SGRs Long term variability

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- SGRs (and AXPs): long term spectral variability
- A "magnetar" at work? Interpretation of SGRs
- Post flare evolution
- SGRs fading

Gian Luca Israel, Nanda Rea, Sandro Mereghetti, Andrea Tiengo, Paolo Esposito, Luigi Stella, Roberto Turolla, Diego Gotz, Marco Feroci, Aldo Treves, Sergio Campana, Mariano Mendez, Frank Haberl, Tim Oosterbroek

MSSL, Univ College London, UK; INAF, IAS, Milan; SRON, Utrecht, Netherlands; INAF, OAR, Rome; Univ. of Padua; MPE; OAB; ESA

SGRs census: 4 confirmed + 1 candidate

	P (s)	dP/dt (10^{-11} s/s)	kT (keV)	Γ	F(2-10 keV) erg/cm^{-2}/s
SGR 1900+14 (G42.8+0.6)	5.2	6.1- 20.0	0.45	2	1.e-11
SGR 1806-20 (G10.0 0.3)	7.5	8.3- 47.0	0.8	1.2	1.5e-11
SGR 0526-66 (N49, in LMC)	8.0	6.6	0.53	3.1	1.e-12
SGR 1627-41 (G337.0-0.1)	6.4?	-		3	3e-13
SGR 1801-23	-	-			

- Class of rare X-ray bursting sources, only 4 of them are confirmed
- Persistent X-ray emitters (L ≈ 10^{35} erg/s).
- BB+PL X-ray spectrum (<10 keV) in quiescence
- Initially confused with GRBs. However, unlike GRBs:
  - SGRs do repeat (hence their name !)
  - They show pulsations
  - large spin down rate
  - Hard X-ray tails up to ~100 keV in SGR1806 and SGR1900 (INTEGRAL, Suzaku..)
  - Infrared counterpart in SGR1806 (Israel et al., 2006)

(For a review see Woods & Thompson 2004; Mereghetti et al 2006)

Why SGRs may be'magnetars'?

Magnetars: neutron stars with ultra strong magnetic field

$B >> B_{QED} \sim 4 \times 10^{13}$ G

(Duncan & Thomson 1992; 1995)

1. **Original suggestion driven by the extreme properties of SGRs bursts and flares (Duncan & Thomson '92-'95)**

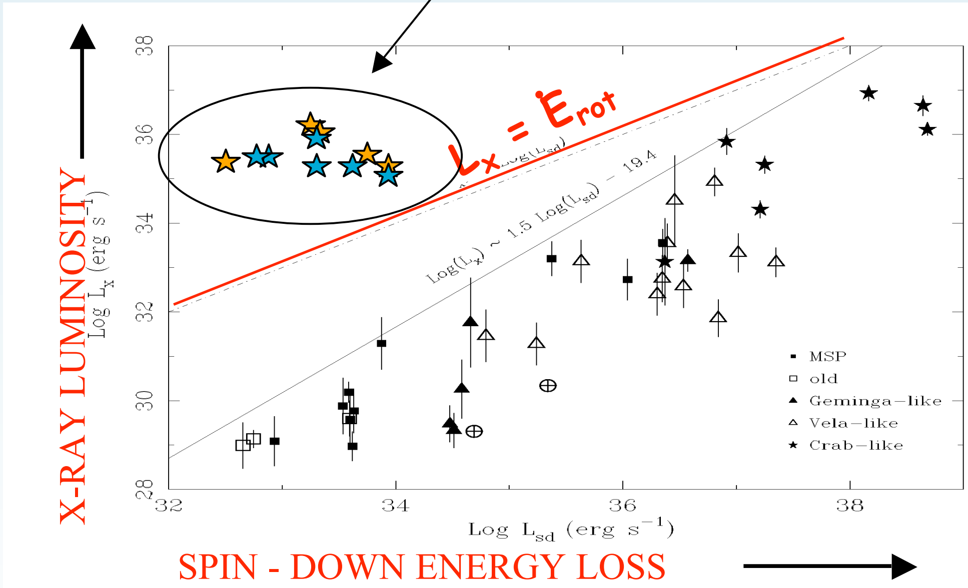
2. **Their X-ray luminosity is by far (~100) larger than their rotational energy resevoir .**

3. **No evidence for a companion star.**

   ⇒ Another energy source is needed to explain their emission!

4. **Interpreting the spin-down as dipolar losses gives $B \sim 10^{14}$-10^{15} G> B_{QED}**

Magnetars (SGRs+AXPs)



$$L_X > \dot{E}_{rot} = I\Omega\dot{\Omega}$$

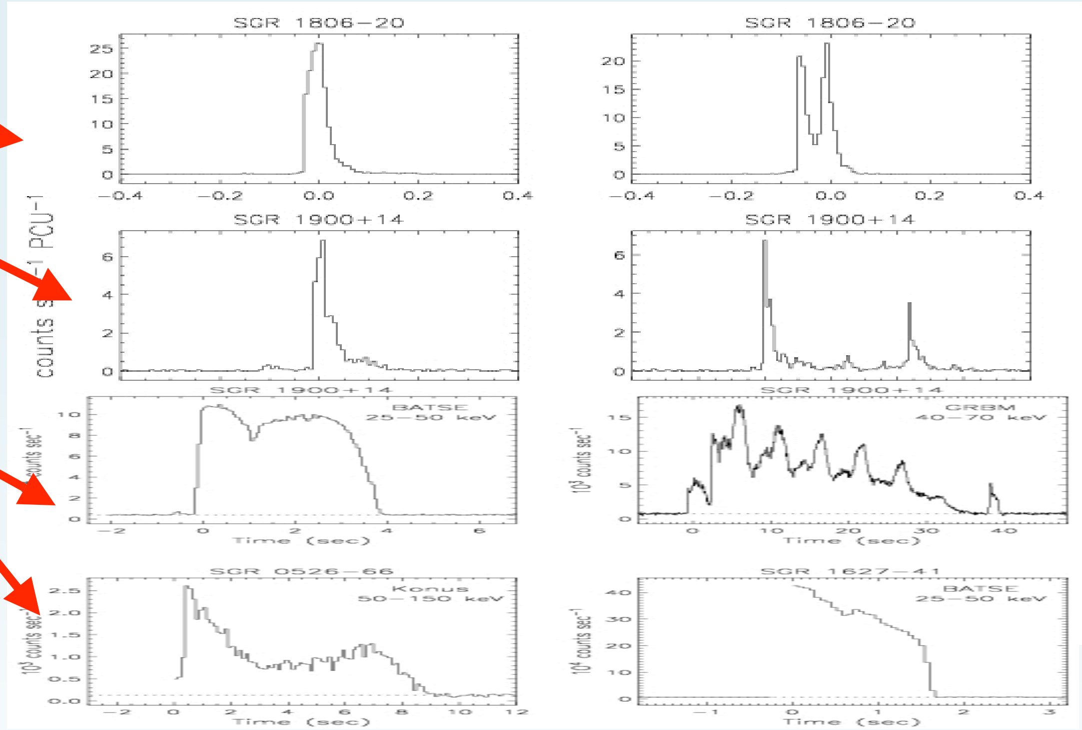
SGRs: different types of X/γ-ray bursts

Short bursts

- most common
- last ~0.1s
- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra

