Radio observations of two isolated neutron stars: RX J0720.4 − 3125 and RX J0806.4 − 4132

Simon Johnston*
School of Physics, University of Sydney, NSW 2006, Australia

Accepted 2003 February 21. Received 2003 February 5; in original form 2002 December 10

ABSTRACT
Radio observations of two isolated neutron stars, RX J0720.4 − 3125 and RX J0806.4 − 4132, have been made with the Australia Telescope Compact Array at a frequency of 1.4 GHz. No continuum emission is detected from either object with a 3σ upper limit of 0.2 mJy. The data were also folded synchronously with the known rotation periods of 8.4 and 11.4 s respectively. No pulsed emission was detected. If the pulse duty cycle is small, the upper limit on pulsed emission can be reduced still further to 0.04 mJy. The best evidence seems to indicate that the isolated neutron stars detected by the ROSAT All-Sky Survey are relatively young objects, born with a very high magnetic field.

Key words: stars: individual: RX J0720.4 − 3125 – stars: individual: RX J0806.4 − 4132 – stars: neutron – radio continuum: stars.

1 INTRODUCTION
A new class of neutron stars has emerged with the discovery of the so-called isolated neutron stars (INS) in the X-ray band with ROSAT. Their identification as neutron stars is secure as they have extremely high X-ray to optical flux ratios. They are isolated in the sense that they have no binary companions, which rules out accretion from the companion as a mechanism for generating the X-rays. They are all extremely close, probably only a few hundred parsecs (at most) from Earth. There is no known radio emission (pulsed or unpulsed) associated with these objects, although deep searches have not yet been reported in the literature. A review of these objects can be found in Treves et al. (2000).

There are three possibilities as to the nature of these neutron stars. First, they might be old stars accreting from the interstellar medium. These still rotate, albeit slowly, but do not produce ‘conventional’ radio or X-ray emission. The second possibility is that they are ‘standard’ (old) neutron stars, with magnetic fields of the order of 10^{12} G which pulsate in X-rays and pulsate in the radio but may or may not be beamed in our direction. Finally, they may be ‘magnetars’, which are young neutron stars with extremely high magnetic fields (greater than 10^{14} G). These have X-ray pulsations but no radio pulsations. The mechanism for producing X-ray pulsations is completely different from that of conventional pulsars: they are powered by magnetic rather than rotational energy.

When the INS were first discovered a few years ago, it seemed unlikely that they were standard radio pulsars (Heyl & Kulkarni 1998). No radio pulsars at that time had periods greater than 4 s and magnetic fields more than 10^{13} G. However, in 1999, PSR J2144 − 3933 was discovered to have a period of 8.5 s (Young, Manchester & Johnston 1999), and Camilo et al. (2000) discovered PSR J1814 − 1744 with a long period and a high magnetic field similar (in parameter space at least) to the so-called ‘magnetars’. PSR J2144 − 3933 has a very low dispersion measure, placing it about 200 pc distant, a similar distance to the known INS. It therefore now seems more likely that the INS are normal pulsars rather than some new exotic species.

One way of determining the nature of these objects is detection of periods and period derivatives. The combination of period and period derivative naturally yields the magnetic field strength, which is the key discriminator in the scenarios outlined above. Four of the seven known INS have X-ray pulsations with rotation periods ranging from 5.2 to 22 s. Of interest here are RX J0720.4 − 3125 and RX J0806.4 − 4132 which have spin periods of 8.4 and 11.4 s respectively (Haberl & Zavlin 2002; Kaplan et al. 2002a; Zane et al. 2002). Timing analysis has so far not yielded a period derivative (and hence magnetic field strength) for these pulsars. Zane et al. (2002) claim a period derivative for RX J0720.4 − 3125 but their phase-connected solution has been called into question by Kaplan et al. (2002a). However, the upper limit on the period derivative seems to rule out the magnetar model. For RX J0806.4 − 4132 the upper limit on the period derivative does not allow discrimination between the models.

