Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **442,** 1884–1886 (2014) doi:10.1093/mnras/stu997

A search for coherent radio emission from RX J0648.0−4418

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Accepted 2014 May 16. Received 2014 April 13; in original form 2014 March 7

ABSTRACT

RX J0648.0−4418is a compact star with a spin period of 13.2 s. It is either the most rapidly rotating white dwarf known or a slowly rotating neutron star. Here, we report on the first searches for coherent pulsar-like radio emission from RX J0648.0−4418, both for sporadic bursts and steady periodic emission. No such emission was detected, with our limits suggesting that no such mechanism is active. We further searched our data for fast radio bursts to a dispersion measure corresponding to a redshift of ∼12. We did not detect any such events.

Key words: stars: neutron – pulsars: general – white dwarfs.

1 INTRODUCTION

RX J0648.0−4418 is a compact star in a 1.548-d binary system with HD 49798, an sdO5.5 subdwarf (Thackeray 1970). HD 49798 is bright at optical wavelengths ($V = 8.287(8)$, Landolt & Uomoto 2007), where studies have enabled measurement of the mass function of the system (Stickland & Lloyd 1994). RX J0648.0−4418 is bright at X-ray wavelengths where the spectrum is well fitted by a blackbody ($kT_{\rm bb}^{\infty} \approx 39$ eV, $T_{\rm bb}^{\infty} \approx 0.45$ MK and $R_{\rm bb}^{\infty} \approx 20$ km) plus power-law (photon index, $\Gamma \sim 2$) combination (Mereghetti et al. 2009). Modelling the observed X-ray eclipse reveals both the inclination angle of the system and the radius of HD 49798, as the distance is known to be 650 ± 100 pc (Kudritzki & Simon 1978). Both of these, combined with the mass function, provide the mass for each star: 1.50(5) $\mathrm{M}_{\odot}$ for HD 49798 and 1.28(5) $\mathrm{M}_{\odot}$ for RX J0648.0−4418. Furthermore, RX J0648.0−4418 shows X-ray pulsations every 13.2 s (Israel et al. 1997), which is interpreted as its spin period, and the spin period derivative is $<6 \times 10^{-15}$ (Mereghetti et al. 2013).

The mass, spin period, spin period derivative, temperature and blackbody radius are all consistent with RX J0648.0−4418 being either a white dwarf (WD) or a neutron star (NS). If RX J0648.0−4418 is a WD, it is the most rapidly spinning one known, ∼2.5 times faster than the second fastest rotator AE Aqr ($P = 33$ s; Patterson 1979). If it is an NS, it is ∼1.5 times slower than PSR J2144−3933, the slowest NS known to show pulsed radio emission ($P = 8.5$ s; Young, Manchester & Johnston 1999). The inferred rotational energy loss rate is $\lesssim 10^{22}$ W ($\lesssim 10^{28}$ W) if it is a WD (NS). In both scenarios, there is the possibility that RX J0648.0−4418 is emitting bursts of coherent radio emission, either as a so-called WD pulsar (Malheiro, Rueda & Ruffini 2012) or as an NS with an ‘almost-dead’ radio pulsar mechanism (Keane & McLaughlin 2011). Despite this, there have been no searches performed to try to detect this radiation. In this paper, we describe such a search. In Section 2, we describe our observations, before detailing the different search methods employed in, Section 3, as well as a fast radio burst (FRB) search which is possible ‘for free’. We provide our conclusions and a discussion in Section 4.

2 OBSERVATIONS

On 2013 October 23, RX J0648.0−4418 was observed for 548 min using the 64-metre Parkes radio telescope in New South Wales, Australia. The telescope was centred on the position of the source: $\alpha_{\rm J2000} = 06^{\rm h}48^{\rm m}04\overset{\rm s}{.}700$, $\delta_{\rm J2000} = -44$ deg $18'58\overset{''}{.}44$ (van Leeuwen 2007). The 20-cm multibeam receiver (Staveley-Smith et al. 1996), which received orthogonal linear polarizations, was used in combination with the Berkeley–Parkes–Swinburne Recorder backend (Keith et al. 2010). A bandwidth of 400 MHz, about a central frequency of 1382 MHz, was Nyquist sampled, channelized to 1024 frequency channels, and then integrated by a factor of 25 for a sampling time of 64 μs. The polarizations were summed to produce total intensity (Stokes I), and the data samples were written to disc as 2-bit numbers. To mitigate radio frequency interference (RFI) using coincidence testing, and to perform a commensal search for FRBs, data were recorded using all 13 beams of the multibeam receiver.

