Magnetic dipole moment of SGRs and AXPs as white dwarf pulsars

Manuel Malheiro and Jaziel G. Coelho

INSTITUTO TECNOLÓGICO DE AERONÁUTICA – ITA

Brazil

I- SGRs and AXPs: Unusual X-Ray Pulsars

• Soft Gamma Repeaters (SGR) and Anomalus X-Ray Pulsars (AXP) are very slow rotating pulsars: long Periods $P \sim (2 - 11)$ s. Periods in a narrow range comparing to ordinary pulsars $P \sim (0.001 - 1)$ s .

• Spin-down rates $dP/dt \sim (10^{-13} - 10^{-10})$ s larger than normal pulsar $(10^{-15} - 10^{-14})$ s .

• Isolated stars and only 18 confirmed (9 SGRs and 11 AXPs) comparing with more than 2000 pulsars known.

• Strong outburst of energies $\sim (10^{41} - 10^{43})$ erg .
  SGRs, giant flares of even large energies $\sim (10^{44} - 10^{47})$ erg.

- High X-ray luminosities Lx ~ (10^{32} – 10^{36}) erg/s >> spin-down rotational energy rate (seen as neutron star pulsars).

- A reservoir of energy to explain the X-ray Luminosity : ultra-strong magnetic fields in the interior and at the surface of the star B ~ (10^{14} -10^{15}) G .

- MAGNETARS - Magnetic-powered X-Ray pulsars (seen as neutron stars).

- Hot Stars – T ~ (0.4 – 0.6) KeV , larger than 10^{6} K.

- Young Stars – spin-down ages (10^{3}-10^{5}) yr ; exception the new SGR 0418+5229 with 24 Myr.

SGRs

- Recurrent sources of soft gamma ray burst, short times t ~ 0.1 s and Energy E ~ 10^{41} erg/s .

- Occasionaly active episodes producing many short X-Ray bursts. lasting weeks or months, separated by quiescent phases of years or decades.

- Intermediate bursts   t ~ 1-40 s, higher energy E ~ (10^{43}-10^{47}) erg showing an Hard X-ray emission T ~ 100 KeV .

- Extremely rare: giant flares E ~ (10^{44}-10^{47}) erg (~ one at each 50 ys). Initial spike t < 0.1 s (Hard X-ray) with a long tail t > 500 s.

AXPs

- Similar to SGR but weaker in intensity. No giant flares.

- No recurrent gamma ray bursts.

McGill catalogue of SGRs&AXPs

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

Recent Review S. Meregheti, Astron. Astrophys. Rev.,15, 255(2008)

Hard and soft short Bursts of SGR 1806-20
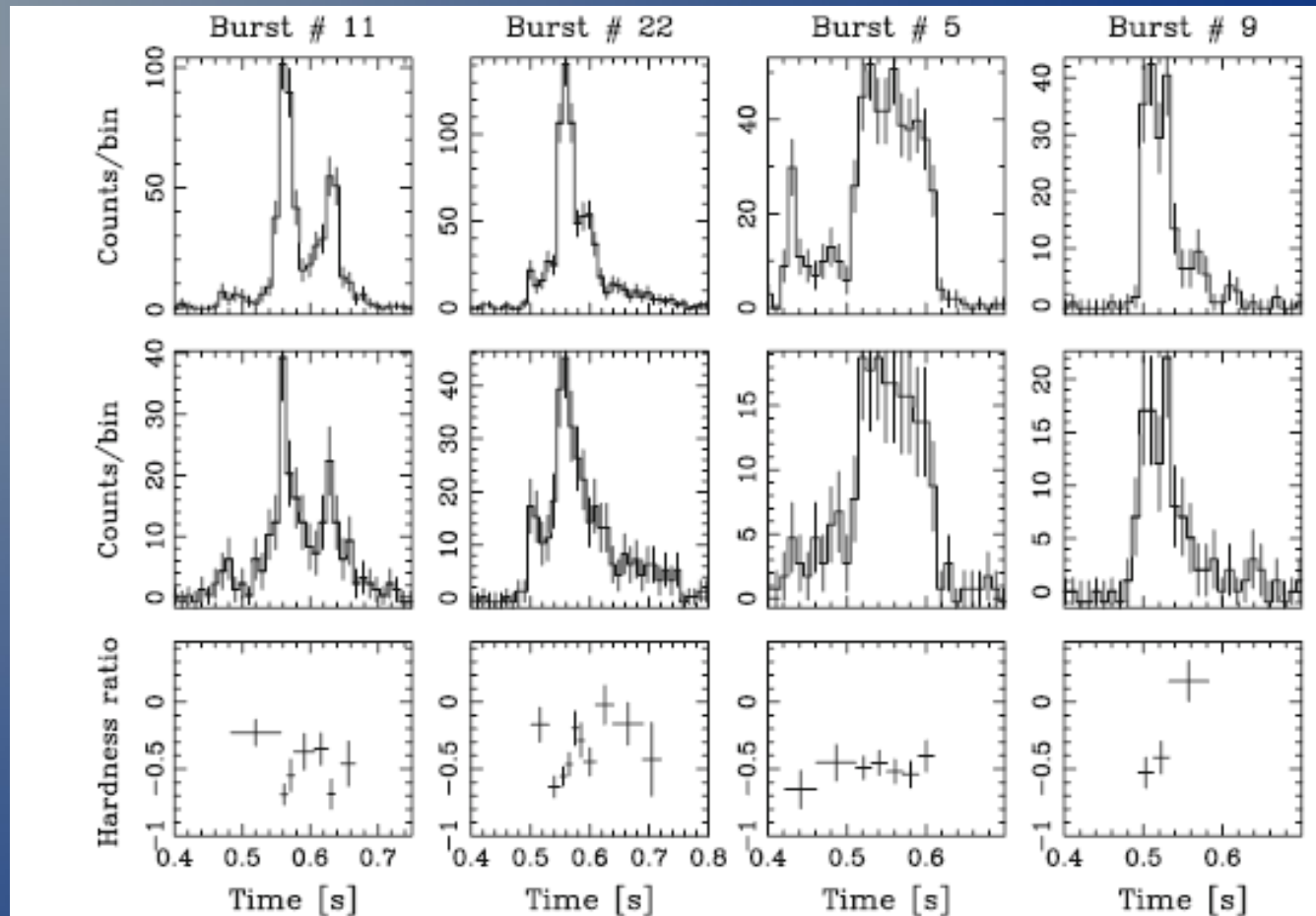