The question then is – are there radio pulses and/or continuum radio emission (e.g. from a wind nebula) from these objects? If radio pulsations are detected then it becomes relatively easy to measure a period derivative and hence determine the nature of these objects. If detected, they would be among the closest radio pulsars, and probably the lowest luminosity pulsars known. This would have implications for the birth rate of pulsars and the low-luminosity cut-off. It is a non-trivial task, however, to detect these long-period

*E-mail: simonj@physics.usyd.edu.au

© 2003 RAS
pulsars using conventional search techniques, as the red noise in the Fourier transform of the time series seriously reduces the sensitivity. Knowledge of the period a priori helps the search process.

2 OBSERVATIONS AND DATA REDUCTION

Observations of RX J0720.4 – 3125 and RX J0806.4 – 4132 were made at the Australia Telescope Compact Array (ATCA) on 2002 December 4 and 5 using the 6A array configuration. In this configuration the shortest baseline is 627 m and the longest is 5940 m. In each observation, two continuum frequencies were observed simultaneously with 32 4-MHz channels across each; all four Stokes parameters were recorded. The centre frequencies were 1384 and 1704 MHz. The pointing centres used were RA (J2000) 07°20′24″, Dec. (J2000) –31°25′19″6 and RA (J2000) 08°06′23″47, Dec. (J2000) –41°22′02″3 respectively, both ~30 arcsec offset from the X-ray location of the INS. The total integration time was 10 h per source. The ATCA is also capable of splitting each correlator cycle into bins corresponding to different phases of the period of a pulsar, and, in this case, the pulse period divided into 32 time bins. The flux density scale of the observations was determined by observations of PKS B1934–638, while polarization and antenna gains and phases were calibrated using 3-min observations every 50 min of PKS B0614–349 for RX J0720.4 – 3125 and PKS B0823–500 for RX J0806.4 – 4132. As a system test, observations were made of the known 8.5-s radio pulsar PSR J2144–3933 using an identical setup to that described above. The source was observed for 30 min.

Data were edited and calibrated using the MIRIAD package. At each frequency the field of interest was imaged using conventional techniques, after first collapsing the phase bins.

The data were also folded to produce a pulse profile. The dispersion smearing was assumed to be negligible compared with the duration of one phase bin. The data were folded according to the ephemeris given in Young et al. (1999) for PSR J2144–3933, assuming a barycentric period of 8.391 115 s for RX J0720.4 – 3125 as given by Kaplan et al. (2002a), and assuming a barycentric period of 11.3714 s for RX J0806.4 – 4132. As a system test, observations were made of the known 8.5-s radio pulsar PSR J2144–3933 using an identical setup to that described above. The source was observed for 30 min.

The data were folded to produce a pulse profile. The dispersion smearing was assumed to be negligible compared with the duration of one phase bin. The data were folded according to the ephemeris given in Young et al. (1999) for PSR J2144–3933, assuming a barycentric period of 8.391 115 s for RX J0720.4 – 3125 as given by Kaplan et al. (2002a), and assuming a barycentric period of 11.3714 s for RX J0806.4 – 4132. As a system test, observations were made of the known 8.5-s radio pulsar PSR J2144–3933 using an identical setup to that described above. The source was observed for 30 min.

Data were edited and calibrated using the MIRIAD package. At each frequency the field of interest was imaged using conventional techniques, after first collapsing the phase bins.

3 RESULTS AND DISCUSSION

3.1 PSR J2144–3933

The pulse profile of PSR J2144–3933 at 1.4 GHz is shown in Fig. 1. The pulsar is known to have a short duty cycle and hence its pulse fits entirely within one phase bin in this instance. The polarization of the pulsar is low, less than 10 per cent of the total intensity. This is consistent with observations at lower frequencies (Manchester, Han & Qiao 1998). The flux density at 1.4 GHz is ~0.8 mJy; the flux density at 436 MHz is 4 mJy (Young et al. 1999), which yields a (fairly typical) spectral index of ~1.4. This observation shows the viability of detecting these long-period pulsars using an interferometer.