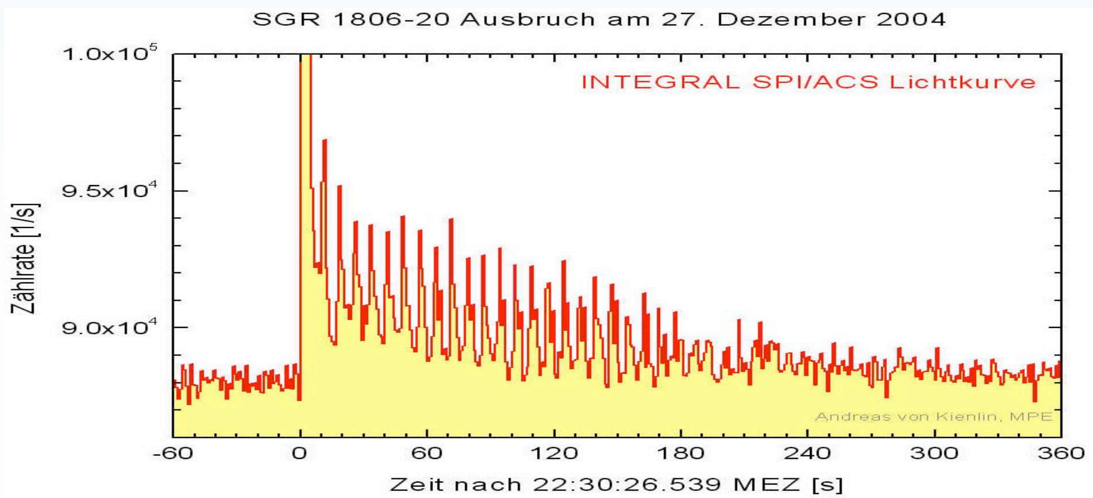
Intermediate bursts

- last 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- usually soft, thermal γ-ray spectra



Giant Flares

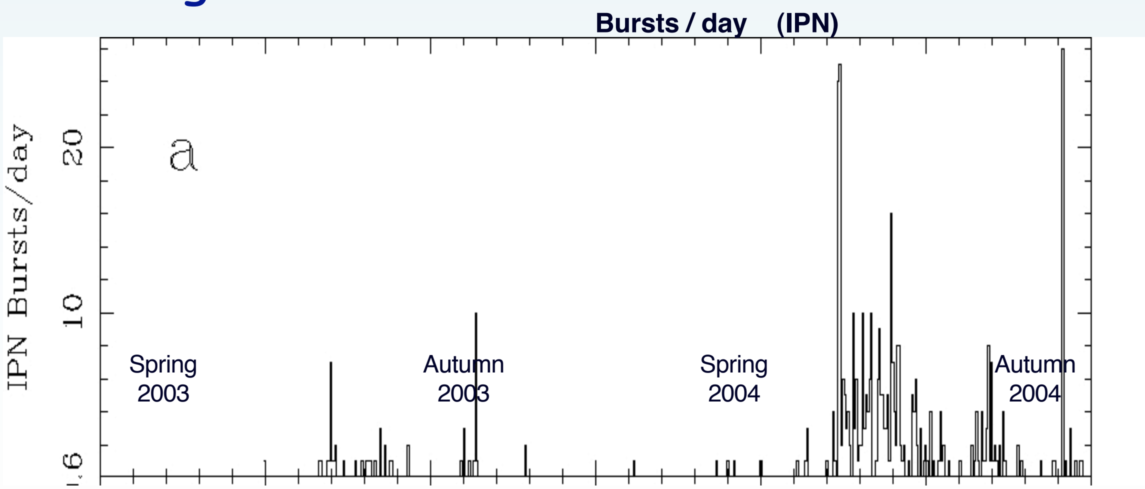
- peak < 1s and ringing tail
- 3 events so far
- isotr. energy release ~10^{44}-10^{46} ergs



Besides the bursting/flaring activity: long term spectral evolution
I- the pre-giant flare evolution in SGR1806-20

SGR 1806-20 displayed a gradual increase in the level of activity during 2003-2004

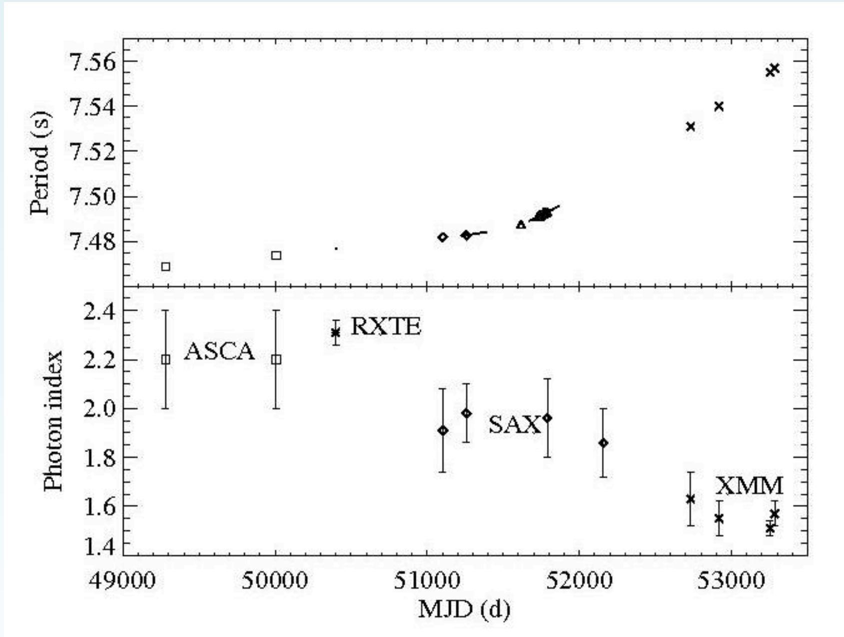
Enlarged burst rate



Woods et al, 2004; Mereghetti et al 2005

I- Pre flare continue…

- Four XMM-Newton observations (April 2003 to October 5 2004, Mereghetti,… SZ et al 2005)
- Harder spectra: $\Gamma \sim 1.5$ vs. $\Gamma \sim 2$
- The 2-10 keV luminosity almost doubled ($L_X \sim 10^{36}$ erg/s)
- dP/dt ~ 5.5×10^{-10} s/s, higher than the "historical" value (but see Woods et al 2006)

