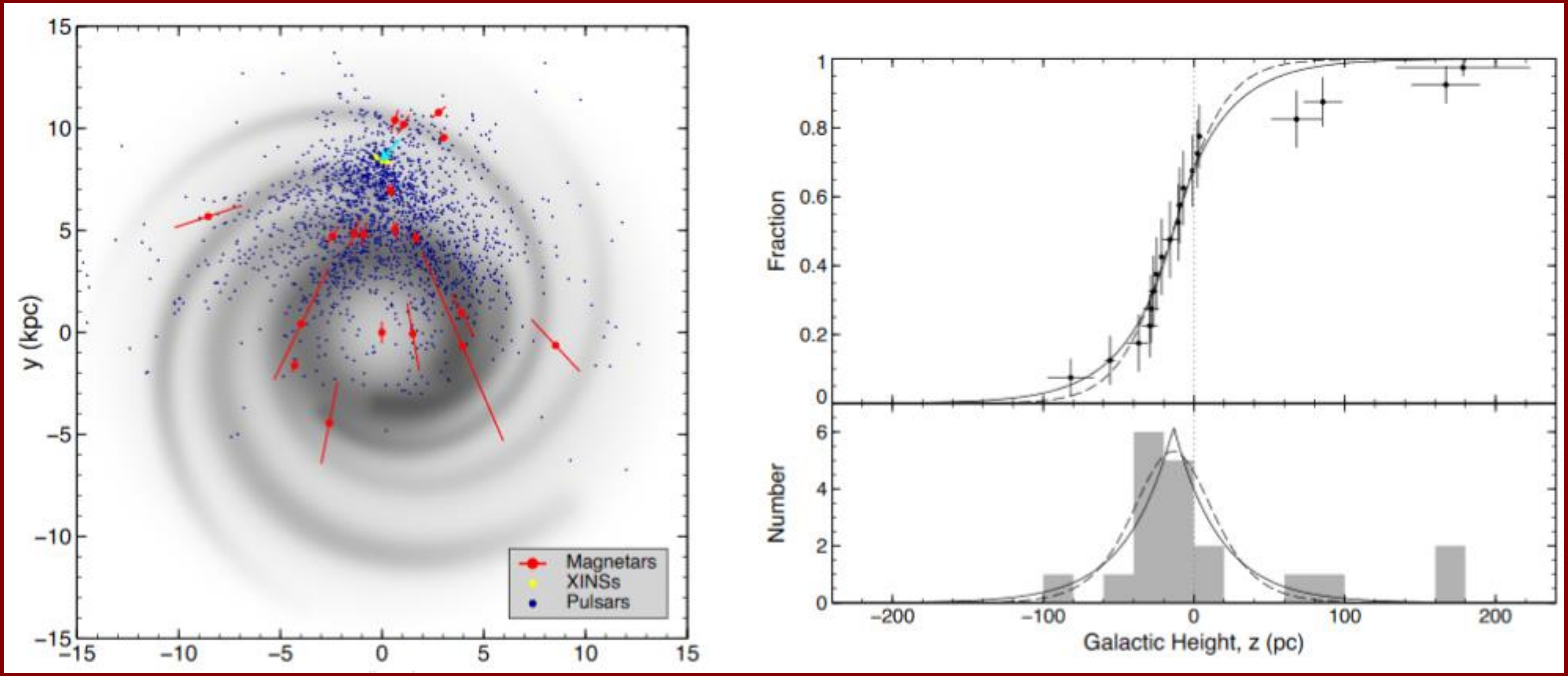
Many of magnetars show glitches.

Name[b]	P (s)	B[c] (10^{14} G)	Age[d] (kyr)	$\dot{E}$[e] 10^{33} erg s^{-1}	D[f] (kpc)	L_X[g] 10^{33} erg s^{-1}	Band[h]
CXOU J010043.1-721134	8.02	3.9	6.8	1.4	62.4	65	...
4U 0142+61	8.69	1.3	68	0.12	3.6	105	OIR/H
SGR 0418+5729	9.08	0.06	36000	0.00021	~2	0.00096	...
SGR 0501+4516	5.76	1.9	15	1.2	~2	0.81	OIR/H
SGR 0526−66	8.05	5.6	3.4	2.9	53.6	189	...
1E 1048.1-5937	6.46	3.9	4.5	3.3	9.0	49	OIR
(PSR J1119−6127)	0.41	4.1	1.6	2300	8.4	0.2	R/H
1E 1547.0-5408	2.07	3.2	0.69	210	4.5	1.3	O?/R/H
PSR J1622−4950	4.33	2.7	4.0	8.3	~9	0.4	R
SGR 1627−41	2.59	2.2	2.2	43	11	3.6	...
CXOU J164710.2−455216	10.6	<0.66	>420	<0.013	3.9	0.45	...
1RXS J170849.0−400910	11.01	4.7	9.0	0.58	3.8	42	O?/H
CXOU J171405.7−381031	3.82	5.0	0.95	45	~13	56	...
SGR J1745−2900	3.76	2.3	4.3	10	8.3	<0.11	R/H
SGR 1806−20	7.55	20	0.24	45	8.7	163	OIR/H
XTE J1810−197	5.54	2.1	11	1.8	3.5	0.043	OIR/R
Swift J1822.3−1606	8.44	0.14	6300	0.0014	1.6	>0.0004	...
SGR 1833−0832	7.56	1.6	34	0.32	...	...	...
Swift J1834.9−0846	2.48	1.4	4.9	21	4.2	<0.0084	...
1E 1841−045	11.79	7.0	4.6	0.99	8.5	184	...
(PSR J1846−0258)	0.327	0.49	0.73	8100	6.0	19	...
3XMM J185246.6+003317	11.56	< 0.41	> 1300	< 0.0036	~7	< 0.006	...
SGR 1900+14	5.20	7.0	0.9	26	12.5	90	H
SGR 1935+2154	3.24	2.2	3.6	17	...	...	...
1E 2259+586	6.98	0.59	230	0.056	3.2	17	OIR/H
SGR 0755−2933	...	...	...	...	...	...	...
SGR 1801−23	...	...	...	...	...	...	...
SGR 1808−20	...	...	...	...	...	...	...
AX J1818.8−1559	...	...	...	...	...	...	...
AX J1845.0−0258	6.97	...	...	...	...	2.9	...
SGR 2013+34	...	...	...	...	...	...	...

1703.00068

Spatial distribution

Scale height ~20 pc

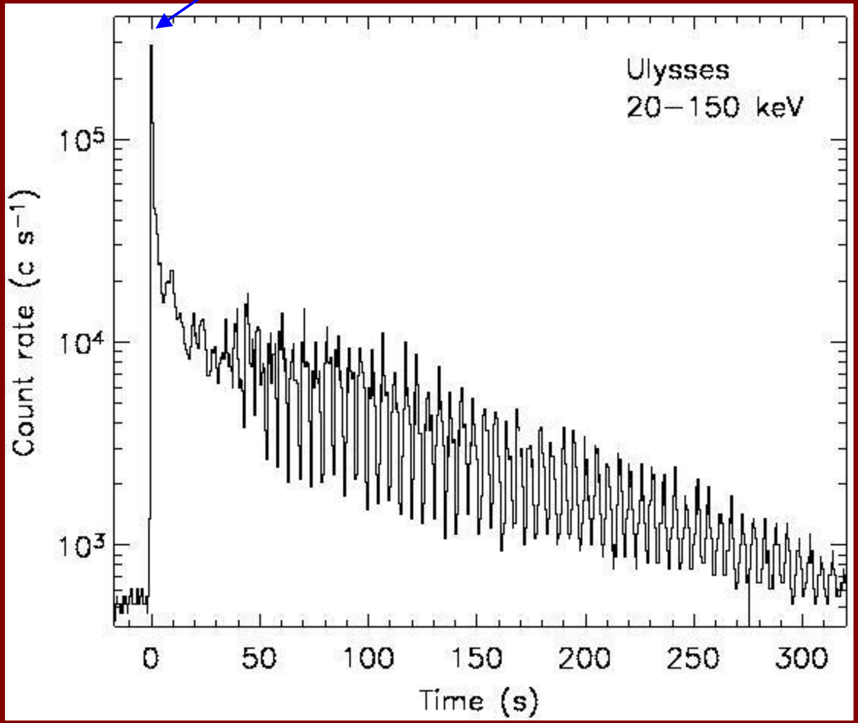


1703.00068

Soft Gamma Repeaters: main properties

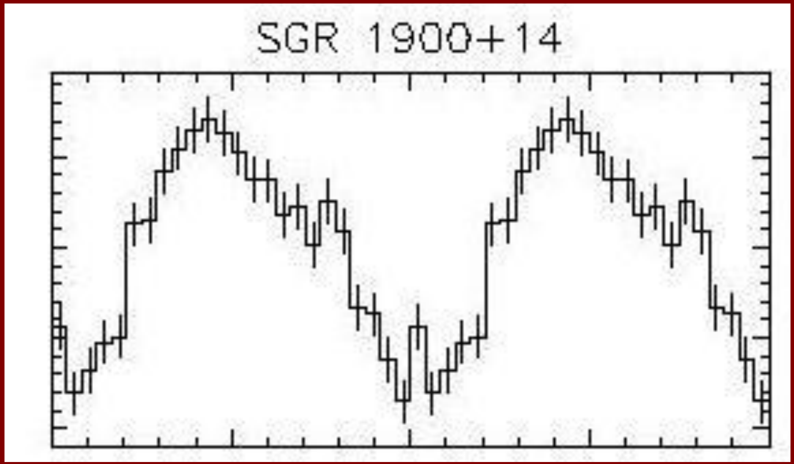
- Energetic “Giant Flares” (GFs, L ≈ 10^{45}-10^{47} erg/s) detected from 3 (4?) sources
- No evidence for a binary companion, association with a SNR at least in one case
- Persistent X-ray emitters, L ≈ 10^{35} - 10^{36} erg/s
- Pulsations discovered both in GFs tails and persistent emission, P ≈ 5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

Saturation of detectors



SGRs: periods and giant flares

	P, s	Giant flares
0526-66	8.0	5 March 1979
1627-41	2.6	18 June 1998 (?)
1806-20	7.5	27 Dec 2004
1900+14	5.2	27 Aug 1998



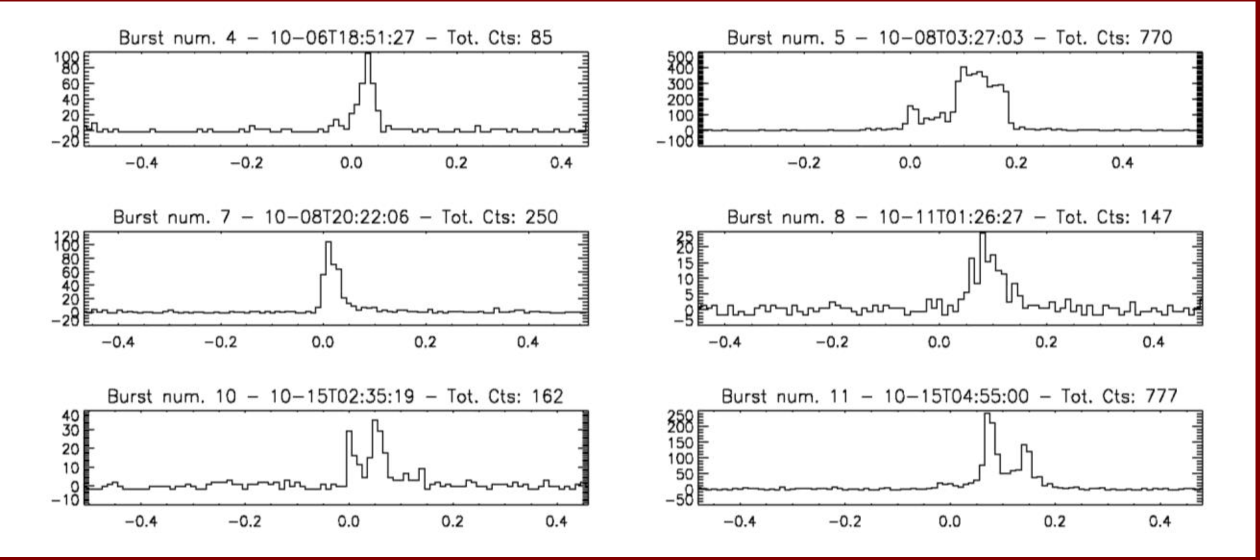
See reviews in Turolla et al. arXiv: 1507.02924

Beloborodov, Kaspi arXiv: 1703.00068

Soft Gamma Repeaters

- Rare class of sources, ~12 confirmed
- Frequent bursts of soft γ-/hard X-rays:

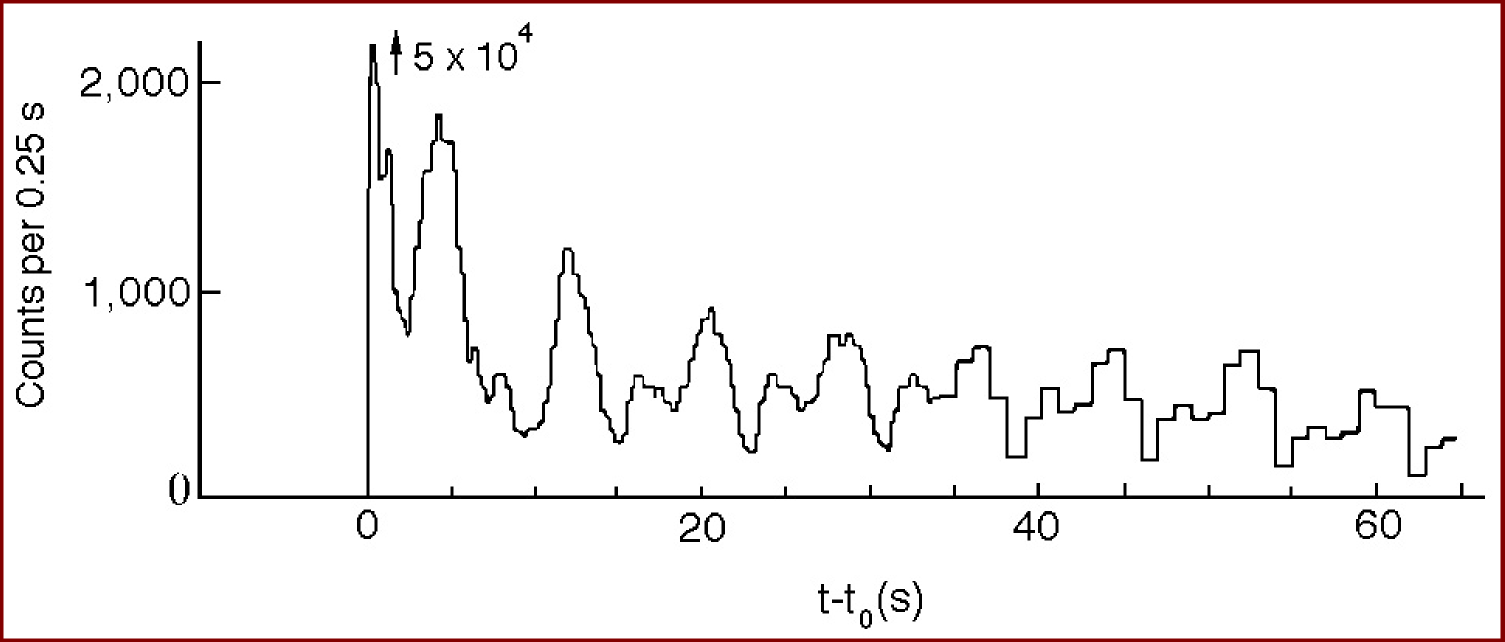
  $L < 10^{42}$ erg/s, duration < 1 s



Bursts from SGR 1806-20 (INTEGRAL/IBIS, Gőtz et al 2004)

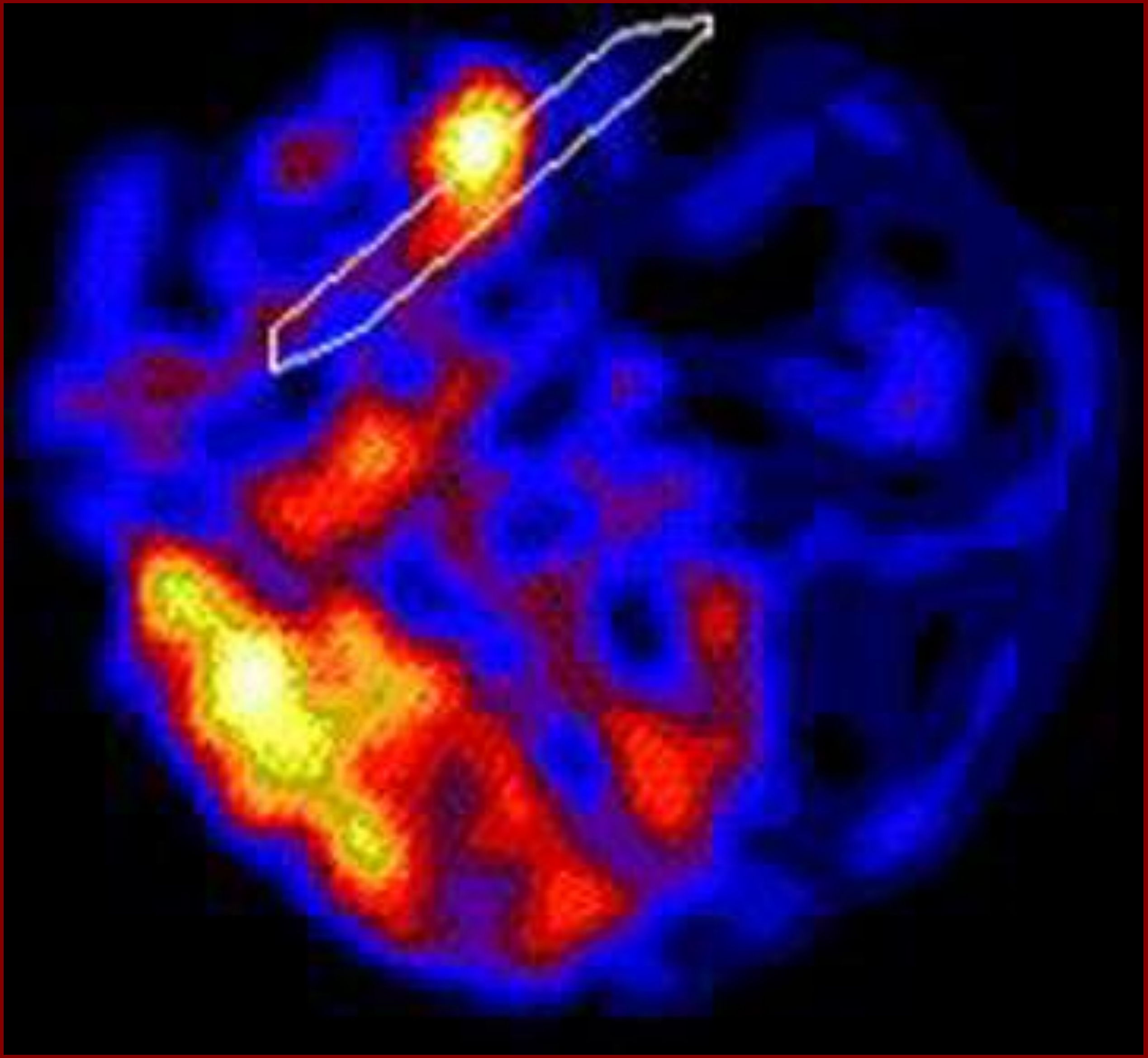
Historical notes

- 05 March 1979. The ”Konus” experiment & Co.
  Venera-11,12 (Mazets et al., Vedrenne et al.)
- Events in the LMC. SGR 0520-66.
- Fluence: about 10^{-3} erg/cm^2



Mazets et al. 1979

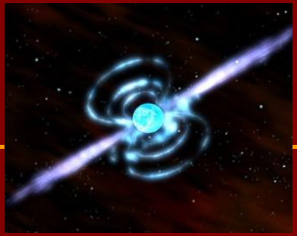
N49 – supernova remnant in the Large Magellanic cloud
(e.g. G. Vedrenne et al. 1979)



Main types of activity of SGRs

- Weak bursts. $L<10^{42}$ erg/s
- Intermediate. $L\sim10^{42}$–10^{43} erg/s
- Giant. $L<10^{45}$ erg/s
- Hyperflares. $L>10^{46}$ erg/s

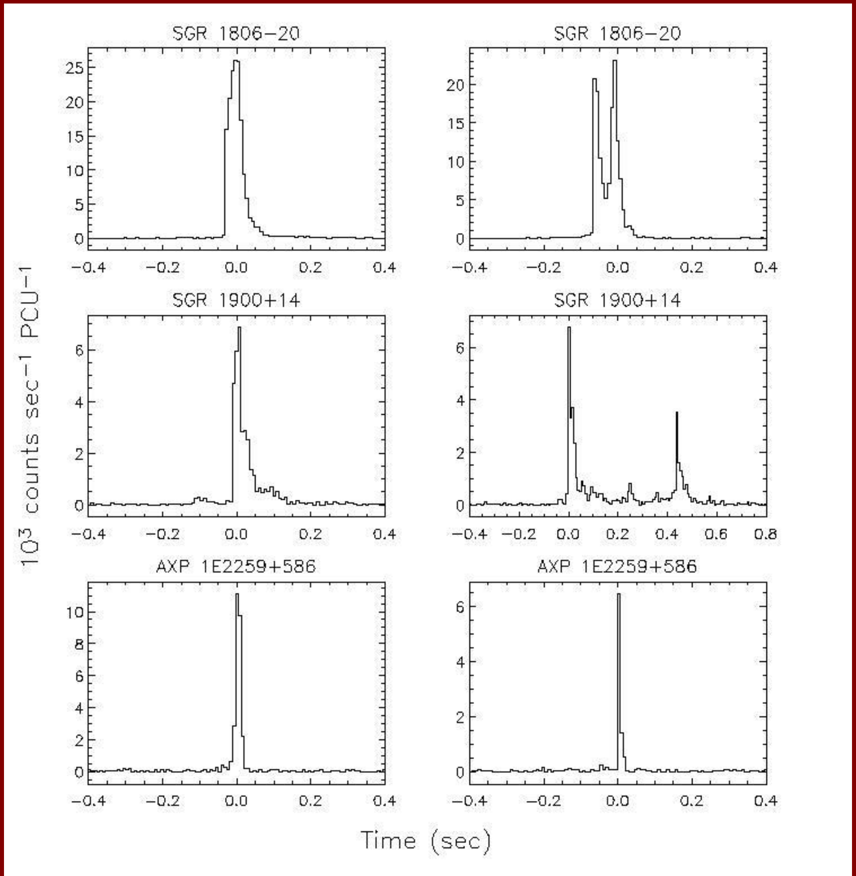
Power distribution is similar to the distribution of earthquakes in magnitude



See the review in Rea, Esposito 1101.4472

Normal bursts of SGRs and AXPs

- Typical weak bursts of
  SGR 1806-29,
  SGR 1900+14 and of
  AXP 1E 2259+586
  detected by RXTE

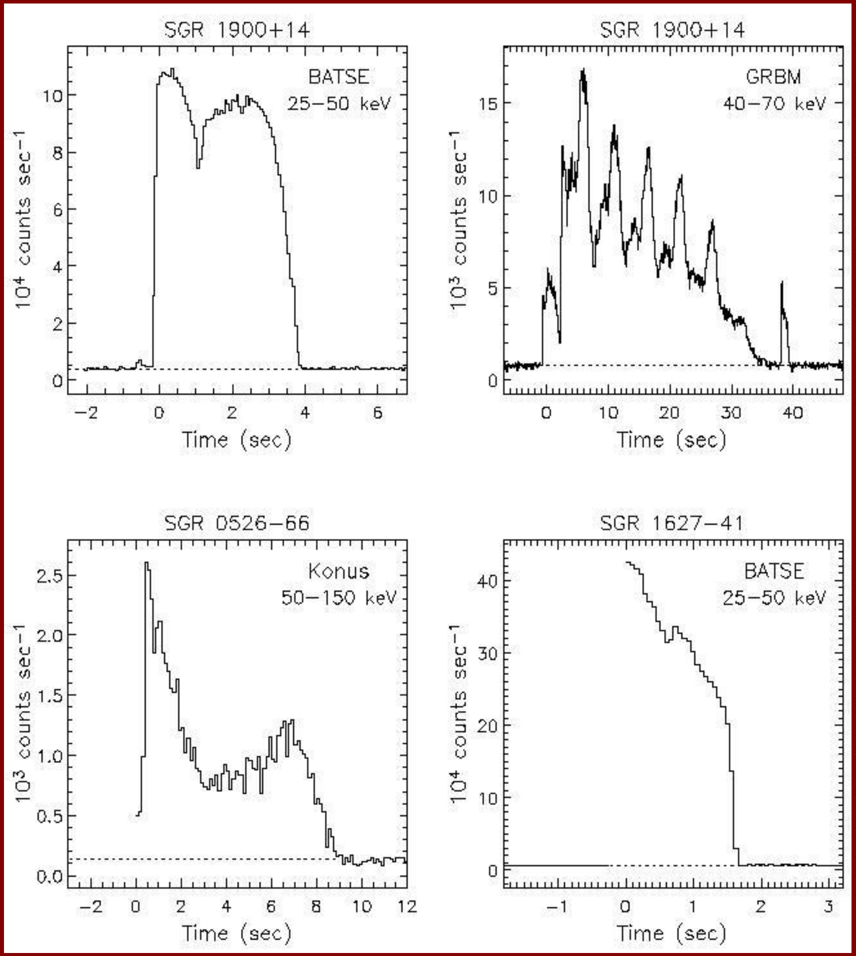


(from Woods, Thompson 2004)

Intermediate SGR bursts

Examples of intermediate bursts.

