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Radio Emission from Anomalous X-ray Pulsars

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Abstract Observations of AXP 1E 2259+586 and XDINS 1RXS J1308.6+212708 at 111, 87, 61 and 42 MHz are reported. Mean pulse profiles, as well as, the estimation of the dispersion measures, distances, spectral indices, and integrated radio luminosities of both objects are presented. Comparison with X-ray data shows large differences in the mean pulse widths and luminosities. The detection of radio emission from these two X-ray pulsars, together with other data, suggests the need to revise the radio-emission mechanisms in the magnetar model or the magnetar model itself.

Key words: pulsars: X-ray pular — magnetar model: radio-emission:observatory — individual: AXP 1E 2259+586/XDINS 1RXS J1308.6+212708

1 INTRODUCTION

Space-based gamma-ray and X-ray observations have led to the discovery of a few special groups of pulsars: anomalous X-ray pulsars (AXPs) (Mereghetti 2001), soft gamma-ray repeaters (SGRs) (Harley 2000) and nearby dim isolated neutron stars with strong magnetic fields (XDINS) or the magnificent seven (MS), for example Treves et al. (2001) and Haberl (2005). It is now generally accepted that these neutron stars have different parameters than typical of the larger group of "normal" radio pulsars and ordinary X-ray pulsars do. These objects have long periods, which lie in the narrow range of 5–12 s (two XDINS have period in the same range), and large period derivatives, $10^{-11} - 10^{-13}$ s s^{-1}. They are young objects with characteristic ages of up to several hundred thousand years. Most of AXPs and SGRs objects are located close to the plane of the Galaxy, and nearly half of them are inside supernova remnants. The most important difference between these objects and other X-ray pulsars is the absence of a detectable companion; i.e., they are single neutron stars. One of the most intriguing problems connected with these objects is the source of their energies, which sometimes imply luminosities that are two to three orders of magnitude higher than can be provided by the rotational kinetic-energy losses. All the models proposed until recently, including the most popular magnetar model of Duncan & Thompson (1992), to explain this energy source encounter serious difficulties (Malov et al. 2003). One of the key arguments in favor of the magnetar model was the absence of radio emission from AXPs and SGRs: this could be naturally explained as a consequence of the absence the electron-positron cascades that are responsible for radio emission in many models in the presence of such high fields (Barring & Harding 2001). This was the situation until recently, it was changed when pulsed radio emission was detected from the SGR 1900+14 (Shitov et al. 2000) and the AXP 1E 2259+586 (Malofeev & Malov 2001). This led to searches for mechanism of pair production, such as two-photon process for the generation of radio emission in the framework of the magnetar model by Zhang (2001, 2003), as well as completely new models, such as the action of drift waves at the periphery of the magnetosphere (Malov et al. 2003). The importance of searches for and studies of the radio emission of AXPs, SGRs and XDINS is obvious. In this report we present data on the radio emission of the AXP 1E 2259+586 and the XDINS member J1308.6+212708.

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The X-ray object 1E 2259+586 (G109.1.1.0) was detected in the direction toward the supernova remnant CTB 109 in 1980 by Gregory and Fahlman, who also detected pulsed emission (1E 2259+586). The second object, 1RXS J1308+21, was discovered in 2001 by Hambaryan et al. (2002). It has a period of $P = 5.16$ s and an uncertain period derivative $\dot{P} = (0.7 - 2.0) \times 10^{-11}$ s s^{-1}. The rotational period for this pulsar was recently redetermined; as in the earlier case of the AXP 1E 2259+586, the period was doubled, i.e., $P = 10.32$ s (Haberl et al. 2003). Since the properties of this object are similar to those of AXPs, it was considered a candidate member of this group for the beginning, but now it is considered as the XDINS or member of MS (Haberl 2005).