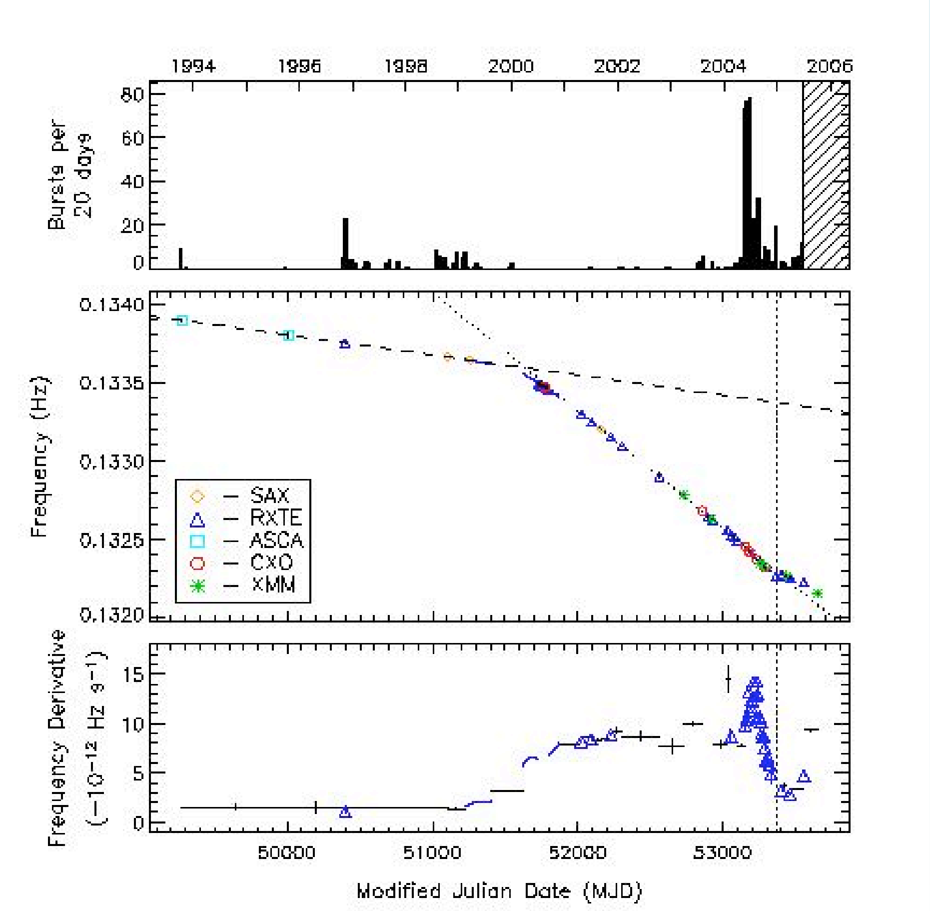


From Mereghetti, …SZ et al 2005

Increase of spectral hardness/Luminosity and of average spin-down rate are roughly correlated.

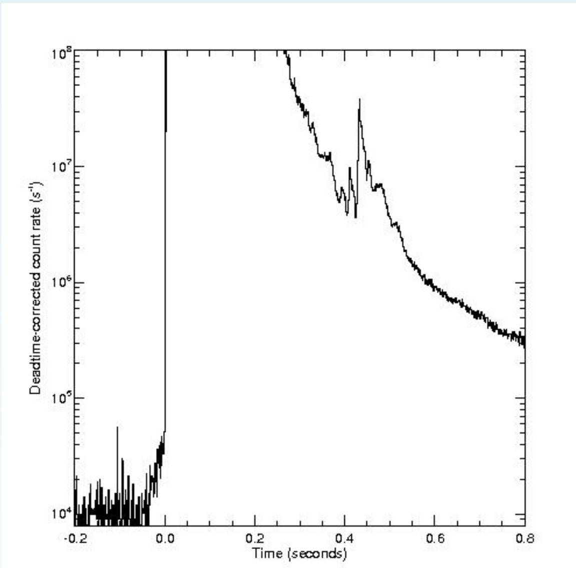
I- Pre flare continue…

- Erratic behaviour in the timing evolution

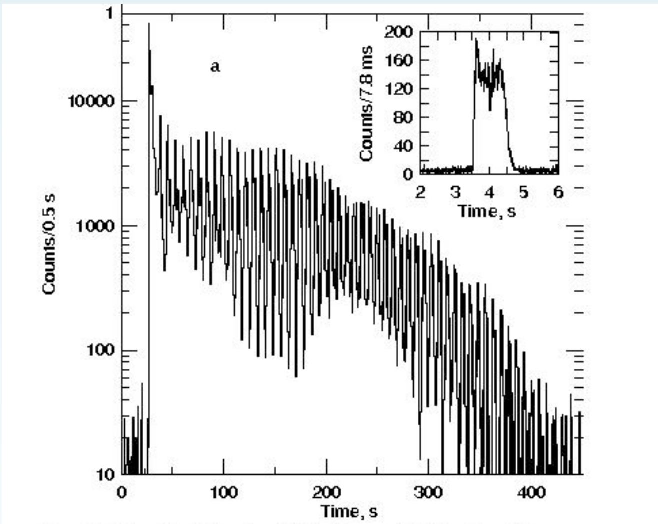


Woods et al, 2006, ApJ, 654, 470

27 Dec 2004: Eruption of a giant flare



BAT/Swift lightcurve (Palmer et al 2005)



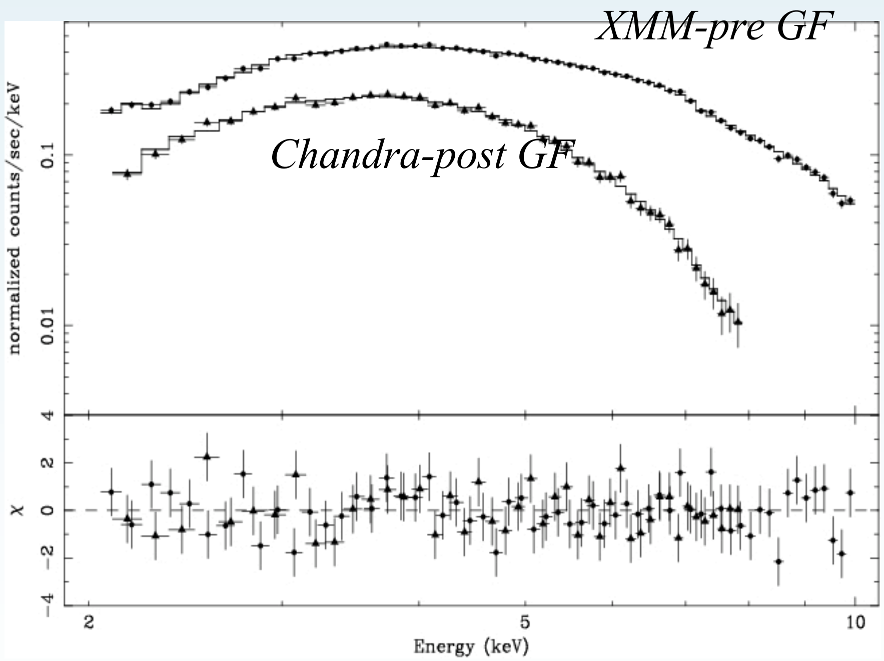
RHESSI lightcurve, From Hurley et al 2005