3.2 RX J0720.4 – 3125

Continuum images of the region around RX J0720.4 – 3125 are shown in Figs 2 and 3. The position of RX J0720.4 – 3125 as given by the Chandra observations of Kaplan et al. (2002a) is shown by the + symbol. The extended source seen in Fig. 3 does not appear to have an optical counterpart in the Deep Sky Survey or in the deeper images of Kulkarni & van Kerkwijk (1998). It is likely that it is a background extragalactic source. No radio emission is detected from RX J0720.4 – 3125 with a 3σ upper limit of 0.2 mJy. A more stringent limit can be placed on the flux density if we assume that the pulse is contained within one phase bin (as is the case for PSR J2144–3933 above). The upper limit is then reduced by a factor of \( \sqrt{32} \) to 0.05 mJy.

If RX J0720.4 – 3125 is a conventional pulsar (i.e. not a magnetar), limits on the efficiency of the coupling of the relativistic wind with the interstellar medium can be determined. Following...
Radio observations of two isolated neutron stars

3.3 RX J0806.4—4132

A continuum image of a 2-arcmin region around RX J0806.4—4132 is shown in Fig. 4. The position of RX J0806.4—4132 as given by the XMM–Newton observations of Haberl & Zavlin (2002) is shown. The area covered by the + symbol is three times larger than the error box given by Haberl & Zavlin (2002). Only one source is seen in the field. It has a flux density of 0.4 mJy and is offset from the position of RX J0806.4—4132 by 34 arcsec. A search for pulsations at the

\[ \epsilon = \frac{d^2 S}{2.1 \times 10^2 E_{\text{vis}}}, \]

where \( d \) is the distance to the source in kpc, \( S \) is the flux density upper limit in mJy and \( E \) is the spin-down energy in units of \( 10^{31} \text{ erg s}^{-1} \). For RX J0720.4—3125, therefore, with \( d = 0.2 \text{ kpc} \) and \( E < 2 \times 10^{33} \text{ ergs}^{-1} \), \( \epsilon \) would be \(<5 \times 10^{-3} \), a value not atypical of other middle-aged pulsars. Therefore we cannot conclude from the lack of a radio nebula that this is not a neutron star powered by spin-down.

Unfortunately, the lack of radio emission from RX J0720.4—3125 does little to help our understanding of the nature of this source. The beaming fraction of these long-period pulsars is expected to be less than 10 per cent on theoretical grounds (Tauris & Manchester 1998) and the radio luminosity is low, as seen in PSR J2144—3933. The upper limit to pulsed emission from this source is a factor of 10 better than for PSR J2144—3933. Assuming a similar distance of 180 pc, it is unlikely that it is beaming in our direction and is below the sensitivity limit. It is therefore most probable that this is a conventional pulsar in which the radio beams do not intersect Earth (Brazier & Johnston 1999). The question then remains as to whether it is an old pulsar, with an age similar to that of PSR J2144—3933, or a much younger pulsar. The former implies that the age derived from the blackbody fits to the X-ray spectrum was incorrect, whereas the latter implies that it must have been born with a very long period, unlike the bulk of the known pulsars.

Table 1 lists the seven known radio pulsars and the X-ray pulsar Geminga within 400 pc of Earth (excluding the millisecond pulsars), ranked in descending order of \( E \) along with the two INS observed here.

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Period (s)</th>
<th>Distance (pc)</th>
<th>( E ) ( \times 10^{31} \text{ erg s}^{-1} )</th>
<th>X-ray</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geminga</td>
<td>0.237</td>
<td>157(^a)</td>
<td>3000</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B1929 + 10</td>
<td>0.226</td>
<td>331(^a)</td>
<td>390</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B0950 + 08</td>
<td>0.253</td>
<td>262(^a)</td>
<td>56</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B0823 + 26</td>
<td>0.531</td>
<td>375(^b)</td>
<td>45</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B1133 + 16</td>
<td>1.19</td>
<td>350(^a)</td>
<td>8.5</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>J0108 — 1431</td>
<td>0.808</td>
<td>128(^b)</td>
<td>0.58</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>J2307 + 2225</td>
<td>0.536</td>
<td>385(^b)</td>
<td>0.22</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>J2144 — 3933</td>
<td>8.51</td>
<td>179(^b)</td>
<td>0.0032</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>RX J0720.4 — 3125</td>
<td>8.39</td>
<td>&lt;2.4</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>RX J0806.4 — 4132</td>
<td>11.37</td>
<td></td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
</tbody>
</table>

