Search for radio pulsations in four Anomalous X-ray Pulsars and discovery of two new pulsars

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ABSTRACT

We report on observations of four southern Anomalous X-ray Pulsars, (1RXS J170849.0–400910, 1E 1048.1–5937, 1E 1841–045 and AX J1845–0258), obtained at 1.4 GHz using the Parkes radio telescope. Radio pulsations from these sources have been searched (i) by directly folding the time series at a number of trial periods centered on the value of the spin rate obtained from the X-ray observations; (ii) by performing a blind search; (iii) using a code sensitive to single dedispersed pulses, in the aim to detect signals similar to those of the recently discovered Rotating Radio Transients. No evidence for radio pulsations with an upper limit of $\sim 0.1$ mJy for any of the four targets has been found. The blind search led to the serendipitous discovery of two new pulsars, rotating with a spin period of about 0.7s and of 92 ms respectively, and to the further detection of 18 known pulsars, two of which were also detected in the single-pulse search.

Key words: pulsars: searches - AXPs: individual (1E 1048.1–5937, 1RXS J170849.0–400910, 1E 1841–045, AX J1845–0258)

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 pulsars, namely the Anomalous X-Ray Pulsars (AXPs) and the Soft Gamma-Ray Repeaters (SGRs). These relatively bright X-ray sources ($10^{34} - 10^{36}$ erg s$^{-1}$), discovered either as peculiar short X-ray bursts or steady X-ray emitters, were soon recognised as a distinct class of neutron stars with respect to the well known radio pulsar or X-ray binary populations (see Woods & Thompson 2004 for a review).

The arguments that lead to this conclusion are the following: first, AXPs and SGRs are X-ray pulsators with spin periods in the range 5-12 s. Furthermore, their rotational energy loss $\dot{E}$ inferred from their spin-down rate ($\dot{E} = I \dot{\Omega}$, where $I$, $\Omega$ and $\dot{\Omega}$ are respectively the neutron star moment of inertia, angular velocity and angular velocity time derivative) is insufficient to power the observed X-ray luminosity (note that for the large majority of isolated pulsars, detected both in radio and X-ray band, the X-ray luminosity is typically 0.1% of the $\dot{E}$; Becker & Trümper 1997; Possenti et al. 2002). Second, there is no evidence for a companion star (through the search for Doppler orbital modulation of the X-ray spin period, and through observations at other wavelengths; Mereghetti et al. 1998; Wilson et al. 1999; Hulleman et al. 2000), which might power their emission through the accretion mechanism, at least with a mass greater than 0.1 $M_\odot$. An alternative source of energy is therefore required to power the X-ray emission of AXPs and SGRs.

Assuming these sources being isolated X-ray pulsars with a dipole magnetic field configuration and purely magnetic dipole losses, their inferred magnetic fields are extremely high, $B \sim 3.2 \times 10^{19} \sqrt{P \dot{P}} \sim 10^{14} - 10^{15}$ G: these magnetic fields have been identified as the possible additional energy reservoir. In fact, if AXPs and SGRs are indeed “magnetars”, i. e. isolated highly magnetic neutron stars, many of their bizarre X-ray properties might be explained: the X-ray luminosity is naturally provided by the decay of these ultra-strong magnetic fields, while their peculiar short bursts may result from magnetic induced...
cracks on the neutron star surface (Duncan & Thompson 1992, Thompson & Duncan 1993, 1995). Moreover, the long lasting flux enhancements observed in some magnetars (Rea et al. 2004; Mereghetti et al. 2003) may be associated to single fractures on a larger spatial scale, or to the episodic onset of a wind energised by frequent, small scale fractures and/or quasi-steady seismic vibrations (Thompson et al. 2002). In this scenario, the magnetars’ magnetic fields are all above the so-called “quantum critical field” $B_c = 4.4 \times 10^{13}$ G, at which the radio pulsations are expected to be suppressed by processes such as photon splitting which may inhibit pair-production cascades (Baring & Harding 1998) responsible for creating the radio emission of the normal radio pulsars. However, the discovery of high magnetic field radio pulsars (Camilo et al. 2000; McLaughlin et al. 2003) and transient radio pulsed emission from one AXP (Camilo et al. 2006) put many uncertainties with this respect making again theoretically plausible a link between AXPs and radio pulsars.