- **QPOs** (Israel et al 2005) , **crustal fracture** (Schwartz, SZ et al. 2005)
- **Radio afterglow** (Cameron et al 2005; Gaensler et al 2005)
  $\Rightarrow$ **precise localization!**
- **IR counterpart** (Kosugi et al 2005; Israel et al 2005)

Aftermath

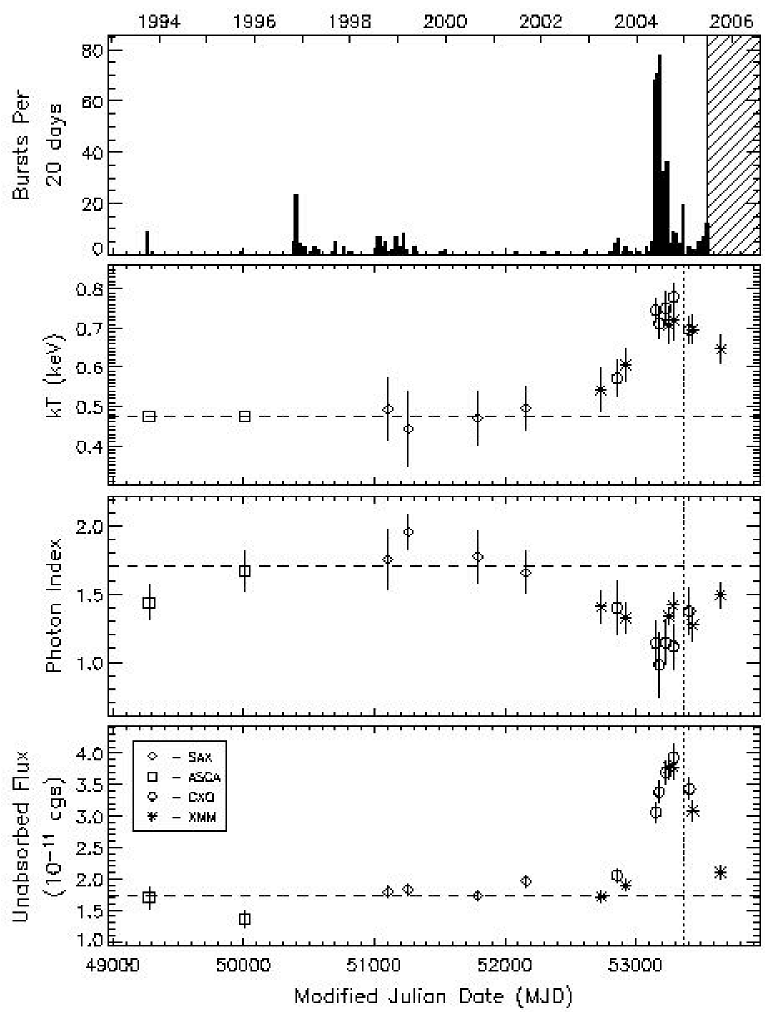
TOOs of SGR 1806-20 performed after ~1 month with CHANDRA (Rea,… SZ et al 2005) and ~2 months with XMM (Tiengo,… SZ et al 2005)

- Source still burst active
- Definite spectral softening (Γ~1.5 → Γ~1.8 with Chandra, with XMM)
- Rapid decay of the persistent flux



(Rea, …SZ et al. 2005)

Aftermath



Woods et al, 2006, ApJ, 654, 470

Discovery of long term evolution of flux and spectral hardening in the AXP 1RXS J1708-4009

- Two glitches in the last 4 yrs (Kaspi et al 2000/2003, Dall'Osso et al 2003)

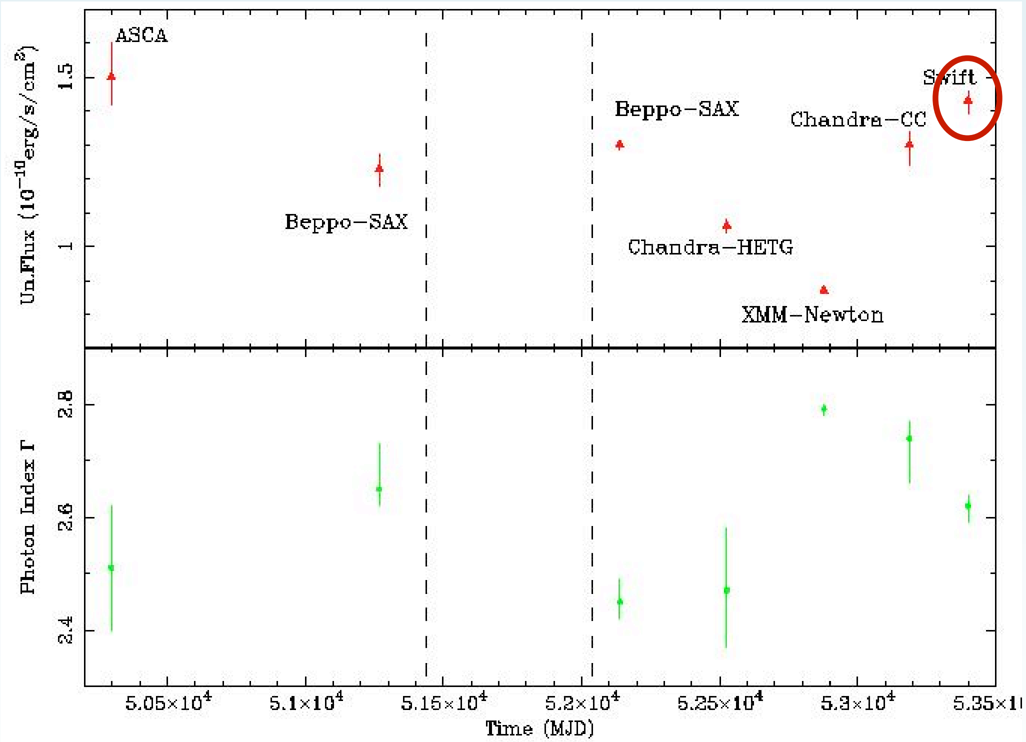
- Rea, ...SZ et al 2005:

