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Monitoring magnetar outbursts

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Abstract. We report on recent results concerning the timing properties of two transient sources, namely SGR 0418+5729 and Swift J1822.3-1606, for which dedicated monitoring programs have been carried out in the latest years. The timing analysis allowed us to obtain the first measurement of the first period derivative of SGR 0418+5729, $\dot{P} = 4(1) \times 10^{15}$ss^{-1}, significant at a $\sim 3.5\sigma$ confidence level. This leads to a surface dipolar magnetic field of $B_{dip} \sim 6 \times 10^{12}$ Gauss, confirming SGR 0418+5729 as the lowest magnetic field magnetar. The X-ray timing analysis of Swift J1822.3-1606 showed that a second period derivative is needed in order to fit well the pulsation phases. The period derivative of $\dot{P}$=1.1(4)×10^{-13}s s^{-1}leads to an estimate of the dipolar surface magnetic field of $B_{dip} = 3 \times 10^{13}$ G. This measurement makes Swift J1822.3-1606 the second magnetar with a dipolar magnetic field lower than the electron critical field (after SGR 0418+5729; Rea et al. 2010).

Key words. stars: magnetic fields — stars: neutron

1. Introduction

Magnetars are young (age of ~10^{4}-10^{6} yrs) and isolated X-ray pulsars, believed to have the highest magnetic fields known to date (~ 10^{14}–10^{15} G; Duncan & Thompson 1992; Thompson & Duncan 1993). This class comprises the Anomalous X-ray Pulsars (AXPs) and the Soft Gamma-ray Repeaters (SGRs), observationally very similar in many respects (see Mereghetti 2008 for a recent review): spin periods in the 2–12 s range, large period derivatives (10^{-13}–10^{-10} s s^{-1}), unpredictable bursting activity on different timescales (from ms to hundreds of seconds) and luminosities (10^{38}–10^{46} erg s^{-1}). Until not long ago AXPs were thought as persistent and stable X-ray sources. In 2003 the first unambiguous event of long term transience from an AXP was discovered by *RXTE*, namely XTE J1810–197, which displayed a factor of >100 flux enhancement with respect to the pre-outburst luminosity level as seen by the *ROSAT* and *Einstein* missions (~10^{33} erg s^{-1}; Gotthelf et al. 2004; Gotthelf & Halpern 2005; Bernardini et al. 2009). The transient nature of this AXP provided the first hint that a relatively large number of members of this class had not been discovered yet, and suggested that others would manifest themselves in the future through a phenomenology (bursts or outbursts) similar to that displayed by XTE J1810–197(see also Woods et al. 2005).

Since 2003, thanks to the specific observing capabilities of a number of space missions such as *Swift*, *INTEGRAL* and Fermi, several new magnetars have been discovered

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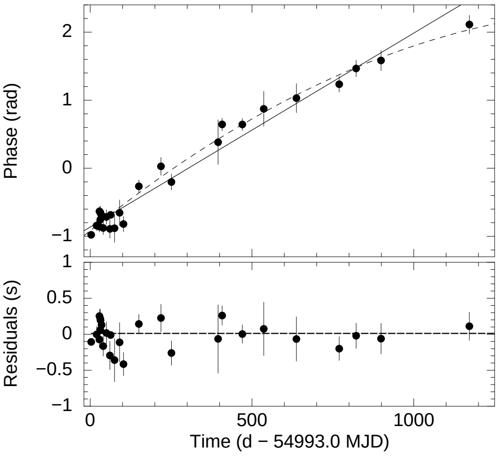

Fig. 1. 2–10 keV *RXTE*, *Swift*, *XMM-Newton* and CXOU J010043–7211 pulse phase evolution with time, together with the time residuals (lower panel) with respect to the phase-coherent timing solution with the $\dot{P}$ component. The solid and stepped lines in the upper panel represent the timing solution without and with the first period derivative component.

mainly through the detection of rapid bursts events (10-100ms duration) and/or long-term (in the week-year range) outbursts (see Rea & Esposito 2011; Rea 2012 for recent reviews). Among others are SGR 0418+5729 and Swift J1822.3-1606 discovered in 2009 and 2011 respectively, and which have been object of extensive observational campaigns in order to monitor their timing and spectral properties as a function of the decaying X-ray emission.

Inferring magnetic field strengths of transient magnetars is routinely done by monitoring the timing properties of the source when in outburst. These are inferred through the assumption that, as ordinary pulsars, they are spun down via magnetic dipolar losses: $B_{dip} \sim 3.2\times10^{19}(P\dot{P})^{1/2}$ Gauss, where$P$ is the spin period in seconds, $\dot{P}$ its first derivative (assuming a neutron star mass and radius of $R \sim 10^{6}$ cm and $M \sim 1.4M_{\odot}$, respectively).

2. SGR 0418+5729

SGR 0418+5729 was discovered in June 2009 when the Fermi Gamma-ray Burst Monitor (GBM) observed two magnetar-like bursts (van der Horst et al. 2010). Follow-up observations with several X-ray satellites show that it has x-ray pulsations at ~9.1 s, well within the range of periods of magnetar sources. Further studies show that SGR 0418+5729 exhibits all the typical characteristics of magnetars with the exception of the first derivative of the period which was not detected after almost six months of observations (3σ first period derivative upper limit of $|\dot{P}| < 1.2 \times 10^{-14} s\, s^{-1}$; Rea et al. 2010). All the CXOU J010043–7211 and *XMM-Newton* event files collected between November 2009 and August 2012 were used in order to extend the already derived coherent timing solution. Photon arrival times were corrected to the barycentre of the Solar system. Timing analysis was carried out by means of a phase-fitting technique (details on this technique are given in Dall'Osso et al. 2003; see also Esposito et al. 2010 for further details on this source).