In the past years, radio observations of AXPs and SGRs, performed using different antennas and arrays, have given always negative results (e.g. Crawford et al. 2002) both to timing and interferometry searches, but revealing in a few cases some reliable associations with SNRs (Gaensler et al. 2001) and in one case an interesting stellar wind bubble blown by the massive progenitor (Gaensler et al. 2005). However, in some peculiar circumstances radio counterparts were detected: a) the SGRs’ Giant Flares, rare, catastrophic and highly energetic events, have been discovered powering a radio outburst, which slowly faded with a timescale of weeks (Frail et al. 1992, Cameron et al. 2003, Gaensler et al. 2003), b) during the outburst of the only confirmed transient AXP, XTE J1810-197, the Very Large Array (VLA) observations (with angular resolution of 6") revealed a point source of flux density $4.5 \pm 0.5$ mJy at 1.4 GHz (Halpern et al. 2003), which has recently been discovered as pulsed at the neutron star spin 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 1841–0450) 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 the context of the magnetar scenario 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 multi-beam receiver Staveley-Smith et al. 1996 of the Parkes radio telescope (NSW Australia) at a frequency of 1374 MHz, with the central beam pointed on 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 splitted 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.

The data for the central beams have been first analysed using the pdm programme: 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. Since at the time of the data analysis most of the X-ray timing solutions had big uncertainties, the range explored (see Table 2) is much wider than would have been necessary with the present knowledge. A number of trial DM values, ranging from 0 up to the value $DM_{\max}$ giving a maximum pulse broadening in a 3 MHz frequency channel of 10% of the pulse period (see Table 2) has been explored. $DM_{\max}$ is well beyond what expected for a source in the Milky Way on the basis of the available models for the distribution of free electrons in the Galaxy (Taylor & Cordes 1993, Cordes & Lazio 2002), but may take into account the possibility of the presence of dense local matter.

Making use of the relation derived by Bhat et al. 2004 between the broadening of the pulse due to the scattering caused by the ISM, $\delta t_{\text{scatt}}$, and the DM, we note that already a DM $\sim 1200$ pc cm$^{-3}$ results in a broadening of $\sim 10$ seconds at 1.4 GHz. However the relation by Bhat et al. 2004 has a very high scattering in principle allowing for reasonable values of $\delta t_{\text{scatt}}$ also for much higher DMs. Hence, for the relatively fast search performed with pdm we have ex-
The bottom panel is the integrated pulse profile obtained as a function of the pulse phase in three sub-integrations and sub-bands. The central panel on the right shows the folded time series in eight frequency sub-bands. The top grey-scale showing the S/N (the darkest the highest) is one of the blind search codes used for the de-dispersed time series, obtained, for each different DM, by summing with the appropriate delay the 96 frequency channels in which the total band is splitted. The “Tree” algorithm (Taylor et al. 1993) has been applied to the 13 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. 2004, 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 \( B = 3.2 \times 10^{13} \sqrt{PP} \), 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. 2004. Numbers in parentheses are the errors on the last quoted digit.

With the aim to search for signals from the AXPs with periods different from the ones detected in X-rays and in the hope to discover new radio pulsars, the data for all 13 beams have been analysed searching for pulsations over a wide range of periods. To do so the pmsearch code (see e.g. Manchester et al. 2001) has been used. This code is based on the analysis of the Fourier spectra of the de-dispersed time series, obtained, for each different DM, by summing with the appropriate delay the 96 frequency channels in which the total band is splitted. The “Tree” algorithm (Taylor 1974) used for the de-dispersion works in such a way that the maximum DM explored in this case is 10495 pc cm\(^{-3}\), corresponding to a broadening of the pulse in a single channel equal to the sampling time doubled five times. Pmsearch includes also a time domain search algorithm (Fast Folding Algorithm; Faulkner et al. 2004) sensitive to periods greater than \( \sim 3 \) s, where the frequency resolution of the Fourier spectra is very poor and the FFT is consequently less efficient.

Pmssearch is one of the blind search codes used for the major pulsar surveys performed using the Parkes radio telescope and led to the discovery of more than 700 new pulsars (see e.g. Faulkner et al. 2004 and references therein).

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.