• a set of obs spanning 5 years

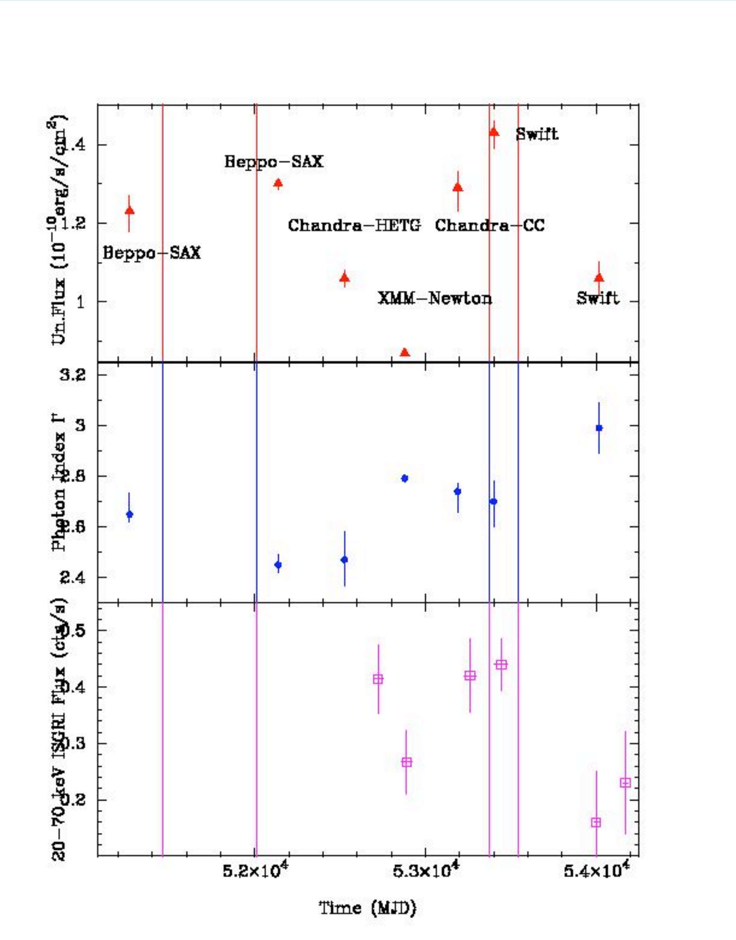
• Γ-L correlation: The spectrum became harder as the flux rose in correspondence of the two glitches and then softened as the luminosity dropped, following the glitch recovery

- Campana, ...SZ et al, 2006:

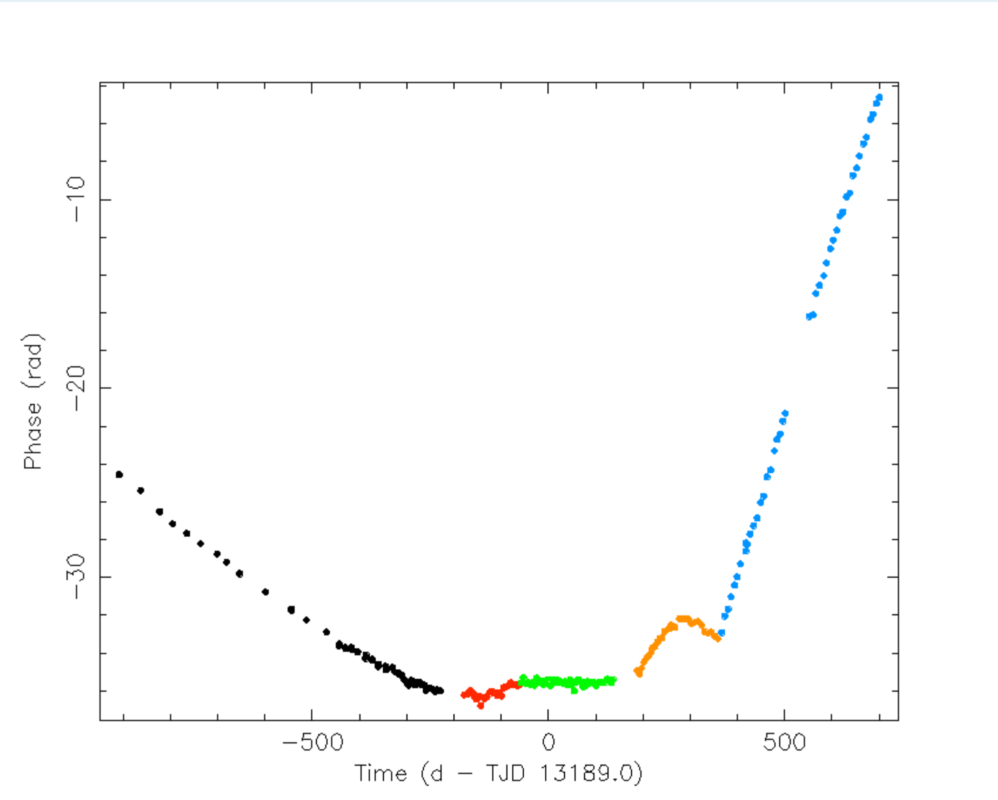
• More recent Swift observations confirm the flux-hardness correlation... But the trend monitored since 2000 has been REVERSED!



Two new glitches close to the flux maximum
(Israel… SZ et al., to be submitted)



Israel, …SZ et al., to be submitted)



First glitch Crab like

Epoch 13375.5
P pre 11.00261388960010400 s
P post 11.00260054079972960 s

ΔP = 0.00001334880037440
ΔP/P = 0.0000012132397452

Second glitch Vela like

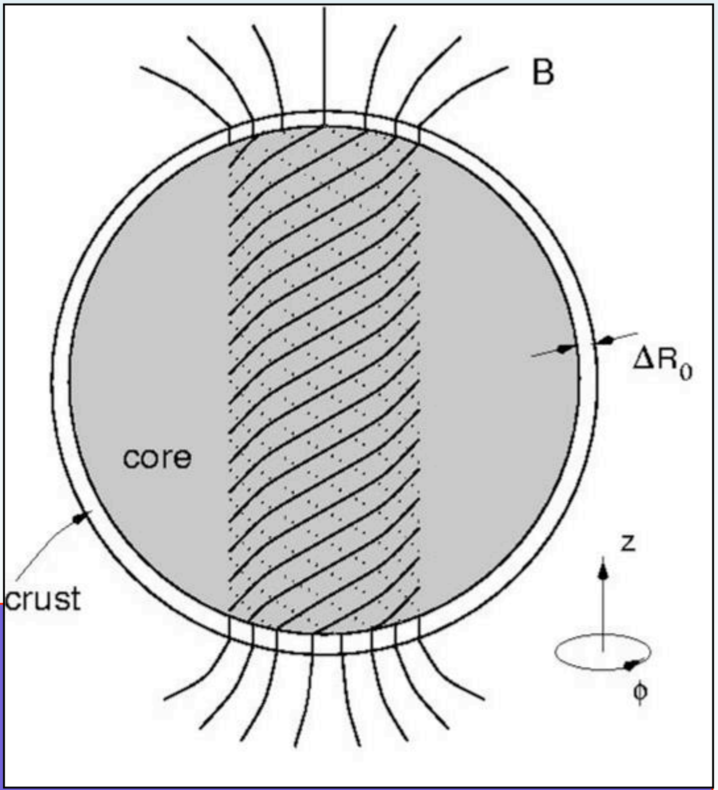
Epoch 13544
P pre 11.00289979947191732 s
P post 11.00287636657393264 s