The fit of the pulse phases with a linear component results in a reduced $\chi^2_r \sim 3.2$ for 26 degree of freedom (d.o.f. hereafter). The inclusion of a quadratic term, corresponding to a first period derivative component, resulted to be significant at a confidence level of 3.5σ (by means of a F-test; a MC simulation gave similar results; Rea et al. 2013). The resulting best-fit solution corresponds to $P = 9.07838822(5)$ s (1σ c.l., 2 parameters of interest; epoch 54993.0 MJD) and $\dot{P} = 4(1) \times 10^{-15}$ s s^{-1} with a reduced $\chi^2_r \sim 2.1$ (for 25 d.o.f.; see also Figure 1). The new timing solution implies a r.m.s. variability of only 0.2s.

Finally, we inferred a magnetic field strength $B_d = (6 \pm 2) \times 10^{12}$ Gauss, well below the critical value B_{QED}=4.4×10^{13} Gauss: fully consistent with the 3σ upper limit reported in Rea et al. 2010 (more details are in Rea et al. 2013).

Based on the above phase-coherent timing solution we also studied the pulse shape and pulse fraction evolution. There is an evident increase trend starting soon after the burst detection with a recovery towards a possible asymptotic value which seems to be at about 70-80% level. However, we note that at this rate the 100% pulsed fraction level is expected to be

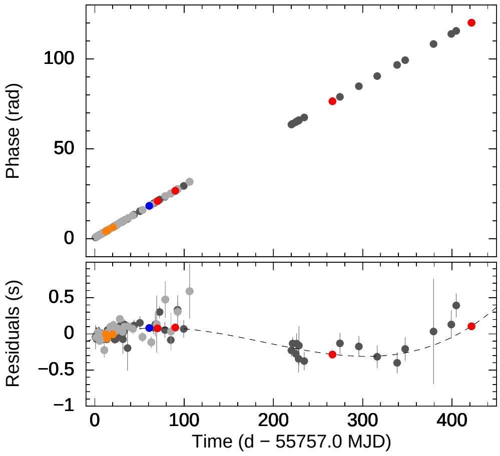

Fig. 2. Same as Figure 1 but for Swift J1822.3-1606. The pulsation phases as inferred from *Swift*, *RXTE*, *Suzaku*, *XMM-Newton* and CXOU J010043–7211 mission have been collected and fitted with a quadratic plus a cubic terms (upper panel). Time residuals with respect to a timing solution including the first period derivative component, only are also shown (lower panel). The stepped line refers to the coherent solution which also includes the second derivative component.

reached within 3000÷4000 days since the initial trigger. Only future observations are expected to shed light on the quiescent level of the pulsed fraction.

3. Swift J1822.3-1606

On July 2011 a new magnetar, namely Swift J1822.3-1606, has been discovered by *Swift* through the detection of a short burst. Subsequently, the source was followed by all the current generation of X-ray satellites. While the results of the first 9 months of X-ray monitoring of this new magnetar, namely Swift J1822.3-1606, has been already presented and discussed by Rea et al. (2012), here the whole dataset of available X-ray pointings until September 2012 has been collected, reduced and analysed. With respect to the previous coherent timing solution reported in literature, we found that a second period derivative is needed (Rea et al. 2012; Scholz et al. 2012; see Figure 2). The new timing solution is: $P = 8.43775793(3)s$, $\dot{P} = 1.11(4)\times10^{-13}\mathrm{s\,s^{-1}}$ and $\ddot{P} = -6.8(5)\times10^{-21} ss^{-2}$ (1σ c.l., 3 parameters of interest; epoch 55757.0 MJD; more details are in Rodriguez et al. 2013). Correspondingly, the inferred dipolar magnetic field is $B = 3.1(1)\times10^{13}$ Gauss. Also in this case the value is below the B_{QED} critical value, making Swift J1822.3-1606 the second lowest magnetic field magnetar. The newly inferred values of $\dot{P}$ and B_{dip} are significantly different from those reported so far in the literature and based on smaller baselines (Scholz et al. 2012; Rea et al. 2012). This finding is suggesting that the timing properties of Swift J1822.3-1606 need a longer observing time in order to properly find and characterize all the period derivative components.

4. Conclusions

After more than three years from its discovery, the first period derivative of SGR 0418+5729 has been finally measured at a 3.5σ c.l., allowing to confirm that this magnetar has the weakest know dipolar magnetic field among the objects of the class. Therefore, for the first time a magnetar with a low dipolar magnetic field is witnessed, showing that a critical magnetic field is not necessary to have magnetar-like activity. It is suggested that a hidden toroidal or multipolar component of the field, larger than the measured dipolar one, can be responsible for the behaviour of this relatively old magnetar (Rea et al. 2010). The monitoring of Swift J1822.3-1606 showed that a second period derivative is needed in order to keep the phase-coherence of the timing solution, suggesting that a longer monitoring is necessary in order to be sure that the inferred value of B_{dip} is stable. So far the latter quantity is below the B_{QED} field, the second lowest value after that of SGR 0418+5729.

Although the fact that both sources have a sub-critical dipole field is not relevant per se, and that the dipolar field in Swift J1822.3-1606 is at least four times higher than that of SGR 0418+5729, it is worth stressing that the discovery of a second magnetar with a magnetic field in the radio-pulsar range strengthens the idea that magnetar-like behaviour may be much more widespread than what believed in the past, and that it is related to the intensity and topology of the internal and surface toroidal components, rather than to the surface dipolar field (Rea et al. 2010; Turolla et al. 2011; Perna & Pons 2011).

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