### Table 1

| Name                  | \( P \) (s) | \( \dot{P} \) \((10^{-11} \text{ s s}^{-1})\) | \( B \) \((10^{14} \text{ G})\) | \( D \) \((\text{ kpc})\) | \( \text{DM}_{\text{norm}} \) \((\text{pc cm}^{-3})\) | Association          |
|----------------------|-------------|---------------------------------|-------------------------------|----------------|----------------------------|----------------------|
| 1E1048.1–5937        | 6.456109(5) | 3.3                             | 4.7                           | 5              | 279.7                      | HI bubble            |
| 1RXS J1708.490–400910 | 11.00170(4) | 1.9                             | 4.6                           | 8              | 742.5                      |                      |
| 1E1841–045           | 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           |

### Figure 2

Output plot of the pm search programme for the high magnetic field pulsar J1847–0130. From the top, the panels show a grey-scale of the S/N as a function of the trial values of P and DM (top), the intensity of the pulsed signal as a function of the pulse phase in three time sub-integrations (left) and in eight frequency bands (right) and the integrated pulse profile (bottom) obtained with the P and DM values maximising the S/N.
3 RESULTS

3.1 Upper limits on the radio pulsation from the observed sample of AXPs

No radio pulsation has been found in the four AXPs observed. An upper limit for pulsed radio flux can be estimated by using equation 1 (e.g. Manchester et al. 1996), representing the minimum detectable flux density from a pulsar of period $P$.

$$S_{\text{min}} = \frac{n_{\sigma} T_{\text{sys}} + T_{\text{sky}}}{G \sqrt{N_p \Delta t \Delta \nu \Delta MHz}} \sqrt{\frac{W_c}{P - W_c}} \text{ mJy} \quad (1)$$

Here $n_{\sigma}$ is the minimum S/N considered (in this case 6.0), $T_{\text{sys}}$ and $T_{\text{sky}}$ the system noise temperature and the sky temperature in K respectively, $G$ the gain of the radio telescope in K/Jy, $\Delta t$ is the integration time in seconds, $N_p$ the number of polarisations and $\Delta \nu \Delta MHz$, the total bandwidth in MHz. $\epsilon$ is a factor $\sim 1.4$ accounting for sensitivity reduction due to digitisation and other losses. $W_c$ is the effective width of the pulse:

$$W_c = \sqrt{W^2 + \delta t^2 + \delta t_{\text{DM}}^2 + \delta t_{\text{scatt}}^2} \quad (2)$$

Its value depends on the intrinsic pulse width $W$, on the sampling time $\delta t$ and on the broadening of the pulse introduced both by the dispersion of the signal in each 3 MHz channel ($\delta t_{\text{DM}}$) and by the scattering induced by inhomogeneities in the ISM ($\delta t_{\text{scatt}}$).

To digitisation, the signals are high-pass filtered by hardware in order to eliminate slowly varying baseline levels. This introduces, depending on the period of the pulsar, a further degrading factor of the sensitivity of the data acquisition system. Following Manchester et al. (2001) we estimate a degradation of $\sim 40\%$ for periods around 6 – 7 s and of $\sim 50\%$ for periods around 10 – 12 s.

Adopting the appropriate numbers for the central beam of the multibeam receiver ($G = 0.735 \text{ Jy/K}$, $T_{\text{sys}} = 23 \text{ K}$, $N_p = 2$), an intrinsic pulse width of 5% of the pulse period and the values reported in Table 2, we obtain, depending on the source and considering the aforementioned degrading factors, upper limits in the range $\sim 0.06 - 0.1 \text{ mJy}$.

For 1E1048.1–5937 the flux density limit would have been $\sim 0.04 \text{ mJy}$ but the observations have been mistakenly performed with an offset with respect to the true position of the source. Assuming a Gaussian beam shape of width 14.4 arcminutes (Hobbs et al. 2004), a further degrading factor $\sim 2.5$ caused by the non-uniform beam response must hence be added for estimating the flux upper limit for this object.

Folding the time series for 1E1048.1–5937 with a trial period of 6.16 s and a DM of 334 pc cm$^{-3}$, the pulsar J1058–3943 (Kramer et al. 2004) has been detected through its tenth sub-harmonic, confirming the reliability of the detection algorithm used.

3.2 Discovery of two new radio pulsars

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. Since their precise celestial coordinates are yet to be determined, their provisional names are PSR J1712–3943-1 and PSR 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$^{-3}$ (see Table 3). Given the large difference in the DMs, we can exclude a physical association between the two pulsars. An immediate confirmation of the detection of the new pulsars has been possible thanks to the duplication of the pointings performed on three of our four targets. The average pulse profiles of the new pulsars, obtained summing the data relative to the detection and confirmation observations, are shown in Figure 3.