ΔP = 0.0000234328979846
ΔP/P = 0.0000021297042929

Onset of a twist in the magnetosphere?

- Increase in bursting activity culminating with the flare

- Observed Γ-L (−dP/dt?) correlation



Thompson, Lyutikov and Kulkarni (2002):

Magnetars (AXPs and SGRs) differ from radiopulsars 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, crustal fractures, glitches.

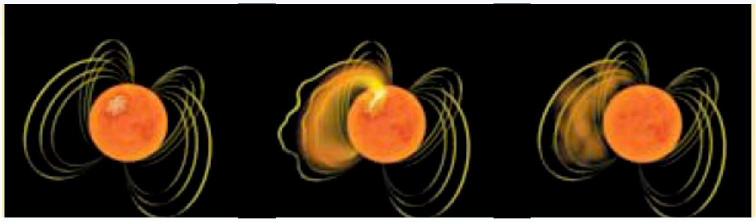
Twisted magnetospheres

- A key feature of twisted MSs is that they support current flows (in excess of the Goldreich-Julian current).
- Charged particles (e- and ions) produces both an extra heating of the star surface (by returning currents) and a large resonant cyclotron scattering depth
- e- distribution spatially extended + $\omega_{res} = \omega_{res}$ (B)
  $\Rightarrow$ repeated scatterings could lead to the formation of a high energy tail (instead of a narrow line)
  $\Rightarrow$ spectral hardening
- The B-field flare out slightly $\Rightarrow$ open field flux > then in a dipole
  $\Rightarrow$ spin down torque increases (but details depends on where the torque is concentrated)

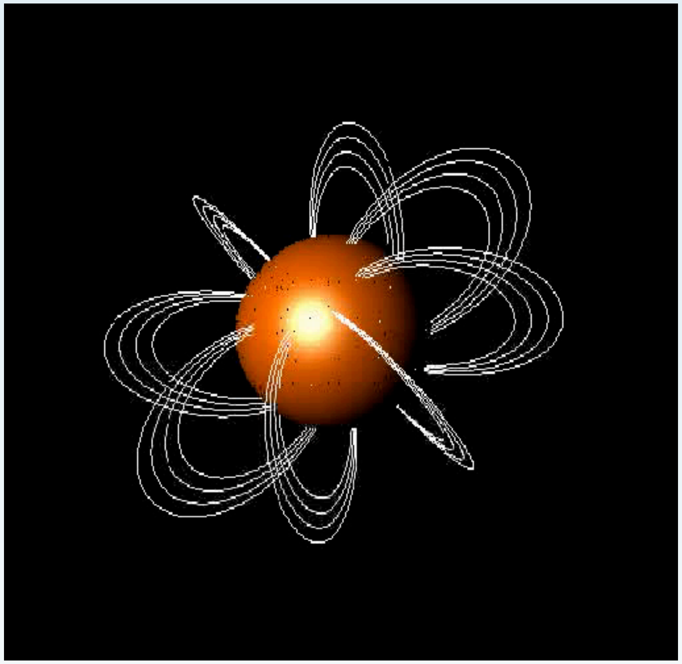
What can we get through all these…

1. **The twist starts growing…** The twisted internal magnetic field stresses the NS solid crust and propagate outwards ⇒The twist build up in the external B-field
 ⇒ flux increases, the spectrum hardens, the period derivative increases.

2. **…it culminated with the Giant Flare…** a) when the crust is no more able to respond plastically to the imparted stress (crack) or b) by a global rearrangement of the field lines. ⇒ a forced opening of the field outwards ⇒ launch of an hot fireball



3. **… then the untwisting.** The GF is followed by a simplification of the external B-field and by a partial magnetospheric untwisting ⇒ rapid drop in the flux, spectral softening, period derivative decrease..



- force-free magnetic equilibria $(\vec{J}\times\vec{B}=0)$
- A sequence of models labeled by the twist angle $\Delta\phi_{N-S} = 2\int_0^{\frac{\pi}{2}} \frac{B_\phi}{B_\theta}\frac{d\theta}{\sin\theta}$

A Monte Carlo Approach

(Nobili, Turolla, Zane & Sartore, in prep)

See Roberto's talk

How much energy is deposited in the NS crust after bursting/flaring activity? How this energy is dissipated?

Cooling and fading of SGRs persistent emission:

⇒ SGR1900+14 and SGR1627-41 excellent candidates

⇒ compute the "thermal echo" of the crust: transient afterglow following heat release below the surface (Eichler & Cheng 1989; Lyubarsky et al, 2002)

⇒ 1-D treatment of the heat transfer equation

$$C_V \frac{\partial T}{\partial t} = \frac{\partial F}{\partial z}, \qquad F = k \frac{\partial T}{\partial z}$$

Heat capacity

Thermal conductivity

Eichler & Cheng 1989; Lyubarsky et al, 2002 (LEC2002):

Heat released:

- deep below the surface (e conduction > neutrino losses) ⇒ mostly sucked into the star and steadily radiated away in cooling time scales (~100s yrs)
- at shallower depths ⇒ creates a thermal echo lasting about 10^4 s or less.
- BUT transient afterglow could also occur on a timescale~months if it involves only a small fraction of the energy.

⇒ Probably observable only if the outburst E>10^{43} erg.

⇒ Most of the heat goes into the body of the star, but the surface stays hot long enough to provide a transient tail of X-ray emission.