Fig. 5 Short bursts from SGR 1806−20 observed with the IBIS instrument on board INTEGRAL (from Götz et al. 2004). *Top panels* light curves in the soft energy range $S = 15$–40 keV. *Middle panels* light curves in the hard energy range $H = 40$–100 keV. *Bottom panel* hardness ratios, defined as $(H − S)/(H + S)$, showing that spectral evolution is present in some burst
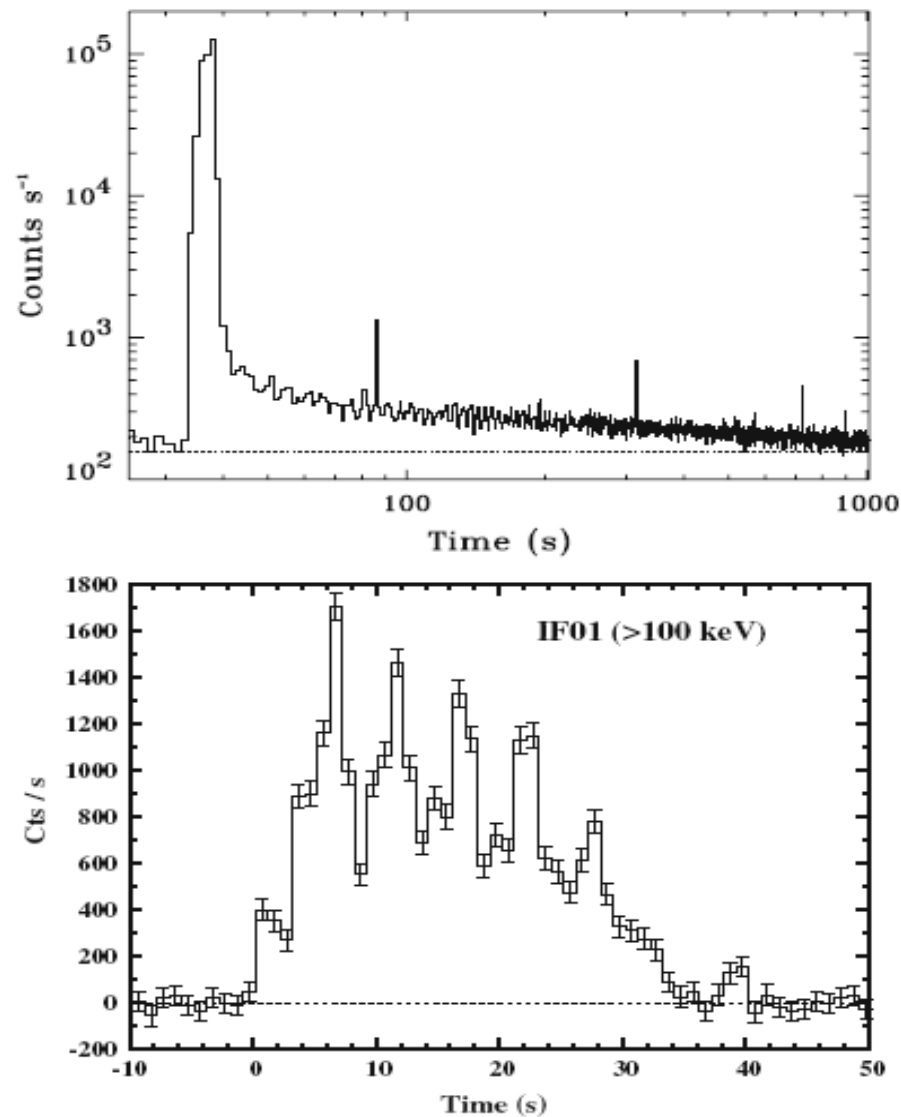
Two intermediate bursts of SGR 1900+14

Fig. 9 Light curves of two intermediate flares from SGR 1900+14. *Top panel* August 29, 1998 (RXTE, 2–90 keV, from Ibrahim et al. (2001)). *Bottom panel* April 18, 2001 (BeppoSAX GRBM, from Guidorzi et al. 2004)

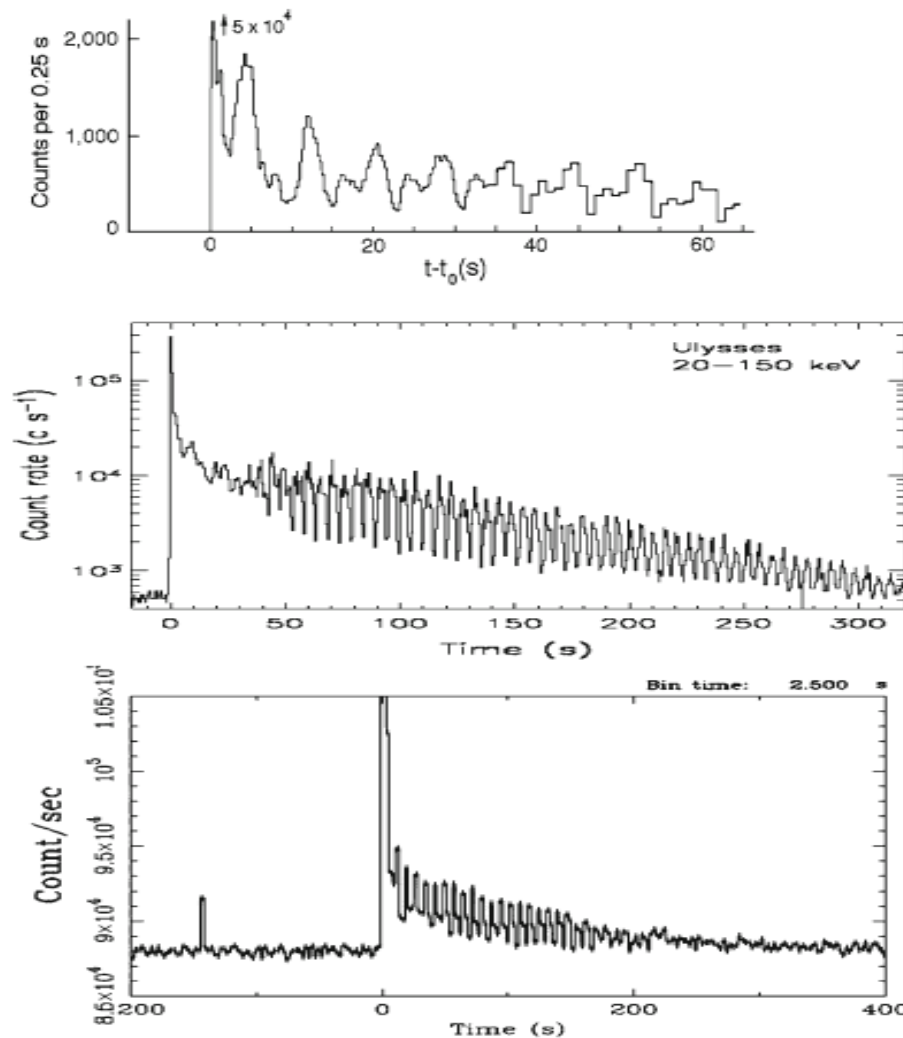# Three giant flares: SGR 0526-66, SGR 1900+14, and SGR 1806-20

**Fig. 7** Light curves of the three giant flares from SGRs. *Top panel* SGR 0526–66 (Venera data in the 50–150 keV range, from Mazets et al. 1982), *middle panel* SGR 1900+14 (Ulysses data in the 20–150 keV range, courtesy K. Hurley), *bottom panel* SGR 1806–20 (INTEGRAL SPI/ACS at $E > 80$ keV, from Mereghetti et al. 2005). The initial peaks of the flares for SGR 0526–66 and SGR 1806–20 are out of the vertical scale