2 OBSERVATIONS AND RESULTS

The observations of the AXP 1E 2259+586 began on March 1999. Regular observations every one-two months began in February 2001. The second object, 1RXS J1308+21, has been observed in the same mode since December 2001. We consider here data obtained for both pulsars until April 2005. Most of the observations were carried out on the high-sensitivity Large Phased Array (LPA) of the Lebedev Physical Institute (Pushchino) at a frequency of 111 MHz. We also occasionally carried out simultaneous observations at 87, 61 or 42 MHz on the East - West arm of the DKR-1000. This antenna operates at 30–110 MHz. The effective area is $\sim 20000\,\mathrm{m}^2$ and ~ 7000 m^2 for LPA and the East-West arm of the DKR-1000, respectively. Both radio telescopes are transit instruments; the durations of each observational session on the LPA were 6.2 and 3.3 min for 1E 2259+586 and 1RXS J1308+21, respectively, and those on the DKR-1000 were longer by factor of three for each pulsar. A filter-bank receiver with a bandwidth of 20 kHz and 64 channels at 111 MHz and 32 channels at 87, 61 and 42 MHz was used. As a rule, the data-sampling interval was 25.6 or 51.0976 ms and the receiver time constant was 30 or 100 ms. These parameters were used for integrating a signal with a known period. In addition, we used a method to search for the pulsed radio emission with unknown period (Malofeev et al. 2005). To increase the reliability we carried out numerous observations, using double the period. We have used a technique that has been tested with observations of faint pulsars, as well as the Geminga pulsar (Malofeev & Malov 1997).

We detected weak periodic pulsed radio emission from the AXP 1E 2259+586 at the end of 2000. This result has been reported recently (Malofeev & Malov 2001; Malofeev et al. 2004, 2005). After only one month of observations, we detected periodic pulsed radio emission from 1RXS J1308+21 at 111 MHz (Malofeev et al. 2004, 2005). In total, we had more than 400 days of observations at 111 MHz, and a few dozen days of them at 87 and 61 MHz for the AXP 1E 2259+586 over the entire observational interval. About one-third of the observations were corrupted by strong interference, and the pulsar signal did not exceed 4σ on more than one-third of the days. Unfortunately, the pulsar signal was not detected at 61 MHz, probably due to interference. We obtained more 80 and more 10 records being useful for analysis for 1RXS J1308+21 at 111 MHz and at every lower frequency (87, 61 and 42 MHz), respectively. We used the search programm on the base of Fourier-amplitude spectra. Tests of this method using observations of known pulsars demonstrate that pulsars with fluxes > 70 mJy can be confidently detected. We were able to obtain good spectra for both pulsars, some examples of which were presented by Malofeev et al. (2004, 2005).

Since the integrations for individual days were carried out over only 53 pulses (1E 2259+586), the signal-to-noise ratio of the mean pulse rarely reached five. Accordingly, we improved the signal-to-noise ratio by summing the data for a number of different days. Since we did not have precise timing for this pulsar, we summed days when the observations were carried out using the double period, and the pulses were aligned using visible pulses. In this case, we should observe two pulses separated by precisely one pulsar period in the summed profile, as is shown in Figure 1a. Folding these data using the pulsar period (Fig. 1b) yielded a very narrow profile with a mean duration of 120 ± 20 ms, or 1.7% of the period. This is one of the narrowest pulses observed for radio pulsars. Furthermore, in contrast to the X-ray profile, we observe no interpulse with an amplitude 20% of the main pulse. We were also able to detect pulsed periodic emission from this pulsar at 87.5 MHz (Fig. 2). The low signal-to-noise ratio (~ 5) is due to the small number of accumulated periods (80). We observe a narrow pulse at 111 MHz in 1RXS J1308+21, which has a duration of 140 ± 20 ms, or 1.35% of the period ($P = 10.32$ s). Figure 3 shows the mean pulse obtained by integrating 25 periods for four days using the same technique as for 1E 2259+586. We also detected the pulsar at 87, 61 and 42 MHz (Fig. 4abc). In addition to a narrow pulse, this pulsar displays an interpulse at a longitude of ~ 175, which is clearly visible in Figures 3b and 4.