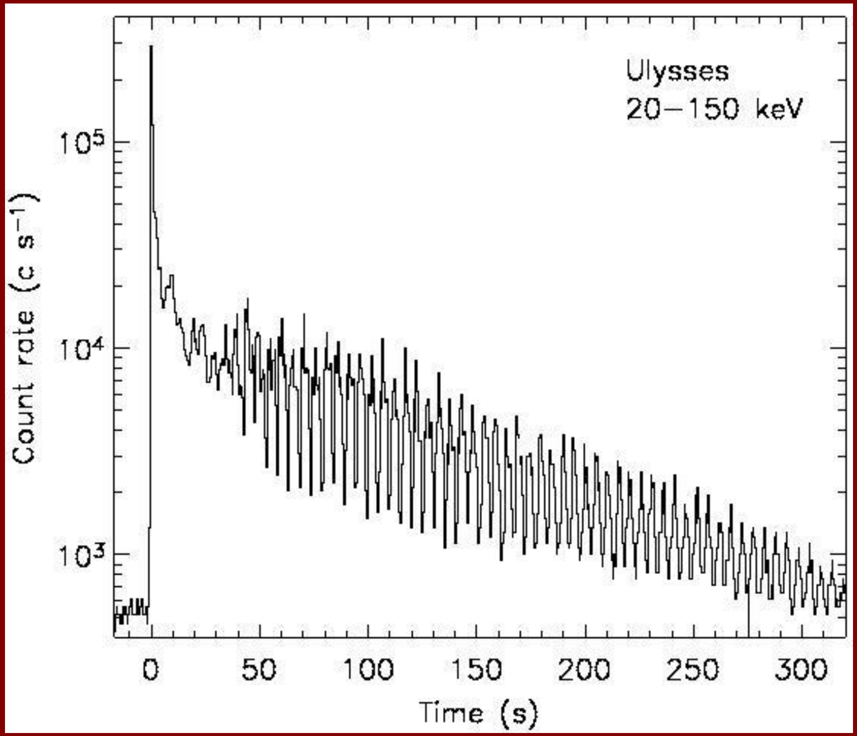
The forth (bottom right) is sometimes defined as a giant burst (for example by Mazets et al.).



(from Woods, Thompson 2004)

Giant flare of the SGR 1900+14 (27 August 1998)

- Ulysses observations (figure from Hurley et al.)
- Initial spike 0.35 s
- P=5.16 s
- L>3 10^{44} erg/s
- $E_{TOTAL}>10^{44}$ erg

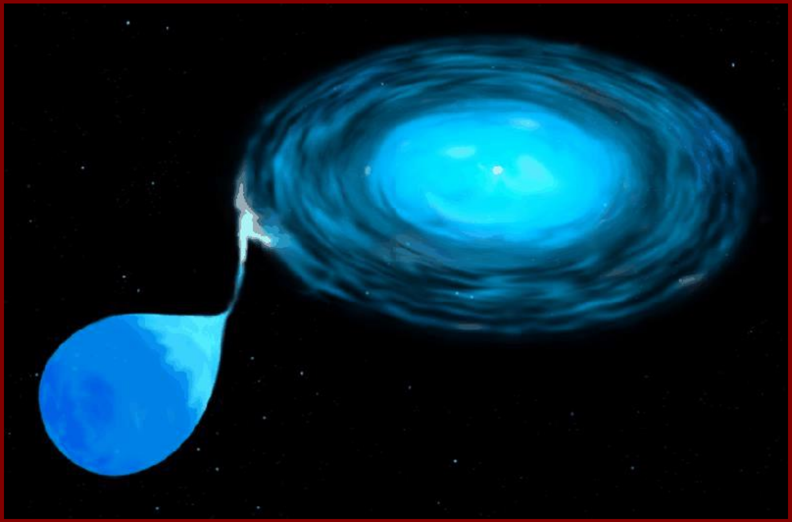


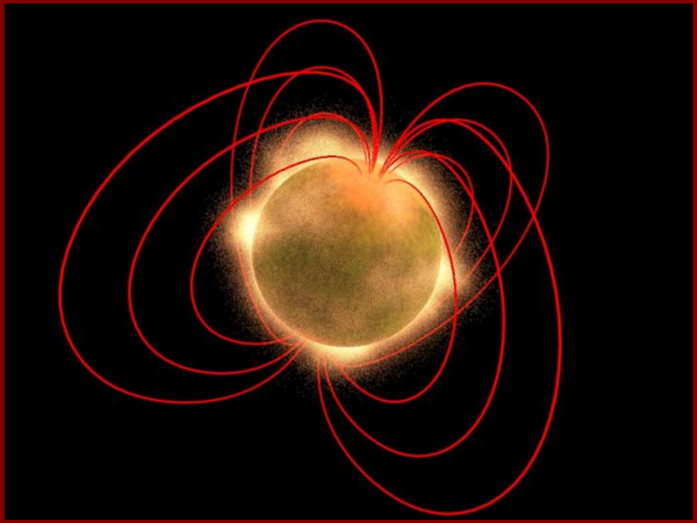
Hurley et al. 1999

Anomalous X-ray pulsars

Identified as a separate group in 1995.
(Mereghetti, Stella 1995 Van Paradijs et al.1995)

- Similar periods (5-10 sec)
- Constant spin down
- Absence of optical companions
- Relatively weak luminosity
- Constant luminosity





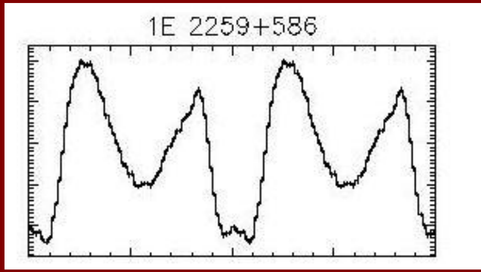
Anomalous X-ray Pulsars: main properties

- Twelve sources known:

  1E 1048.1-5937, 1E 2259+586, 4U 0142+614,
  1 RXS J170849-4009, 1E 1841-045,
  CXOU 010043-721134, AX J1845-0258,
  CXOU J164710-455216, XTE J1810-197,
  1E 1547.0-5408, PSR J1622-4950, CXOU J171405.7-381031
- Persistent X-ray emitters, $L \approx 10^{34}$ -10^{35} erg/s
- Pulsations with $P \approx 2$ -10 s (0.33 sec for PSR 1846)
- Large spindown rates, $\dot{P}/P \approx 10^{-11}\ s^{-1}$
- No evidence for a binary companion, association with a SNR in several cases

Known AXPs

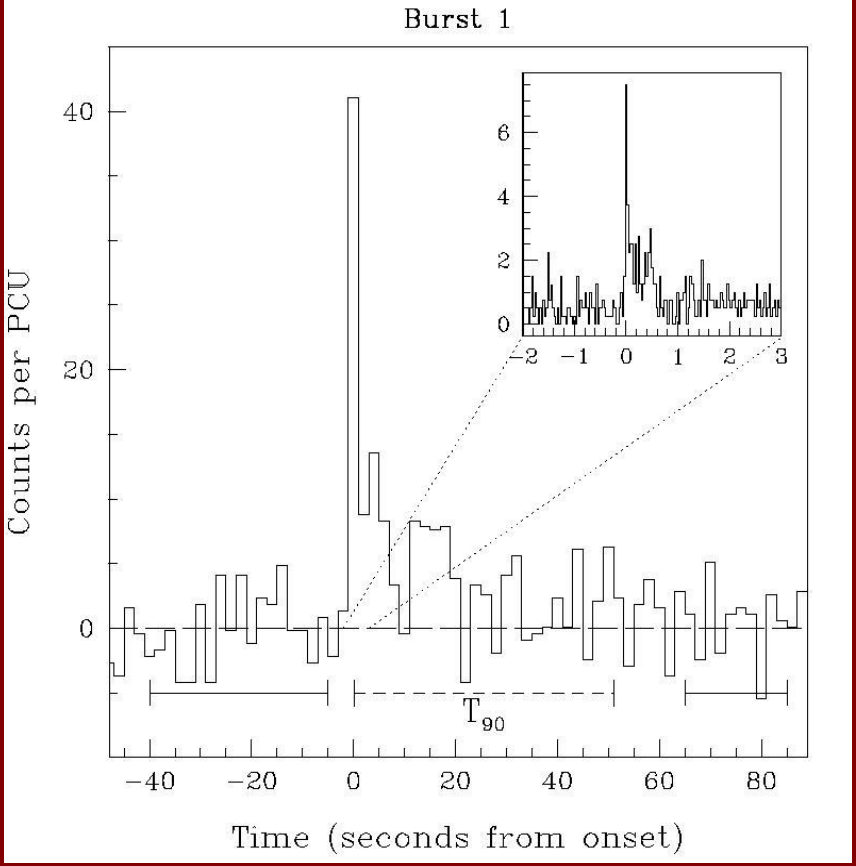
Sources	Periods, s
CXO 010043-7211	8.0
4U 0142+61	8.7
1E 1048.1-5937	6.4
1E 1547.0-5408	2.1
CXOU J164710-4552	10.6
1RXS J170849-40	11.0
XTE J1810-197	5.5
1E 1841-045	11.8
AX J1845-0258	7.0
PSR J1622-4950	4.3
CXOU J171405.7-381031	3.8
1E 2259+586	7.0



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

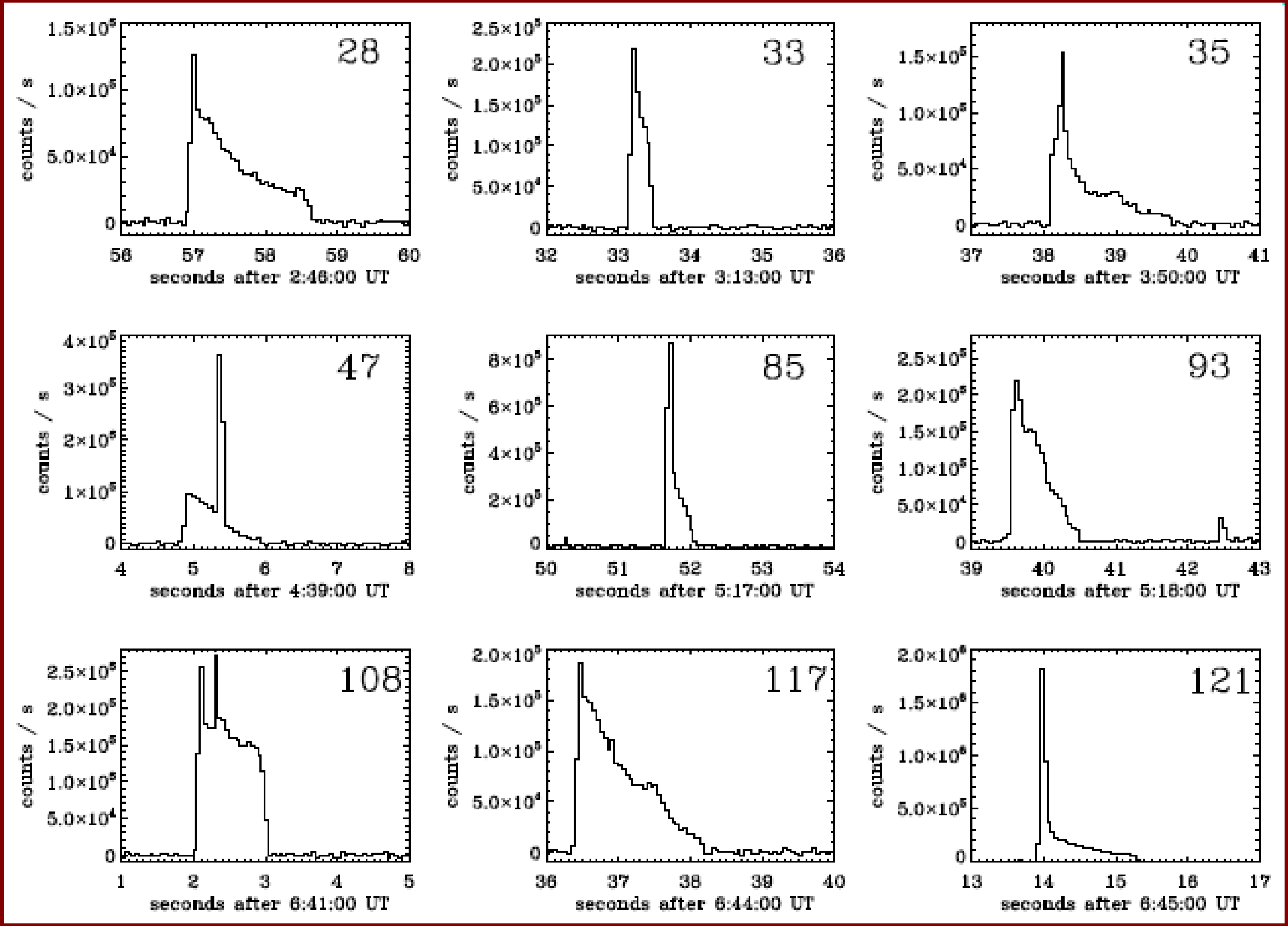
Are SGRs and AXPs brothers?

- Bursts of AXPs
  (more than half burst)
- Spectral properties
- Quiescent periods of SGRs (0525-66 since 1983)



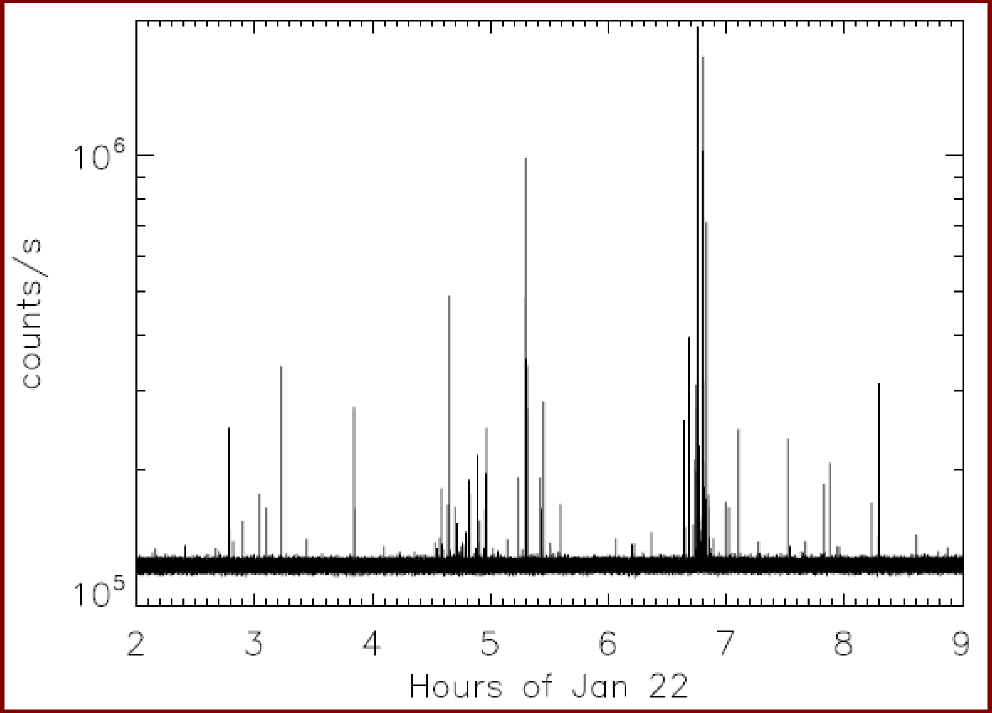
Gavriil et al. 2002

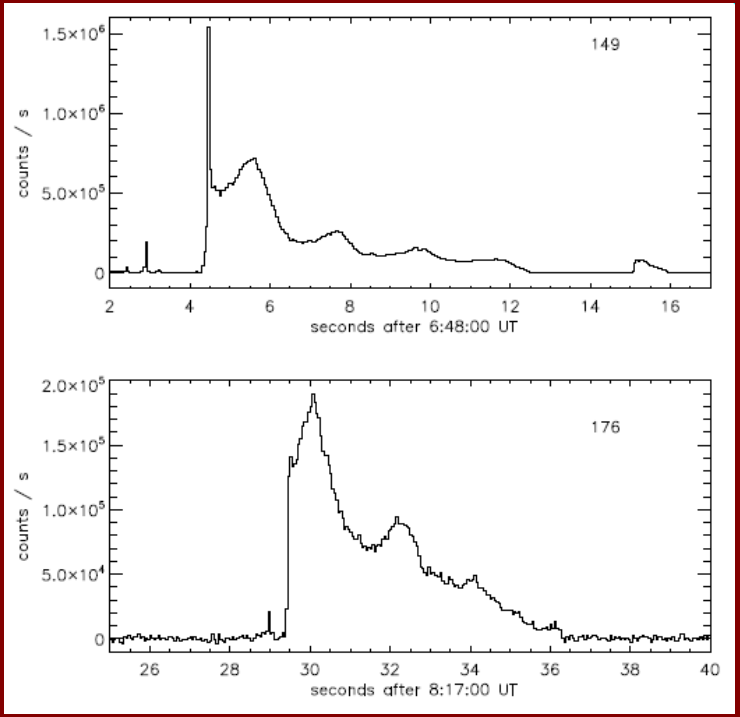
Bursts of the AXP 1E1547.0-5408



0903.1974

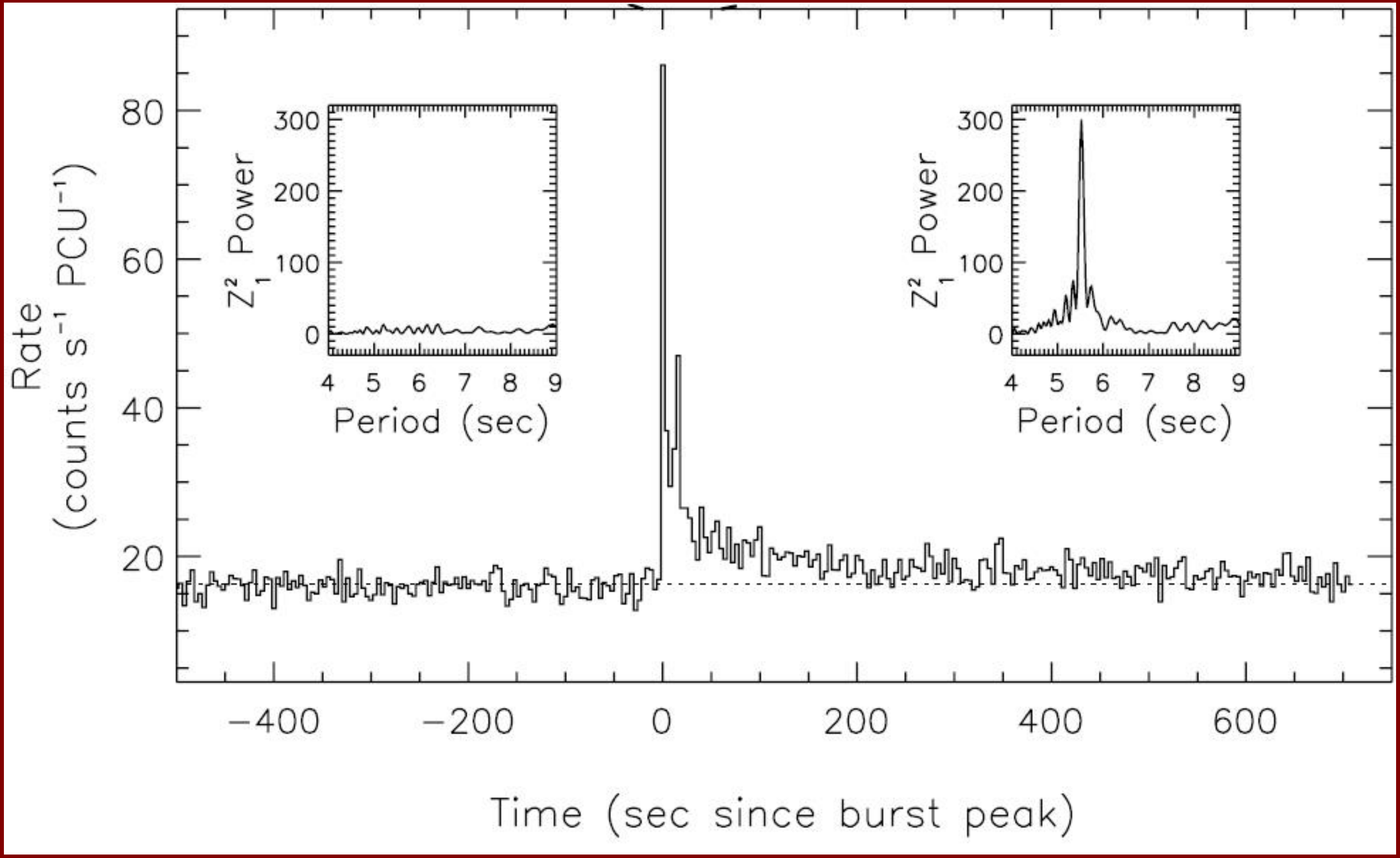
Bursts of the AXP 1E1547.0-5408





Some bursts have pulsating tails with spin period.

Unique AXP bursts?



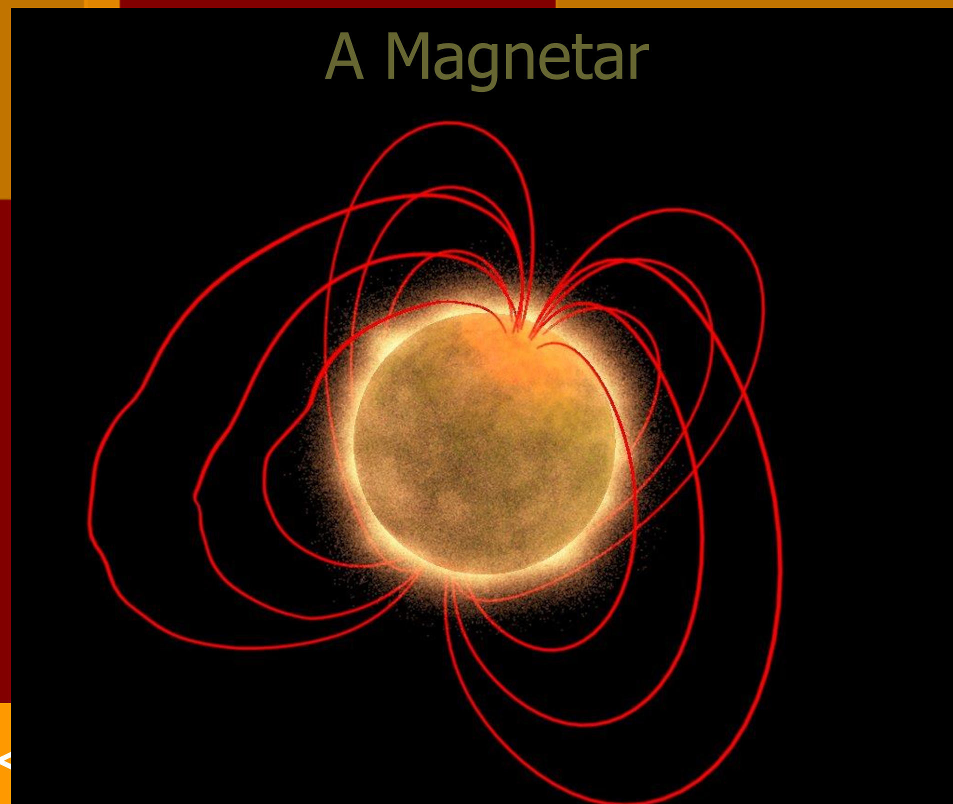
Bursts from AXP J1810-197. Note a long exponential tail with pulsations.

(Woods et al. 2005 astro-ph/ astro-ph/0505039)

A Tale of Two Populations ?