\(^a\)Parallax measurement; \(^b\)estimated from the dispersion measure.

3.4 Speculation on the nature of the INS

Table 1 lists the seven known radio pulsars and the X-ray pulsar Geminga within 400 pc of Earth (excluding the millisecond pulsars), ranked in descending order of \( E \) along with the two INS observed here.

The pulsed fraction in X-rays is very low for RX J0806.4—4132, only 6 per cent. Haberl & Zavlin (2002) speculate that perhaps the neutron star has its magnetic axis and rotational axis nearly aligned. If this is the case, then radio emission might also be expected. The lack of a detection in the radio implies that this proposition is not correct, or that the radio pulsar is an order of magnitude less luminous than PSR J2144—3933, already one of the lowest luminosity pulsars known, or perhaps that it has crossed the death-line and is incapable of producing radio emission.

3.3 RX J0806.4—4132

A continuum image of a 2-arcmin region around RX J0806.4—4132 is shown in Fig. 4. The position of RX J0806.4—4132 as given by the XMM–Newton observations of Haberl & Zavlin (2002) is shown. The area covered by the + symbol is three times larger than the error box given by Haberl & Zavlin (2002). Only one source is seen in the field. It has a flux density of 0.4 mJy and is offset from the position of RX J0806.4—4132 by 34 arcsec. A search for pulsations at the
here. Of these, the four with the highest $\dot{E}$ have been detected in the X-ray band, essentially as a result of the sensitivity of the ROSAT All-Sky Survey. Nearby, spin-powered pulsars must have $\dot{E}$ greater than $\sim 5 \times 10^{31}$ erg s$^{-1}$ in order to be detected. Only PSR B1133+16 of the non-detected pulsars has an $\dot{E}$ slightly in excess of this value. PSR J2144−3933 has an $\dot{E}$ which is three orders of magnitude less than this and therefore not only is the lack of X-ray emission from this pulsar not surprising, but also it seems unlikely that the INS share the same characteristics.

It therefore seems most likely that the INS will turn out to have $\dot{E}$ in excess of $5 \times 10^{31}$ erg s$^{-1}$, consistent with the inferred $\dot{E}$ of RX J1856.5−3754 (van Kerkwijk & Kulkarni 2001; Kaplan, van Kerkwijk & Anderson 2002b) and marginally consistent with the upper limit derived by Kaplan et al. (2002a) for RX J0720.4−3125. For RX J0806.4−4132, the combination of an $\dot{E}$ of $5 \times 10^{31}$ erg s$^{-1}$ and the spin period of 11.4 s would imply a high value of the period derivative ($\sim 2 \times 10^{-12}$) and a magnetic field in the magnetar range ($\sim 2 \times 10^{14}$ G); and even more extreme parameters would result for the 22.7-s INS RX J0420.0−5022. These could then be magnetars where the energy source derives from the magnetic field rather than the spin-down. In summary, the INS appear to be one of the manifestations of neutron stars born with high magnetic fields.

Their number suggests that they must form a substantial fraction of the population of neutron stars in the Galaxy but that their radio emission may be inhibited.

ACKNOWLEDGMENTS

The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by the CSIRO.

I thank Warwick Wilson for his efforts beyond the call of duty in programming the correlator to ensure maximum efficiency for these long-period pulsars.

REFERENCES

Young M. D., Manchester R. N., Johnston S., 1999, Nat, 400, 848

This paper has been typeset from a TeX/LaTeX file prepared by the author.