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# Search for Radio Pulsations in four Anomalous X-ray Pulsars and Discovery of two New Pulsars

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**Abstract** We have performed deep searches for radio pulsations from four southern anomalous X-ray pulsars (AXPs) to investigate their physical nature in comparison with the rotation powered pulsars. The data were acquired using the Parkes radio telescope with the 1.4 Ghz multibeam receiver. No pulsed emission with periodicity matching the X-ray ephemeris have been found in the observed targets down to a limit of $\sim$ 0.1 mJy. A blind search has also been performed on all the 13 beams of the multibeam receiver (the central beam being pointed on the target AXP), leading to the serendipitous discovery of two new radio pulsars and to the further detection of 18 pulsars. Also a search for single dedispersed pulses has been performed in the aim to detect signals similar to those of the recently discovered rotating radio transients.

**Keywords** AXPs: individual (1E 1048.1–5937, 1RXS J170849.0–400910, 1E 1841–045, AX J1845–0258) · Pulsar

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## 1 Introduction

In the last two decades, a significant amount of observational and theoretical effort has been dedicated towards the understanding of an unusual class of X-ray pulsars, namely the Anomalous X-Ray pulsars (AXPs) and the Soft Gamma-Ray Repeaters (SGRs). These relatively bright X-ray sources were soon recognized as a distinct class of neutron stars with respect to the well known radio pulsars or X-ray binary populations. In particular, they are not pulsating in the radio band, their rotational energy loss alone is not sufficient to power the observed X-ray luminosity, and there is no evidence for a companion star.

Instead, the X-ray emission from these sources is thought to be powered by the decay of the ultra-strong magnetic field according to the magnetar theory (Damour & Taylor 1992; Thorsett & Dewey 1993; Thompson & Duncan 1995). This is suggested by the fact that, for an isolated neutron stars characterised as a magnetic dipole, their inferred magnetic fields are extremely high ($B \sim 10^{14} - 10^{15}$ Gauss). These field strengths lies above the so-called "quantum critical field" $B_c = 4.4 \times 10^{13}$ G, above which the radio emission of pulsars is expected to be suppressed by processes such as photon splitting, which may inhibit pair-production cascades (Baring & Harding 1998). However, the efficacy of this process is put in doubt by the discovery of high magnetic field radio pulsars (Camilo et al. 2000; McLaughlin et al. 2003) and transient radio pulsed emission from at least one AXP (Camilo et al. 2006).

In the past years searches for radio pulsations from AXPs and SGRs have always given negative results (e.g. Crawford et al. 2002). However, in two peculiar circum-

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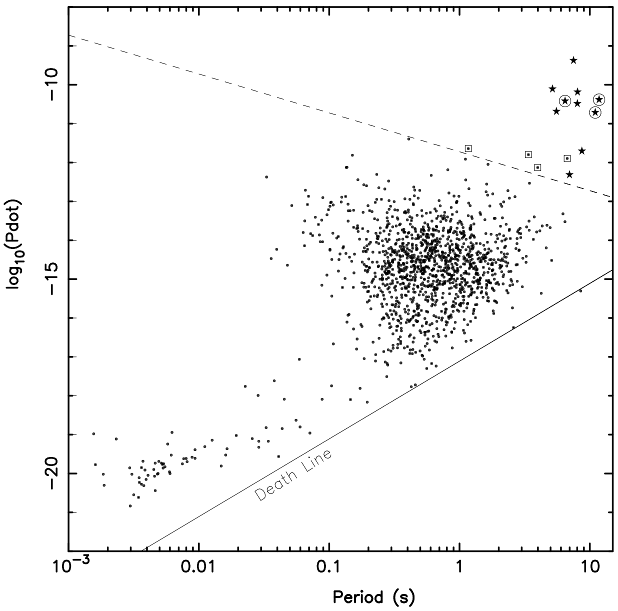

**Fig. 1** $P-\dot{P}$ diagram for radio pulsars (dots) and magnetars (stars). The dashed line represents the limit for radio emission quenching due to photon splitting (Baring & Harding 1998). The four sources surrounded by a square emit in radio besides being above this line. The three confirmed AXPs of our sample are surrounded by a circle.

stances radio emission have been detected a) following the rare and highly energetic giant flare events from SGRs (Frail et al. 1999; Cameron et al. 2005; Gaensler et al. 2005), and b) during the outburst of the only confirmed example of a transient AXP, XTE J1810-197. In the former case, the radio emission slowly fades on a timescale of weeks and in the later, the radio emission, initially discovered as a VLA point source (with angular resolution of 6″) of flux density $4.5 \pm 0.5$ mJy at 1.4 GHz (Halpern et al. 2005), has also been recently found to be pulsed at the X-ray period (Camilo et al. 2006).