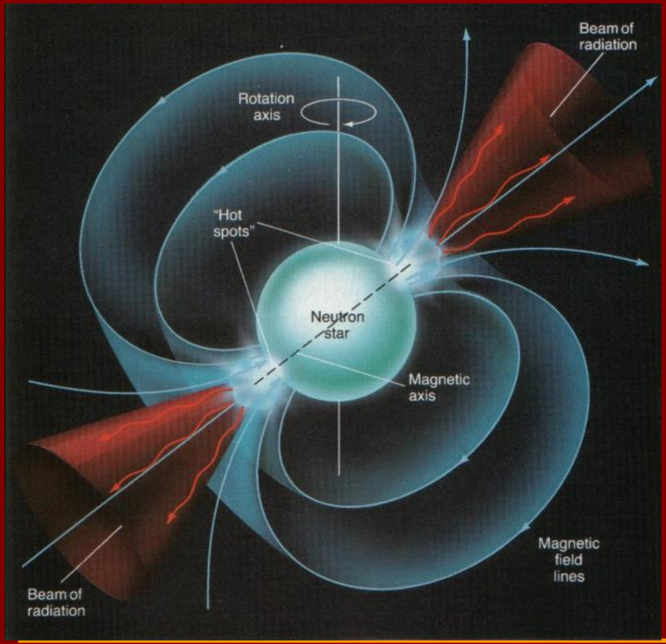
SGRs: bursting
X/γ-ray sources

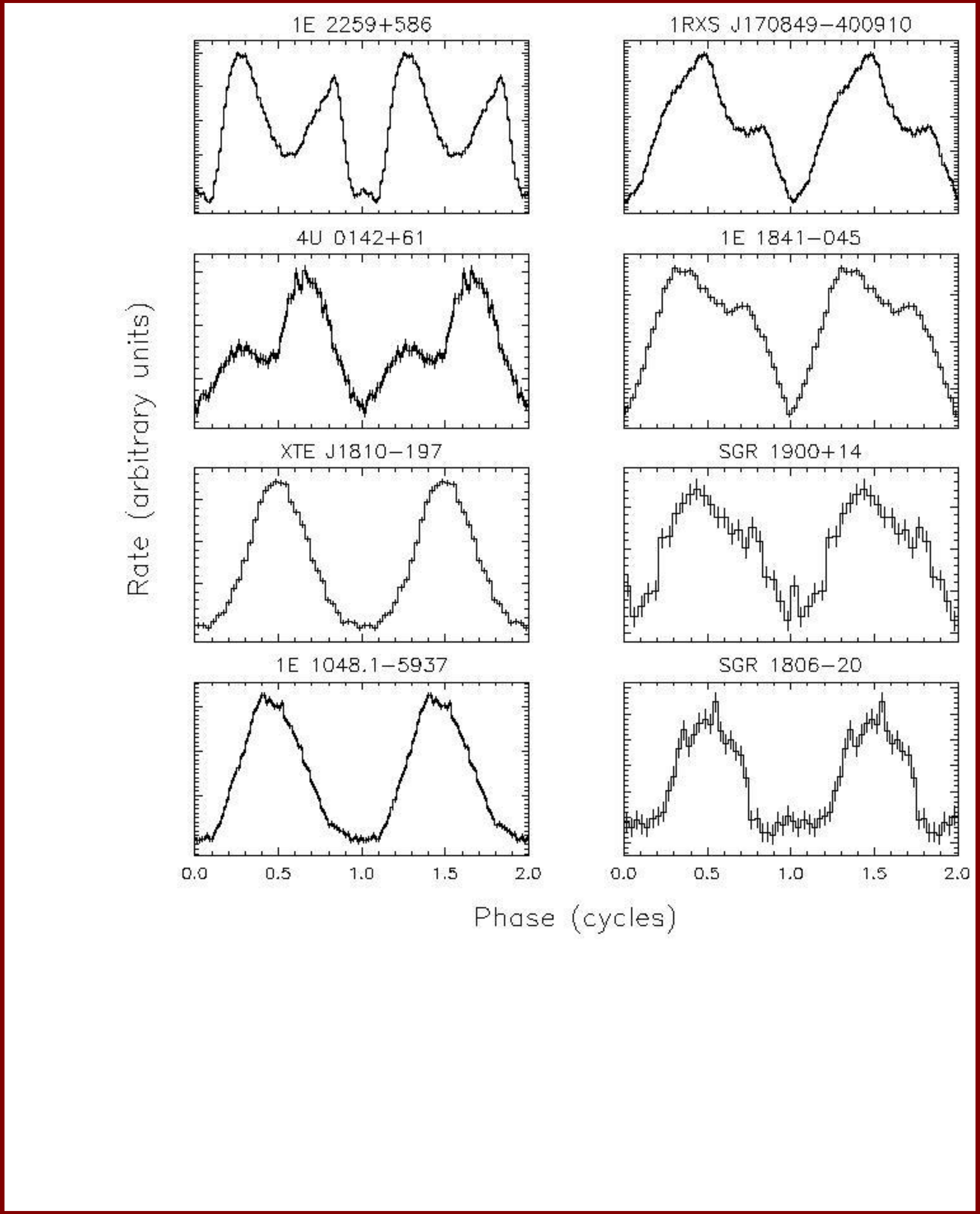
ss



R < ct
Pulsed X-ray emission: a neutron star

Pulse profiles
of SGRs and AXPs



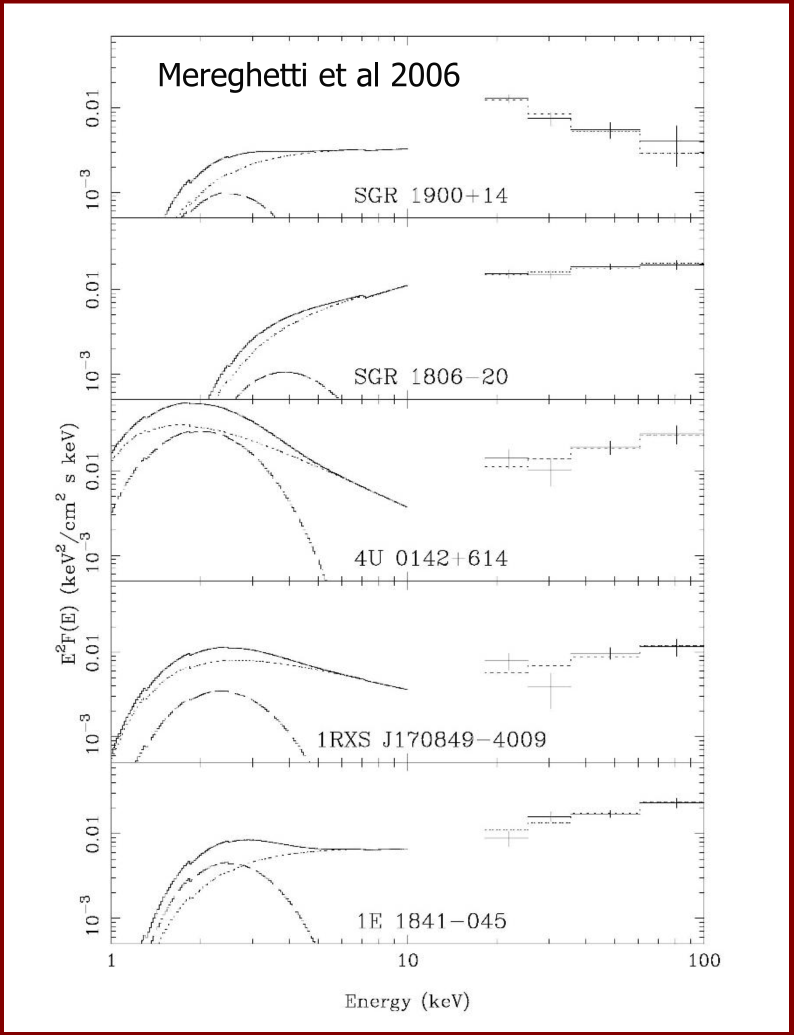


Hard X-ray Emission

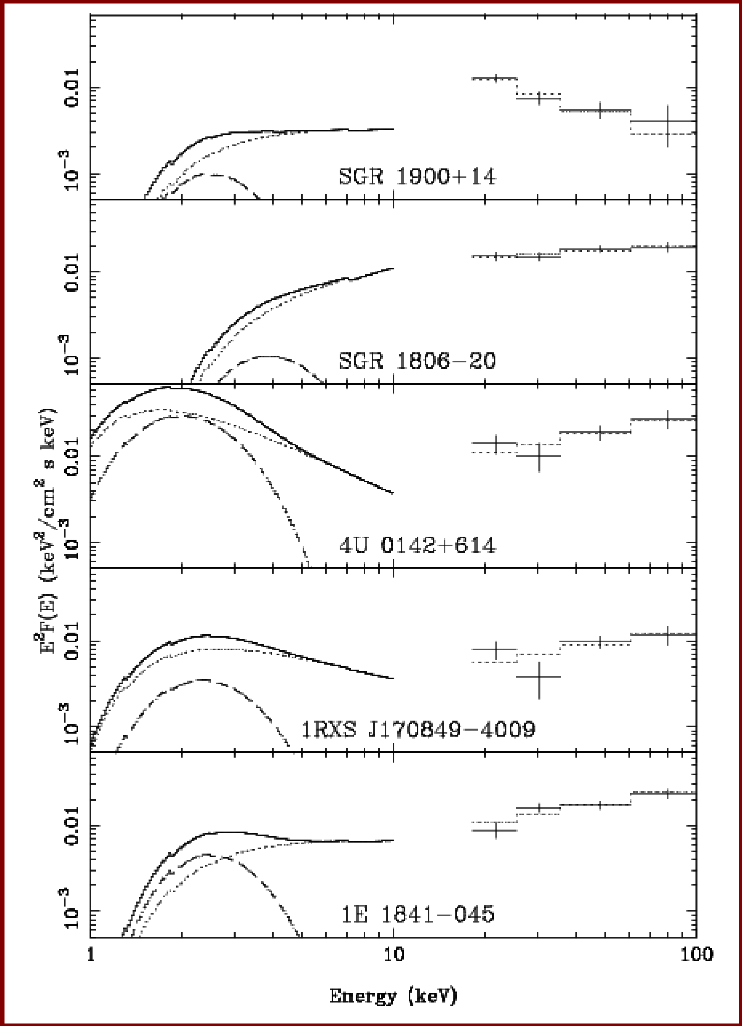
INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and APXs

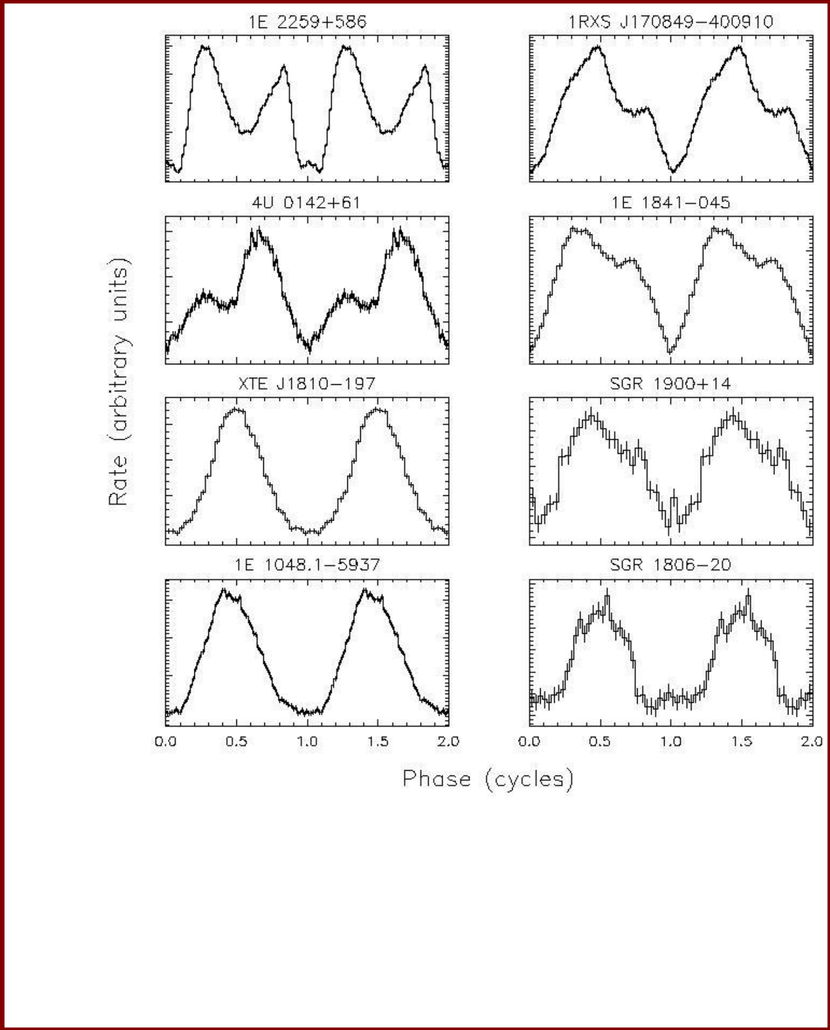
Hard power law tails with $\Gamma \approx 1\text{-}3$
(see 1712.09643 about spectral modeling)

Hard emission pulse



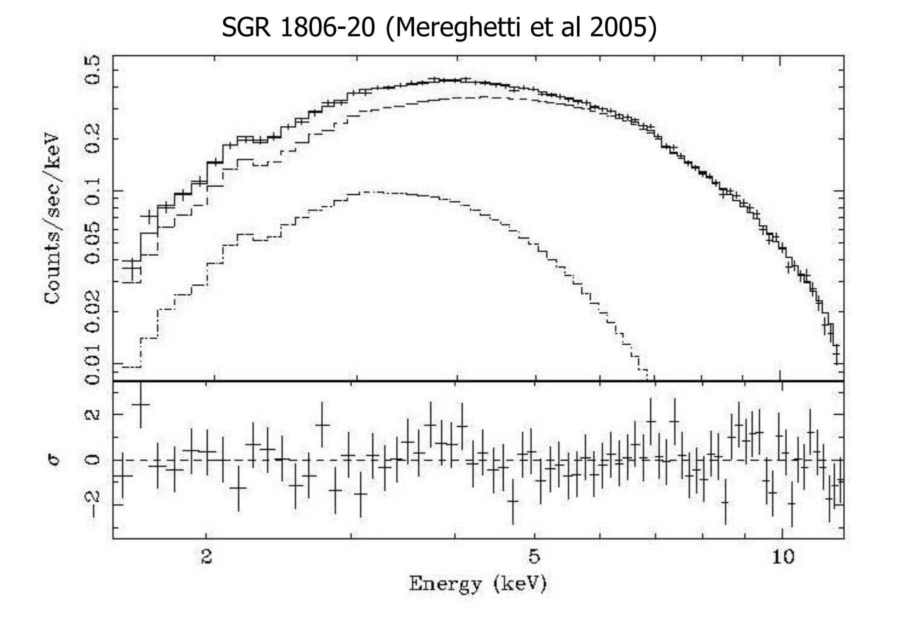
SGRs and AXPs

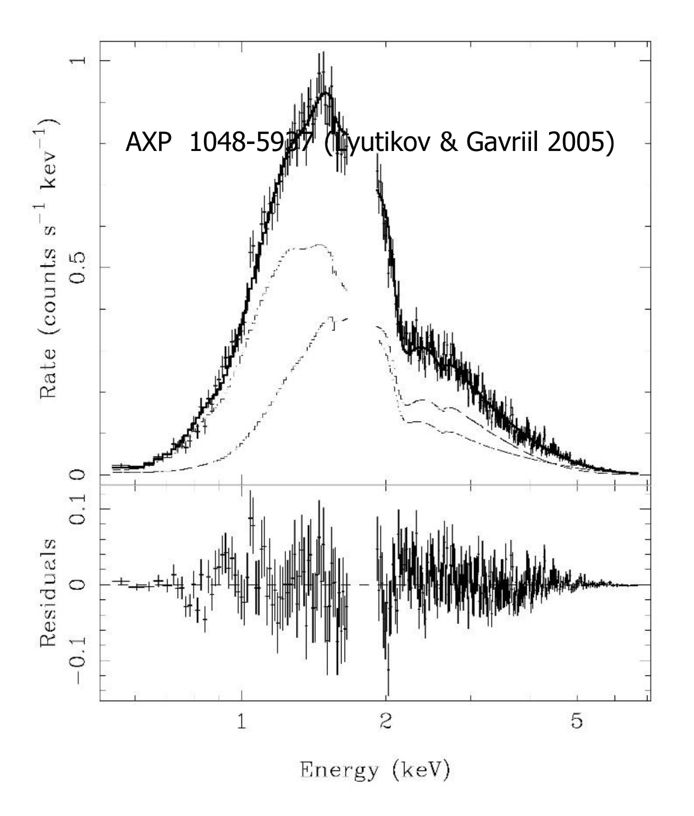




SGRs and AXPs soft X-ray Spectra

- 0.5 – 10 keV emission is well represented by a blackbody plus a power law





See also discussions in:
arXiv: 1001.3847, 1009.2810

SGRs and AXPs soft X-ray Spectra

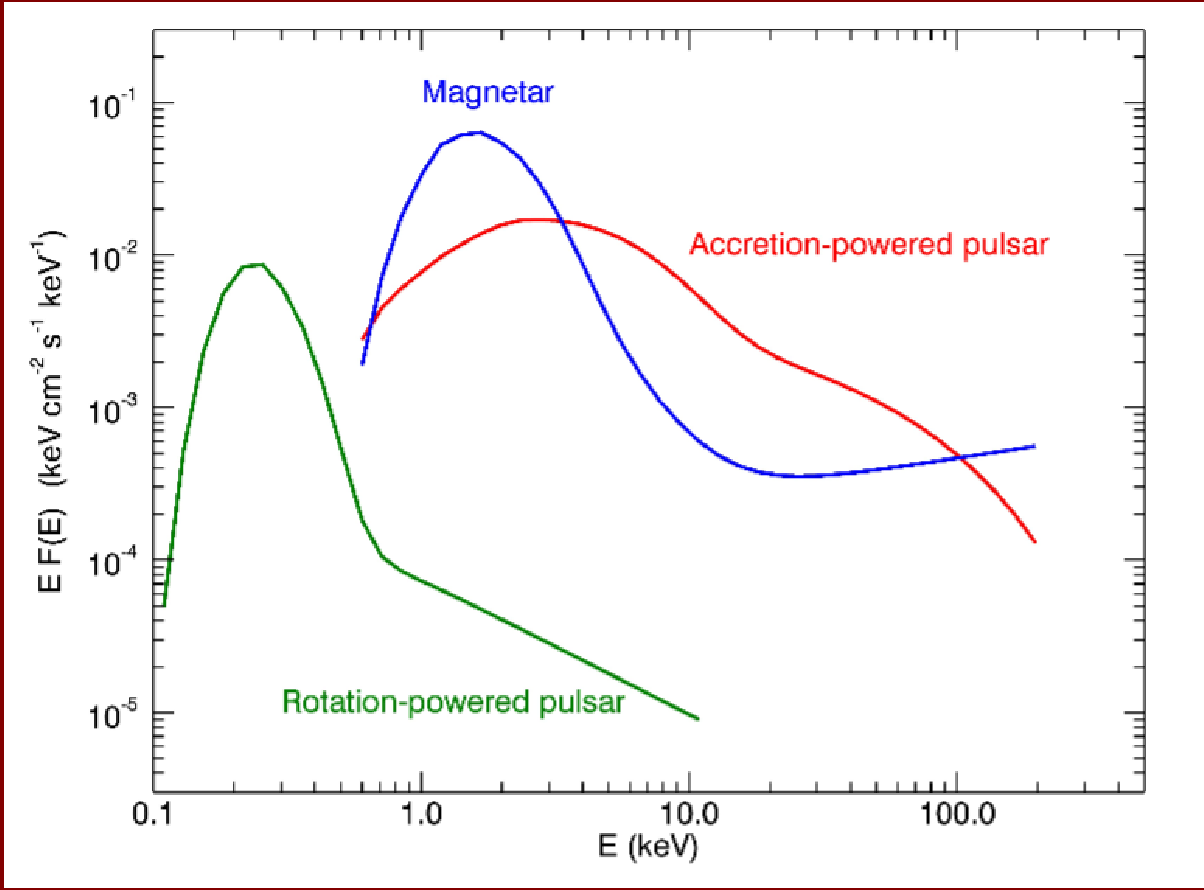
- kT_{BB} ~ 0.5 keV, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$,

  AXPs tend to be softer
- SGRs and AXPs persistent emission is variable (months/years)
- Variability is mostly associated with

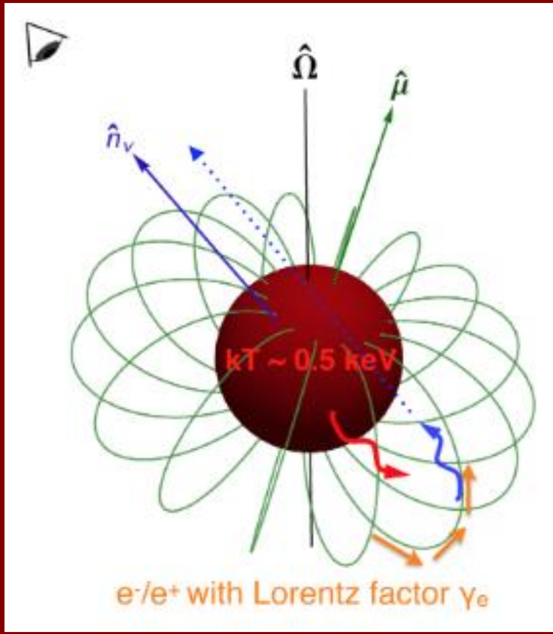
  the non-thermal component

Magnetar spectra in comparison

1503.06313



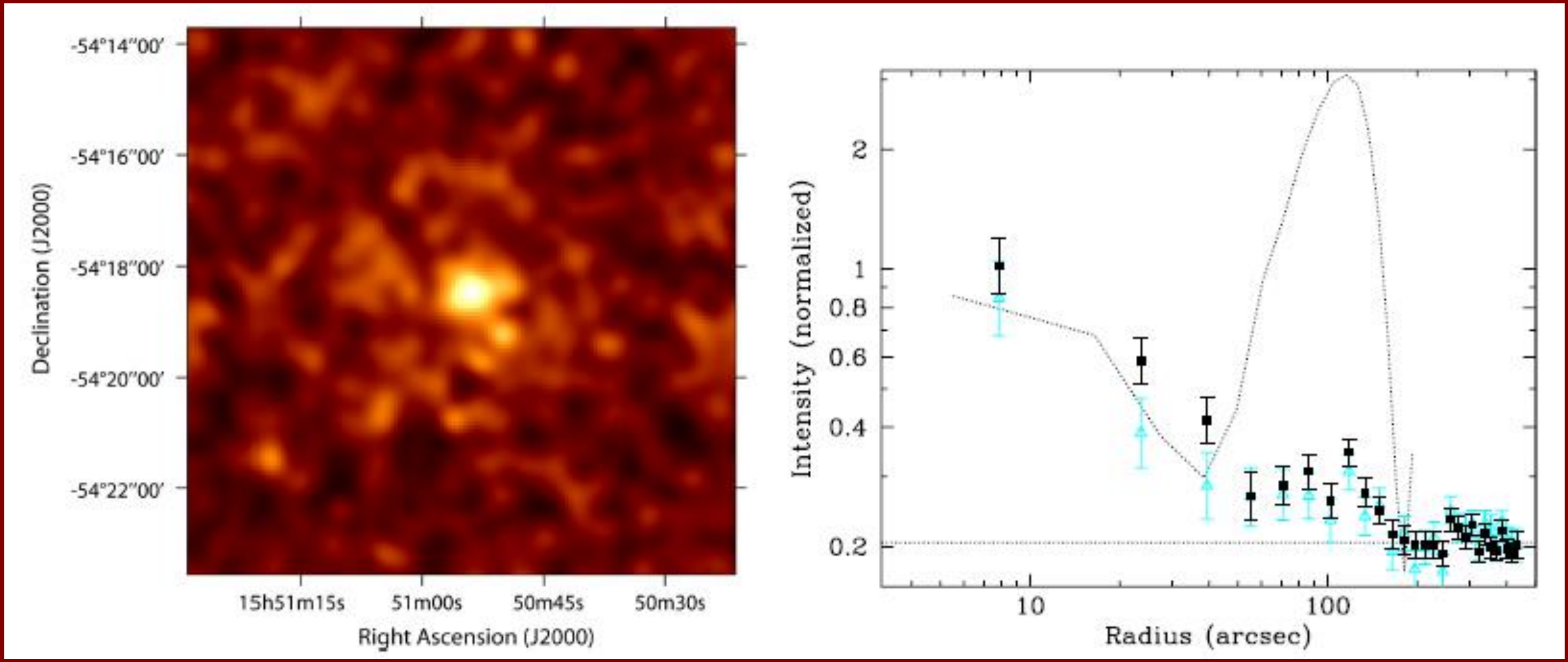
Hard tails can be due to upscattering of
thermal photons from the surface in the magnetosphere.



1903.05648

And what about AXPs and PSRs?

1E1547.0-5408 – the most rapidly rotating AXP (2.1 sec)
The highest rotation energy losses among SGRs and AXPs.
Bursting activity.

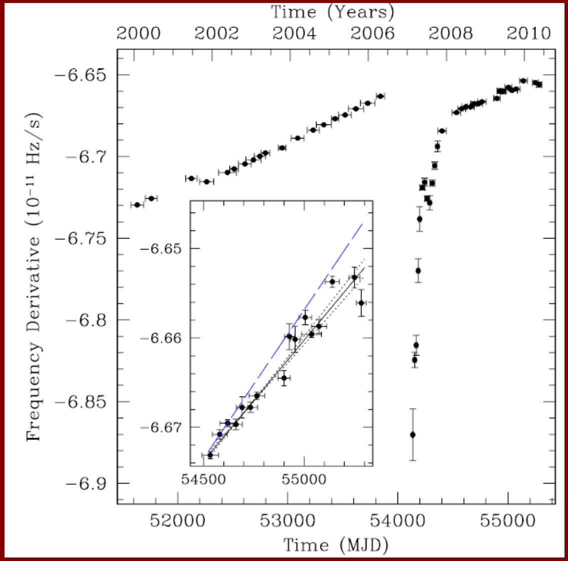


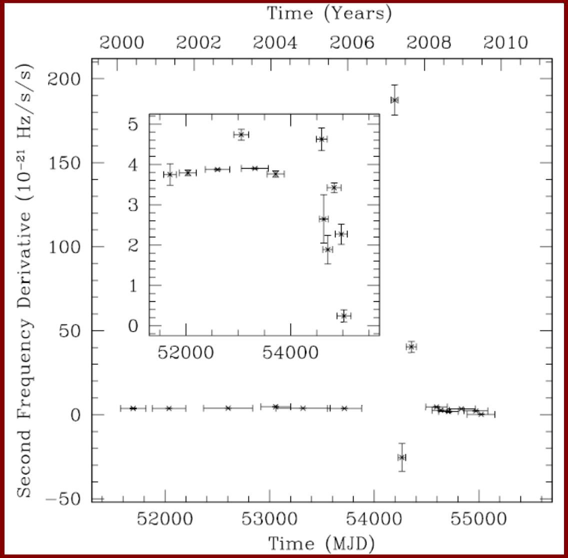
Pulsar wind nebulae around an AXP.

0909.3843

See 1902.10712 about radio observations of magnetars.