Heat capacity dominated by relativistic e^-: $$C_V = \pi^2 n_e k_B T / E_F \propto z^2 T$$

Thermal conductivity in the Coulomb liquid: $$k = (\pi/3) E_F k_B T / Z e^4 \Lambda_c \propto zT$$

Initial T profile: $$T(z,o) = (2U_{th} / Kz^2)^{1/2} \propto 1/z$$

⇒ a broad temperature maximum forms and propagates inward

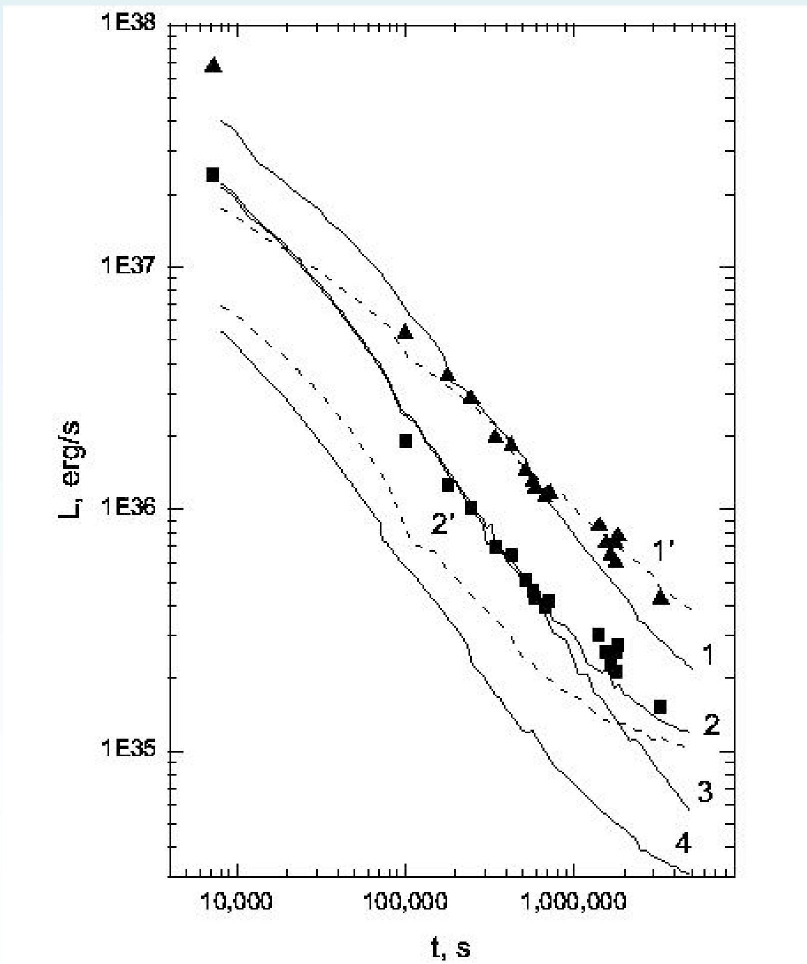
If the skin layer is a perfect insulator: $$T(\varepsilon,t) = \left[\Gamma \frac{1}{3}\frac{U_{th}}{2K}\right]^{1/2} \left(\frac{K't}{K}\right)^{-1/3}$$

If k had the same linear dependence on T through the skin layer:

1) a constant fraction of the heat would escape through the surface

2) the surface flux would scale as $t^{-2/3}$

LEC2002: 40d decay of SGR1900+14 after the GF of Aug 27 1998



$L \sim t^{-0.7}$

Squares: d=9kpc
Triangles: d=16kpc

Data from Woods et al. 2001

Uniform heat density

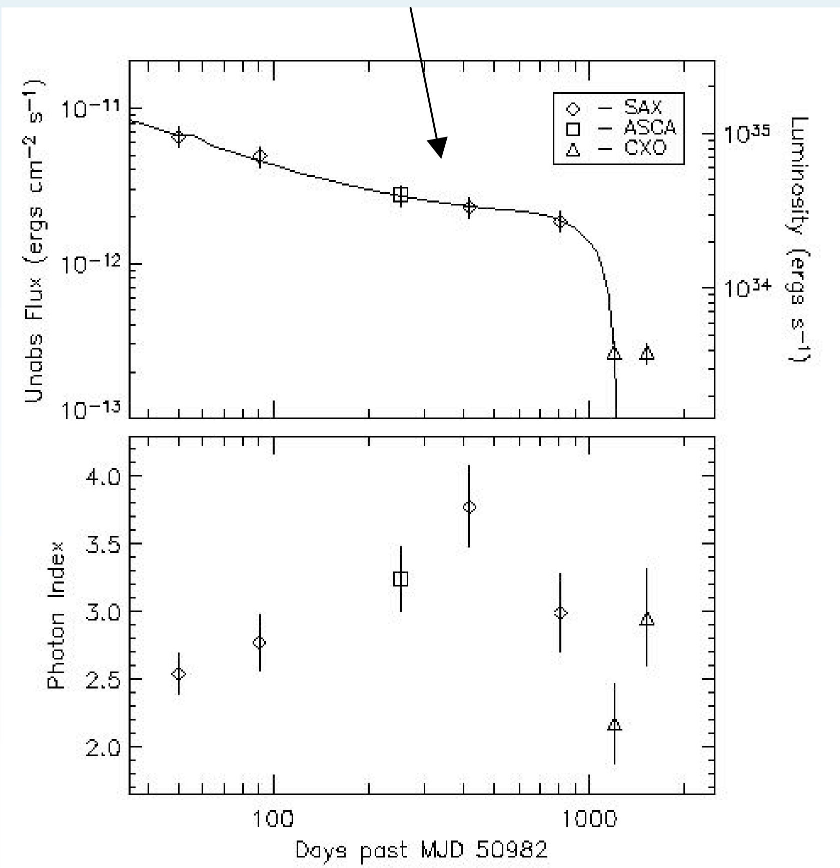
Model parameters:

- T_{int} = initial T at the inner boundary
- T_{max} = T at the bottom of the skin zone
- B

Kouveliotou et al, 2003:

3 yrs monotonic decline of SGR1627-41 after bursting activity of 1998

Plateau between 400d and 800d (?)