We note that at a distance of 12.2 arcmin from the centre of the beam where the new pulsars have been found there is the central compact object (CCO) 1WGA J1713.4–3949 in the supernova remnant G347.3–0.5 (Lazendic et al. 2003). This source could be associated with the 92.5 ms pulsar PSR J1712–3943-2: the distance of the CCO from the nominal detection position of the radio pulsar is, in fact, compatible with the width of the beam of the telescope and the DM derived distance of the pulsar $D = 7.7 \text{ kpc}$ (using the Cordes & Lazio 2002 model, for which a typical 20% uncertainty is expected) is in agreement with the distance of the supernova remnant ($\pm 1 \text{ kpc}$; Slane et al. 1999). If this pulsar is indeed the same object as 1WGA J1713.4–3949, we can give a rough estimate of the spin period first derivative $\dot{P}$ that results $\sim 10^{-14}$ by imposing that the observed X-ray luminosity $L_x = 6 \times 10^{34} \text{ erg s}^{-1}$ (Lazendic et al. 2003) is, as for the bulk of isolated millisecond pulsars detected in X-ray and radio, 0.1% of the spin down energy $E$ (Becker & Trümper 1997; Possenti et al. 2002). Unfortunately the period first derivative, calculated using our two detections of PSR J1712–3943-2 and assuming that its true position is that of the CCO, is totally unconstrained ($\dot{P}_{\text{obs}} = [1.9 \pm 2.7] \times 10^{-9}$) and cannot be compared with the value estimated above. The observations where PSR J1712–3943-2 has been detected are infact only few hours apart and the periods measured in the two datasets are identical, at 12.2 s.

For 1E1048.1–5937 the flux density limit would have been $\sim 0.04 \text{ mJy}$ but the observations have been mistakenly performed with an offset with respect to the true position of the source of 8 arcminutes in right ascension. Assuming a Gaussian beam shape of width 14.4 arcminutes (Hobbs et al. 2004), a further degrading factor $\sim 2.5$ caused by the non-uniform beam response must hence be added for estimating the flux upper limit for this object.

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| Name               | P range (s) | DM<sub>max</sub> (pc cm<sup>-3</sup>) | DM<sub>gal</sub> (pc cm<sup>-3</sup>) | δt<sub>scatt</sub> (ms) | δt (ms) | T<sub>sky</sub> (K) | S<sub>min</sub> (mJy) |
|--------------------|-------------|-------------------------------------|-------------------------------------|------------------------|---------|----------------|-------------------|
| 1E 1048.1–5937     | 6.0438 – 7.2524 | 62754                               | 682.4                               | 0.6                    | 1.2     | 5.4            | 0.11              |
| 1RXS J170849.0–400910 | 9.6247 – 12.3734 | 107069                              | 1695.5                               | 127.6                  | 1.0     | 13.1           | 0.06              |
| 1E 1841–045        | 10.3026 – 13.2451 | 114611                             | 1581.5                               | 118.9                  | 1.0     | 11.8           | 0.06              |
| AX J1845–0258      | 6.0999 – 7.8426 | 67861                               | 1494.4                               | 88.8                   | 1.0     | 12.9           | 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 values used to calculate (according to equation 1) the upper limit on the flux densities reported in column 8: column 4 reports the maximum DM compatible with the pulsar being in the Galaxy (chosen as the maximum between the values given by the Taylor & Cordes (1993) and the Cordes & Lazio (2002) models), column 5 the expected broadening induced by the scattering in the ISM at 1.4 GHz, column 6 the sampling time and column 7 the sky temperature at 1.4 GHz in the direction of the source.