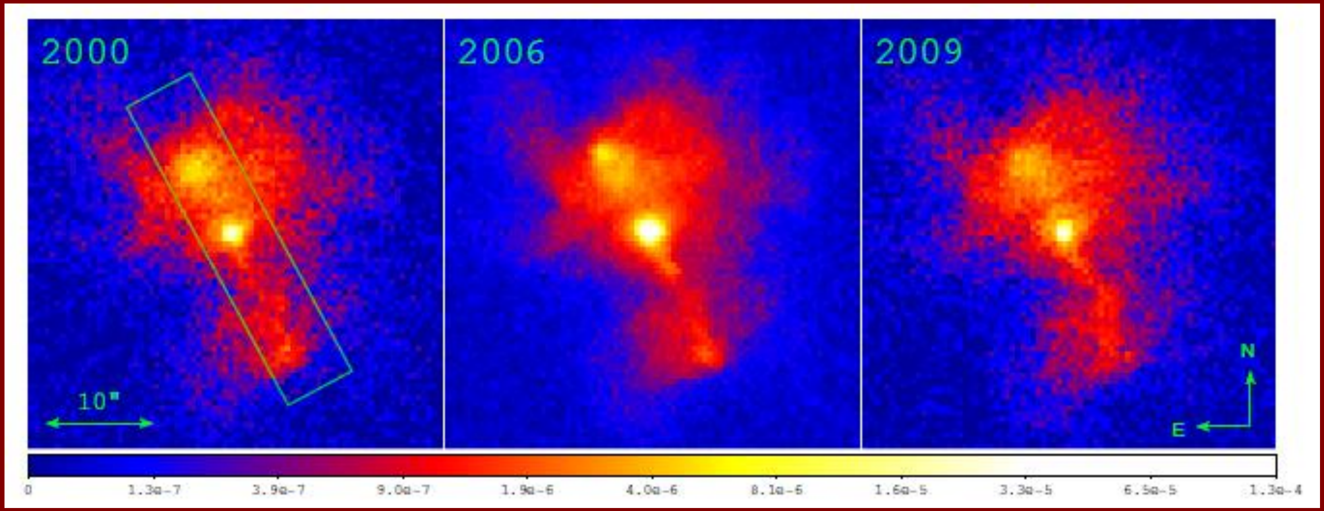
Postburst properties of PSR J1846-0258





The pulsar showed a glitch.
A period of magnetar-like activity was started.
After the burst parameters of the pulsar changed.

n=2.65 -> n=2.16
Timing noise was increased (was very small for a magnetar before bursts)

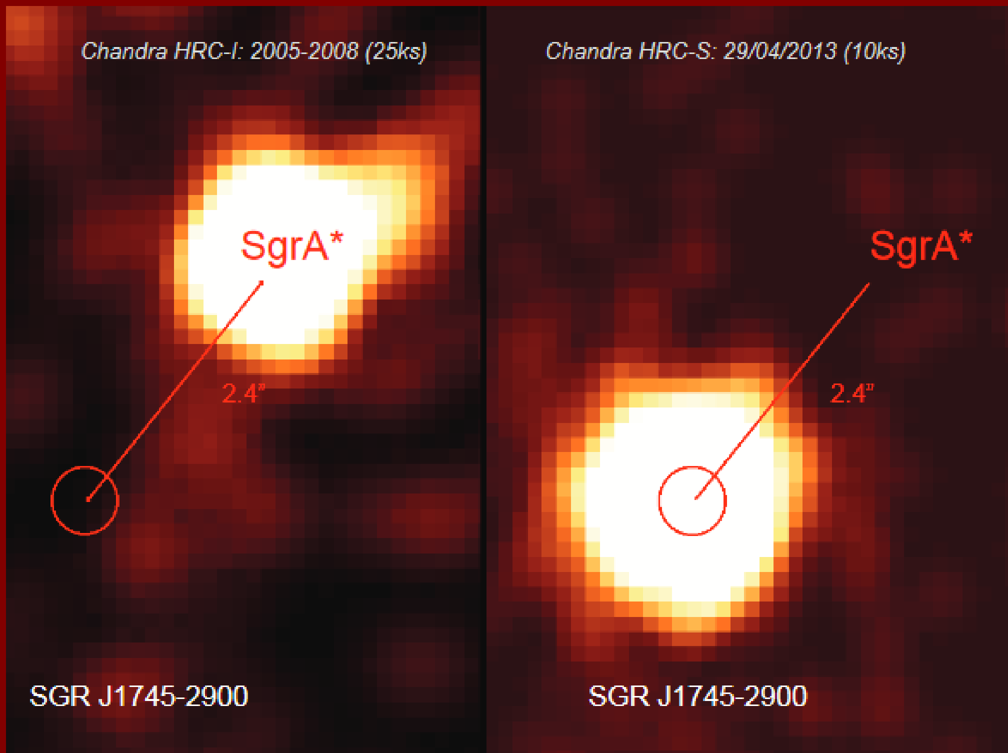


1007.2829

Galactic center magnetar

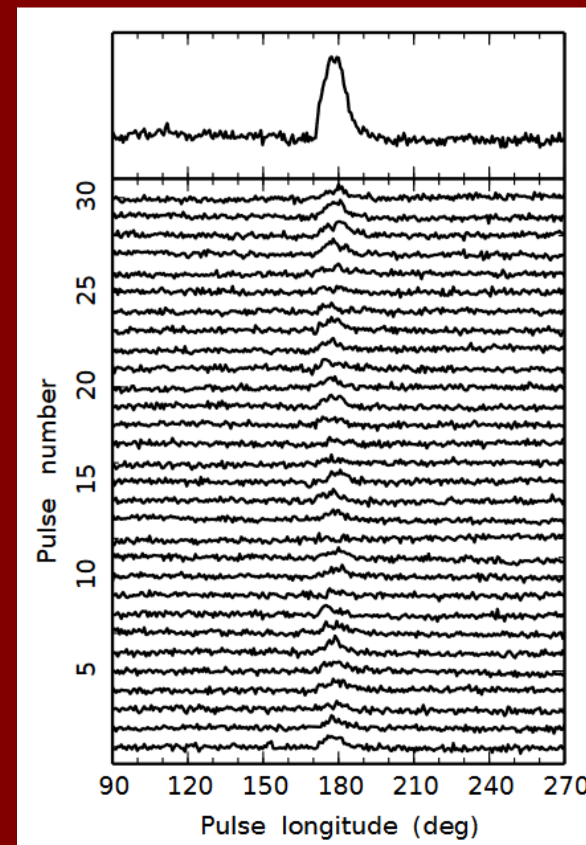
SGR/PSR J1745−2900

1307.6331



<1 pc from Sgr A*

Radio pulsations detection in 2013
The largest dispersion measure and rotation measure among PSRs.



1802.07884

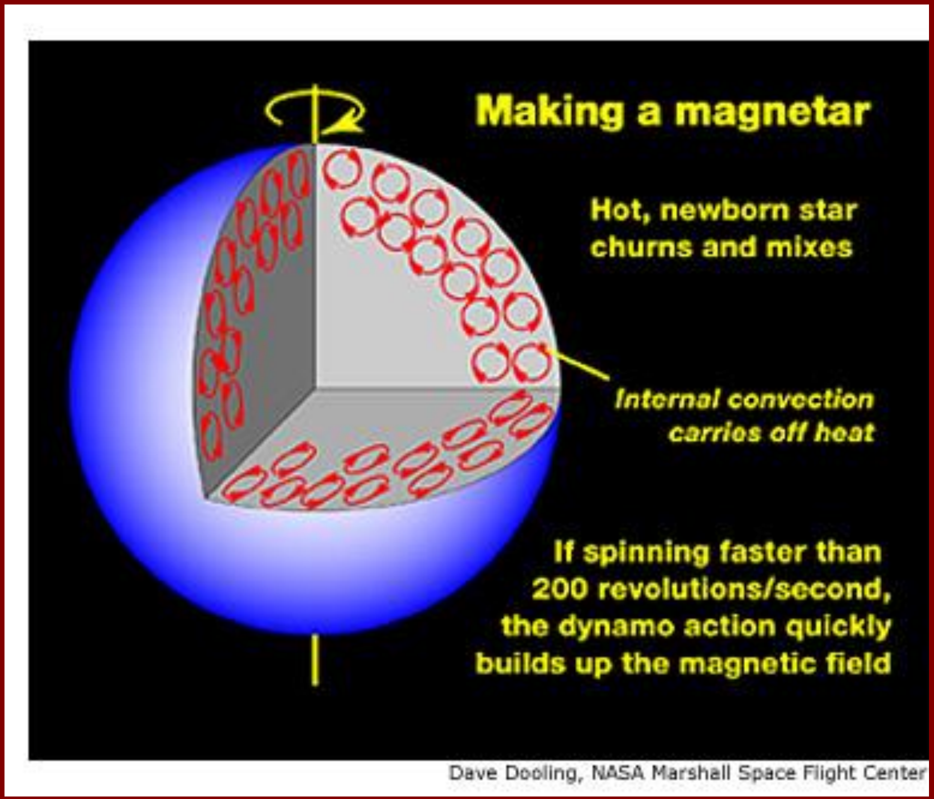
Generation of the magnetic field

The mechanism of the magnetic field generation is still unknown.

Turbulent dynamo

α-Ω dynamo (Duncan,Thompson)
α^2 dynamo (Bonanno et al.)
or their combination

In any case, initial rotation of a protoNS is the critical parameter.



Strong field via flux conservation

There are reasons to suspect that the magnetic fields of magnetars are not due to any kind of dynamo mechanism, but just due to flux conservation:

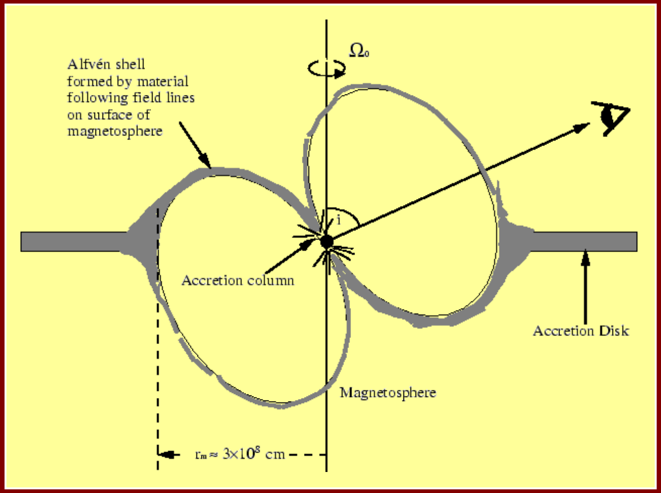
1. Study of SNRs with magnetars (Vink and Kuiper 2006, see also 1708.01626). If there was a rapidly rotating magnetar then a huge energy release is inevitable. No traces of such energy injections are found.

2. There are few examples of massive stars with field strong enough to produce a magnetars due to flux conservation (Ferrario and Wickramasinghe 2006)

Still, these suggestions can be criticized (Spruit arXiv: 0711.3650)

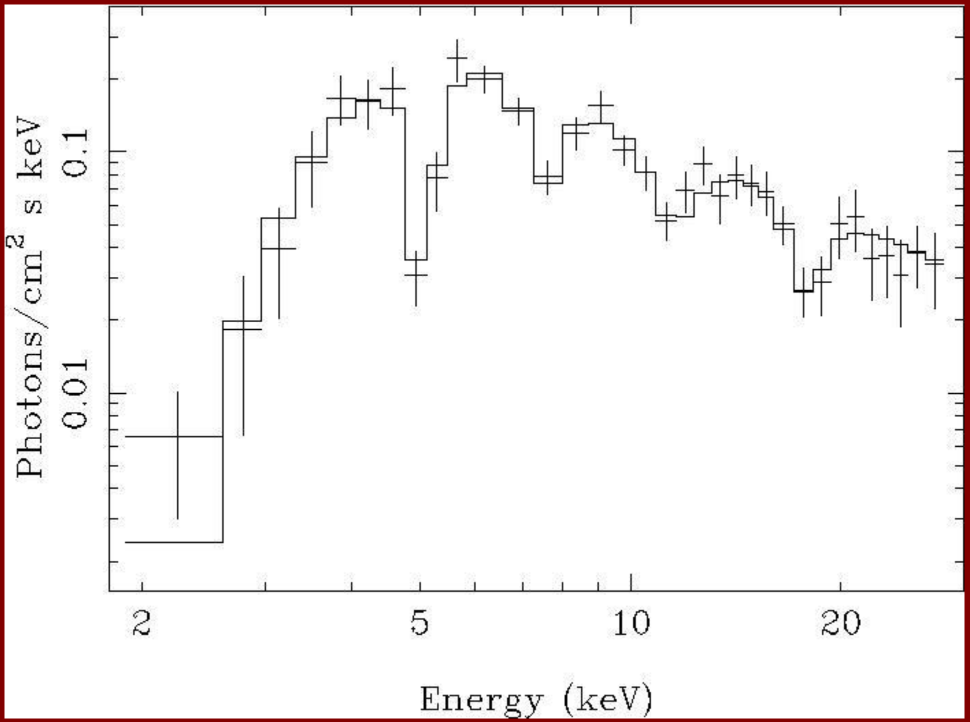
Alternative theory

- Remnant fallback disc
- Mereghetti, Stella 1995
- Van Paradijs et al.1995
- Alpar 2001
- Marsden et al. 2001
- Problems …..
- How to generate strong bursts?
- Discovery of a passive
  disc in one of AXPs
  (Wang et al. 2006).
  A new burst of interest
  to this model.
- Timing noise analysis
  contradicts accretion (1806.00401)



Magnetic field estimates

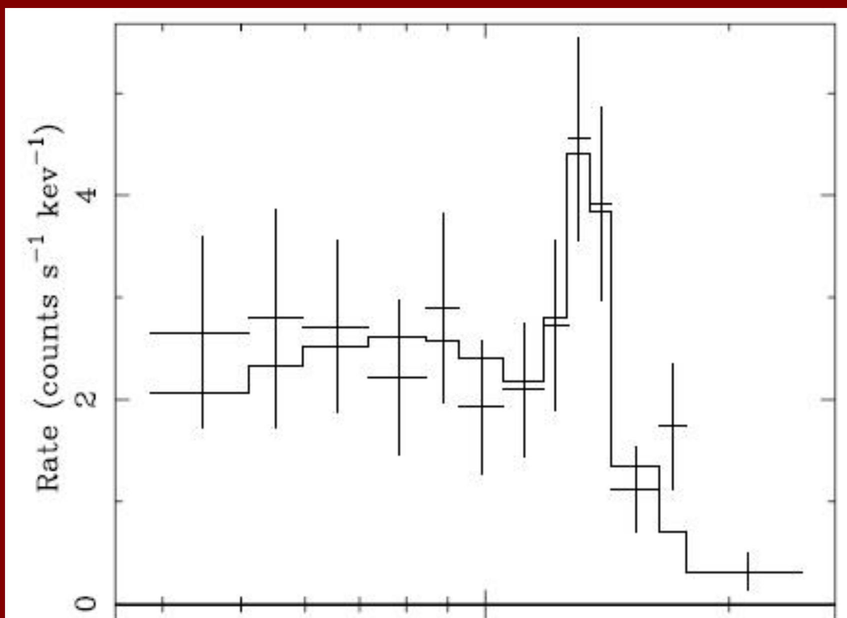
- Spin down
- Long spin periods
- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)
- Direct measurements of magnetic field (cyclotron lines)

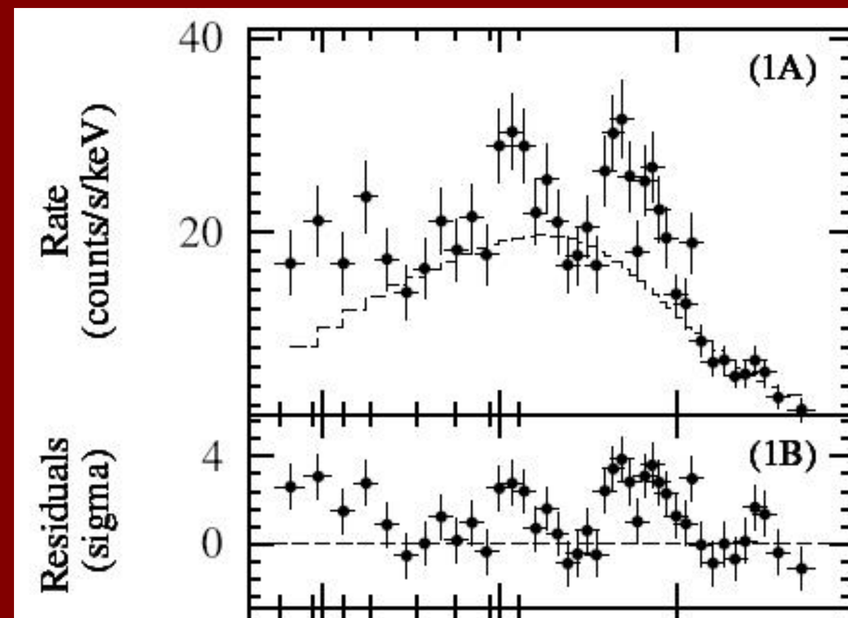


Ibrahim et al. 2002

Spectral lines claims

All claims were done for RXTE observations (there are few other candidates).
All detections were done during bursts.

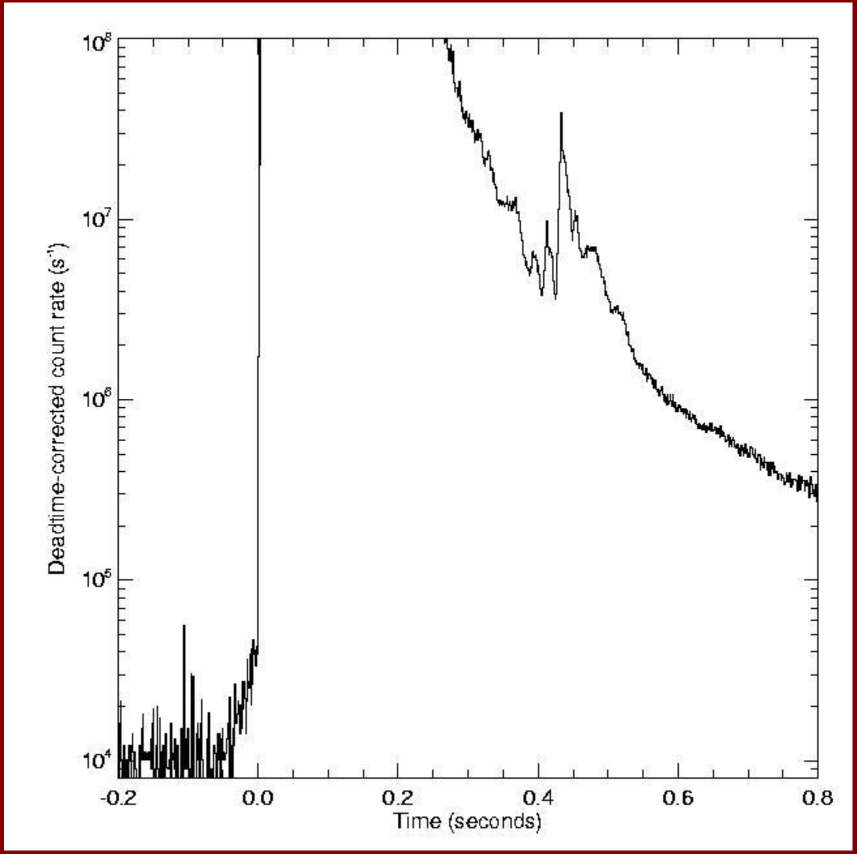




1E 1048.1-5937 Gavriil et al. (2002, 2004)   4U 0142+61 Gavriil et al. (2007)

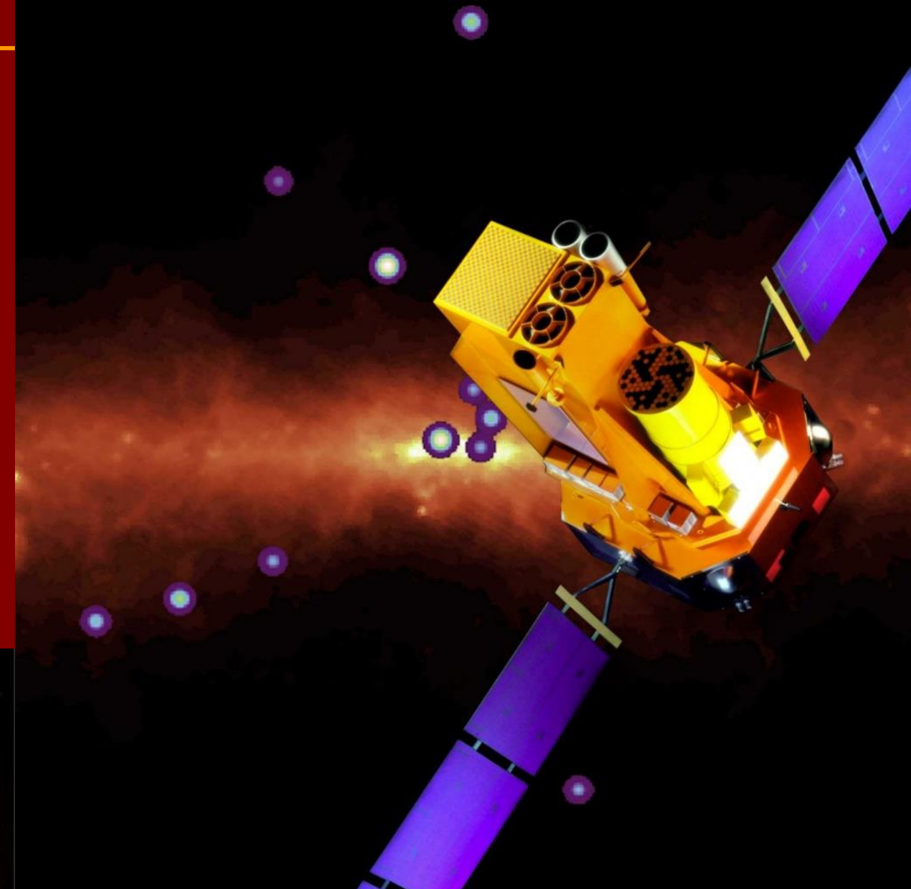
Hyperflare of SGR 1806-20

- 27 December 2004 A giant flare from SGR 1806-20 was detected by many satellites: Swift, RHESSI, Konus-Wind, Coronas-F, Integral, HEND, …
- 100 times brighter than any other!



Palmer et al.
astro-ph/0503030

CORONAS-F

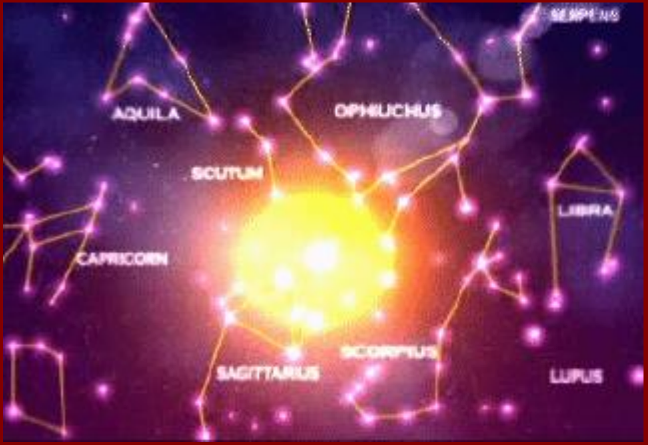


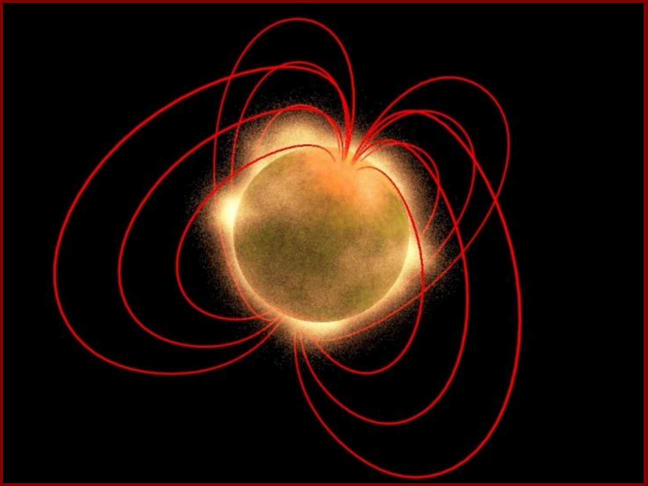
Integral

RHESSI

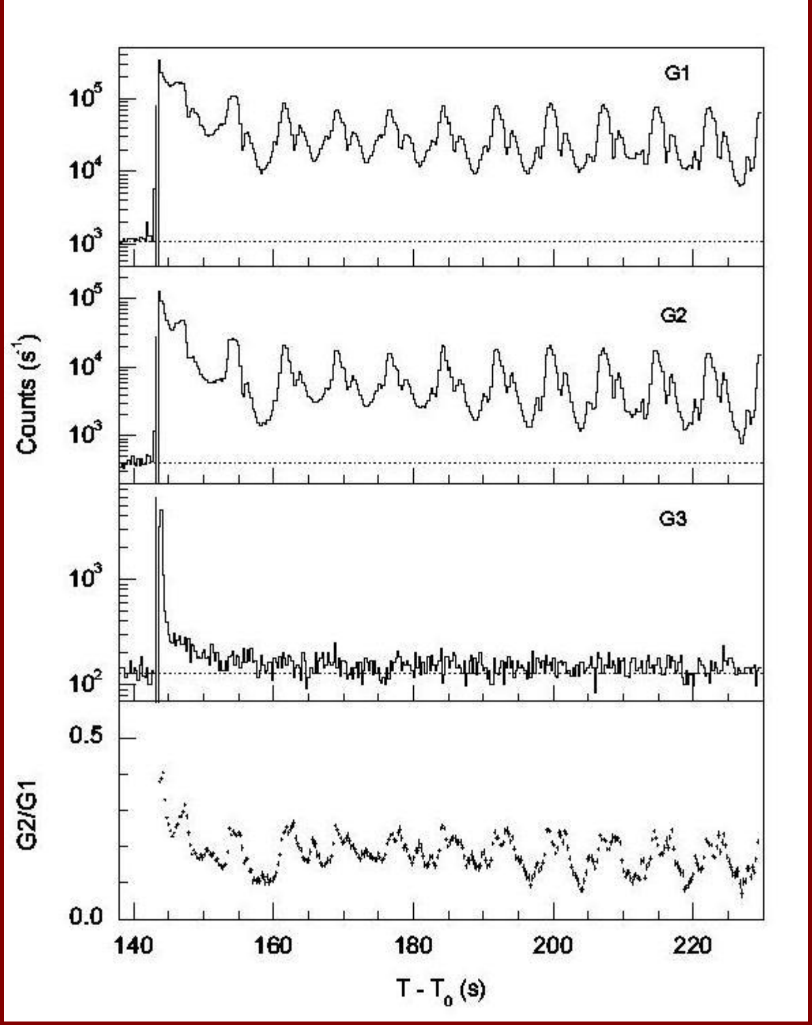
27 Dec 2004:
Giant flare of the SGR 1806-20