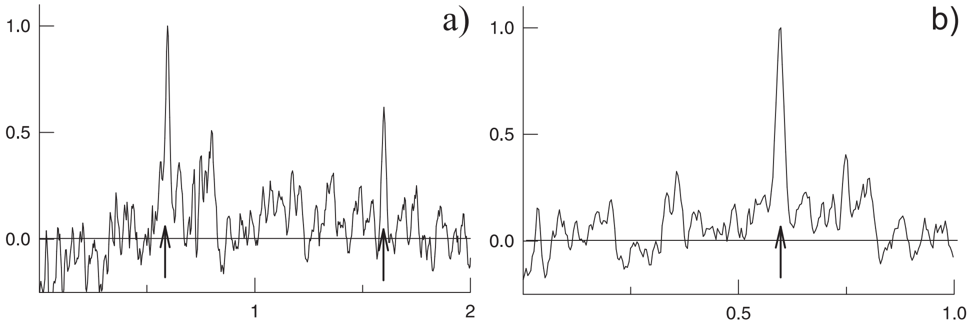

Fig. 1 (a) Integrated profile of the AXP 1E 2259+586 at 111.2 MHz (in arbitrary units) obtained by summing 12 days, when the observing window equals twice the apparent period (312 doubled periods); (b) Integrating profile obtained by the folding of data with one period, i.e., the sum of 624 periods. The arrows mark the pulse phase.

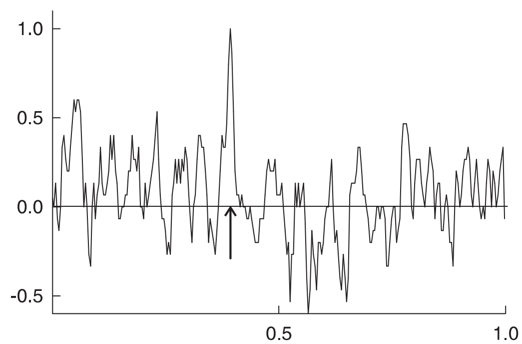

Fig. 2 Example of the mean profile of the AXP 1E 2259+586 at 87.5 MHz (in arbitrary units), obtained on October 5, 2002 by integrating over 80 periods. The arrow shows the pulse phase.

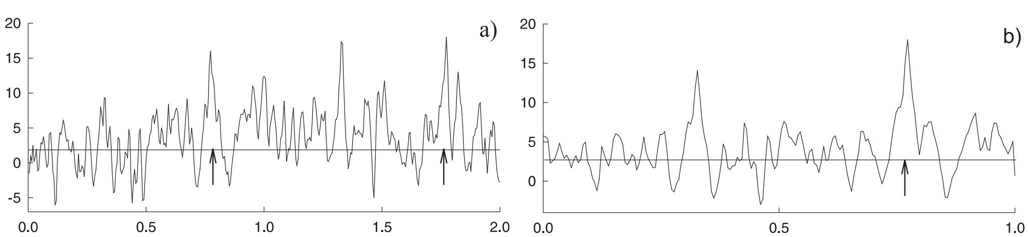

Fig. 3 (a)Mean profile of 1RXS J1308+21 at 111.2 MHz (in arbitrary units), obtained by integrating four days of observations and 25 double pulsar rotational periods $P_H = 20.64$ s. (b) Folding with the rotational period $P = 10.32$ s, i.e., the sum of 50 periods. The arrows show the pulse-arrival phases.

Determination of the dispersion measures is extremely important, since it makes it possible to obtain independent estimates of the distances to the pulsars. We estimated the dispersion measure using the best data in the 111.24–110.60 MHz frequency band, which was covered by 64 receiver channels. The signal-to-noise ratio and pulse duration as a function of the dispersion measure for both pulsars was shown by Malofeev et al. (2004, 2005). We obtained that the pulse had the highest signal-to-noise ratio for DM$=$ 79 ± 4 pc cm^{-3} and 5.7 ± 0.5 pc cm^{-3} for both objects, respectively.