| Pulsar         | P (ms) | DM (pc cm<sup>-3</sup>) | RA (h m s) | DEC (° ′ ′′) | S/N |
|----------------|--------|--------------------------|------------|--------------|-----|
| J1712–3943-1   | 778.149(1) | 525(3)          | 17:12:35   | -39:43:14    | 16.6|
| J1712–3943-2   | 92.5277(1)  | 713(3)           | 17:12:35   | -39:43:14    | 12.1|
| J1054–5943     | 346.9090(4) | 332(2)          | 10:54:16   | -59:53:03    | 25.8|
| J1106–6022     | 396.5869(5) | 278(2)          | 10:58:08   | -60:18:09    | 26.2|
| J1055–6022     | 396.9090(4) | 332(2)          | 10:58:16   | -59:53:16    | 104.4|
| J1058–5957     | 616.271(1)  | 682.4           | 10:58:08   | -60:18:09    | 26.2|
| J1103–6025     | 396.5869(5) | 278(2)          | 10:58:08   | -60:18:09    | 26.2|
| J1705–3949     | 392.4514(5) | 342(2)          | 17:12:36   | -39:43:14    | 14.4|
| J1707–4053     | 581.017(2)  | 348(5)          | 17:04:58   | -39:43:14    | 7.4  |
| J1707–4053     | 581.017(2)  | 348(5)          | 17:04:58   | -39:43:14    | 47.6 |
| J1705–3949     | 392.4514(5) | 342(2)          | 17:12:36   | -39:43:14    | 14.4|
| J1839–0545     | 585.319(1)  | 235(3)          | 18:39:22   | -4:56:11     | 27.8 |
| J1841–0524     | 455.7312(7) | 283(3)          | 18:39:22   | -4:56:11     | 12.8 |
| J1842–0359     | 1839.95(1)  | 187(9)          | 18:41:17   | -5:21:26     | 9.7  |
| J1843–0244     | 754.963(2)  | 434(4)          | 18:41:17   | -5:21:26     | 142.6|
| J1843–0433     | 272.963(1)  | 822(4)          | 18:41:17   | -5:21:26     | 21.0 |
| J1844–0258     | 255.7013(4) | 413(2)          | 18:41:17   | -5:21:26     | 9.7  |
| J1845–0316     | 207.6358(1) | 503(2)          | 18:41:17   | -5:21:26     | 31.1 |

Table 3. New (first two rows) and redetected pulsars. From left to right pulsar name (for the new pulsars is only a provisional name given the position uncertainty), detection period and dispersion measure, right ascension and declination (in coordinates J2000) of the centre of the beam containing the pulsar and detection signal-to-noise ratio. The number in parentheses are the 2-sigma errors on the last quoted digit.

None of the pulsed signals found during this blind search could arise from any of the AXPs that we observed, because of the discrepancy in position. Figure 4 shows, for four different values of the DM, the upper limits on the flux density at 1.4 GHz reached for the four pointed regions of the sky as a function of the spin period. These limits have been estimated using equation 1 with \( n_\sigma = 8 \) and multiplying the limit obtained by a factor \( \sim 2 \) taking into account losses due to the search technique (see Manchester et al. 2001). Note that the \( n_\sigma \) threshold adopted here is higher with respect to the one used in the previous step of the analysis: this is because, given the huge amount of radio frequency interferences (RFI) with which we have to deal with respect to the one used in the previous step of the analysis: this is because, given the huge amount of radio frequency interferences (RFI) with which we have to deal when doing a blind periodicity search (especially at low S/N), we cannot safely state as a good candidate a suspect with S/N less than, usually, 8. The RFI problem is not so important when folding the time series at a specific value of the period, hence in that case we can be less conservative using a lower threshold for the candidate selection and, consequently, for the \( n_\sigma \) to adopt in the \( S_{min} \) calculation.

In order to verify the reliability of the quoted flux density limits, we can compare the catalogued fluxes of the 18 redetected pulsars (obtained from the ATNF Pulsar Catalogue: http://www.atnf.csiro.au/research/pulsar/psrcat/) with those estimated putting in equation 1 their detection periods, DMs and S/Ns (or mean S/N, for pulsars with multiple detections) and considering the offset of the detection beam with respect to the true position of the pulsars. The ratio between the estimated and the catalogued values of the flux densities are shown, as a function of the rotational period, in figure 5. Note that the S/N used to estimate the flux density, may sensibly vary from one observation to another (e.g. because of the different response of different
Figure 3. Mean 1374-MHz pulse profiles of the newly discovered pulsars PSR J1712–3943-1 (left) and PSR 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.

Figure 4. Flux density limits for the four observed AXPs, and surrounding beams, as a function of the spin period and for different values of the DM (from bottom to top: 0, 500, 1000 and 5000). Panels A, B, C and D refer respectively to the pointings centered on 1E 1048.1–5937, AX J1845–0258, 1E 1841–045 and 1RXS J170849.0–400910. For panel A the solid lines refer to the flux limit for the pulsation from the AXP (taking into account the 8’ offset of the central beam with respect to the source position) while the dashed line is the flux limit for the blind search in all the 13 beams.

