A Search for Pulsed and Bursty Radio Emission from X-ray Dim Isolated Neutron Stars

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Abstract. We have carried out a search for radio emission from six X-ray dim isolated neutron stars (XDINSs) observed with the Robert C. Byrd Green Bank Radio Telescope (GBT) at 820 MHz. No bursty or pulsed radio emission was found down to a 4σ significance level. The corresponding flux limit is 0.01–0.04 mJy depending on the integration time for the particular source and pulse duty cycle of 2%. These are the most sensitive limits yet on radio emission from these objects.

Keywords: XDINS, X-ray dim isolated neutron star, search, radio periodicity, bursty emission

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INTRODUCTION

The ROSAT mission discovered a group of seven nearby low-luminosity isolated neutron stars, termed the X-ray dim isolated neutron stars (XDINSs). They share very similar properties and are characterized by soft blackbody-like spectra in the range ∼40–100 eV, very faint optical counterparts (V > 25), long spin periods of 3–12 s (see Table 1). For a recent review see Haberl [1].

So far, no confident detections of pulsed radio emission were found from XDINSs. The aim of this project is to search for pulsed and bursty radio emission from XDINSs to link them in their evolutionary scenarios with other classes of neutron stars, such as magnetars and rotating radio transients (RRATs). All three populations of neutron stars have similar properties, such as period, period derivative, age, and magnetic field so that connections between them are plausible.

OBSERVATIONS AND DATA PROCESSING

The observations were conducted with the GBT on May 28–31, 2006 at a center frequency of 820 MHz. The Spigot pulsar backend was used to record a signal with 81.92 µs time resolution in 1024 channels covering a 50-MHz receiver bandpass.

All known XDINSs except for RX J0420.0−5022 were observed. Table [1] lists the name of the source, X-ray period P, the total observing time Tobs, the largest trial value DMtop of dispersion measure (DM), and the 4σ upper limit on pulsed radio emission, Slim, for pulse duty cycle of 2%. The chosen DM range was determined by the NE2001 model of free electron density in our Galaxy [2]. We assumed distances < 1 kpc for all sources but J1856.5−3754 and minimum pulse widths of 1 ms. For J1856.5−3754 the DMtop corresponds to the distance of 250 pc. This is half as much again as the true value of 161+18−14 pc based on the parallax measurement by van Kerkwijk and Kaplan [3]. For RX J0720.4−3125, the chosen distance of < 1 kpc is also compatible with doubled value of parallax distance of 360+170−90 pc [4].

| XDINS     | P (s) | Tobs (h) | DMtop (pc cm⁻³) | Slim (μJy) |
|-----------|-------|----------|-----------------|------------|
| J0720.4−3125 | 8.39  | 4        | 98              | 10         |
| J0806.4−4123  | 11.37 | 2        | 172             | 40         |
| J1308.6+2127   | 10.31 | 4.25     | 27              | 20         |
| J1605.3+3249   | 6.88  | 4        | 50              | 10         |
| J1856.5−3754   | 7.055 | 4        | 12              | 20         |
| J2143.7+0654   | 9.44  | 4.08     | 33              | 20         |

The data were processed using both SIGPROC1 and PRESTO2 packages. First, the data were filterbanked into the “Sigproc” format and decimated by 6 samples. After an excision of radio frequency interference (RFI), the

1 http://sigproc.sourceforge.net
2 http://www.cv.nrao.edu/~rsansom/presto
FIGURE 1. The single-pulse search diagnostic plot for 1RXS J1308.6+2127. Top: the histograms of the number of bursts versus SNR and DM, and the dependence of SNR versus DM (from left to right). Bottom: the main time-DM plot with points’ size corresponding to SNR of the burst. The detection threshold is 5σ. Two vertical lines of bursts on the bottom plot are either stronger at zero DM or pretty constant over all the DM range. Both are RFI signatures rather than real pulse which would appear as vertical segment of bursts centered at its strongest burst at non-zero DM with SNR of other bursts gradually fading to the edges of the segment. If there is a train of such segments at the same non-zero DM than it is surely a manifestation of burst emission of the pulsar.

The data were dedispersed for a number of different DMs from zero to DM$_{top}$ (see Table 1) with a step size of roughly 1 pc cm$^{-3}$. Finally, a single-pulse search, FFT search, and Fast Folding Algorithm (FFA) search were applied for every dedispersed time series. A new FFA search code ffasearch was written to implement the FFA algorithm [5]. This code has been successfully proven to detect known long-period pulsars with higher signal-to-noise ratios (SNR) than traditional FFT searches.

