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Transient phenomena in anomalous X–ray pulsars and soft γ–ray repeaters

The strongest magnets in the Universe

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Abstract. In 2003 a previously unpulsed Einstein and ROSAT source cataloged as soft and dim (L_X of few $\times 10^{33}$erg s^{-1}) thermal emitting object, namely XTE J1810-197, was identified as the first unambiguous transient Anomalous X-ray Pulsar. In September 2006 *Swift* Burst Alert Telescope (BAT) detected an intense burst from the candidate AXP CXOU J164710.2−455216, which entered in an outburst state reaching a peak emission of at least a factor of 300 higher than quiescence. In March 2006 *Swift* recorded a rare 30s-long sequence of short bursts and intermediate flares from SGR 1900+14. Here, we briefly outline the recent results concerning the transient phenomena observed in these magnetars. In particular, XTE J1810-197 and CXOU J164710.2−455216 have probed to be important laboratories to study the timing and spectral properties of the transient AXP class from outburst to quiescence, while new important information have been inferred from X-ray and radio band simultaneous observations of XTE J1810-197. For the first time ever, the *Swift* dataset of SGR 1900+14 allowed to test the magnetar prediction for the trapped fireball through time resolved spectroscopic study on timescales down to <10ms.

Key words. Pulsars; Magnetars; X-rays; Variability

1. Introduction

Two small classes of isolated neutron stars are known to show spectacular events during which their luminosity may change up to 10 orders of magnitude on timescales down to few milliseconds. These objects are better known as Anomalous X–ray Pulsars (AXPs; 10 objects plus 1 candidate) and Soft γ-ray Repeaters (SGRs; 4 objects plus 2 candidates; for a review see Woods & Thompson 2006). It is believed that AXPs and SGRs are linked at some level, owing to their similar timing properties (spin periods in the 2-12 s range and period derivatives $\dot{P}$ in the 10^{-13}–10^{-11} s s^{-1} range). Both classes have been proposed to host neutron stars whose emission is powered by the decay of their extremely strong magnetic fields ($> 10^{15}$ G; Duncan & Thompson 1992; Thompson & Duncan 1995).

Different types of X-ray flux variability have been displayed by AXPs and SGRs. From slow and moderate flux changes (up to a fac-

Send offprint requests to: G.L. Israel tor of few) on timescales of years (virtually all the object of the class), to moderate-intense outbursts (flux variations of a factor up to 10) lasting for 1-3 years (1E 2259+586, and 1E 1048.1−5937), to intense burst activity (fluence of 10^{36} – 10^{42} ergs) on sub-second timescales (4U 0142+614, XTE J1810-197, 1E 2259+586 and 1E 1048.1−5937; see Kaspi 2007, for a review on the X-ray variability), to dramatic and hyper-energetic Giant Flares, during which up to 10^{47} ergs s^{-1} may be released.

It was only in 2003 that the first transient AXP was discovered, namely XTE J1810-197, which displayed a factor of >100 persistent flux enhancement with respect to the unpulsed pre-outburst quiescent luminosity level ($\sim 10^{33}$ erg s^{-1}; Ibrahim et al. 2004; Gotthelf et al. 2004; Israel et al. 2004; Rea et al. 2004). Two years later this source was also found to be a bright highly polarized transient radio pulsar, a unique property among both AXPs and radio pulsars citeperic05. In 2006 another AXP, namely CXOU J164710.2−455216, displayed a bursting-outbursting behavior with a maximum flux variability of > 300, followed by extreme and daily changes both in the spectral and timing properties Muno et al. (2006a,b); Israel et al. (2007a).

These two sources currently represent our best opportunity in order to study the evolution of the main spectral and timing parameters as a function of flux by keeping fixed other parameters (such as distance and geometrical angles) otherwise difficult to infer (similarly to the pioneering studies on accreting X–ray pulsars). In the following we will briefly outline the recent results obtained from the analysis of these two AXPs.