Table 2 Comparison of the three giant flares from SGRs

Source	SGR 0526−66	SGR 1900+14	SGR 1806−20
Date	March 5, 1979	August 27, 1998	December 27, 2004
Assumed distance (kpc)	55	15	15
Initial spike			
Duration (s)	∼0.25	∼0.35	∼0.5
Peak luminosity (erg s^{-1})	3.6×10^{44}	$> 8.3 \times 10^{44}$	$(2 \div 5) \times 10^{47}$
Fluence (erg cm^{-2})	4.5×10^{-4}	$> 1.2 \times 10^{-2}$	$0.6 \div 2$
Isotropic energy (erg)	1.6×10^{44}	$> 1.5 \times 10^{44}$	$(1.6 \div 5) \times 10^{46}$
Pulsating tail			
Duration (s)	∼200	∼400	∼380
Fluence (erg cm^{-2})	1×10^{-3}	9.4×10^{-3}	5×10^{-3}
Isotropic energy (erg)	3.6×10^{44}	1.2×10^{44}	1.3×10^{44}
Spectrum	$kT \sim 30$ keV	$kT \sim 20$ keV	$kT \sim 15$–30 keV
Pulse period (s)	8.1	5.15	7.56
QPO frequencies (Hz)	43	28, 54, 84, 155	18, 30, 92.5, 150, 625, 1,840

From review of S. Meregheti, Astron. Astrophys. Rev. 15, 255 (2008)

- Magnetars differ from radio pulsars since their internal magnetic field is twisted up to 10 times the external dipole. At intervals, it can twist up the external field, stresses build up in the NS crust causing glitches, flares, and all sort of instabilities.

- The surface of a young magnetar (with age less than a few kyr) is so hot that it glows brightly in X-rays.

- The shifting magnetic field outside the star must drive electrical currents along arched magnetic field lines. The streaming charged particles inevitably impart energy to X-ray photons by scattering against them.

- Streaming charged particles also slam against the star reaching the footpoints of magnetic field lines, heating spots on the surface.
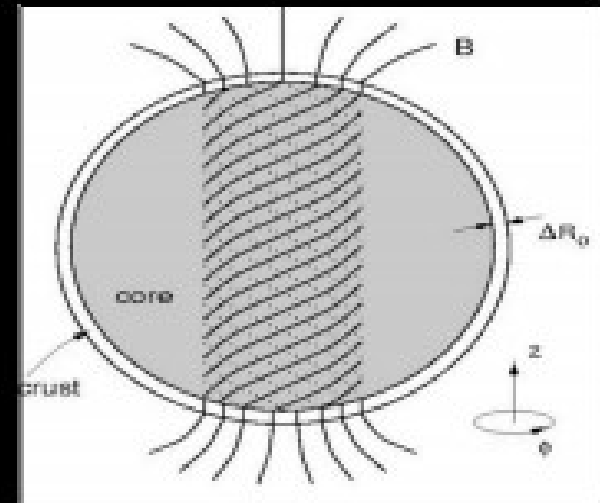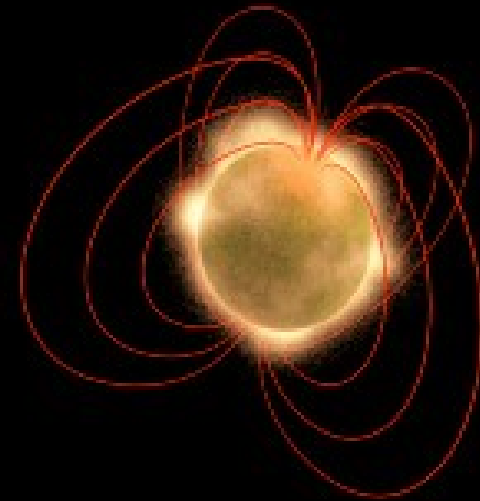
(Thompson & Duncan 1992; 1993; 1995;1996)

Nanda Rea ICE-CSIC

Magnetic instability!

The twisted magnetic lines stress the crust which is not able anymore to respond plastically, then it cracks. e+e- are created and trapped in a fireball (small or large depending on the crack). Depending on how baryon loaded the fireball is it will behave in different manners.

We see in fact flux and spectral changes correlated to the bursting activity, as well as glitches.

$$\oint B \cdot d\ell = \frac{4\pi}{c} I$$

(Thompson & Duncan 1992; 1993; 1995;1996)
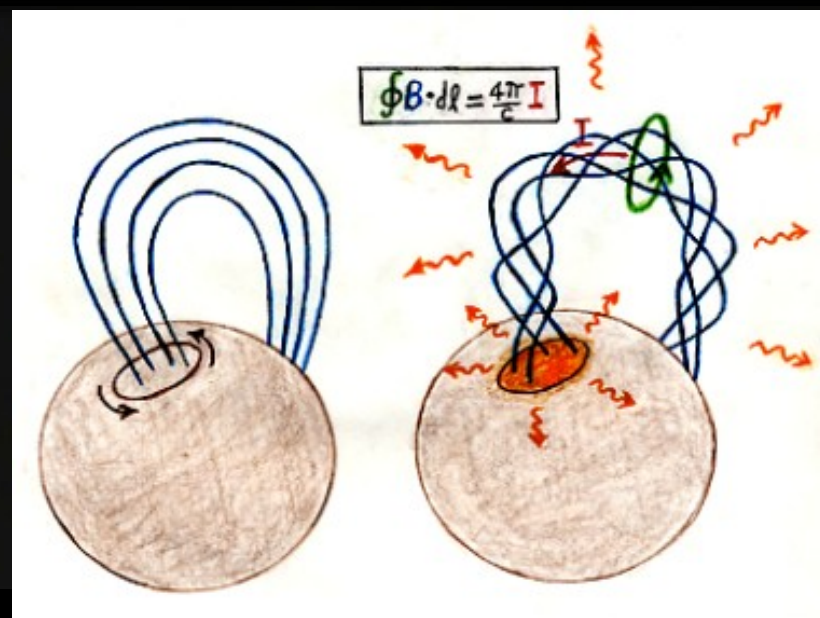
II - SGRs/AXPs AS FAST ROTATING - POWERED MAGNETIC WHITE DWARF PULSARS
(M. Malheiro, J. A. Rueda and R. Ruffini – PASJ 64, 56 2012)

In this new description several observational properties are easy understood and well explained as a consequence of the large radius of a massive white dwarf that manifests a new scale of mass density, moment of inertia and rotational energy:

I - The existence of stable WDs can explain, the range of long rotation periods ($2 \leq P \leq 12$ s) observed in SGRs and AXPs.

II - The long standing puzzle of the energetic balance of the SGRs/AXPs pulsars is solved: the steady X-ray luminosity L_x observed is smaller than the loss of rotational energy of the WD.

III - The large steady luminosity L_x seen of $L_x \sim 10^{35}$ erg/s, for so slow pulsars ($\Omega \sim 1$ Hz) is also understood, as a consequence of the large radius of the dense WD that produces a large magnetic dipole moment, in the range of the magnetic white dwarfs.

IV – The large dP/dt observed (10^{-10} - 10^{-13} s/s) are also consequence of the large WD magnetic dipole moment, as well of the large radius and the momentum of inertia, and not only of the magnetic field as it is the case for NS in the magnetar model.

II - The long standing puzzle of the energetic balance of the SGRs/AXPs pulsars is solved: the steady X-ray luminosity L_x observed is smaller than the loss of rotational energy of the WD.

III - The large steady luminosity L_x seen of $L_x \sim 10^{35}$ erg/s, for so slow pulsars ($\Omega \sim 1$ Hz) is also understood, as a consequence of the large radius of the dense WD that produces a large magnetic dipole moment, in the range of the magnetic white dwarfs.