Figure 5. Ratio between the estimated (through equation 1) and the catalogued value of the flux density of the 18 redetected pulsars. The errorbars are drawn assuming, besides the errors on the measured values, a 20% error on the estimated fluxes. The mean value of the ratio calculated over the 18 sources is 1.15±0.3 (2-σ error).

4 DISCUSSION AND CONCLUSIONS

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

Comparing the upper limits on the luminosity at 1400 MHz (defined as $L_{1400} = S_{\text{min}} \times D^2$) for our targets with the luminosity of the observed radio pulsar population in the Galactic field (Figure 6), we note that the limits reached by our search are a factor of six lower than the median of the population. The values obtained for our sample are in fact in the range $2.8 - 3.8$ mJy kpc$^2$ (shaded region in Fig. 6) while the median of the distribution in luminosity of the observed radio pulsars in our Galaxy is $18.0$ mJy kpc$^2$. If the luminosity function of AXPs reflects that of observed canonical pulsars we can calculate that the probability for all our four targets to have luminosities below our limits is only $5 \times 10^{-4}$.

Similar results are obtained comparing the upper limits on $L_{1400}$ for our sample with the luminosity distribution of only young pulsars (with characteristic ages $< 10^4$ yr) or long period pulsars (with $P > 3$ s).

A comparison with the few high magnetic field radio pulsars (having magnetic field strengths above the quantum critical field line; Figure 1) is not statistically significant, having only four objects in this class. However we note that all their luminosities, as well as the radio luminosity of XTE J1810–197 (Camilo et al. 2006), are greater than the limits obtained for the AXPs.
Note however that, if we compare our results with the intrinsic luminosity distribution of the radio pulsars (dashed line in figure 6 [Lorimer et al. 2006]), 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 $\sim 5\%$ (hence a beam semi-aperture $\geq 9\degree$), 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, following e.g. [Burgay et al. 2003], 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 et al. 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. 2002], 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 2007], 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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**REFERENCES**

Baring M. G., Harding A. K., 1998, ApJ, 507, L55
Becker W., Trümper J., 1997, A&A, 326, 682
Bhat N. D. R., Cordes J. M., Camilo F., Nice D. J., Lorimer D. R., 2004, ApJ, 605, 759
Burgay M., Burderi L., Possenti A., D’Amico N., Manchester R. N., Lyne A. G., Camilo F., Campana S., 2003, ApJ, 589, 902
Cameron P. B., Chandra P., Ray A., Kulkarni S. R., Frail D. A., Wieringa M. H., Nakar E., Phinney E. S., Miyazaki A., Tsuboi M., Okumura S., Kawai N., Menten K. M., Bertoldi F., 2005, Nature, 434, 1112
Camilo F., Kaspi V. M., Lyne A. G., Manchester R. N., Bell J. F., D’Amico N., McKay N. P. F., Crawford F., 2000, ApJ, 541, 367
Camilo F., Ransom S. M., Halpern J. P., Reynolds J., Helfand D. J., Zimmerman N., Sarkissian J., 2006, submitted to Natue, astro-ph/0605429
Cordes J. M., Lazio T. J. W., 2002, astro-ph/0207156
Cordes J. M., McLaughlin M. A., 2003, ApJ, 596, 1142
Crawford F., Pivovaroff M. J., Kaspi V. M., Manchester R. N., 2002, in Slane P., Gaensler B., eds, ASP Conf. Ser. 271: Neutron Stars in Supernova Remnants A sensitive targeted search campaign at parkes to find young radio pulsars at 20 cm. pp 37+
Duncan R. C., Thompson C., 1992, ApJ, 392, L9
Faulkner A. J., Stairs I. H., Kramer M., Lyne A. G., Hobbs G., Possenti A., Lorimer D. R., Manchester R. N., McLaughlin M. A., D’Amico N., Camilo F., Burgay M., 2004, MNRAS, 355, 147
Frail D. A., Kulkarni S. R., Bloom J. S., 1999, Nature, 398, 127

![Figure 6. Distribution in luminosity at 1400 MHz of the observed pulsar population of the galactic field (solid line) and of the intrinsic population (dashed line). The shaded region indicates the luminosity limits reached in the present search.](image-url)