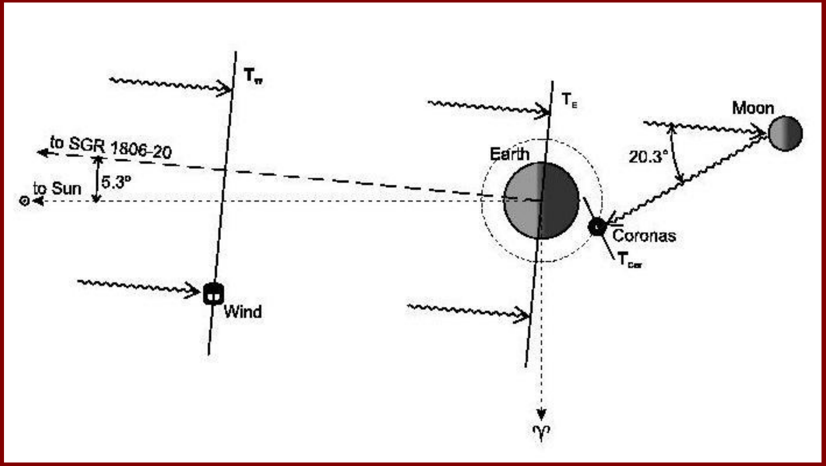
- Spike 0.2 s
- Fluence 1 erg/cm^2
- E(spike)=3.5 10^{46} erg
- L(spike)=1.8 10^{47} erg/s
- Long «tail» (400 s)
- P=7.65 s
- E(tail) 1.6 10^{44} erg
- Distance 15 kpc – see the latest data in arXiv: 1103.0006

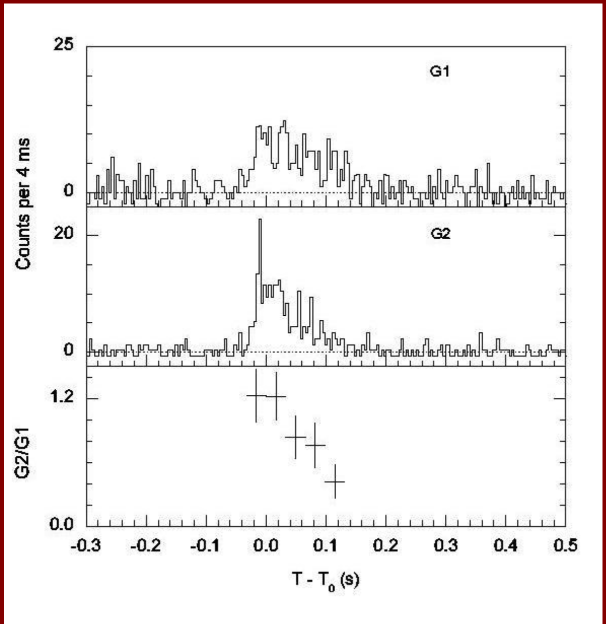




Konus observations

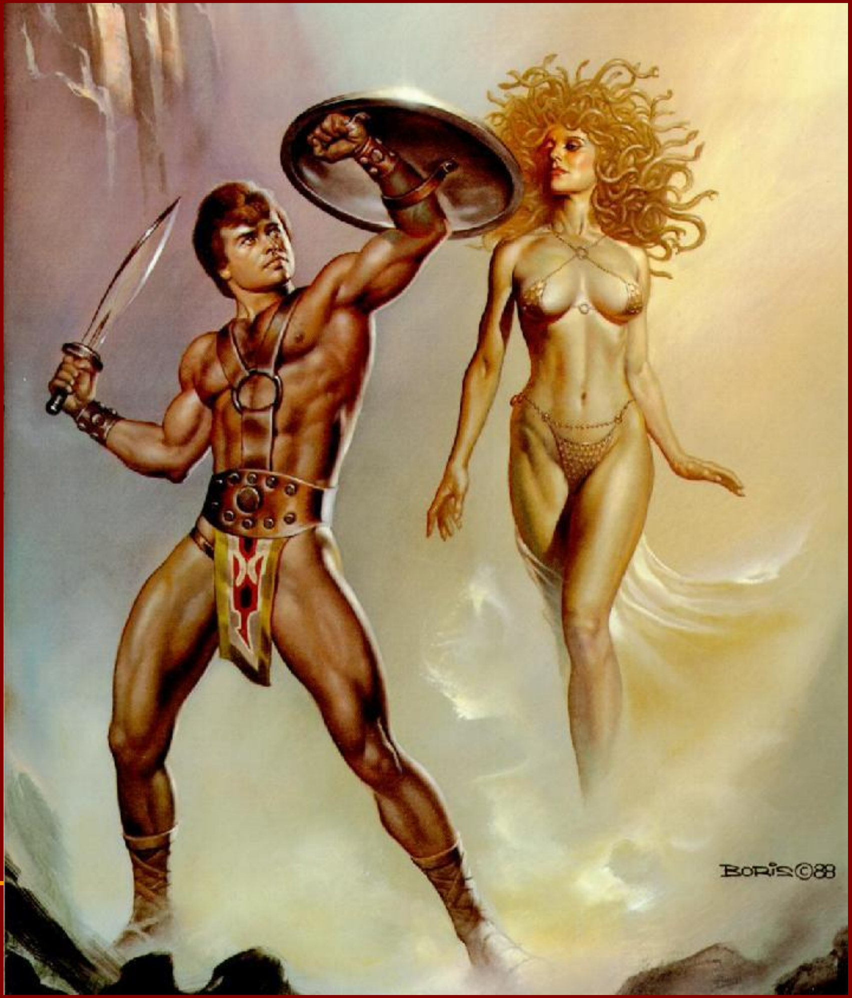






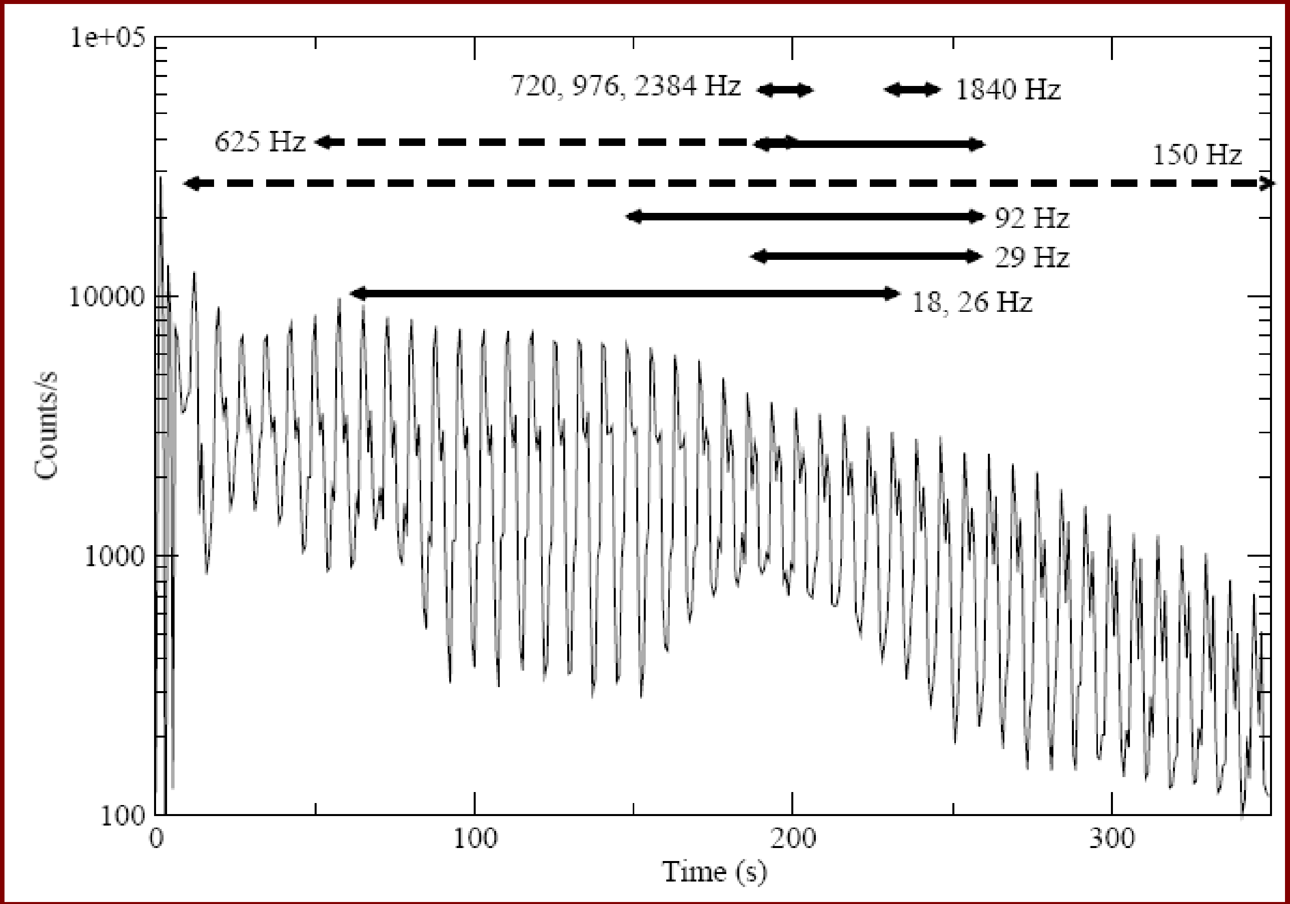
Mazets et al. 2005

The myth about Medusa



QPO in tails of giant flares of SGRs

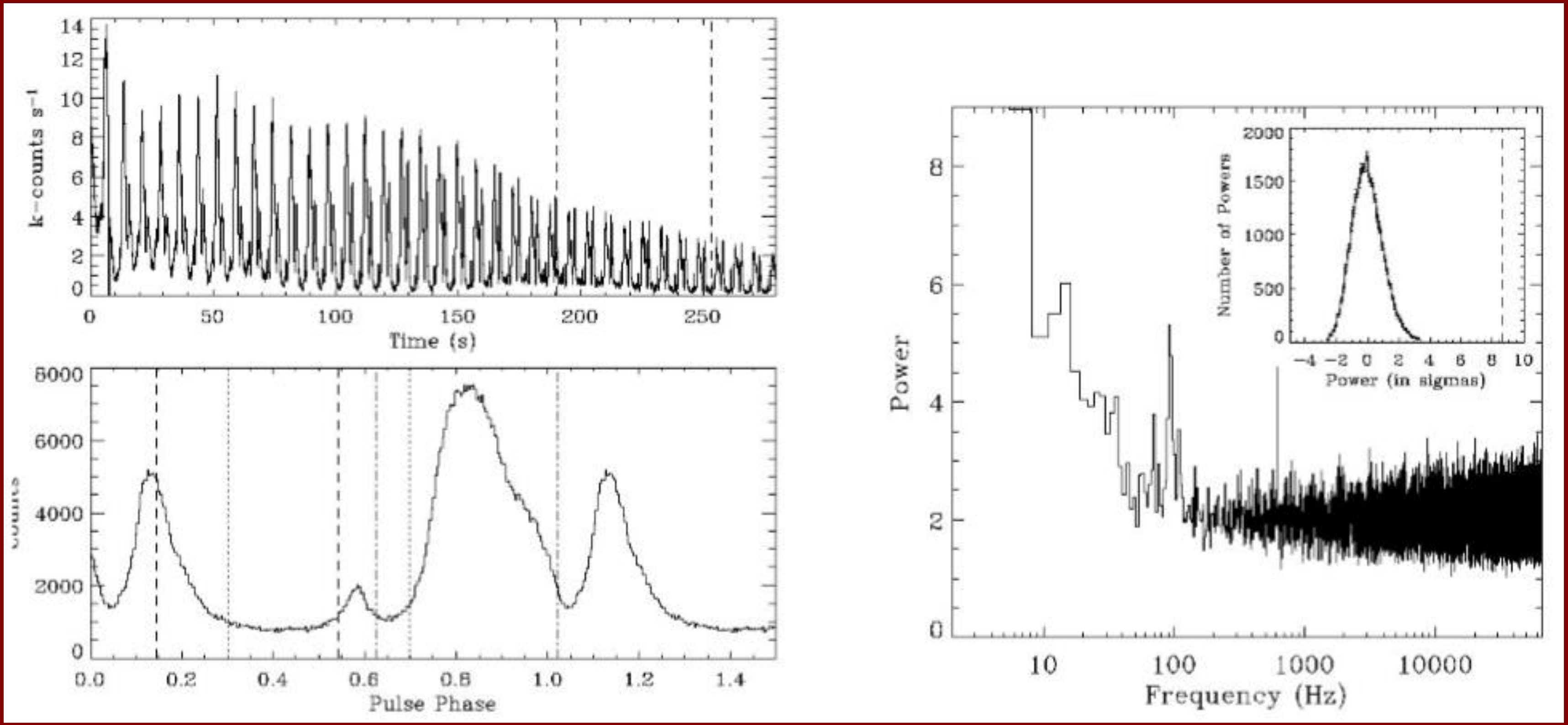
A kind of quasi periodic oscillations have been found in tail of two events (aug. 1998, dec. 2004). They are supposed to be torsional oscillations of NSs, however, it is not clear, yet.



(Israel et al. 2005 astro-ph/0505255,
Watts and Strohmayer 2005 astro-ph/0608463)

QPO in SGR 1806-20 giant flare

Power spectrum made by averaging nine 3 s segments from the time interval marked by dashed lines in the top left panel. The 92 Hz and 625 Hz QPOs are clearly visible, and the inset illustrates the significance of the 625 Hz feature (from Strohmayer & Watts, 2006)



1507.02924

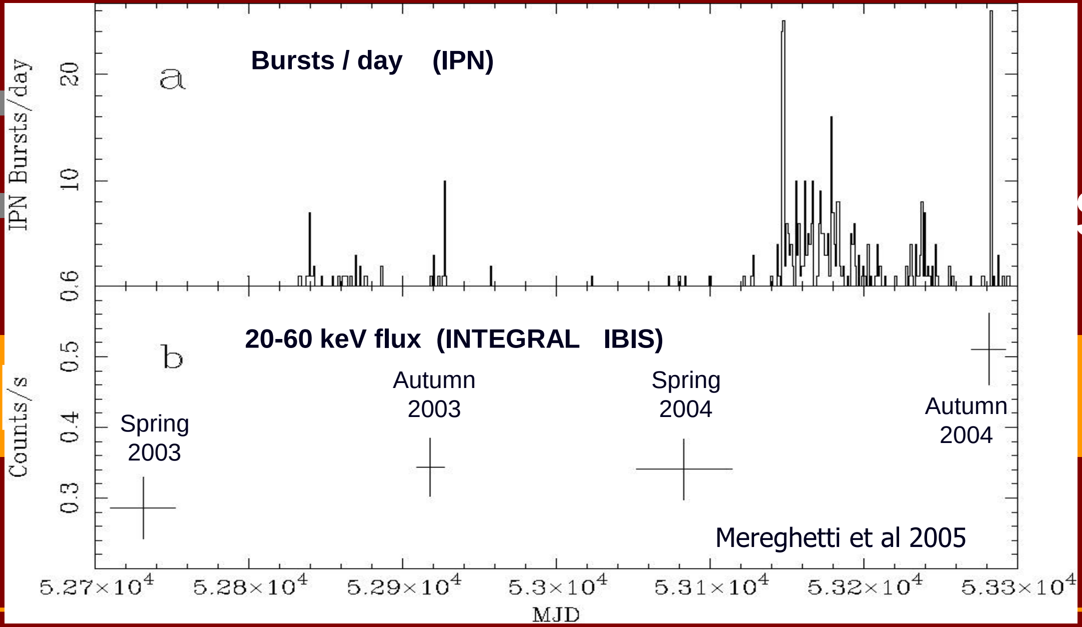
See fresh analysis in 1808.09483

SGR 1806-20 - I

SGR 1806-20 displayed a gradual increase in the level of activity during 2003-2004 (Woods et al 2004; Mereghetti et al 2005)

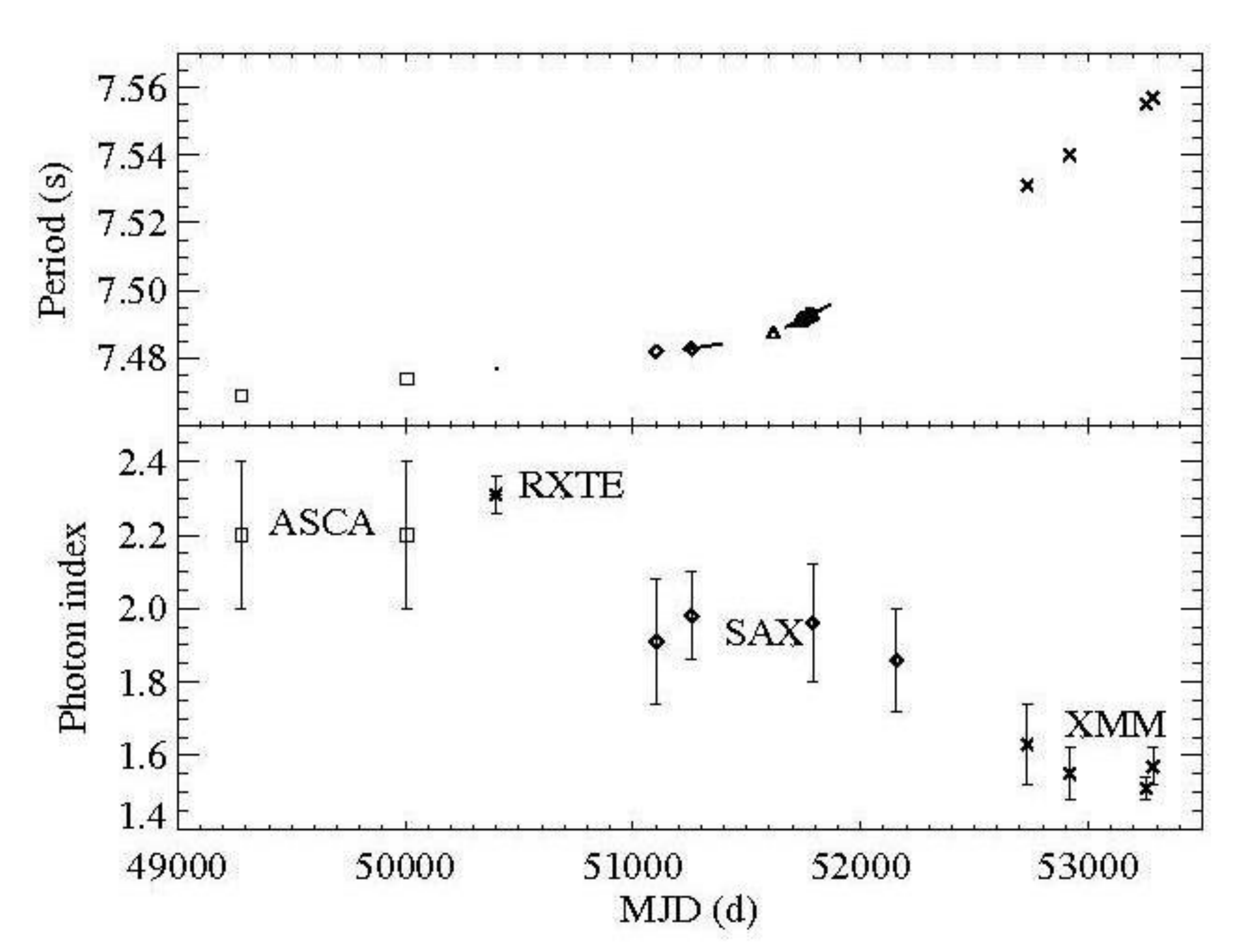
sity

T



SGR 1806-20 - II

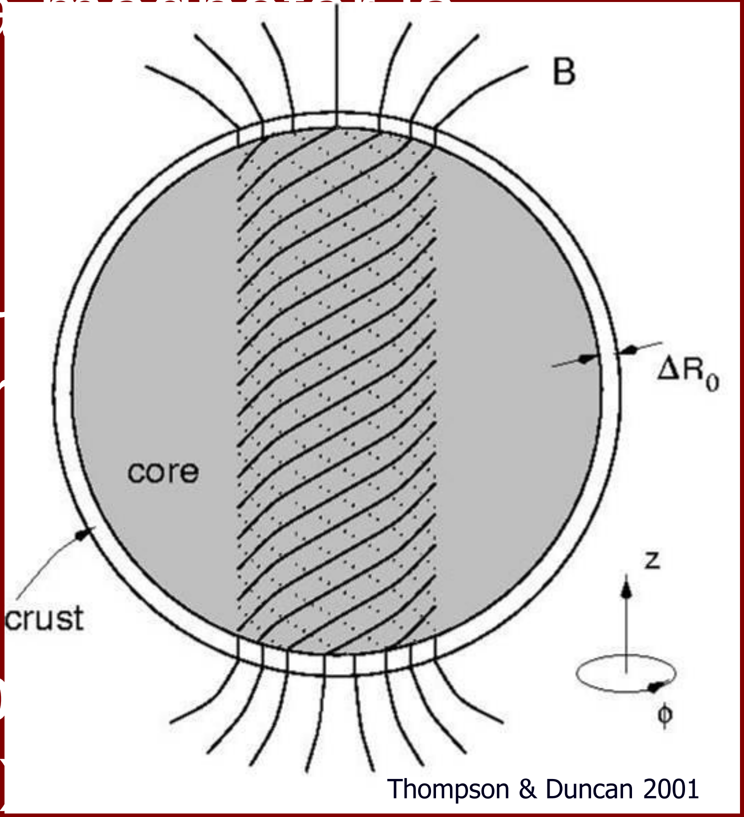
- Fou… …urst
  (the… …l 2005)
- Puls… …s
- Ṗ ~… …value
- Bla… …rbed
  pow…
- Har…
- The… ~ 10^{36}
  erg/…



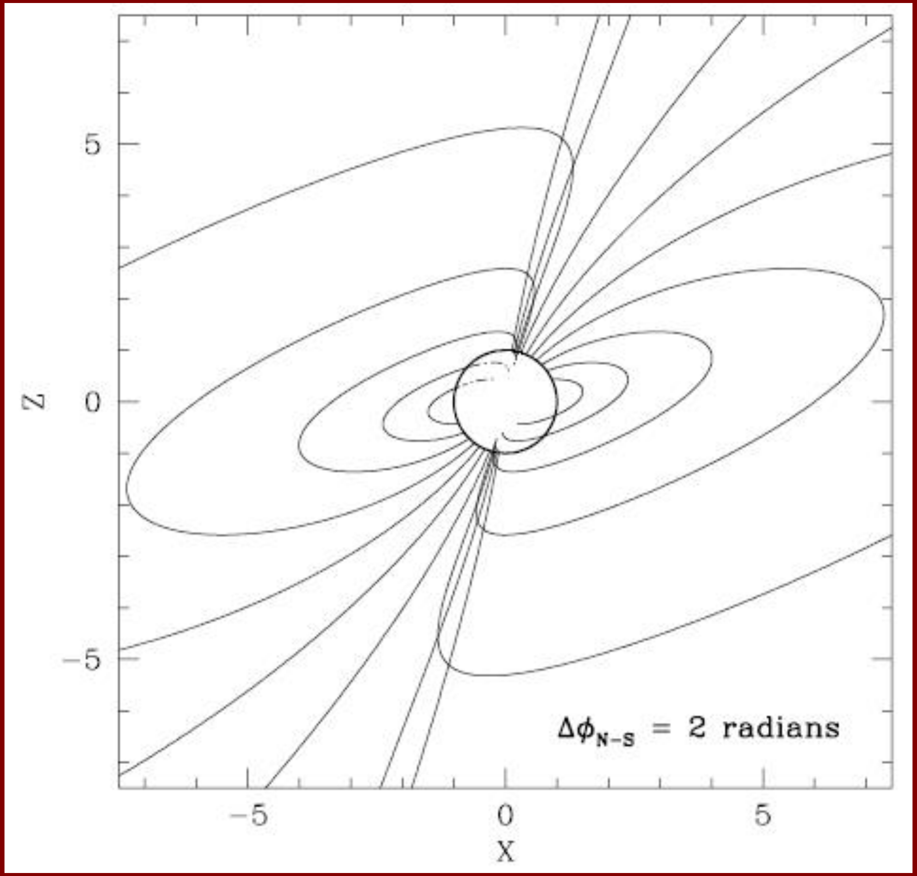
Twisted Magnetospheres – I

- The magnetic field inside a magnetar is “wound up”
- The presence of a toroidal induces a rotation of the su
- The crust tensile strength r
- A gradual (quasi-plastic ?) crust
- The external field twists up

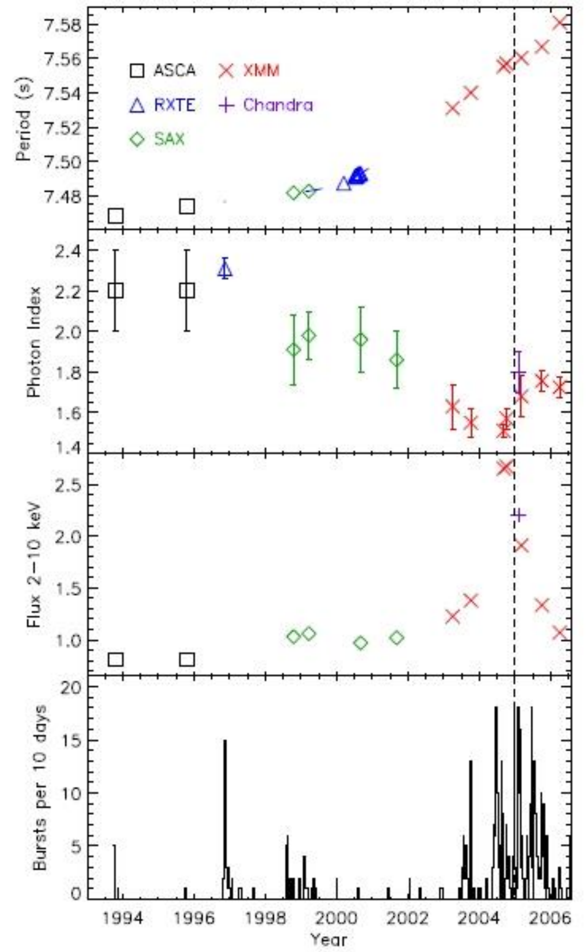
(Thompson, Lyutikov & Kulkarni 2002)



Growing twist

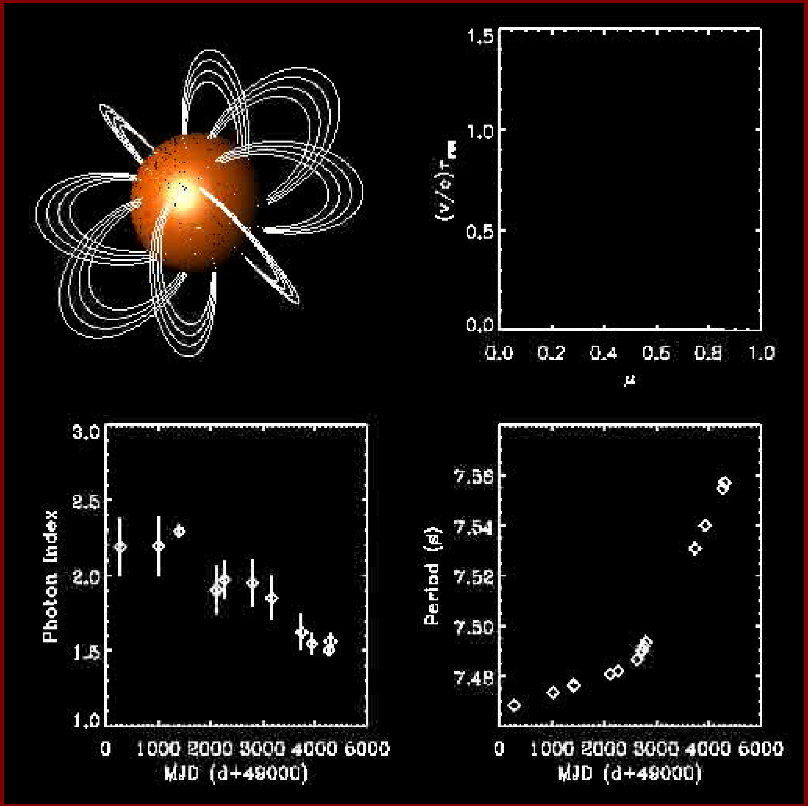


(images from Mereghetti arXiv: 0804.0250)



A Growing Twist in SGR 1806-20 ?