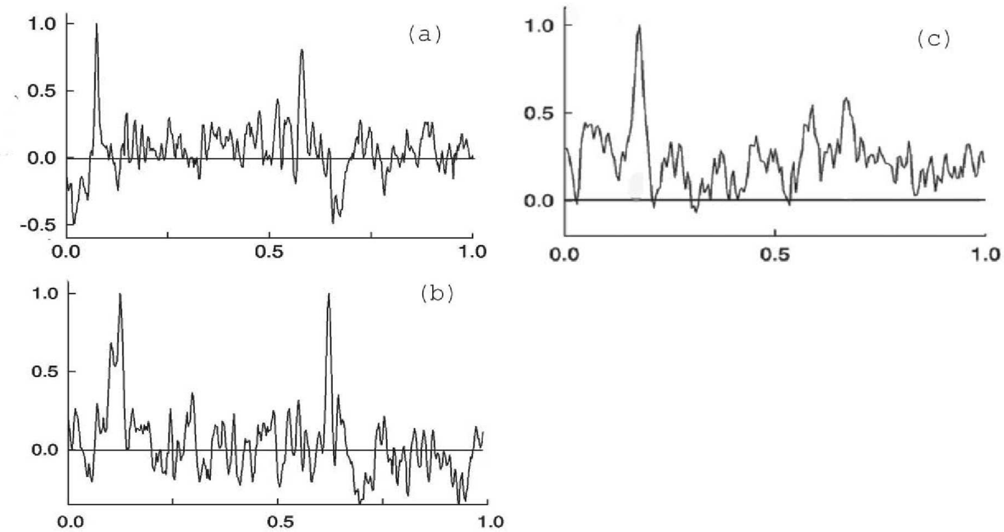

Fig. 4 Mean profiles of 1RXS J1308+21 (in arbitrary units) at (a) 87.7 MHz, summed over two days and 14 periods; (b) 61.8 MHz, summed over three days and 100 periods and (c) 42.3 MHz summed over four days and 206 periods.

We measured the fluxes at 111 MHz via calibration using the radio sources with known fluxes. The flux of 1E 2259+586 was measured by averaging of 30 days of observations over 3.5 years, and that of 1RXS J1308+21 on 10 days of observations over 1.5 years. The mean flux densities are 35 ± 25 and 50 ± 20 mJy for 1E 2259+586 and 1RXS J1308+21, respectively. At the lower frequencies, we could estimate only upper limits for the flux densities of both pulsars: $S < 150$ mJy and $S < 200$ mJy at 87 MHz for 1E 2259+586 and 1RXS J1308+21.

The period and period derivative for both pulsars (Malofeev et al. 2004) are in agreement with X-ray measurements by Gavriil & Kaspy (2002) and Hambaryan et al. (2002).

3 DISCUSSION AND CONCLUSIONS

The table lists the main parameters of the radio emission from the two pulsars. Comparison with the X-ray data shows that the radio measurements both extend our knowledge about these objects and carry fundamentally new information. We have detected strongly different durations of the mean pulses, and derived independent estimates of the distances to both sources based on their dispersion measures. The existence of the radio emission itself represents a fundamentally new fact, which raises doubts about either the magnetar model or our understanding of radio emission in superstrong magnetic fields.

We obtained an estimation of $\dot{P} = 130 \times 10^{-13}$ s s^{-1} for 1RXS J1308+21 during MJD 52300–52743 (Malofeev et al. 2004). The period history of this object have been published recently by Schwope et al. (2005). They combined 6 epoch of X-ray observations at ROSAT, Chandra and XMM-Newton between June 1997 and March 2004 (MJD 50824–53095) and obtained much smaller value of $\dot{P} = (4.0 \pm 0.4) \times 10^{-13}$ s s^{-1}. After a discussion they concluded, that the presently available data insufficient to determine the spin history unequivocally. In this case the timing radio observations of this pulsar are very necessary.

Distance estimates for the pulsar 1E 2259+586 (or rather for the supernova remnant CTB 109; the pulsar is almost at its center) in the literature are between 3.5 and 4.5 kpc (see, e.g., Gregory & Fahlman 1980). Our measurements of the dispersion measure, 79 ± 4 pc cm^{-3}, yield a distance of 3.6 ± 0.7 kpc for the model electron density distribution in the Galaxy of Taylor & Cordes (1993). Estimates of the distance to 1RXS J1308+21, or, more precisely, the star RBS 1223, obtained using several methods lies in the broader interval from 0.1 to 1.5 kpc (Hambaryan et al. 2002). Our dispersion measure (Table) and the model for the Galaxy yield an estimated distance to the pulsar of $0.25^{+0.2}_{-0.1}$ kpc. This suggests that the pulsar