IV – The large dP/dt observed (10^{-10} - 10^{-13} s/s) are also consequence of the large WD magnetic dipole moment, as well of the large radius and the momentum of inertia, and not only of the magnetic field as it is the case for NS in the magnetar model.

III – MAGNETAR x WHITE DWARF PHYSICAL SCALES

- Morini (1988) and Paczynski (1990) – Massive fast rotating highly magnetized white dwarf for 1E 2259+586 (AXP) at SNR G109.1-1.0   (period of P = 6.98 s).

- Kepler frequency $W_k = (G\,M/R^3)^{1/2} \sim (G\rho)^{1/2}$; $W < W_k$

  $P \sim 1$ s , the average density $\rho > 10^8$ g/cm^3 .

- Low density stars cannot spin fast .
  High density and massive white dwarfs: M= 1.4 M$_{sun}$ and

  maximal radius R ~ 3000Km = 3 × 10^2 R$_{NS}$.

- Momentum of Inertia I$_{NS}$ ~ M R^2 = 10^{45} g.cm^2

  I$_{WD}$ = 10^5 I$_{NS}$ = 1.26 × 10^{50} g.cm^2

Dipole magnetic moment

$$| \vec{m} | = \frac{B_p R^3}{2},$$

New scale of magnetic dipole moment

$$m = \left(\frac{3c^3 I}{8\pi^2} P\dot{P} \right)^{1/2}.$$

White Dwarf

$$m_{\mathrm{WD}} = 1.14 \times 10^{40} (P\dot{P})^{1/2} \mathrm{emu},$$

$$B_{\mathrm{WD}} = 4.21 \times 10^{14} (P\dot{P})^{1/2} \mathrm{G}.$$
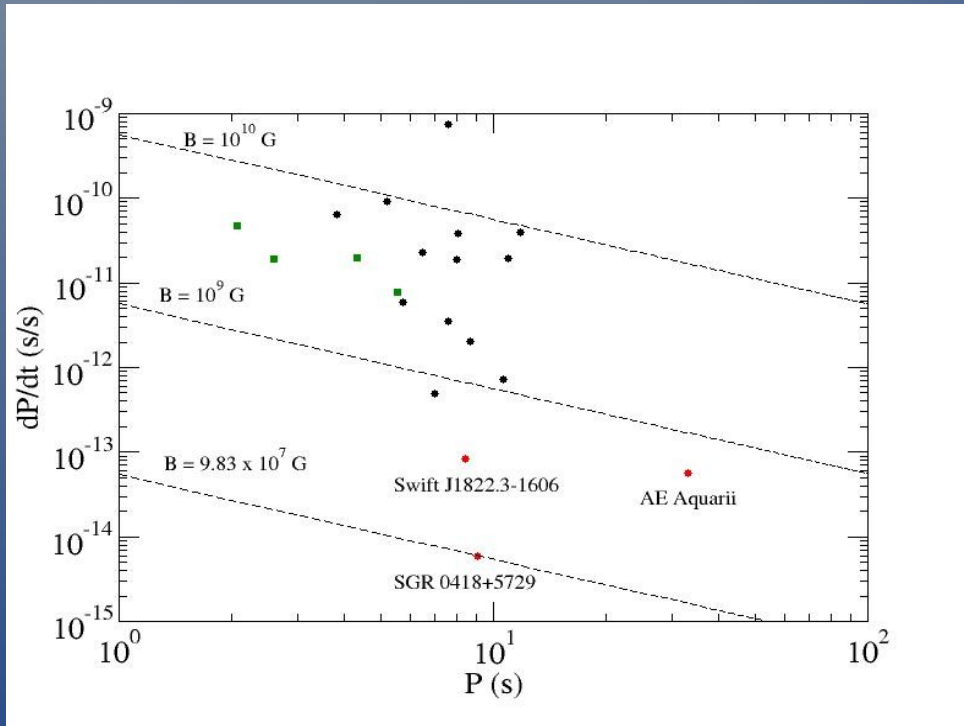
Magnetar

$$m_{\mathrm{NS}} = 3.2 \times 10^{37} (P\dot{P})^{1/2} \mathrm{emu},$$

$$B_{\mathrm{NS}} = 3.2 \times 10^{19} (P\dot{P})^{1/2} \mathrm{G}.$$
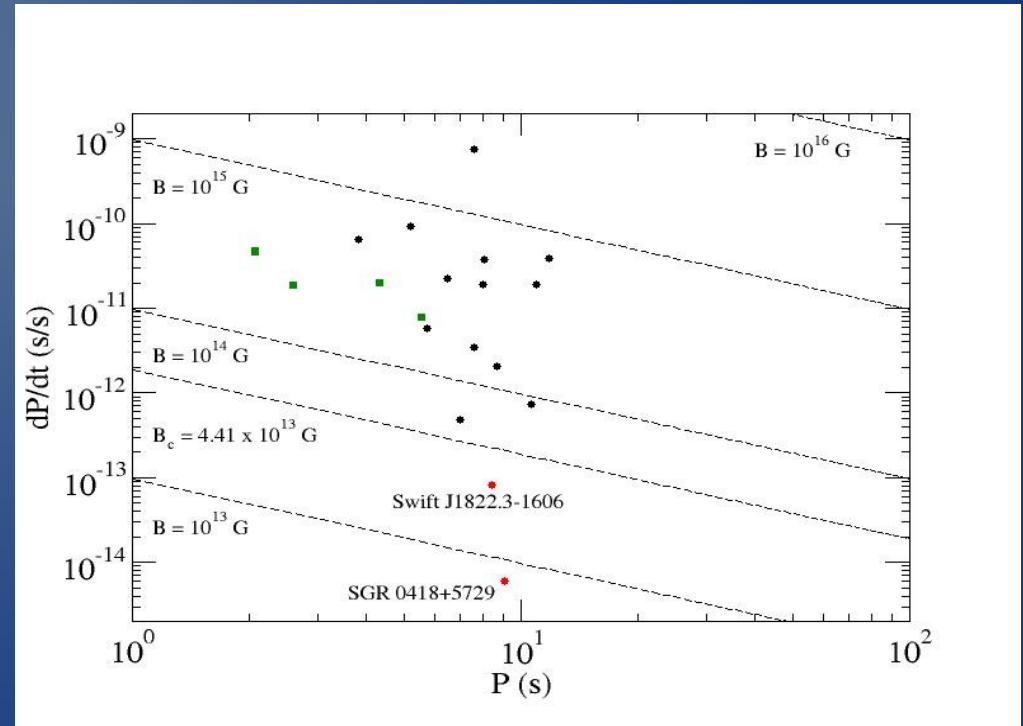
Very Different Magnetic Field Scales