2. XTE J1810–197: from outburst to quiescence

Since the very first *XMM-Newton* 2003 observations of XTE J1810-197, carried out approximately one year after the onset of the outburst, it was evident Gotthelf et al. (2004) that the source spectral shape (two blackbodies with kT=0.29±0.03 keV and R_{BB} ≈5.5 km, and kT=0.70±0.02 keV and R_{BB} ≈1.5 km; L_X $\sim 5\times10^{34}$ erg s^{-1} in the 0.5-10 keV range) was significantly different from that serendipitously recorded by ROSAT in 1992 (one BB with kT≈160 eV and R_{BB} ≈10 km; L_X $\sim 7\times10^{32}$ erg s^{-1} in the 0.1-2.5 keV range and for a distance of 3.6 kpc). Moreover, the source showed a 5.54 s pulsation with a pulsed fraction of nearly 45% during outburst, while an upper limit of 24% was inferred from the ROSAT data. The above issues originated a number of important questions: is the soft BB component detected by *XMM-Newton* evolving into the quiescent BB component seen by ROSAT? Alternatively, is the emission from the whole surface always present? What happens to the higher temperature BB component as the source approaches to quiescence? Which is the pulsed fraction level of the source in quiescence (if detectable)?

In order to try answering to the above questions we made use of all the archival (6) and proprietary (3) *XMM-Newton* observations (for the details see Rea et al 2007; Bernardini et al. 2008) and fitted the nine spectra all together. In particular, we can outline the obtained results as follows:

2BB model: By extending the spectral recipe outlined by Gotthelf et al. (2004); Gotthelf & Halpern (2005) we applied the two BB spectral fit analysis to the fading phases of XTE J1810-197 until March 2007 when the flux source was ∼1.2 times above the pre-outburst level (reduced χ^2 ∼1.23 for 975 degree of freedom, d.o.f.; N_H=0.58±0.02 $\times10^{22}$ cm^{-2}). While the soft BB component smoothly approaches to that in quiescence, we note a number of ambiguities difficult to account for by means of simple assumptions. The hard component BB radius is not monotone and it increases after 2.5 years of smooth decrease while the temperature approaches to that of the soft BB in 2003. Moreover, none of the spectral parameters or components is able to account for the flattening, at the 25% level, showed by the pulsed fraction evolution Bernardini et al. (2008).

3BB model: The addition of a further BB component gives a better fit (reduced χ^2 ∼1.15 for 973 d.o.f.; N_H=0.70±0.02 $\times10^{22}$ cm^{-2}; F-test probability gives 7.3σ) though not yet satisfactory. Notably, the fit gives parameters and flux (for the coldest BB) which are virtually equal to those inferred in quiescence. Even more interesting, the hottest BB components show a nearly constant evolution of the temperatures, leaving the radii as the only variable parameters to account for the decaying phases of the outburst. Since September 2006 the hottest BB is not anymore needed to fit the spectra (upper limit $\sim 5 \times 10^{-14}$ erg cm^{-2} s^{-1}). In this scenario, the already mentioned flattening of the pulsed fraction might be easily accounted for by the disappearance of the hot BB.

X–ray and radio campaigns: The simultaneous radio and X–ray observations of XTE J1810-197 carried out in September 2006, March 2007 and September 2007 showed that the pulse alignment between the two bands is high and stable (Israel et al. 2008a). This suggests that the X–ray and radio emitting ragions are likely different but nearby (or superimposed), the X–rays likely coming from a larger area. Moreover, during the first campaign large radio flux (~50%) and pulse shape variations have been detected which do not correlate with any change (at a few percent level) of the X–ray timing and/or spectral parameters. This suggests that the X–ray emission likely originates deep in the crust and, more in general, the radio and X–ray mechanisms appear different.

We emphasize that the spectral model used above (three BBs) is a first attempt to infer the evolution of a number of physical quantities while making use of well assessed and reliable components. The three BB model has the advantage of being model-independent, and of minimizing the number of variable parameters during the outburst (only the radii are changing and both decreasing). With respect to other model recently developed (see for example Güver et al. 2007) we carried out a cross check with the timing properties and rejected all those models/components not able to reproduce the pulsed fraction evolution.