Table 1 Measured and Calculated Parameters of the Two Pulsars

Parameter	1E 2259+586	1RXS J1308 +21
DM, pc cm^{-3}	79 ± 4	5.7 ± 0.5
S_{111}, mJy	35 ± 25	50 ± 20
$w_{0.5}$ (111 MHz), ms	120 ± 20	140 ± 20
D, kpc	3.6 ± 0.2	0.25 ± 0.02
$L_{\rm R}$, erg s^{-1}	3×10^{28}	3×10^{26}
$L_{\rm x}$, erg s^{-1}	7.9×10^{34}	3×10^{31}
E, erg s^{-1}	5.6×10^{31}	4.6×10^{32}

is close to the Earth, as was also proposed by Reach et al. (1993) and Schwope et al. (2005), who reported a distance estimate for the star of 0.1–0.38 kpc. The X-ray luminosity of 1E 2259+586 for a distance of 3.6 kpc $\log L_{\rm x}$(erg s^{-1})= 34.9 (Malov et al. 2003) remains three orders of magnitude higher than the rate at which this star is losing rotational kinetic energy. The X-ray luminosity of 1RXS J1308+21 for a distance of 0.25 kpc is $L_{\rm x} = 0.26 \times 10^{32}$ erg s^{-1}. The rate of loss of rotational energy for this neutron star ($P = 10.32$ s and $\dot{P} = 130 \times 10^{-13}$ s s^{-1}) is $E = 4.6 \times 10^{32}$ erg s^{-1}, which is 18 times more than the X-ray luminosity. If $\dot{P} = 4.10^{-13}$ s s-1 (Schwope et al. 2005) we obtain $E = 0.14 \times 10^{32}$ erg s^{-1}, that is close to the X-ray luminosity. To estimate the total radio luminosity, we must know the spectrum of the pulsar, or at least the spectral index. Using our flux density measurement at 111 MHz and the upper limits at 87 MHz, 600 MHz ($S_{600} < 2.3$ mJy (Lorimer et al. 1998)) and 1500 MHz ($S_{1500} < 0.05$ mJy (Coe et al. 1994)), we estimate the spectral index of 1E 2259+586 to be $\alpha > 2.5$.

Our data at 111 MHz with an upper limit for the flux density at 87 MHz and an upper limit from the discrete source toward to 1RXS J1308 +21 at 1.4 GHz $S_{1400} < 0.94$ mJy (White et al. 1997) yields the spectral index $\alpha > 1.7$ at 0.087–1.4 GHz. Given that the spectra of both pulsars are probably steep, we estimated the integral radio luminosities of the two pulsars by adopting the value $\alpha = 2.5$; this yielded $L_{\rm R} = 3\times10^{28}$ erg s^{-1} for 1E 2259+586 and $L_{\rm R} = 3\times10^{26}$ erg s^{-1} for 1RXS J1308+21. Thus, these pulsars do not have extremely high luminosities in the radio. While 1E 2259+586 has a typical radio luminosity, 1RXS J1308+21 has one of the lowest radio luminosities.

Comparison of the radio and X-ray data suggests large differences in two observed parameters. First, the radio and X-ray pulse durations differ by a factor of 16–18. Second, while an interpulse is observed in both the radio and X-ray for 1RXS J1308+21, 1E 2259+586 displays an interpulse only in the X-ray. In addition, there is the huge difference in the radio and X-ray luminosities (five and six orders of magnitude). This result is very important.

1. We have detected periodic pulsed emission from the AXP 1E 2259 +586 and the XDINS 1RXS J1308+21 in observations carried out on two radio telescopes of the Pushchino Radio Astronomy Observatory. The pulsars parameters are listed in the Table 1.
2. We have obtained independent estimates of the distances to both pulsars,which are within the intervals of distances determined using other methods.
3. The main difference between the radio from the X-ray pulsed emission is that the integrated radio pulses of both objects are much narrower. In addition,there is radio interpulse for 1RXS J1308+21 and no appreciable one for AXP 1E 2259+586.
4. The presence of weak radio emission in AXP and SGR (Shitov et al. 2000), together with the recent detection of a radio pulsar (J1847–0130) with a long period ($P = 6.7$ s) and period derivative ($\dot{P} = 1.3 \times 10^{-12}$ s s^{-1}) (McLaughlin et al. 2003), similar to those of AXPs and SGRs, suggests the need to re-examine radio emission mechanisms in the magnetar model, or to consider other AXP and SGR models that do not involve superstrong magnetic fields.

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