White Dwarfs

$$B_{\mathrm{WD}} = 4.21 \times 10^{14} (P\dot{P})^{1/2} \mathrm{G}.$$

Magnetars

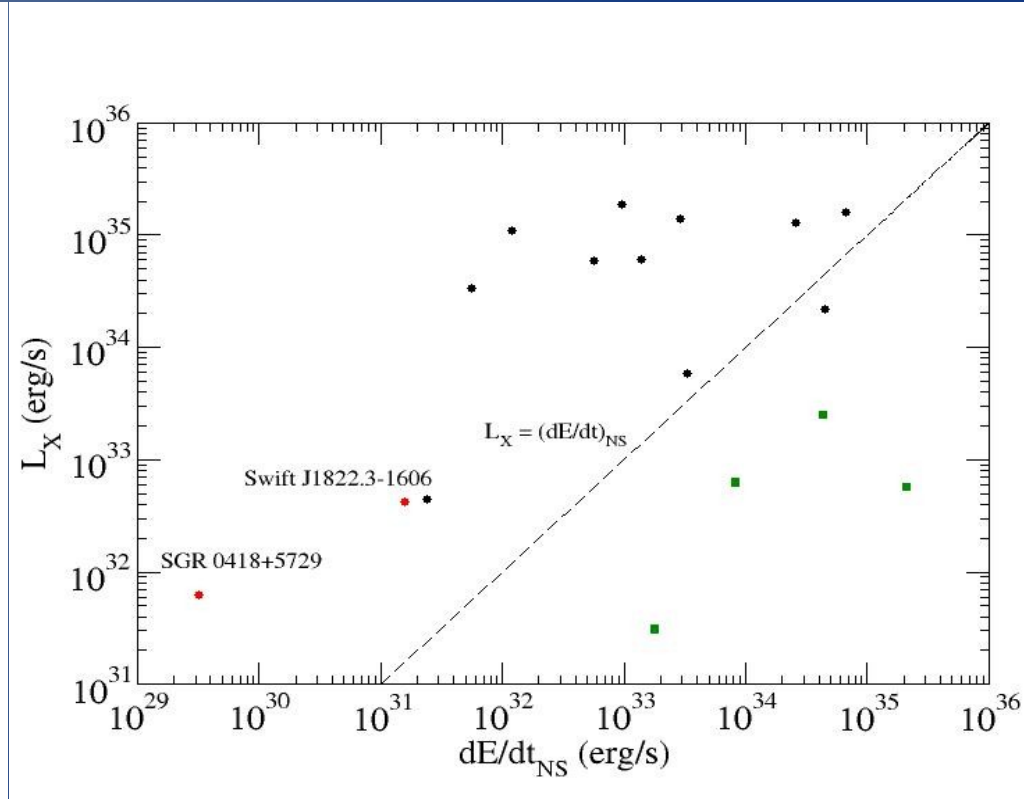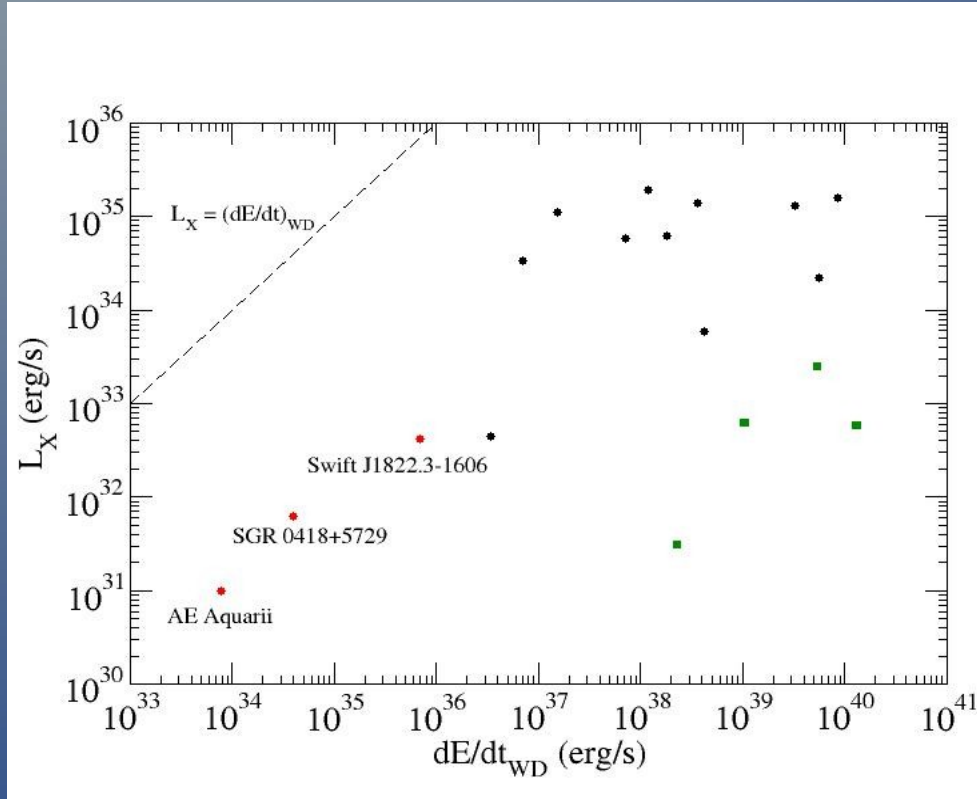$$B_{\mathrm{NS}} = 3.2 \times 10^{19} (P\dot{P})^{1/2} \mathrm{G}.$$

White Dwarf Model – no more huge magnetic fields, all undercritical !!!

SGRs and AXPs as fast rotating-powered Magnetic White Dwarf Pulsars.

White Dwarfs

Neutron Star

The red points corresponds to recent discoveries of SGR 0418+5729 and Swift J1822.3-1606 with low magnetic field, and the green squares are the AXPs transients.

Prediction of spin-down lower limit of SGR 0418+5729

$$L_x P^3 / (4 \pi^2 I) < dP/dt < 6.0 \times 10^{-15} \text{ s/s}$$

$$\boxed{dP/dt > 1.18 \times 10^{-16} \text{ s/s}}$$

- Lower limit for Surface Dipolar Magnetic Field.
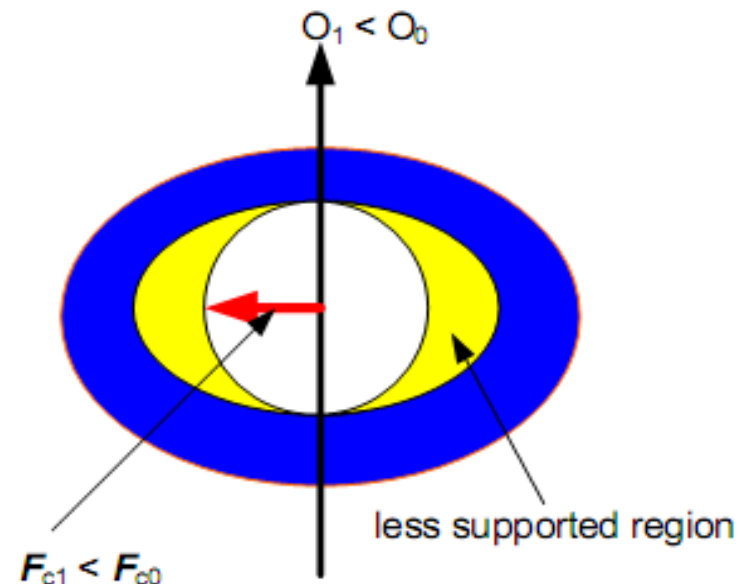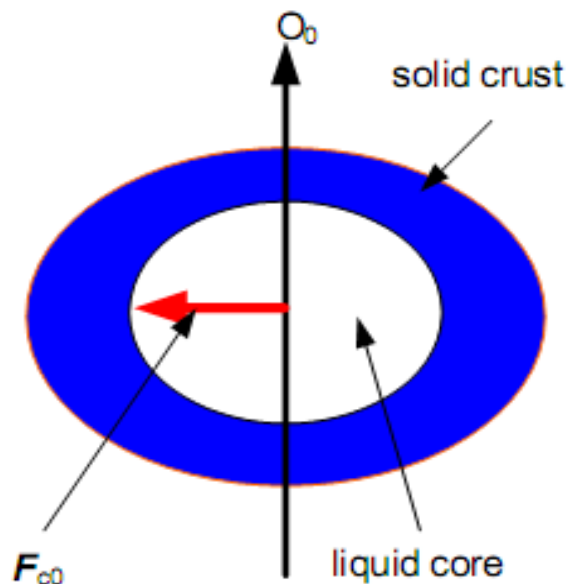
$$1.05 \times 10^8 \text{ G} < B < 7.47 \times 10^8 \text{ G}$$

Outbursts mechanism: change of rotational energy from glitches (spin-up events).