With this picture in mind we have undertaken a systematic deep search for radio pulsations in three confirmed (1RXS J170849.0–400910, 1E 1048.1–5937, 1E 1841–045 ) and one candidate AXP (AX J1845–0258 ), visible from the southern hemisphere using the Parkes radio telescope. Observations and data analysis are described in §2 while in §3 we report on the obtained results, discussed in 4.

## 2 Observations and Data Analysis

In Table 1 the sample of observed AXPs is presented. For each object the name, period and period derivative of X-ray pulsations, the derived surface magnetic field, the estimated distance D and the association with a SNR or with a nebula are listed.

The radio observations have been performed between October 12 and 15 1999 using the 13 beams of the multibeam receiver (Staveley-Smith et al. 1996) of the Parkes radio telescope (NSW Australia) at a frequency of 1374 MHz, with the central beam pointed at the target AXP. In order to mitigate the effects of the dispersion of the signals in the interstellar medium (ISM), the total 288 MHz bandwidth is split into 96 frequency channels each 3-MHz wide. The outputs from each channel are summed in polarisation pairs, high-pass filtered and 1-bit sampled every 1.0 or 1.2 ms. Each source has been pointed for 2.8 hours and for all but 1E1841−0450 the observation has been performed twice.

Data from the central beam of the multibeam receiver (pointed on the AXPs) have been analysed using the programme `pdm`: the code takes as input a period P and a dispersion measure DM and folds the time series according to a number of trial values around the input ones, searching for the combination of P and DM for which the signal-to-noise ratio S/N is maximised. The period range searched for each source has been obtained from the X-ray ephemeris and their errors (see Table 1). A number of trial DM values, ranging from 0 up to the value giving a maximum broadening of the pulse of 10% of the period, has been explored.

The observations relative to all the 13 beams have been subsequently analysed with the blind search code `pmsearch` (an FFT based code; see Manchester et al. 2001) to search for possible radio counterparts of the AXPs pulsating at a different period with respect to the one measured in X-rays and to search for new radio pulsars in the vicinity of our main targets.

Finally a code sensitive to strong single dispersed pulses (Cordes & McLaughlin 2003) has been applied to the 13 beams of each pointing with the purpose to discover signals similar to those seen in the class of the rotating radio transients (RRATs, McLaughlin et al. 2006). The aim was to test if AXPs have RRAT-like emission and to search single pulses from nearby sources.

## 3 Results

No radio pulsation has been found in the four AXPs observed down to a limit of $\sim 0.06-0.1$ mJy (depending on the source; see Table 2).

Folding the time series for 1E 1048.1–5937 with a trial period of 6.16 s and a DM of 334 pc cm$^{-3}$, the pulsar J1058-5957 (Kramer et al. 2003) has been detected through its tenth sub-harmonic, confirming the reliability of the detection algorithm used.

Analysis of the data collected in all the 13 beams of the Parkes multibeam receiver used during this work led to the serendipitous discovery of two new radio pulsars, both detected in the same beam and hence having the provisional names J1712–3943-1 and J1712–3943-2. The first pulsar has a spin period of 0.78 s and a dispersion measure of 525 pc cm$^{-3}$, while the second source has a period of 92.5 ms and a DM of 713 pc cm$^{-3}$. The average

| Name | $P$ (s) | $\dot{P}$ ($10^{-11}\,\mathrm{s\,s^{-1}}$) | B ($10^{14}$ G) | D (kpc) | DM$_{nom}$ (pc cm$^{-3}$) | association |
|---|---|---|---|---|---|---|
| 1E 1048.1–5937 | 6.456109(5) | 3.3 | 4.7 | 5 | 279.7 | HI bubble |
| 1RXS J170849.0–400910 | 11.00170(4) | 1.9 | 4.6 | 8 | 742.5 | – |
| 1E 1841–045 | 11.77505(5) | 4.1 | 7.0 | 7 | 529.7 | G27.4+0.0 |
| AX J1845–0258 | 6.9712(1) | – | – | 8 | 646.1 | G29.6+0.1 |

**Table 1** For each of the four AXPs of our sample columns 2 and 3 report the most recent period and period derivative from the X-ray timing (1E1048: Tiengo et al. 2005, 1RXS J1708: Rea et al. 2005, 1E 1841: Gotthelf et al. 2002, AXJ 1845: Gotthelf & Vasisht 1998), column 4 is the surface magnetic field derived from the dipole formula $B = 3.2 \times 10^{19}\sqrt{P\dot{P}}$, columns 5 and 6 report the distance estimated and the relative dispersion measure derived adopting the Cordes & Lazio (2002) model for the distribution of free electrons in the ISM (the values obtained using Taylor & Cordes (1993) model are similar) and last column shows the association with supernova remnant or with hydrogen bubble (Gaensler et al. 2001; Gaensler et al. 2005). Numbers in parentheses are the errors on the last quoted digit.

| Name | P range (s) | DM$_{max}$ (pc cm$^{-3}$) | $S_{min}$ mJy |
|---|---|---|---|
| 1E 1048.1–5937 | 6.0438 – 7.2524 | 62754 | 0.11 |
| 1RXS J170849.0–400910 | 9.6247 – 12.3734 | 107069 | 0.06 |
| 1E 1841–045 | 10.3026 – 13.2451 | 114611 | 0.06 |
| AX J1845–0258 | 6.0999 – 7.8426 | 67861 | 0.06 |

**Table 2** For each observed AXP we report here the period range and maximum DM explored in the `pdm` search (columns 2 and 3) and the upper limits on the flux densities (column 4).