- Evidence for spectral hardening AND enhanced spin-down
- Γ-Pdot and Γ-L correlations
- Growth of bursting activity
- Possible presence of proton cyclotron line only during bursts



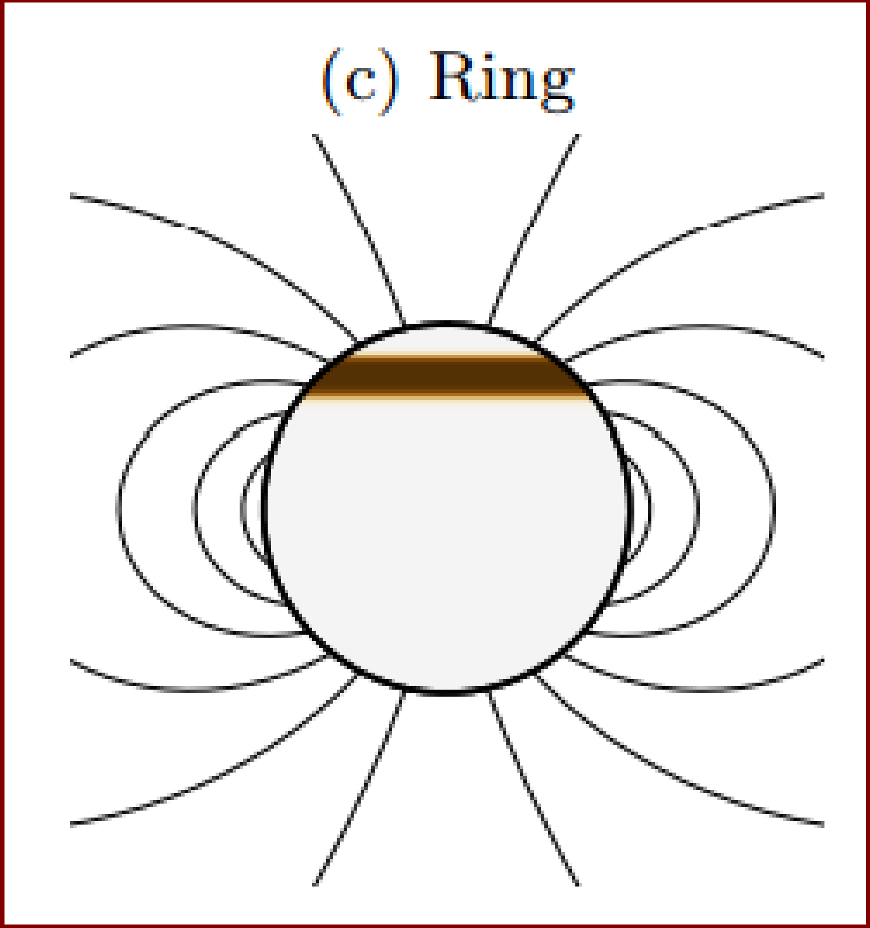
All these features are consistent with an increasingly twisted magnetosphere

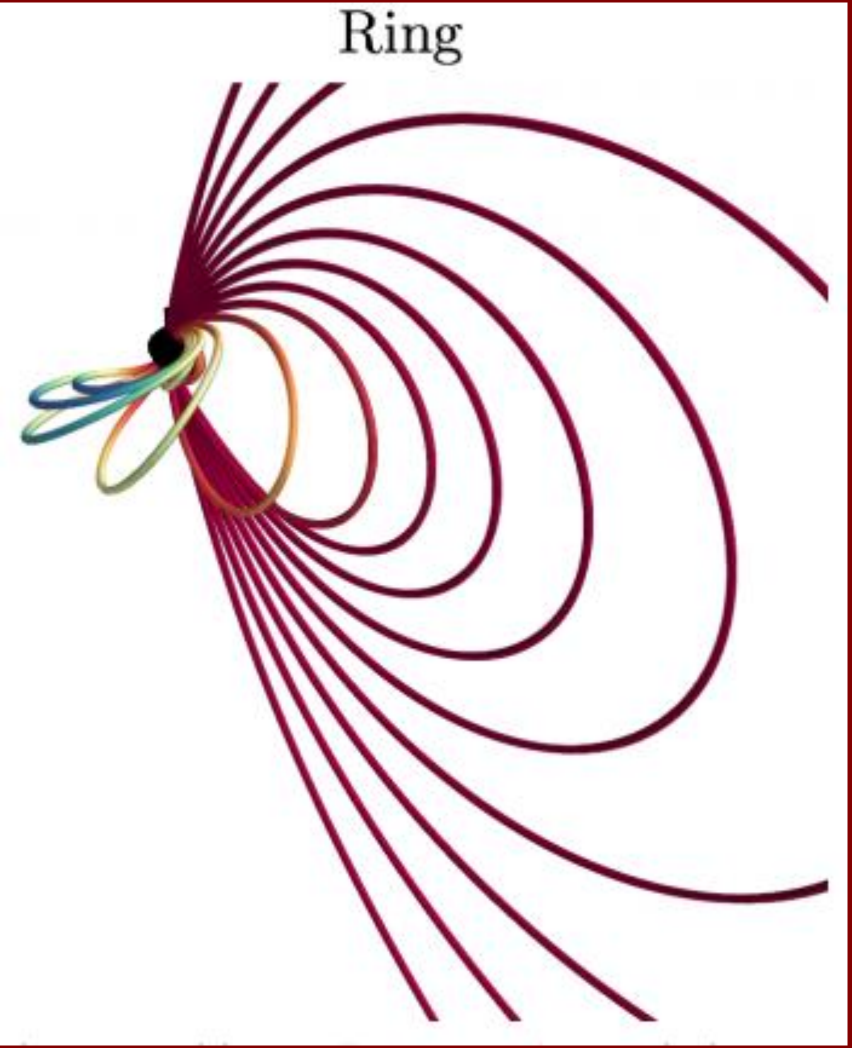
Twisted magnetospheres

- Twisted magnetosphere model, within magnetar scenario, in general agreement with observations
- Resonant scattering of thermal, surface photons produces spectra with right properties
- Many issues need to be investigated further
  - Twist of more general external fields
  - Detailed models for magnetospheric currents
  - More accurate treatment of cross section including QED effects and electron recoil
  - 10-100 keV tails: up-scattering by (ultra)relativistic ($e^{\pm}$) particles ?
  - Create an archive to fit model spectra to observations

See, for example, arXiv: 1008.4388 and references therein
and more recent studies in 1201.3635

Non-global twist model

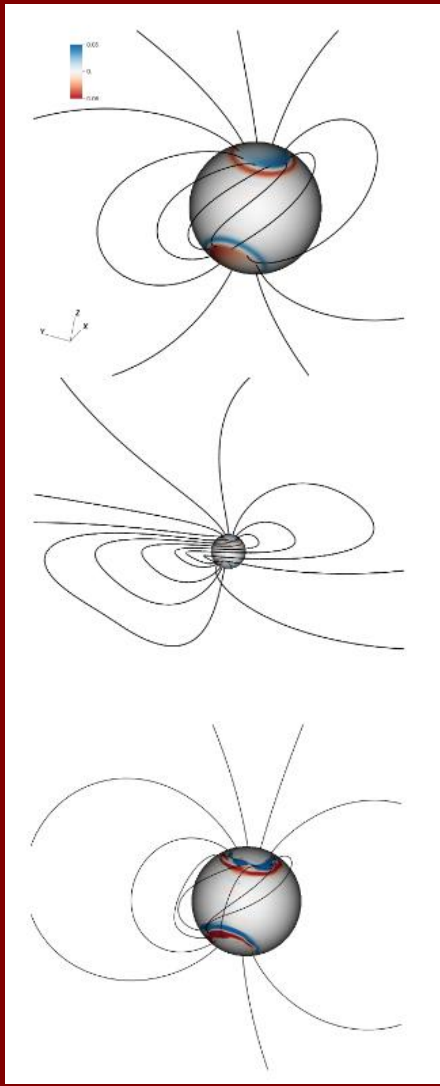


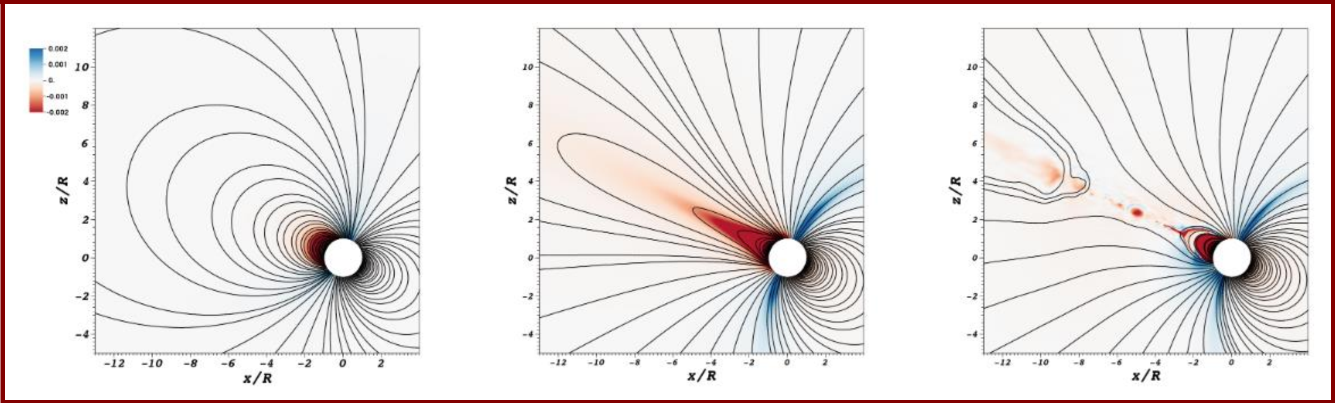


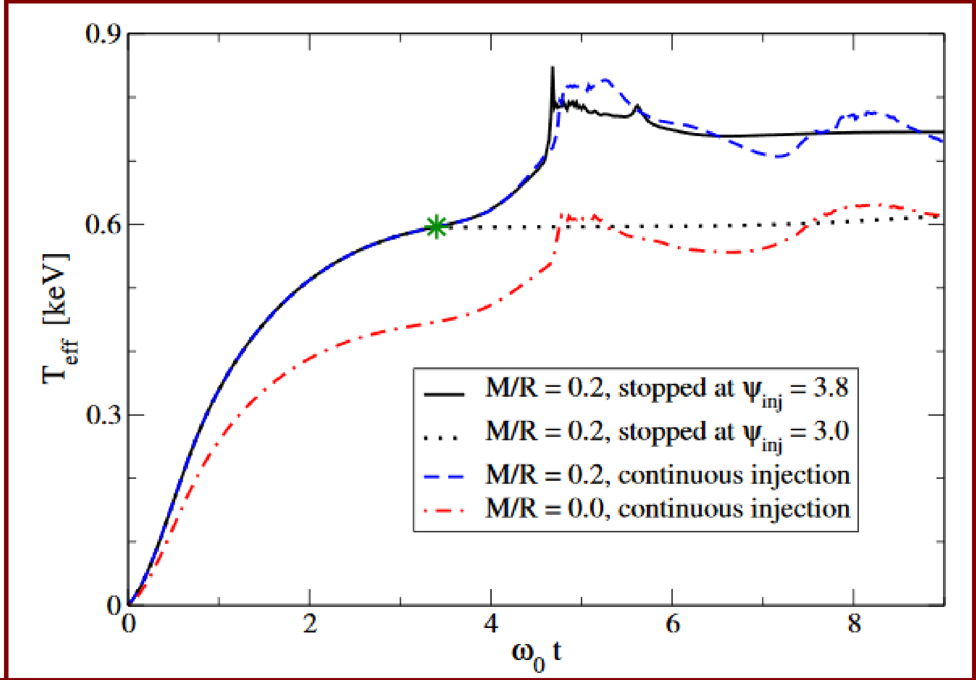
Energy in the twist: ~$I^2 R_{NS}/c^2$
Twist decay time ~1 yr for typical parms

1306.4335

Numerical simulation of the twist

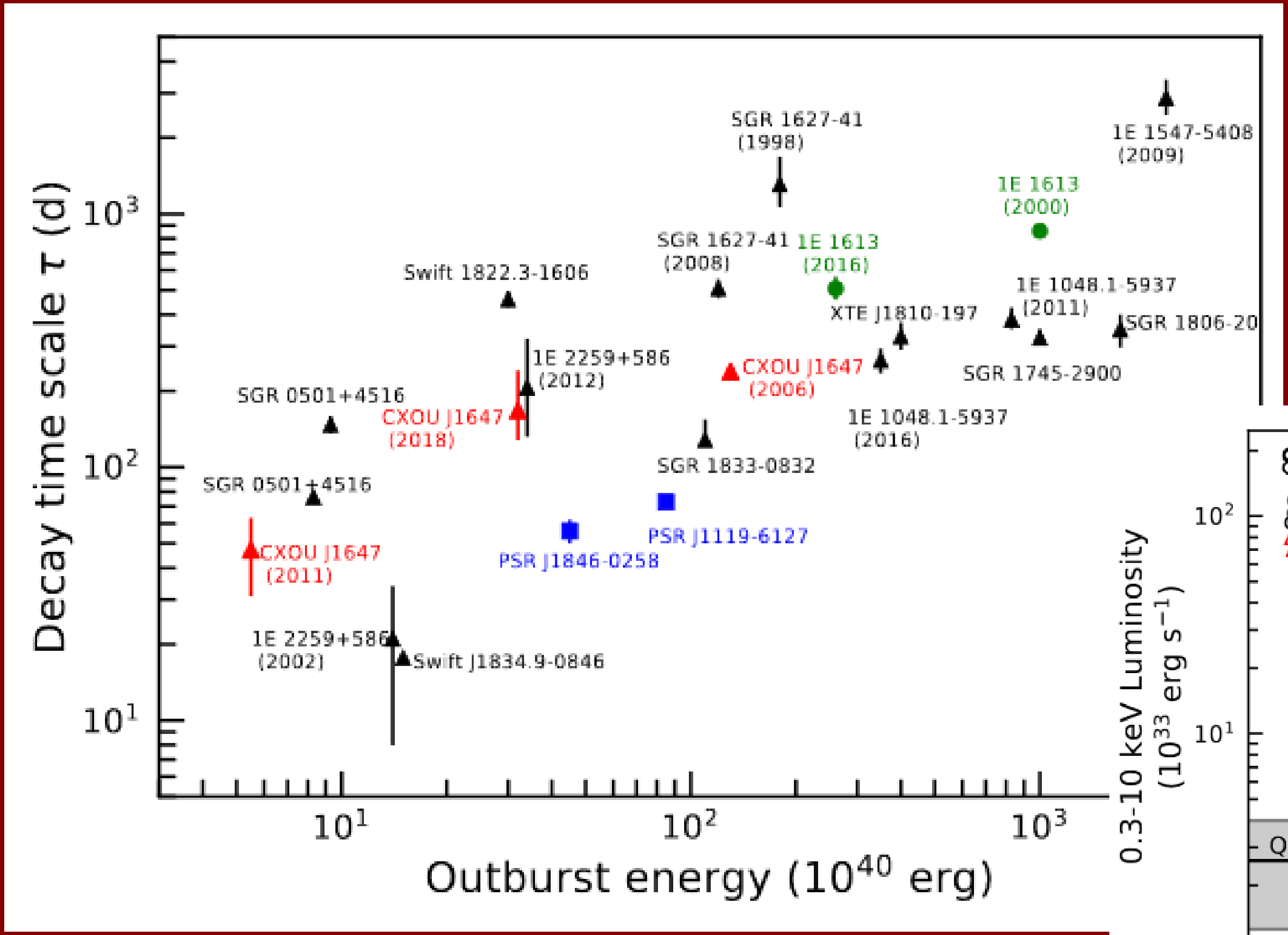


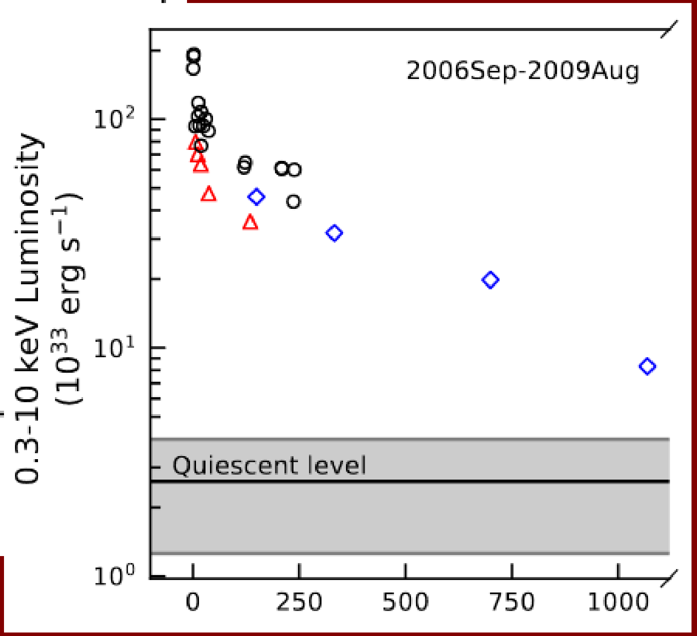




1901.08889

Outburst decay vs. released energy



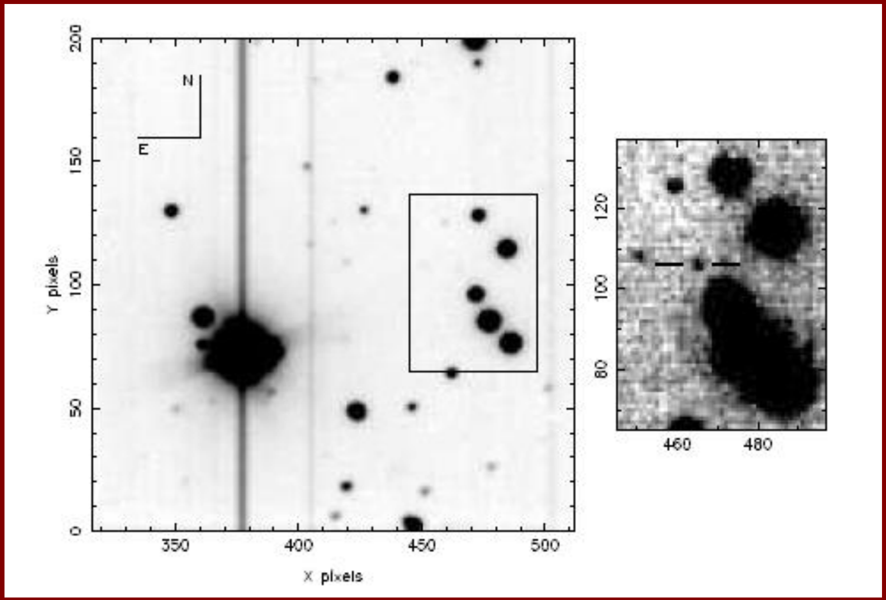


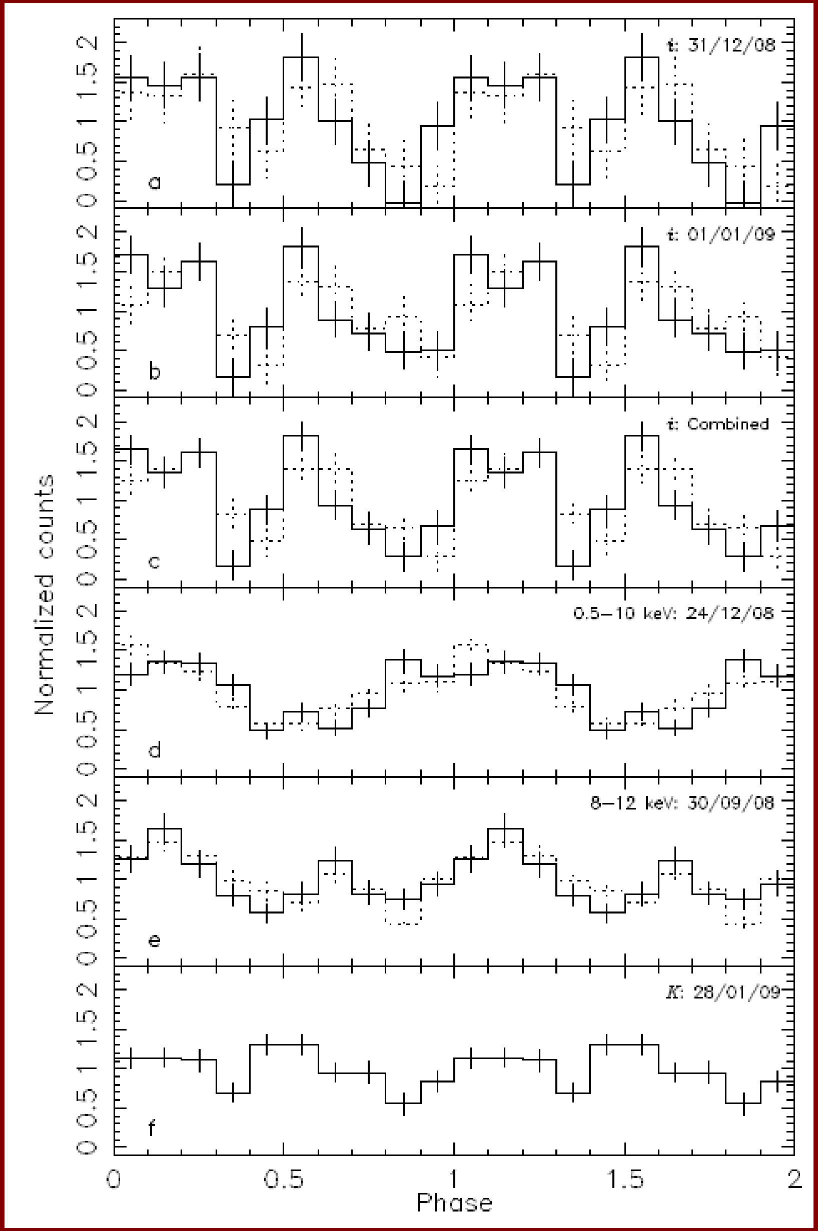
1901.02026

Optical pulsations

SGR 0501+4516
P=5.76 s
d=0.8 kpc – the closest!