- conservation of angular momentun (Ruderman, 1969)

$$\frac{d}{dt}(I\Omega)=0 \Rightarrow \frac{\Delta I}{I}=-\frac{\Delta\Omega}{\Omega}=\Delta\varepsilon, \quad \varepsilon : \text{oblateness parameter } I = I_o(1+\varepsilon)$$

Crab: $\Delta\varepsilon = - \Delta\Omega/\Omega \approx 10^{-7} = 2\Delta R/R \Rightarrow \Delta R \approx 0.06$ cm

observable effects from shrinkage of less than 1mm!
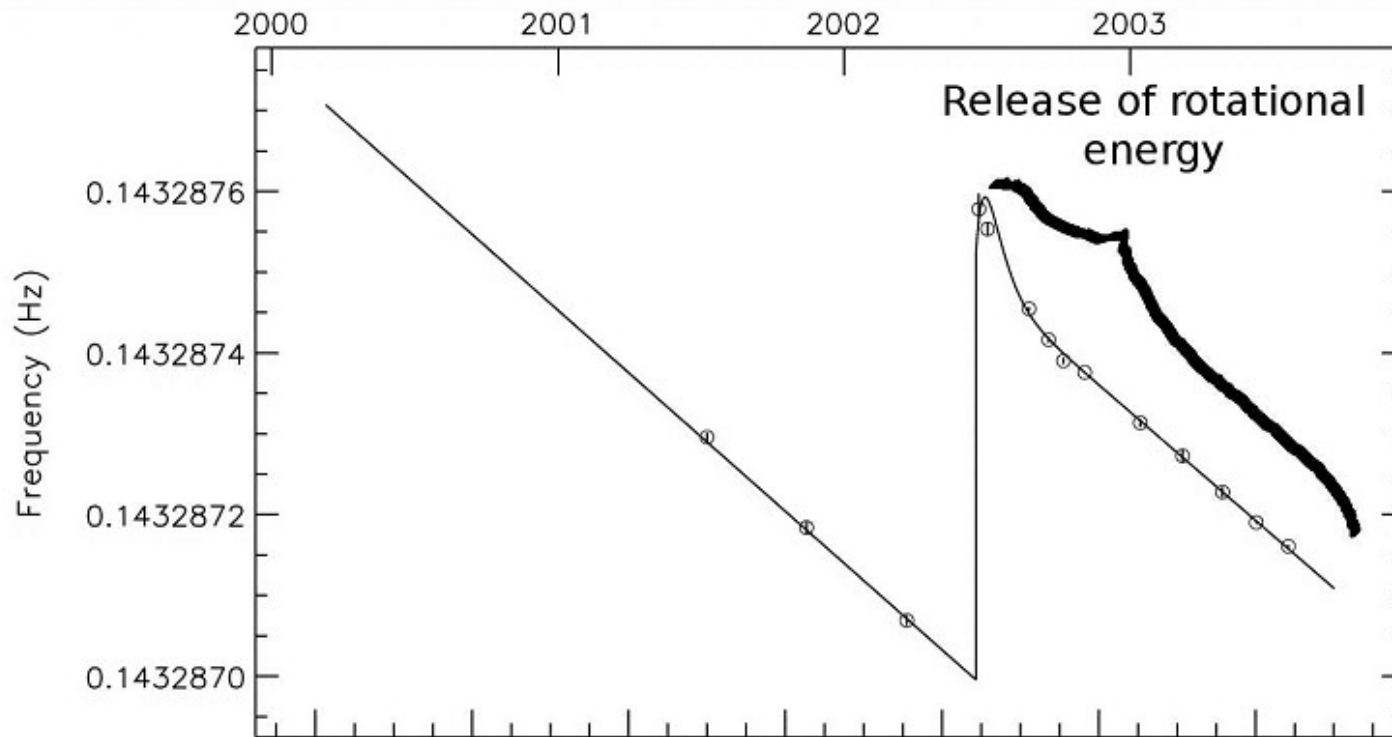
Fig. 6. Timing analysis of the glitch of 1E 2259+586 on June 2002 (from Woods et al. 2004). The vertical axis shows the evolution of the spin frequency and the horizontal axis the date time. The observed fractional change of period is $\Delta P/P \sim -4 \times 10^{-6}$ and the observed energy released during the event is $\sim 3 \times 10^{41}$ erg (Woods et al. 2004). Within the white dwarf model from such a $\Delta P/P$ we obtain $\left|\Delta E_{\text{rot}}^{\text{WD}}\right| \sim 1.7 \times 10^{43}$ erg as given by Eq. 9.