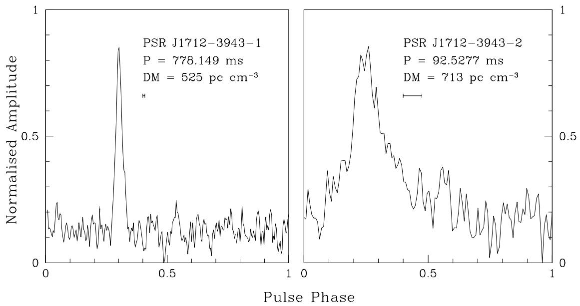

**Fig. 2** Mean 1374-MHz pulse profiles of the newly discovered pulsars J1712–3943-1 (left) and J1712–3943-2 (right) obtained by adding the data of the discovery and confirmation observations. The maximum of each profile is placed at phase 0.3 (the range on the x-axis of each panel being 0 to 1). For each profile, the pulsar name, period and DM are given. The small horizontal bar drawn under the DM indicates the effective resolution of the profile, calculated by adding the bin size, the sampling time and the effects of interstellar dispersion in quadrature.

pulse profiles of the new pulsars, obtained summing the data relative to the detection and confirmation observations, are shown in Figure 2.

The `pmsearch` code also detected 18 previously known pulsars present in the pointed areas.

Finally no new RRAT-like signal has been found in the single pulse search over the 52 observed regions, while two previously known pulsars (J1705-3950 and J1844-0433) have been detected also through their single pulses.

## 4 Discussion and Conclusions

No radio pulsation has been found from the four southern AXPs observed, down to a limit of $S_{min} \sim 0.1$ mJy (Table 2).

Comparing the upper limits on the luminosity at 1400 MHz (defined as $L_{1400} = S_{min} \times D^2$) for our targets with the luminosity of the observed radio pulsar population in the Galactic field we note that the limits reached by our search are a factor of six lower than the median of the population. Note however that, if we compare our results with the *intrinsic* luminosity distribution of the radio pulsars we obtain a probability of $\sim 76\%$ that our observations are not deep enough to detect a radio pulsed signal from our targets.

In considering the causes of the non detection of a radio pulsed signal from our four targets, besides the luminosity bias, we must take into account the possibility that, although the X-ray beam is pointing toward us, the radio beam, usually narrower, is not. Assuming a pulse duty cycle of $\sim 5\%$ typical of long period pulsars and similar to that of the radio pulsed signal detected by Camilo et al. (2006) in the transient AXP XTE J1810–197 ($\sim 4\%$ at 1.4 GHz), we can calculate, that the probability that such a narrow radio beam misses the earth is $\leq 77\%$. The composite probability that the beams of all four AXPs are not pointing toward us is hence $\leq 34\%$.

The non detection of RRAT-like bursts from any of these AXPs, despite our long exposures, seems to weaken the hypothesis that RRAT bursts might be related to the short bursts observed from the magnetars leaving us with other plausible conjectures of a relation with other classes of neutron stars such as middle aged radio pulsars displaying giant pulses (Reynolds et al. 2006; Weltevrede et al. 2006) or with X-ray Dim Isolated Neutron Stars (Popov, Turolla & Possenti 2006).

The only case of a detection of radio pulsations from an AXP concerns the only confirmed transient magnetar XTE J1810–197 (Camilo et al. 2006). Radio emission from this source is strongly related with the occurrence of an outburst of its X-ray emission (Halpern et al. 2005), as well as an IR enhancement (Rea et al. 2004). Furthermore, whereas the X-ray flux is decaying exponentially with timescale of a few hundreds days (Gotthelf & Halpern 2005), XTE J1810–197 radio emission is still on more than 3 years after the X-ray outburst. Interestingly the sole other possible transient AXP is the candidate AX J1845–0258, one of our targets. Our radio observations of this source were performed more than six years after its possible X-ray outburst occurred in 1993, hence unfortunately nothing can be safely concluded from our upper limits, in favor or against the possible radio and X-ray correlation during the outbursts of this source. However, assuming that AX J1845–0258 experienced, after the X-ray outburst, a phase of radio emission similar to that of XTE J1810–197, our null detection implies that the fading of the radio emission has a time scale of the order of few years: in particular, if AX J1845–0258 at the onset of its putative radio emission phase had a similar luminosity as XTE J1810–197, this would imply a decrease in $L_{1400}$ of a factor of $\sim 20$ over six years.

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