4.2m William Herschel Telescope

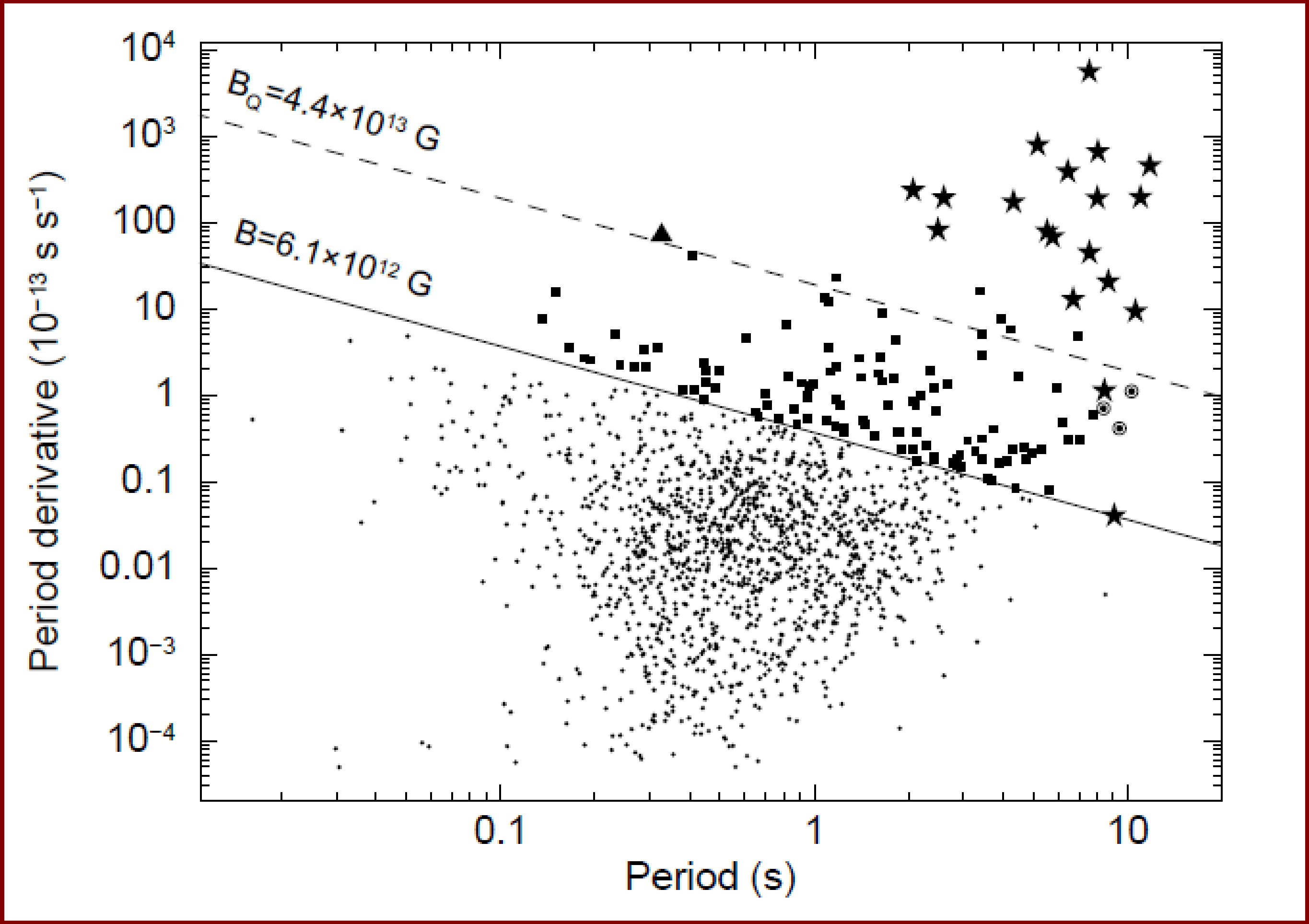




1106.1355

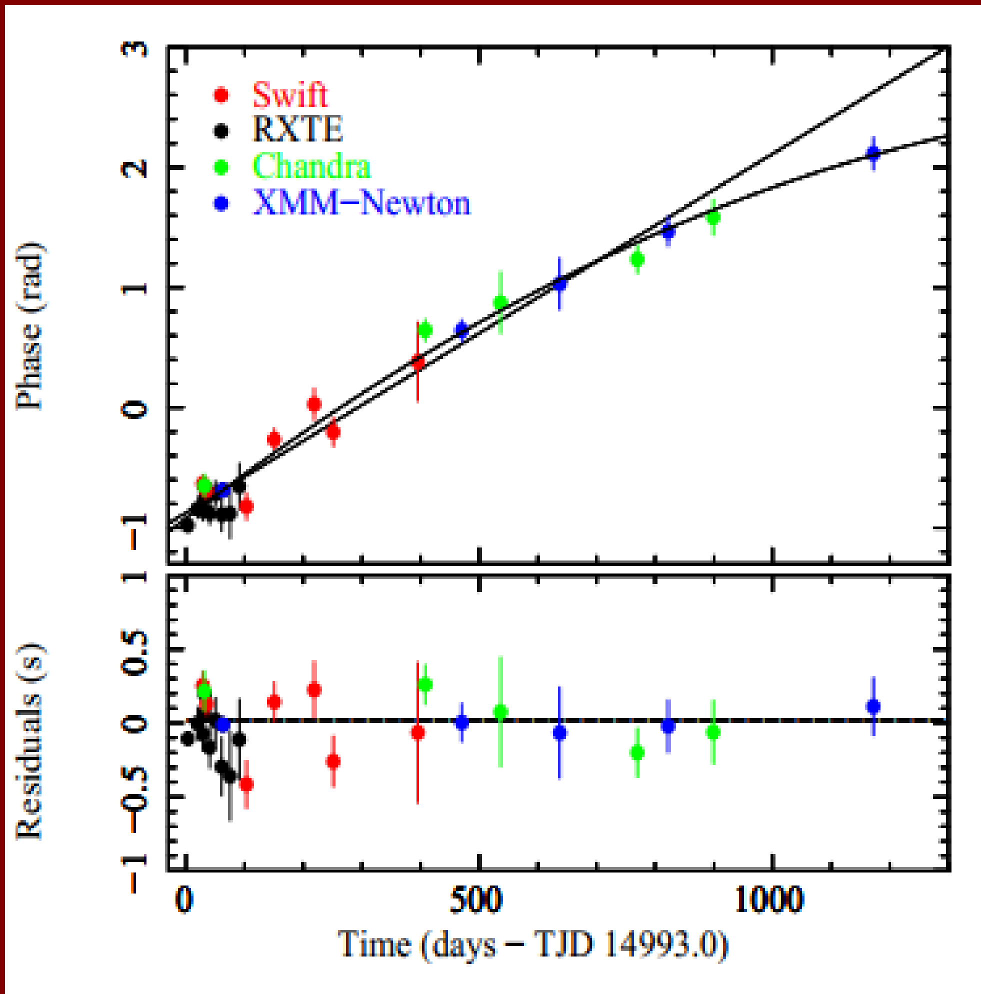
Low-field magnetars

SGR 0418+5729 and Swift J1822.3–160



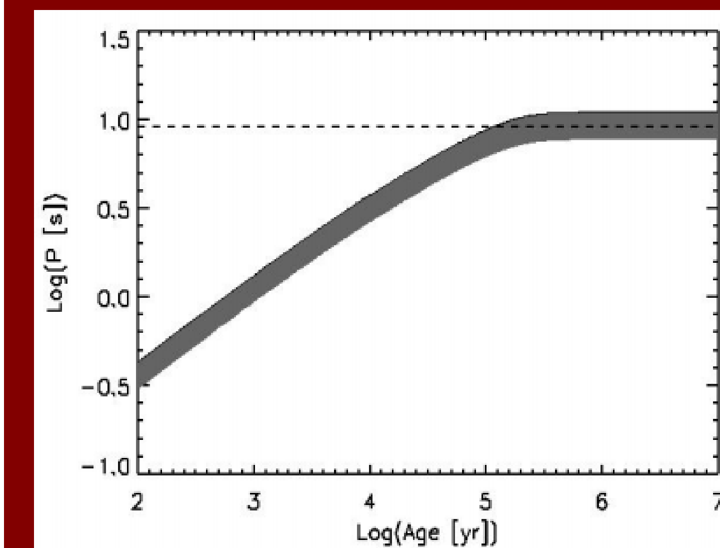
See a review in arXiv:1303.6052

The first low-field magnetar



Only after ~3 years of observations it was possible to detect spin-down.

The dipolar field is ~6 10^{12} G.

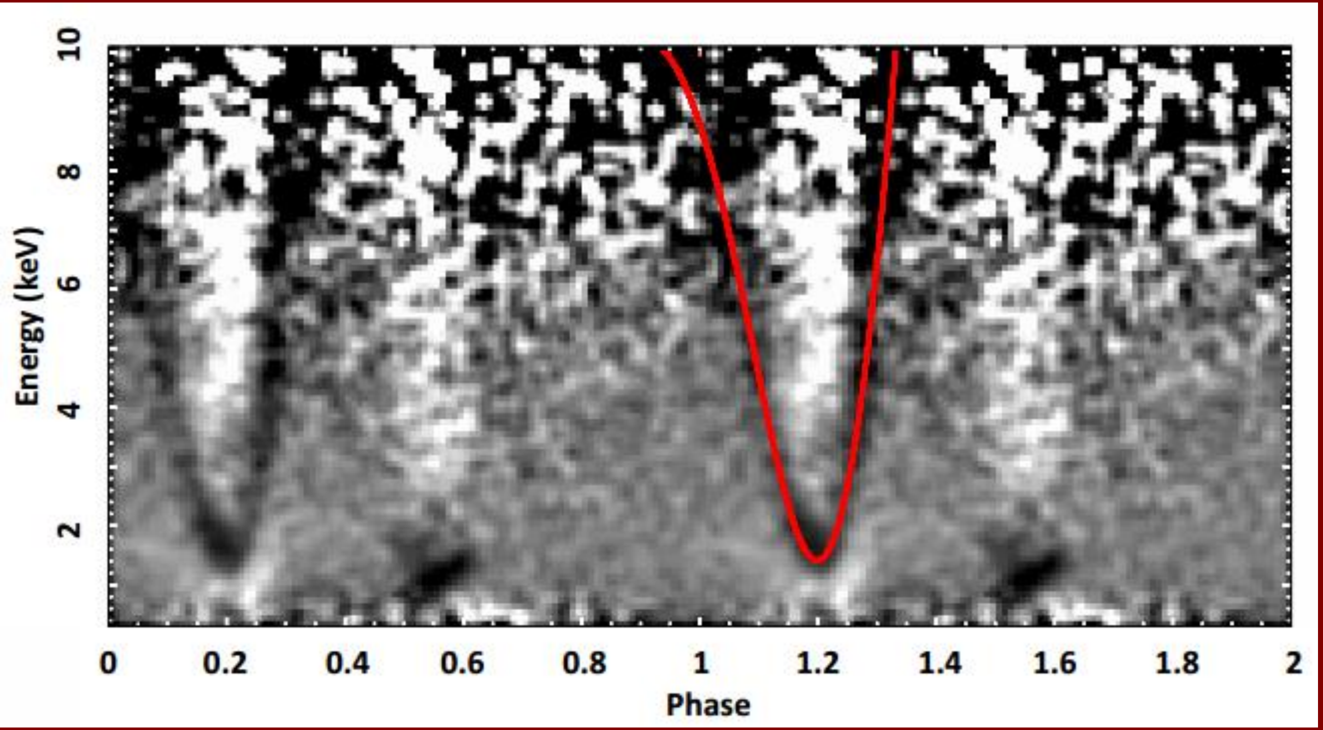


The dipolar field could decay, and activity is due to the toroidal field.

1303.5579

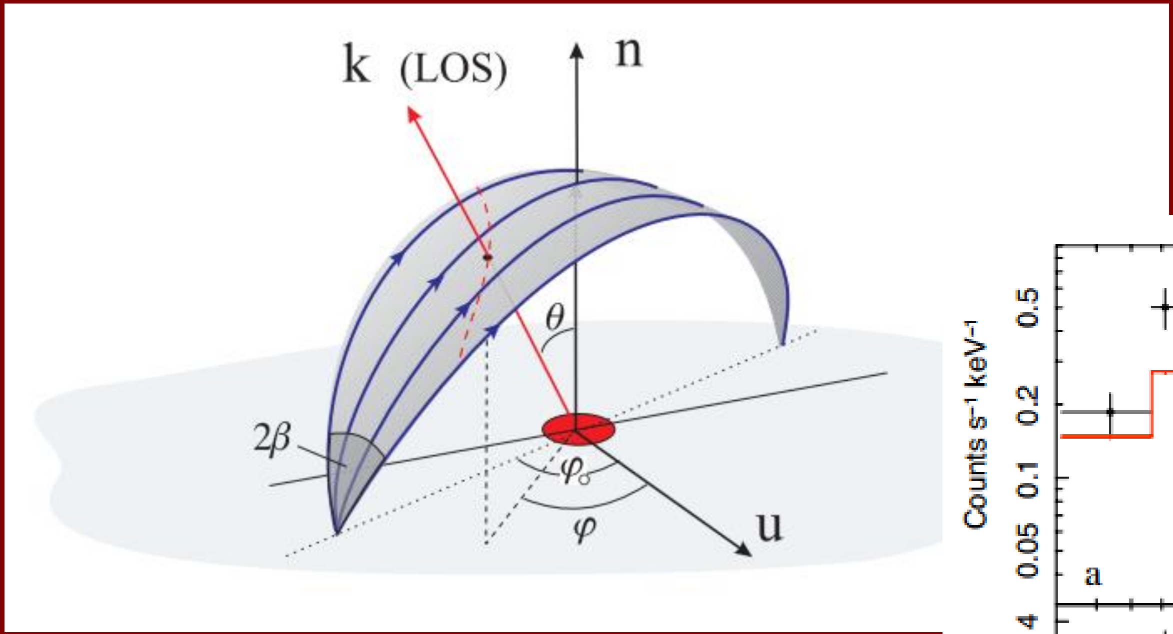
Large field (at last) ... But multipoles!

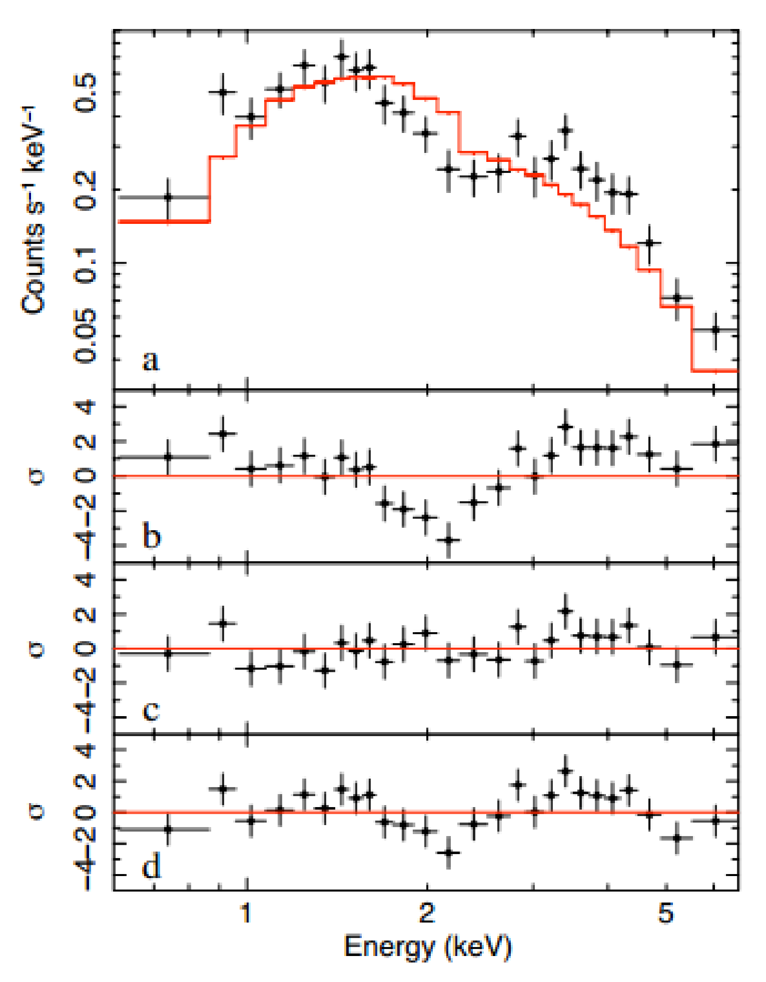
XMM-Newton observations allowed to detect a spectral line which is variable with phase.
If the line is interpreted as a proton cyclotron line,
then the field in the absorbing region is $2\ 10^{14} - 10^{15}$ G



1308.4987

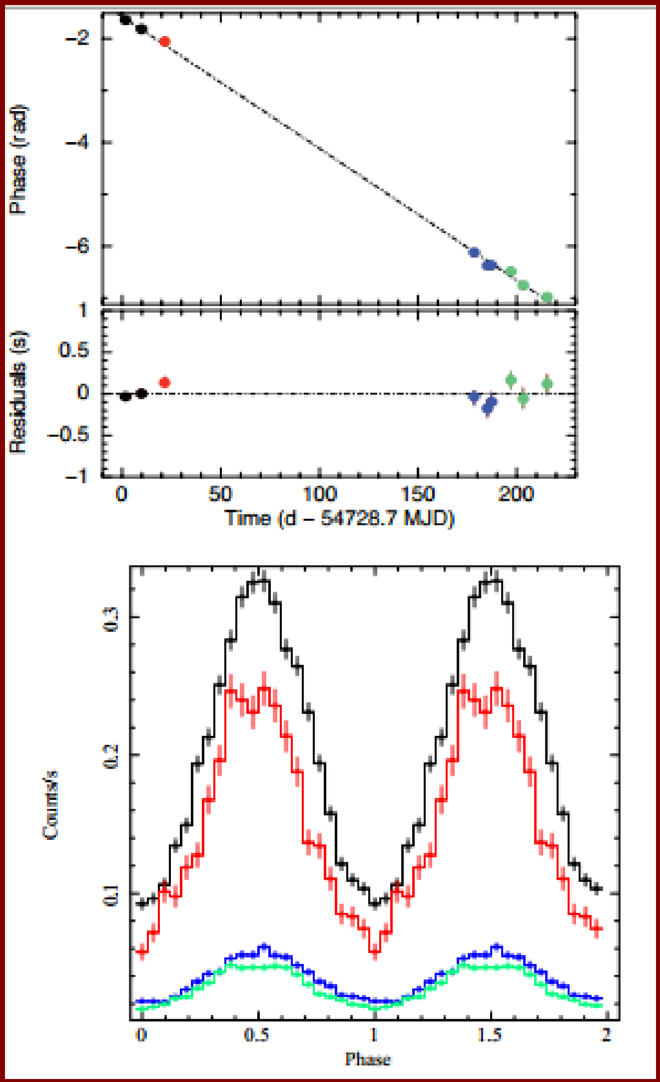
SGR 0418+5729


k (LOS)
n
θ
2β
φ₀
φ
u


Counts s⁻¹ keV⁻¹
0.5
0.2
0.1
0.05
a
b
c
d
σ
Energy (keV)
1
2
5

1308.4987

Another low-field magnetar

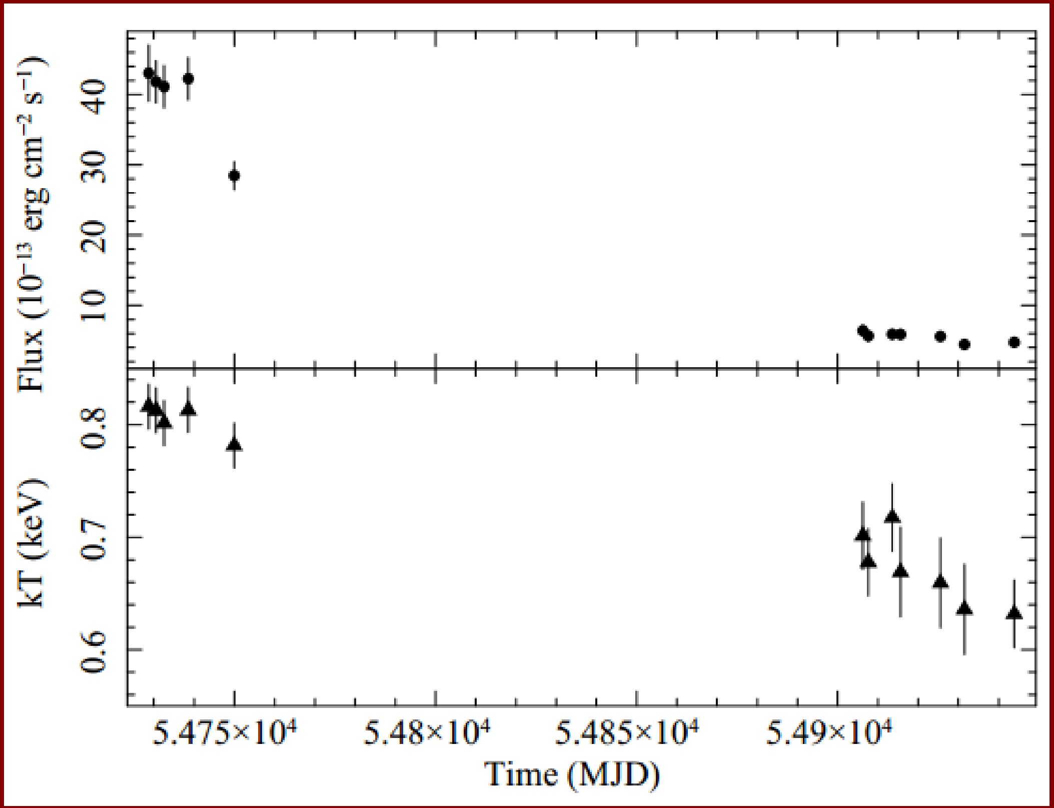


3XMM J185246.6+003317

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

B<4 10^{13} G

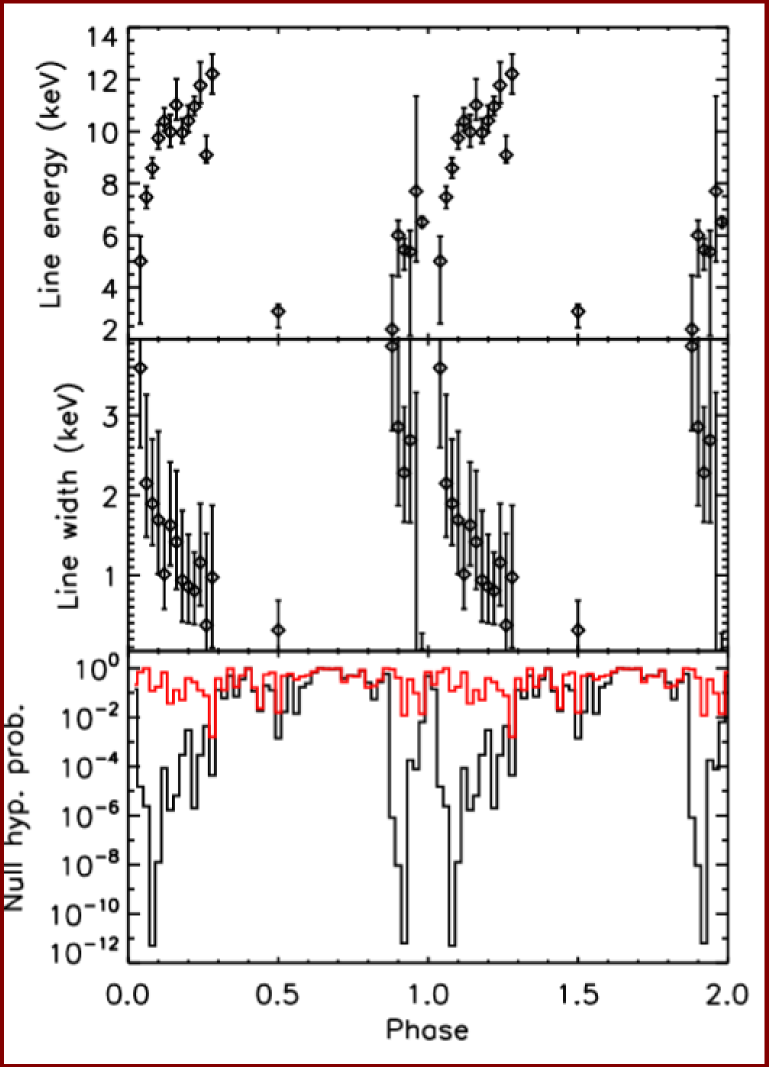
Transient magnetar



1311.3091

More lines in low-field magentars

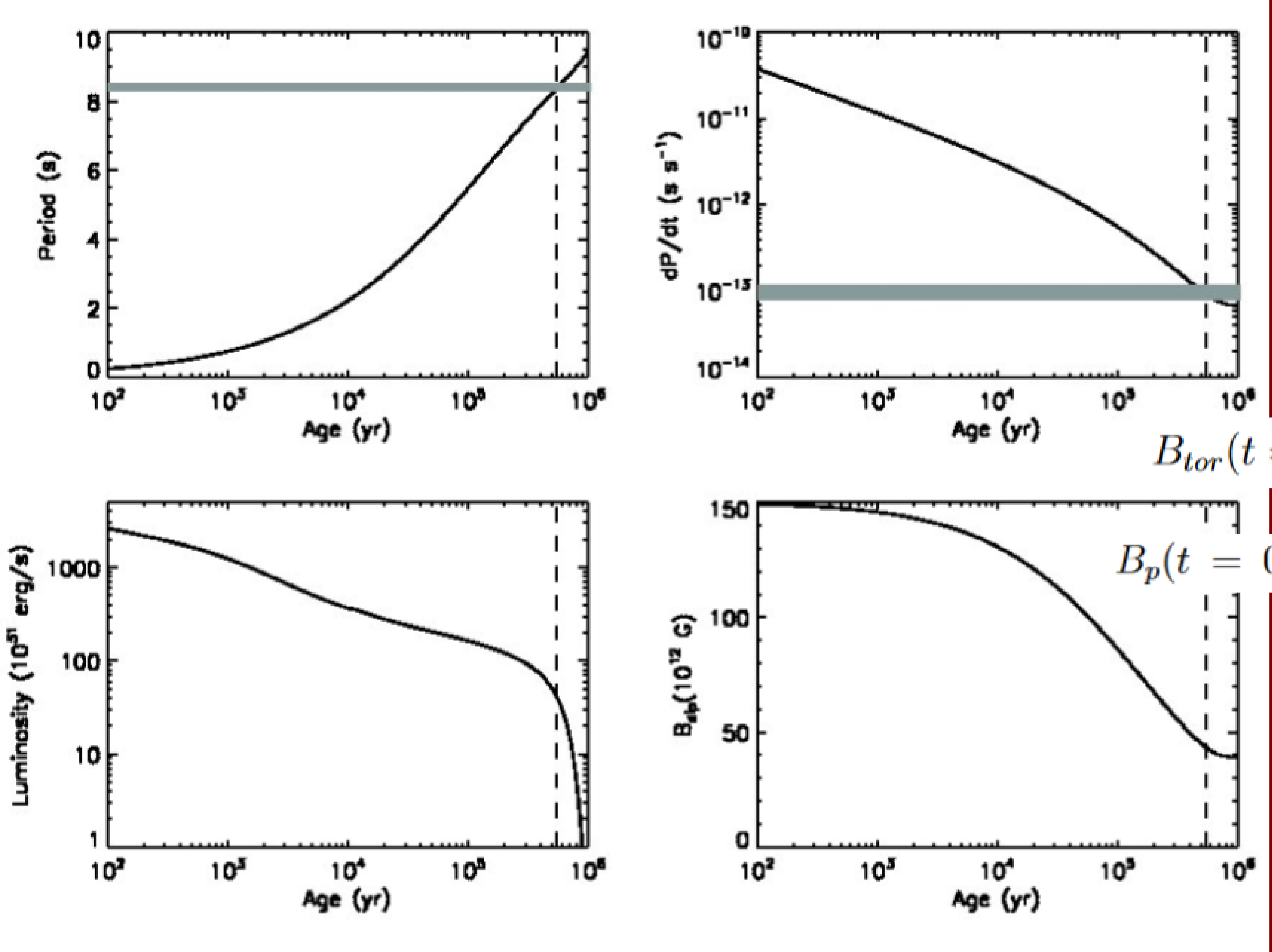
phase-dependent absorption line



SWIFT J1822.3-1606

1510.09157

Old evolved sources?