Delta E_rot = -2*pi^2*I*(Delta P/P)/P^2
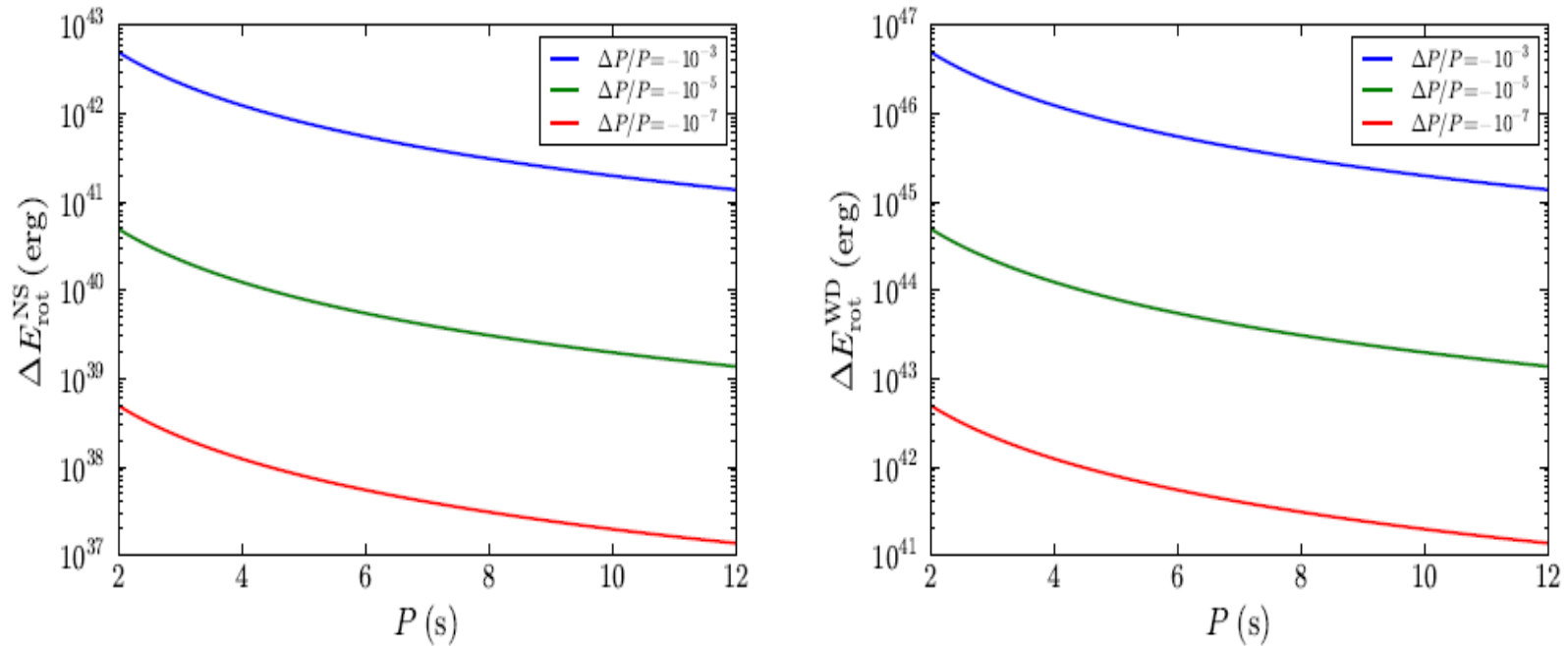

Fig. 2. Change in the rotational energy ΔE_{rot} as a function of the rotational period P of the object for different fractional period changes $\Delta P/P$. The left panel shows the case of neutron stars in the magnetar model and the right panel shows the case of white dwarfs addressed here.

Observed and Predicted Glitches

Table 2. Glitches and Outbursts of some SGRs and AXPs within the white dwarf model.

	SGR 0526-66	1E 2259+586	1E 1048.1-5937	SGR 1806-20
Date	March 1979	June 2002	March 2007	December 2004
Observed Energy (erg)	3.6×10^{44}	3×10^{41}	4.2×10^{42}	$\sim 10^{46}$
$|\Delta P|/P$	1.2×10^{-4} (predicted)	4.24×10^{-6} (observed)	1.63×10^{-5} (observed)	3×10^{-3} (predicted)
Predicted Energy (erg)	3.6×10^{44}	1.7×10^{43}	7.7×10^{43}	$\sim 10^{46}$

Notes. The predicted values of $|\Delta P|/P$ are calculated with Eq. (9) assuming $\left|\Delta E_{rot}^{WD}\right|$ equals the observed energy of the burst event. The predicted values of the energy released in the burst event is calculated with Eq. (9) using the observed fractional change of rotational period $|\Delta P|/P$.

IV - OBSERVATIONS OF SGRS WITH LOW B AND WHITE DWARF PULSARS

J. G. Coelho and M. Malheiro - Int. J. of Mod. Phys.: Conf. Series, 18, 96, 2012

In the last years, two SGRs with low magnetic field were discovered, SGR 0418+5729 and Swift J1822.3-1606

(see N. Rea et al. 2010, 2012).

- SGR 0418+5729 with Period P = 9.04 s with a low surface magnetic field B = 7 x 10^{12} G.

- Large spin down: dP/dt = 5.4 x10^{-15}s/s.

- Old star among SGRs: characteristic age t ~ 26 Myr

- Luminosity L_x = 6.2 x 10^{31} erg/s

- L_x~ 200 dE_{rot}/dt

Massive and Highly Magnetized White Dwarf Pulsars.

- Catalogue of more than 100 isolated massive white dwarfs and 25% are magnetic (M. Nalezyty and J. Madej 2004)

- four most massive white dwarfs M > 1.3 M_{sun} are magnetic with B ~ (10^6 -10^9) G

- Magnetic white dwarfs have higher temperatures T~10^5 K

- **AE Aquarii** : Hard X-Ray White Dwarf Pulsar found by Suzaku (Y. Terada et al. 2008). Very fast and high B.

- Similar properties of SGR 0418+5729: P = 33 s,
  dP/dt = 5.64 x 10^{-14} s/s, L_x~10^{31} erg/s (< 4 Kev),

  B = 3 × 10^8 G , T~ 0.5 KeV,

   characteristic age t~ 9.4 Myr.

Massive and Highly Magnetized White Dwarf Pulsars.

- More recently, X-ray multimirror mission (XMM) – Newton satellite had observed a WD pulsar faster (P=13.2 s) than AE Aquarii. Mereghetti et al. 2009 showed that the X-ray pulsator **RX J0648.0-4418** is a WD with mass M=1.28M$_{sun}$ and radius R=3000 Km.

- As discussed by Mereghetti et al. 2009, the luminosity of L$_x$~10^{31} erg/s is produced by accretion onto the white dwarf of the helium-rich matter from the wind of the companion.

- In this work, we investigate de possibility to describe RX J0648.0-4418 as a rotation powered WD.

Massive and Highly Magnetized White Dwarf Pulsars.

- EUVE J0317-855, a hydrogen-rich magnetized WD discovered as an extreme-ultraviolet (EUV) source by the ROSAT Wide Field Camera and Extreme Ultra-violet Explorer EUVE survey, is another observed WD pulsar candidates.

- Barstow et al. 1995 obtained a period of P ~ 725 s, which is also a fast and very magnetic white dwarf with a dipole magnetic field is B ~ 4.5×10^8 G, and a mass (1.31 − 1.37)M_{sun}

- EUVE J0317-855 has a white dwarf companion, but is supposed to be no interaction between them, because of their large separation ($> 10^3$ UA).

# SIMILARITIES OF SGRs WITH LOW MAGNETIC FIELD AND WHITE DWARF PULSARS

TABLE I. Comparison of the observational properties of five sources: SGR 0418+5729 and Swift J1822.3-1606 (see Nanda Rea et al. 2012) and two observed white dwarf pulsars and the candidate EUVE J0317-855. For the SGR 0418+5729 and Swift J1822.3-1606 the parameters P, $\dot{P}$ and L_X have been taken from the McGill online catalog at www.physics.mcgill.ca/ pulsar/magnetar/main.html. The characteristic age is given by Age $= P/2\dot{P}$ and the WD magnetic moment and surface magnetic field are given by Eqs. (4) and (5) respectively.

	SGR 0418+5729	Swift J1822.3-1606	AE Aquarii	RXJ 0648.0-4418	EUVE J0317-855
P(s)	9.08	8.44	33.08	13.2	725
$\dot{P}$ (10^{-14})	< 0.6	8.3	5.64	< 90	-
Age (Myr)	24	1.6	9.3	0.23	-
L_X (erg/s)	$\sim 6.2 \times 10^{31}$	$\sim 4.2 \times 10^{32}$	$\sim 10^{31}$	$\sim 10^{32}$	-
B_{WD} (G)	$< 9.83 \times 10^{7}$	3.52×10^{8}	$\sim 5 \times 10^{7}$	$< 1.45 \times 10^{9}$	$\sim 4.5 \times 10^{8}$
m_{WD} (emu)	2.65×10^{33}	0.95×10^{34}	$\sim 1.35 \times 10^{33}$	3.48×10^{34}	1.22×10^{34}

Several features of two SGRs with low magnetic field are very similar to the ones of fast and magnetic white dwarfs recently detected.