FIGURE 2. Example of an FFA diagnostic plot for RX J0720.4−3125. The top-left plot is the periodogram, i.e. folded profile’s significance for every period candidate, the top-right plot shows the profile significance versus DM. The plot on the bottom represents the SNR of folded profiles versus DM and the period. The darker points have larger SNRs. Signature of the pulsar on this plot is similar to that for a single-pulse search. Long lines over broad DM range are not real but rather a strong RFI of periodic origin.

vertical lines of bursts on the bottom plot of Fig. 1 are RFI signatures that were still in the data after RFI excision. The powerful RFI masking program rfifind from PRESTO package turned out to be inefficient, because it does not deal with broad impulse non-periodic RFI. Thus, we used a dedicated program rfimarker for all sources except for RX J1605.3+3249.

The search was done for a range of pulse widths using matched filtering techniques [7]. Only the candidate with largest SNR was plotted. No apparent strong pulses were found. This could be due to contaminated data, or a lack of bursty emission from the studied XDINSs, or a rate of burst occurrence of less than 1 every few hours.

SINGLE-PULSE SEARCH

The single-pulse search is a very powerful tool to detect pulsating sources of strong individual bursts that are too weak to be detected through a regular FFT search. The RRATs were discovered in this way [6]. XDINSs show possible connection with the RRATs, thus making the single-pulse search very important.

To detect spiky emission from XDINSs, we have performed the single-pulse search for each isolated neutron star in our analysis. An example diagnostic plot for the single-pulse search for 1RXS J1308.6+2127 is shown in Figure 1. The distinctive feature of a candidate source is the train of strong pulses at some non-zero DM.

Unfortunately, almost all our data were seriously contaminated by RFI of external and equipment nature. The

FFT AND FFA SEARCHES

Though the FFT search is not efficient for long period sources, because of low-frequency noise, we still applied it to every observed XDINS. However, as we expected we did not find any promising candidates.

On the contrary, the FFA search should be very effective. We performed the FFA search for period ranges within a few hundred milliseconds around the actual X-ray period. Figure 2 shows an example of an FFA diagnostic plot for RX J0720.4−3125. It is similar to that for the single-pulse search (see Fig. 1).

The presence of a real pulsed source would show up as elongated train of candidates in both period and DM axes. We have inspected the folded profiles for many
candidates and did not find any significant profiles down to the 4σ level, corresponding to 0.01–0.04 mJy depending on the integration time for the particular source and duty cycle of 2%.

SUMMARY

The sporadicty of the RRATs’ radio emission led to immediate suggestions that they are related to other classes of traditionally “radio-quiet” neutron stars such as XDINSs and magnetars. Popov et al. have shown that the implied birthrate of RRATs is more consistent with that of XDINSs than that of magnetars. As shown in the P-˙P diagram on the Figure, RRATs and XDINSs also have similar periods and period derivatives, implied ages and magnetic fields. However, the RRATs spin-down properties are also consistent with those of the normal pulsar population and X-ray observations of one RRAT reveal properties similar to those of both normal radio pulsars and XDINSs.

The RRATs are powerful sources of isolated radio bursts, and we have not detected such bursts, or any periodic emission, from the six XDINSs we have observed. Because the distances to the XDINSs are believed to be much smaller than those to the RRATs, we should have had high sensitivity to RRAT-like radio emission. However, our non-detection of such emission does not necessarily mean that there is no relationship between these two source classes.

XDINSs may simply be “radio-quiet”, but it is also likely that perhaps the narrow radio beams from these XDINSs are simply misaligned with our line-of-sight. It is possible that searches at lower frequencies, where radio emission beams are believed to be wider, may be more sensitive to radio emission from XDINSs. Indeed, Malofeev and co-authors reported detection of radio emission from RX J1308.6+2127 and RX J2143.7+0654 at the low frequency of 111 MHz. On the other hand, XDINSs could have very steep spectral indices. If the detection of Malofeev and co-authors is real, our non-detection of radio emission from these two XDINSs at 820 MHz sets a lower limit on the spectral index of 3.6. Finally, it is possible that our non-detection of radio emission from these XDINSs is due to the large amount of contamination from RFI. Our search highlights the importance of improved excision algorithms for impulsive, broadband terrestrial interference.

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