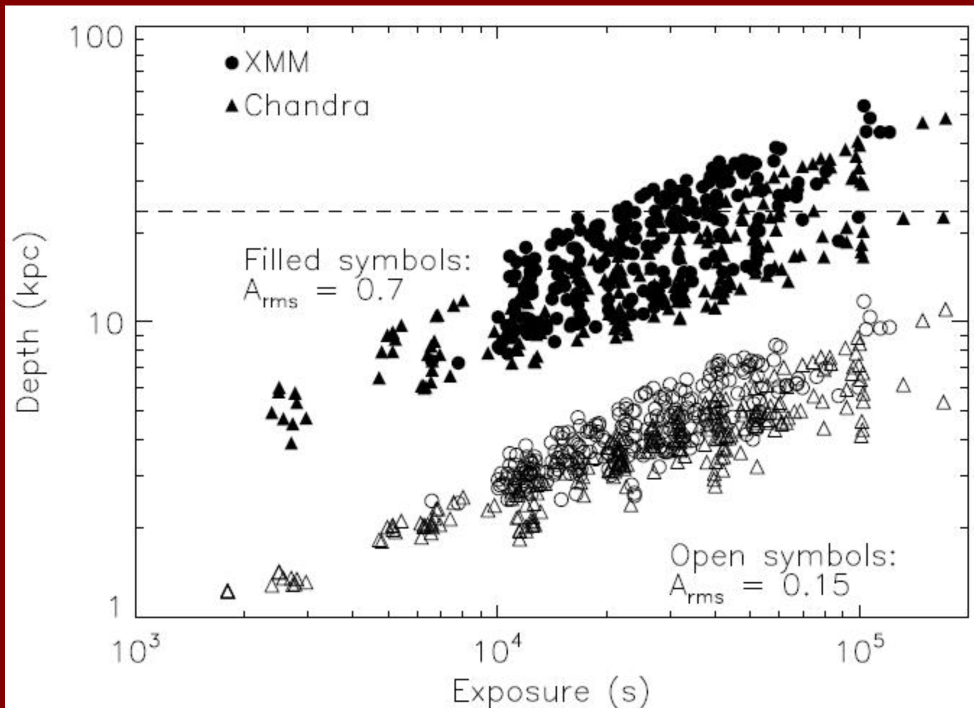
$B_{tor}(t=0) = 5\times10^{15}$ G

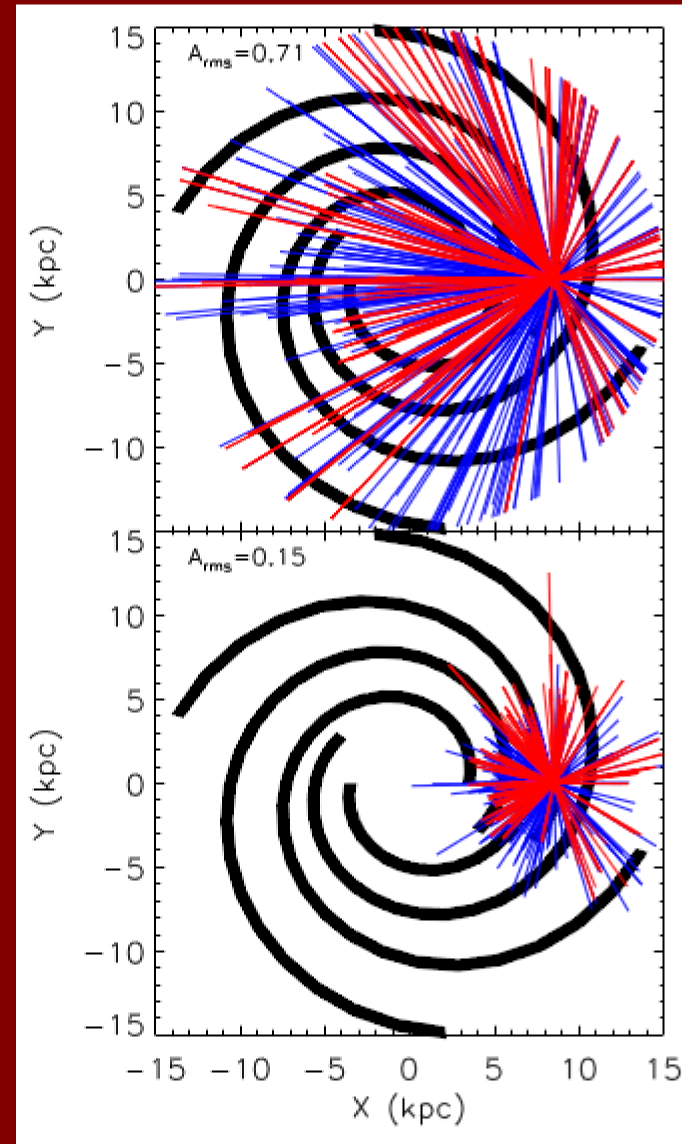
$B_p(t = 0) \sim 2 \times 10^{14}$ G,

Swift J1822.03–160

1507.02924

How many magnetars?





<540 barely-detectable (L=3 10^{33} A_{rms}=15%)
59^{+92}_{-32} easily detectable (L=10^{35} A_{rms}=70%)

Muno et al. arXiv: 0711.0988

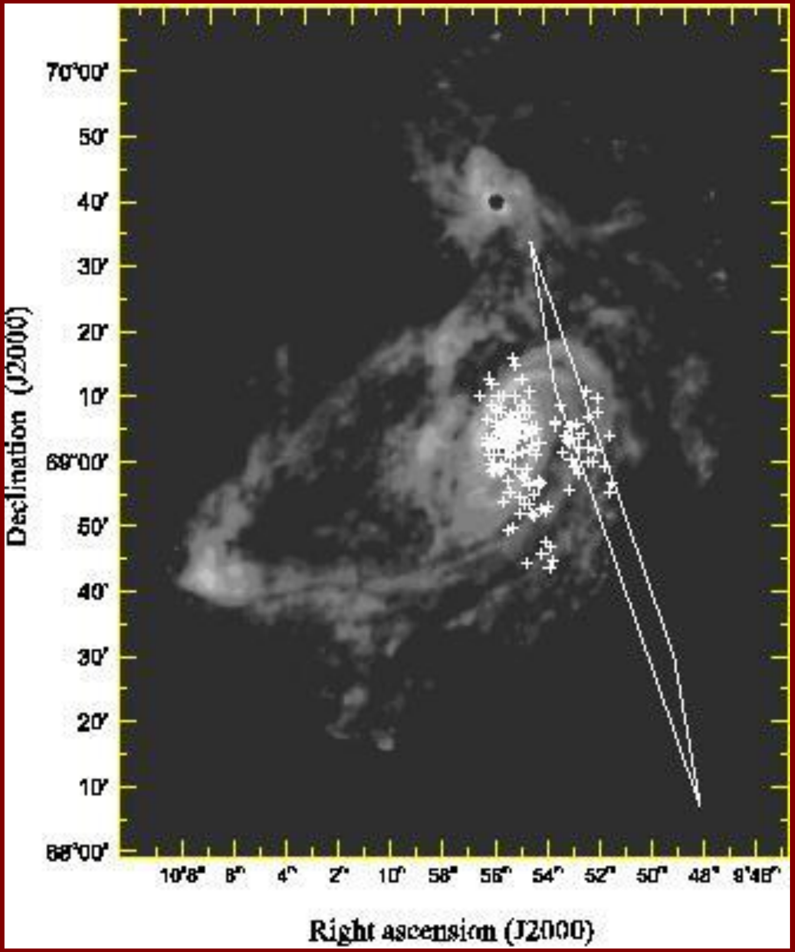
Extragalactic giant flares

Initial enthusiasm that most of short GRBs can be explained as giant flares of extraG SGRs disappeared.

At the moment, we have a definite deficit of extraG SGR bursts, especially in the direction of Virgo cluster
(Popov, Stern 2006; Lazzatti et al. 2006).

However, there are several good candidates.

Extragalactic SGRs



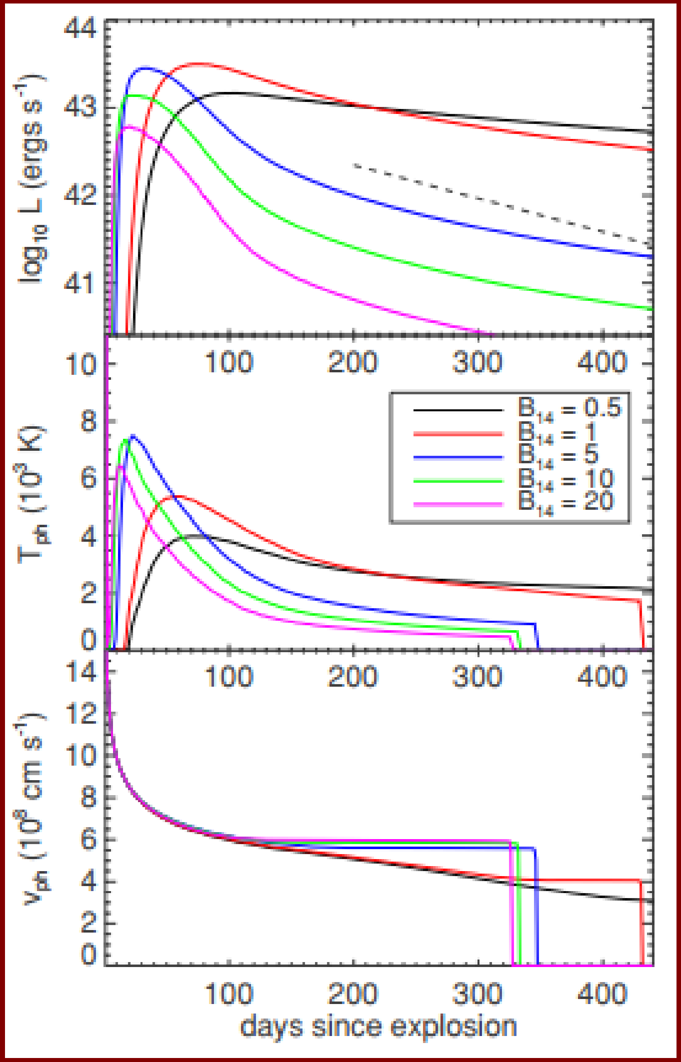
It was suggested long ago (Mazets et al. 1982) that present-day detectors could alredy detect giant flares from extragalactic magnetars.

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

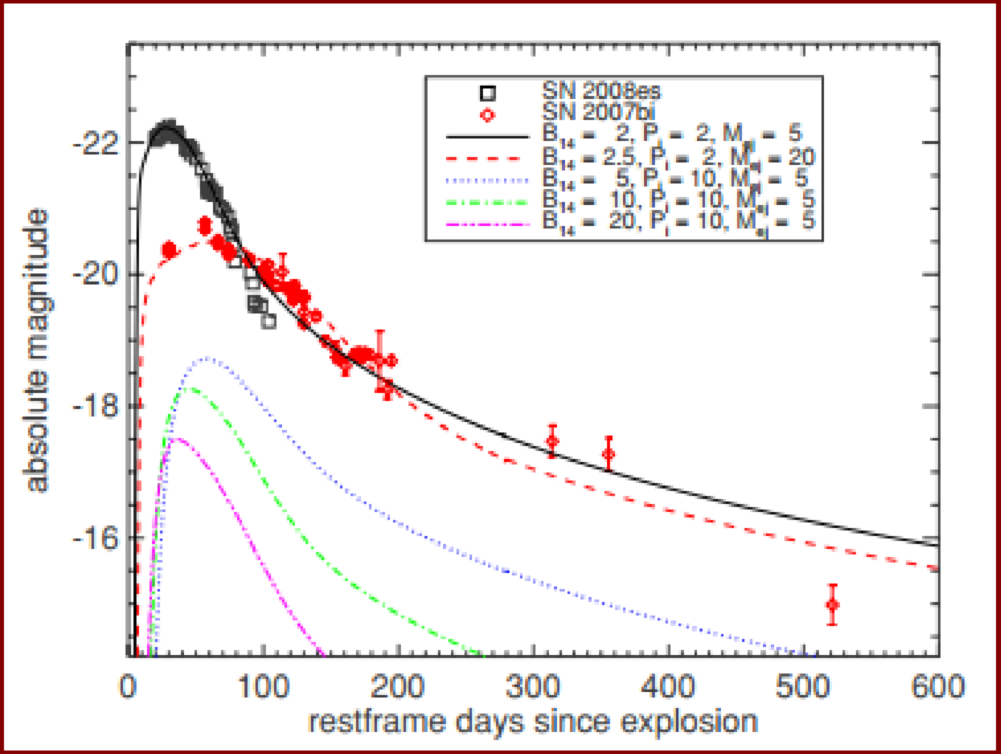
Finally, recently several good candidates have been proposed by different groups (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider ....).

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

Magnetars and supernovae



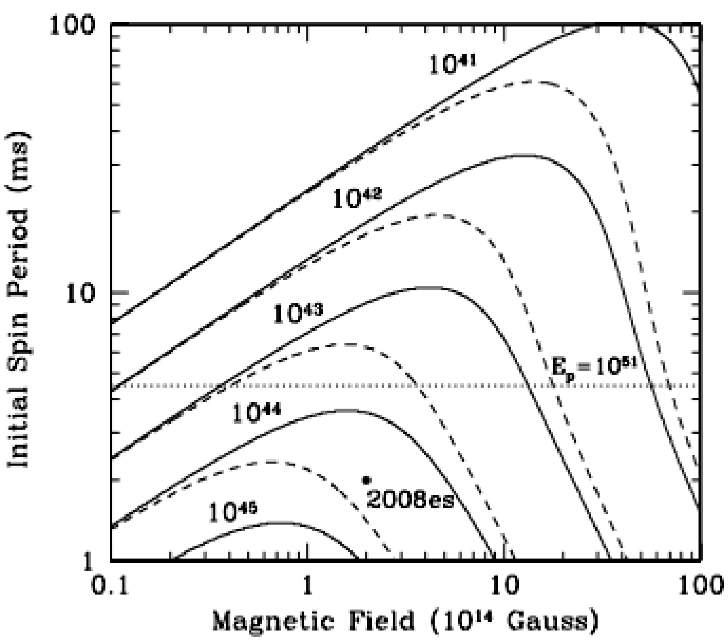
With large field and short spin a newborn NS can contribute a lot to the luminosity of a SN.

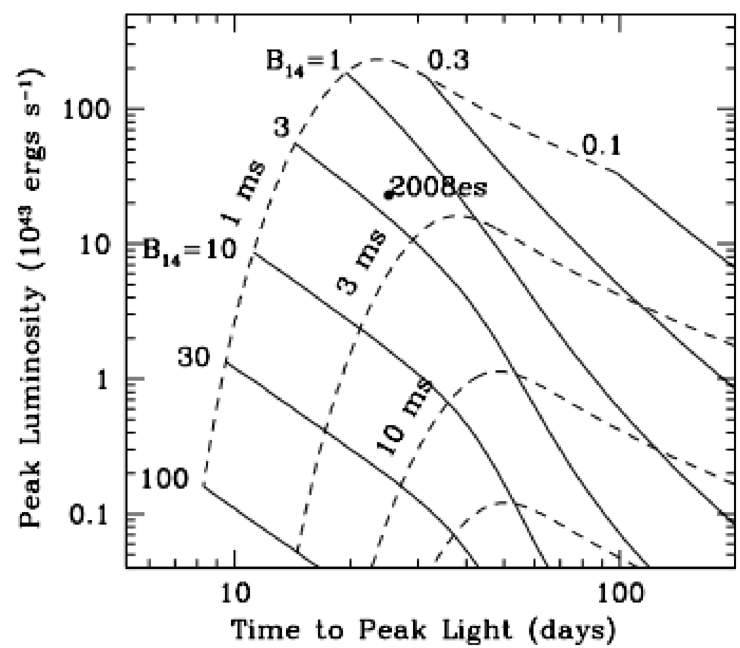


KASEN & BILDSTEN (2010)

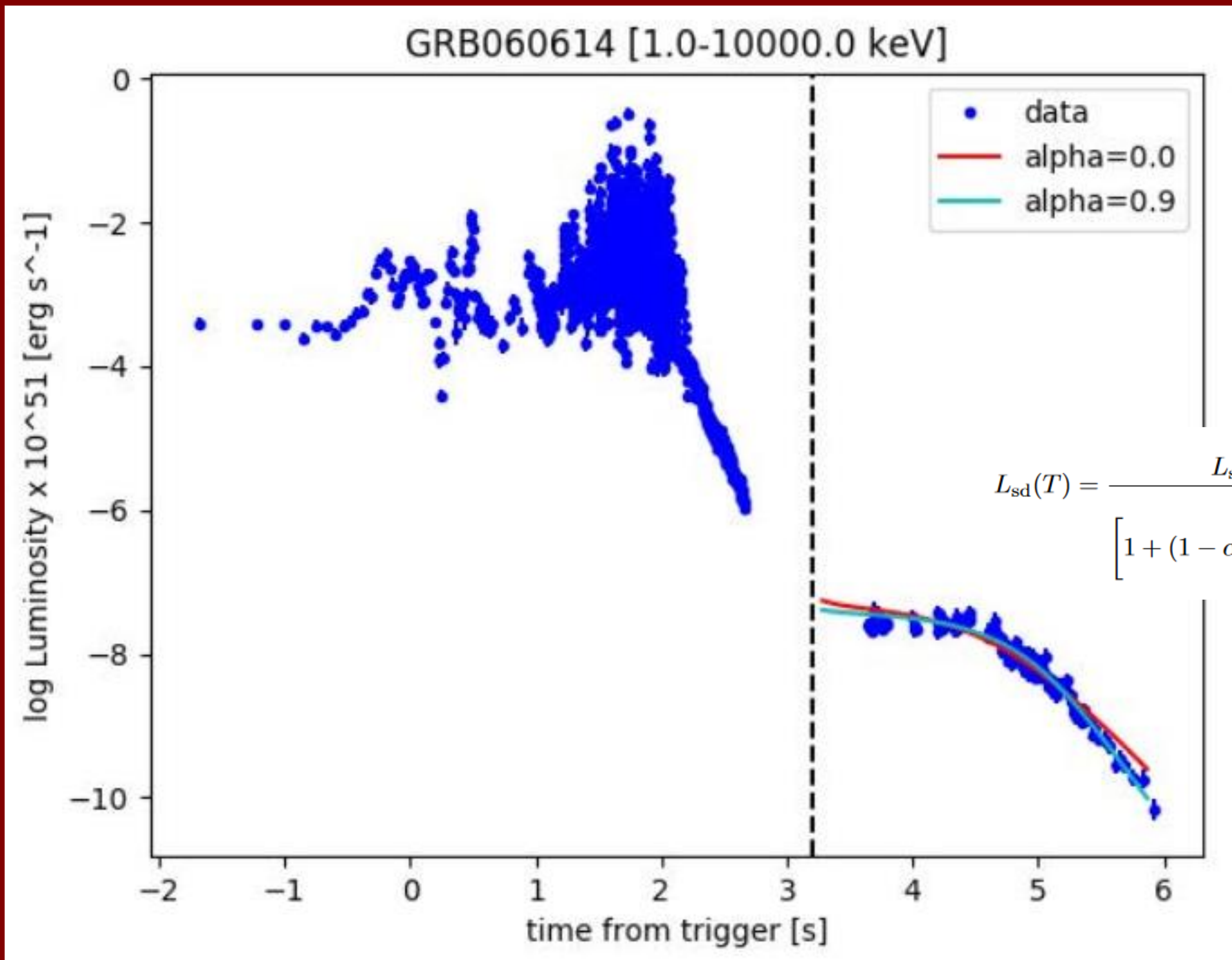
Parameters needed

For short initial spin periods it is not even necessary to have magnetar scale B.





Magnetars and GRBs



$$L_{\rm sd} = \frac{\mu^2}{c^3}\,\Omega^4\left(1+\sin^2\theta\right)$$

$$L_{\rm sd}^{\rm (N-I)} = L_{\rm sd}\left(\frac{\Omega}{\Omega_i}\right)^{-2\alpha}$$

$$n = 3 - 2\alpha.$$

$$L_{\rm sd}(T) = \frac{L_{\rm sd,i}}{\left[1+(1-\alpha)\dfrac{T}{\tau_i}\right]^{\frac{2-\alpha}{1-\alpha}}} = \frac{E_{\rm spin,i}}{\tau_i\left[1+(1-\alpha)\dfrac{T}{\tau_i}\right]^{\frac{2-\alpha}{1-\alpha}}},$$

1804.08652

What is special about magnetars?

Link with massive stars

There are reasons to suspect that magnetars are connected to massive stars (astro-ph/0611589, but see 1708.01626).

Link to binary stars

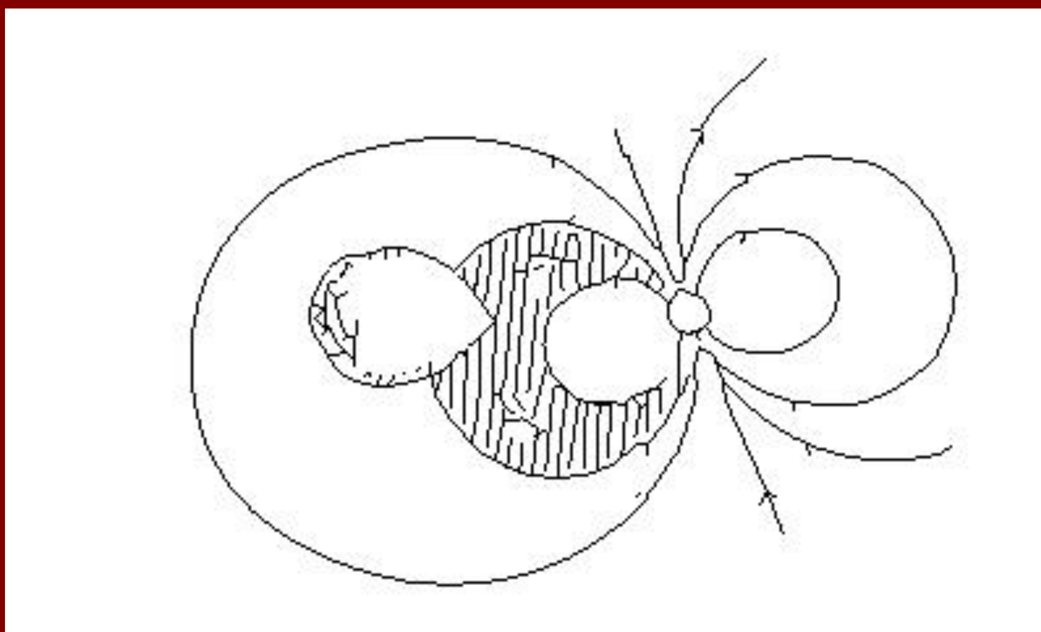
There is a hypothesis that magnetars are formed in close binary systems (astro-ph/0505406, 0905.3238).

The question is still on the list.

AXP in Westerlund 1 most probably has a very massive progenitor >40 Msolar.

Are there magnetars in binaries?

At the moment all known SGRs and AXPs are isolated objects.
About 10% of NSs are expected to be in binaries.
The fact that all known magnetars are isolated can be related to their origin, but this is unclear.



If a magnetar appears in a very close binary system, then an analogue of a *polar* can be formed.
The secondary star is inside the huge magnetosphere of a magnetar.
This can lead to interesting observational manifestations.

Magnetor

arXiv:0803.1373

Few candidates have been proposed based on long spin periods and large Pdots:
1203.1490, 1208.4487, 1210.7680, 1303.5507

Conclusions

- Two classes of magnetars: SGRs and AXPs
- Similar properties (but no giant flare in AXPs, yet?)
- Hyperflares (27 Dec 2004)
- Transient magnetars
- About 10% of newborn NSs
- Links to PSRs (and others?)
- Twisted magnetospheres

Papers to read

- Woods, Thompson astro-ph/0406133 – old classical review
- Mereghetti arXiv: 0804.0250
- Rea, Esposito arXiv: 1101.4472 - bursts
- Turolla, Esposito arXiv: 1303.6052 - Low-field magnetars
- Mereghetti et al. arXiv: 1503.06313
- Turolla, Zane, Watts arXiv: 1507.02924 – Big general review
- Beloborodov, Kaspi arXiv: 1703.00068
- Esposito et al. arXiv: 1803.05716
- Coti Zelati et al. arXiv: 1710.04671 – outbursts
- Gourgouliatos, Esposito 1805.01680 – magnetic fields