All the above inferred information are important in the effort we are currently making in developing and using more detailed and complex (but necessarily model-dependent) scenarios. In particular, the simultaneous fit of the spectra and energy resolved folded light curves might provide a tool to infer the geometry of the surface temperature distribution and to independently check the goodness of the assumed spectral model(s).

3. CXOU J164710.2–455216: from quiescence to outburst

On 2006 September 21, the candidate magnetar CXOU J164710.2−455216 emitted an intense ($\sim 10^{39}$ erg s^{-1}) and short (20ms) burst promptly detected by the *Swift* BAT. Together with the burst, large changes in the timing and spectral properties of the persistent component were detected and seen evolving during the subsequent weeks. In particular, the *Swift* XRT monitoring (plus two proprietary *XMM-Newton* and two archival *Chandra* observations) during the first six months since the outburst allowed to infer the following characteristics:

The phase-coherent timing and the glitch: The pulse phase evolution is consistent with the occurrence of a large glitch ($\Delta\nu/\nu \sim 10^{-4}$), the largest ever detected from a neutron star (the glitch detection was obtained by minimizing the number of variable peaks in the pulse profile; see Israel et al. (2007a) for details). We also detected a quadratic component in the pulse phases corresponding to a $\dot{P} = 9.2(4) \times 10^{-13}$ s s^{-1} and implying a magnetic field strength of $\sim 10^{14}$ G

The flux and pulsed fraction evolution: The first 1-10 keV *Swift* XRT spectrum was carried out ~13 hours after the burst detection and showed, in addition to a $kT \sim 0.65$ keV blackbody ($R_{BB} \sim 1.5$ km) , a $\Gamma \sim 2.3$ power-law component accounting for about 50% of the observed flux. The pulsed fraction of the 10.61 s pulsations was seen to drop from a value of ~ 80% (as recorded by an *XMM-Newton* observation few days before the burst) to ~ 10% few hours after the BAT event.

All these results confirmed unambiguously that CXOU J164710.2−455216 is a transient and bursting AXP. In particular, the comparison of the cumulative properties of CXOU

J164710.2−455216 with those of other AXPs which showed a similar behavior in the latest years confirmed that these outbursting events are more common than previously thought.

4. The Swift gaze into the 2006 burst forest SGR 1900+14

On 2006 March 29, after several days of burst activity, the Soft γ-ray Repeater SGR 1900+14 displayed a series of short bursts and intermediate flares lasting for about 30 s, during which all the *Swift* instruments were pointed to the source. The good statistics, the fine time resolution (4 ms) and the wide energy coverage (0.2–100 keV) allowed us to carry out a detailed study of the timing and spectral properties during both the bursts and persistent emission. Large variations were detected and their evolution studied over a range of timescales. Although not all the observational properties can be accounted for by the current magnetar scenario, the large majority of them are in overall good agreement with it. In particular, we found (Israel et al. 2008b):
(a) a break, around $\sim 10^{41}$ erg s^{-1}, in the known correlation between the luminosities of the two blackbody components which fit well the BAT time-resolved and BAT+XRT integrated spectra. Above this value the softer blackbody shows signs of saturation, while the luminosity of the harder blackbody still increases up to $\sim 3 \times 10^{41}$ erg s^{-1};
(b) the existence of a correlation between temperature and emitting surface of the blackbodies ($R^2 \propto kT^{-3}$), which holds through the most luminous phases of the flares ($L_{\rm tot} \geq 10^{41}$ erg s^{-1}).

The above two findings together can be interpreted in terms of the two populations of photons from the O- and E-mode polarizations modes which are foreseen in the magnetar scenario and the regions from which they escape: larger and colder the O-mode photon region, harder and smaller the E-mode one.

Moreover, we note that the maximum observed luminosity from flares ($\sim 3 \times 10^{41}$ erg s^{-1}) is attained by the harder blackbody component at an effective temperature of $\sim$10 keV and radius of $\sim$15 km, which is similar to the inferred magnetic Eddington luminosity at the same radius, for a surface dipole field $\simeq 8 \times 10^{14}$ G (as deduced from the spindown of SGR 1900+14).

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