V - DIPOLE MAGNETIC MOMENT OF NEUTRON STARS AND WHITE DWARFS

J. G. Coelho and M. Malheiro (2012) - arXiv:1211.6078
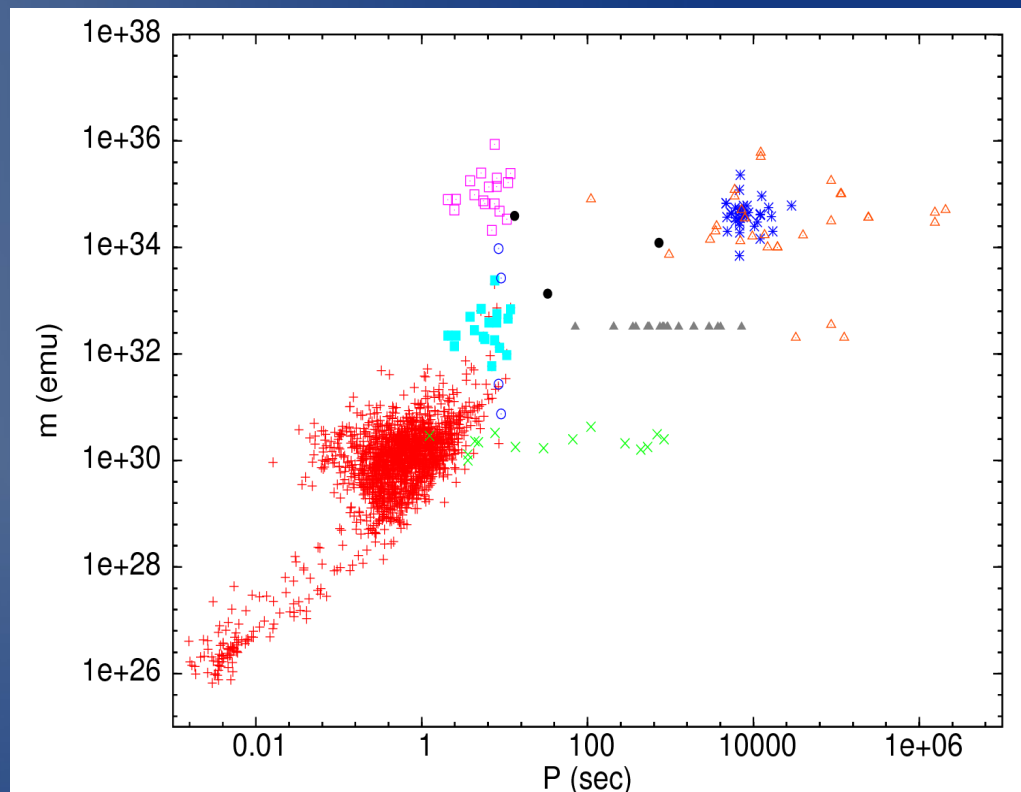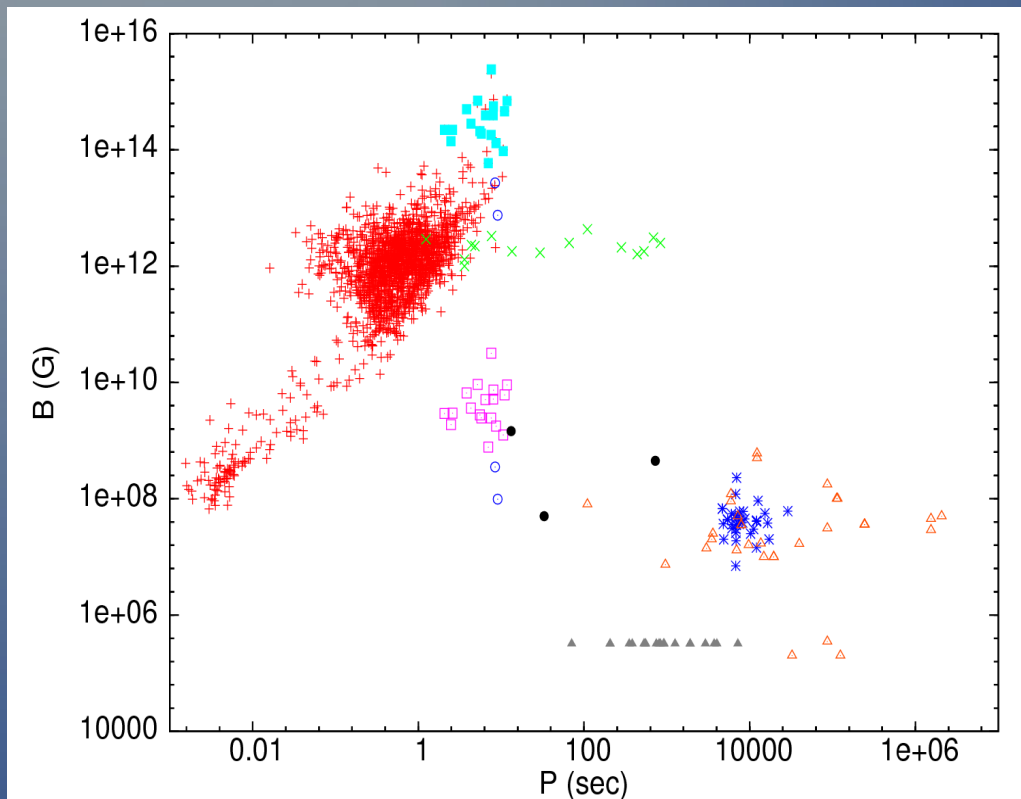
Green cross points - X-ray pulsars. The two blue circle points - SGR 0418+5729 and Swift J1822.3-1606 considering neutron stars and white dwarfs parameters. The black full point are: RX J0648.0-4418, AE Aquarii and EUVE J0317-855. And all the other points points are polar and isolated white dwarfs (see Terada et al. 2008d, for details of these points).

Magnetic dipole moment m ~ (10^{34} - 10^{36}) emu

- Because of the small radius of the fast and massive white dwarf comparing to normal WD, the large magnetic field of the SGRs/AXPs as white dwarfs generated a magnetic dipole moment m (10^{34} - 10^{36}) emu, exactly in the range of *m* for isolated and polar magnetic white dwarfs.

- The values for m ~ (10^{33} - 10^{34}) emu of the two SGRs with low B, are exactly at the same order of the three white dwarf pulsars observed, and in the lower values of the observed isolated and polar white dwarf magnetic dipole moment range.

VI - Conclusions

- The large steady X-ray emission $L_x \sim 10^{35}$ erg/s observed in the SGRs/AXPs is now well understood as a consequence of the fast white dwarf rotation (P ~ 10 s), since the magnetic dipole moment *m* is at the same scale as the one observed for the very magnetic and not so fast WDs.

- This supports the description of SGRs/AXPs as belonging to a class of very fast and magnetic massive WDs perfect in line with recent astronomical observations of fast white dwarf pulsars.