- Initial E release: 10^{44} ergs
- E release varies with z less than the specific heat (⇒ spec. heat dictates the T profile)

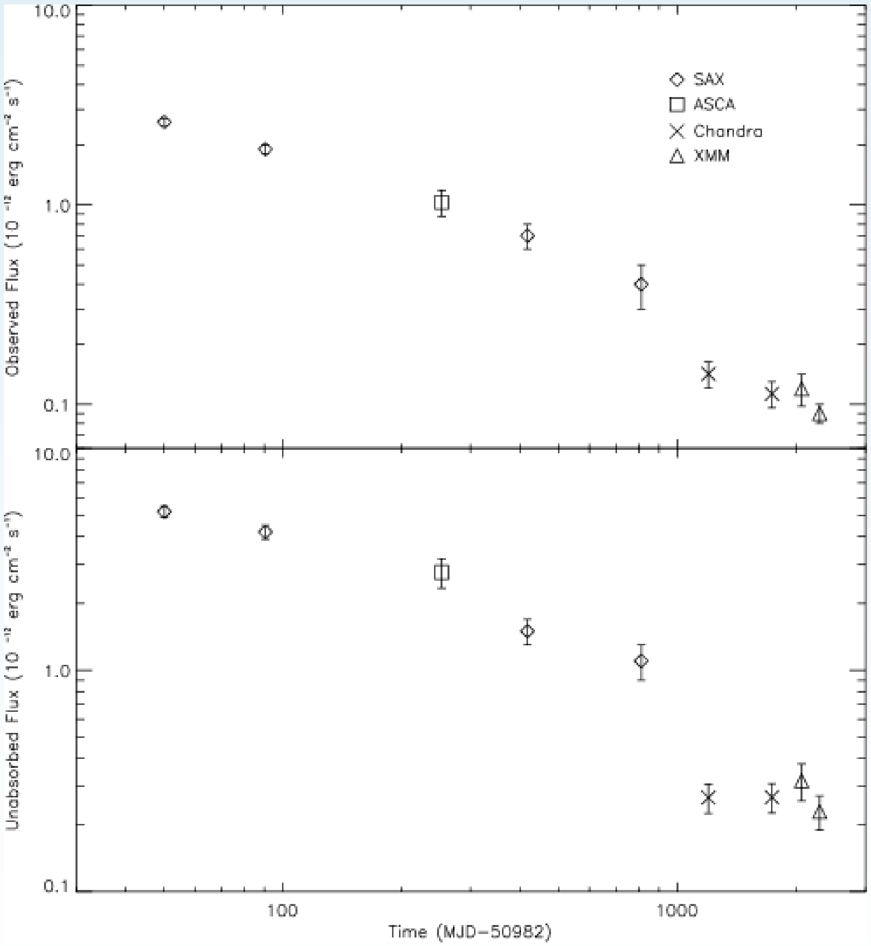
⇒ Sharp rise of specific heat at the onset of the neutron drip (ND) and above T_c at which neutrons are unpaired

⇒ large heat reservoir that keeps T at the ND very stable

- Duration of the plateau ⇔ time required by the cooling wave to propagate outward to the ND point
- Cool core ⇔ M>1.5 Msun (cooling via direct URCA)
- Flux ledge to a persistent level? (March 2003 Chandra data)

BUT (Mereghetti,…SZ et al, 2006a):

3 new XMM observations of SGR 1627-41 in a low luminosity state

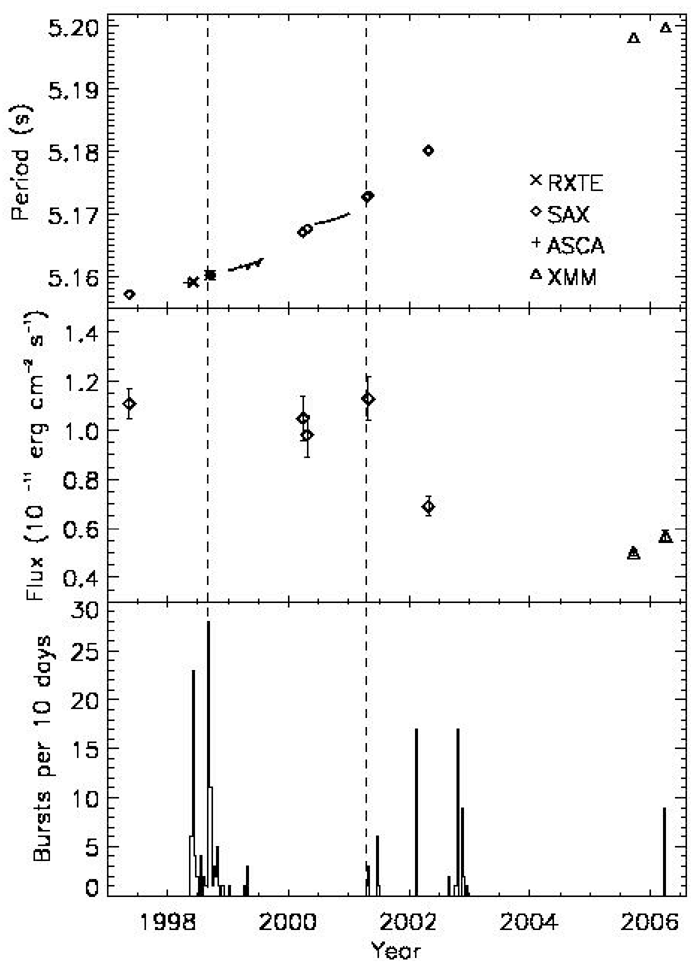


- F_{obs} continues to fade also after Sept 2001
- Lowest ever luminosity from a SGR:$3.5 10^{33} d_{11}^2$ erg/s
- Reanalysis of the sax data: no evidence for a plateaux at 400-800d
- Before the rapid decline seen by Chandra (Sept2001):
  - $F_{unabs} \sim (t-t_0)^{-0.6}$
  - t_0 = time of the outburst discovery

Low luminosity and soft spectrum VERY similar to those of XTE1810-197 after its discovery as bright transient in Jan 2003! (Ibrahim et al, 2004)
⇒ Are XTE1810 and SGR1627 at their steady quiescent level?

Mereghetti,… SZ et al, 2006b:

New, deep XMM observations of SGR 1900+14



- 50ks, after 3yrs during which no bursts have been observed
- Fading in 2002-2005: related to the apparent decrease in bursting activity?
- L decay shown much smaller than that of SGR 1627-41:
  - F only faded by a factor ~2 in 3yrs
  - $F(t) \sim (t-t_0)^{-0.17}$
  - t_0 =time of the intermediate flare of 18 April 2001 (Feroci et al 2003).

Crustal echo, magnetospheric de-twisting (i.e. decrease in the returning currents) or both?

SUMMARY AND HINTS FOR FUTURE WORK:

- A flatter slope may suggest that a mechanism of the second kind (i.e. surface heating by returning currents) is at work.

- BUT the Lyubarsky et al. 2002 only computed a 1-D model

- Increasing theoretical and observational evidence that strong poloidal and toroidal components can be present in the NS crustal magnetic field (e.g. Geppert et al 2006)

  - Heat transfer strongly anisotropic.
  - A strong B-field channels the heat flow along its field lines
  - Large meridional components ⇔ large inhomogeneities in the surface T distribution.
  - Toroidal fields substantially limit the radial conductivity (heat blanketing) forcing energy to be transferred into narrow regions along the polar axis.

- No detailed computations are available!

- Crustal fields with large poloidal and toroidal components might produce flatter L decays (lower efficiency of the radial conductivity in establishing a substantial thermal gradient between the core and the surface; the latter being proportional to the flux of heat outward).