3 DATA ANALYSIS AND RESULTS

To mitigate RFI, two data cleaning steps were performed. (i) The 158 frequency channels where there is known RFI due to powerful transmissions from geostationary communications satellites (Keith et al. 2010) were set to zero in value. (ii) The time samples wherein the total power was seen to be highly correlated across all 13 beams (characteristic of terrestrial interference), judged using the method described in Kocz et al. (2012), were removed. A priori, we do not know whether it will be easier to identify any putative radio emission in a single pulse search or a periodicity search. It is straightforward to show that the ratio of the S/N ratios for these searches is

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Published by Oxford University Press on behalf of the Royal Astronomical Society

$r = (2/\sqrt{N})(S_{\rm peak}/S_{\rm ave})$, where N is the number of pulse periods during the observation. It is clear that, in the long term, the $\sqrt{N}$ term dominates so that a periodicity search is more effective in the large-N limit. For most pulse amplitude distributions seen in pulsars there is a 'sweet spot' at lower N-values, where the single pulse search can be more effective by an order of magnitude (Keane 2010). The pulse amplitude distribution, number of pulse periods observed and brightness of the pulsar (or equivalently the sensitivity of the instrument) together dictate the relative effectiveness of both search methods. We employed both searches, as we describe below.

3.1 Single pulse search

The data were searched for isolated bursts of radio emission using HEIMDALL,[1] a GPU code developed for real-time searches of pulsar survey data (Barsdell et al., in preparation). The data were dedispersed to 1018 trial dispersion measures (DM) in the range 0–100 pc cm^{-3}. The estimated DM for the source, according to the NE2001 model of the Galaxy's electron density content, is 9.85 pc cm^{-3} (Cordes & Lazio 2002). This model, although generally reliable to the ∼20 per cent level, can be wrong by as much as a factor of 2 along specific lines of sight (Deller et al. 2009; Bannister & Madsen 2014). The wide range of DM trials searched was chosen as it was considered extremely unlikely that the NE2001 prediction could be incorrect by more than a factor of 10. We note that the maximum Galactic DM contribution predicted for this line of sight is 77.3 pc cm^{-3}. The spacing of our DM trials was chosen using the prescription of Levin (2012) with a 'DM tolerance' of 1.05, so our DM coverage is at a much higher resolution than is typical for pulsar searches of large surveys (Keith et al. 2010).

Our number of statistical trials is large, as we recorded 15 625 samples per second for 9.1 h, searching each of these 1018 times. We searched for a range of pulses widths from 1 to 2^{12} times the raw sampling time, and this repeated searching further doubled the number of statistical trials (Cordes & McLaughlin 2003). In total, the number of trials is just over 10^{12}, implying that we can expect to find ∼1 event with S/N of 7 by chance in our searches. Due to the dish and receiver geometry, it is impossible for a boresight astrophysical signal to appear in more than three beams. Thus, we filtered out such multibeam events, which are likely to be terrestrial in nature.

We then examined standard single pulse search diagnostic plots for significant events in the DM range 1–100 pc cm^{-3}; events peaking below 1 pc cm^{-3} are likely terrestrial. For events with $W \leq 2^{10} t_{\rm samp} = 65.536$ ms, only six events with S/N ≥ 8 (a more realistic threshold given imperfect RFI excision) were evident, which were all seen to be clearly terrestrial upon inspection of their frequency–time behaviour; a genuine astrophysical signal shows a characteristic $t(\nu) \propto \nu^{-2}$ 'sweep'. For events with $2^{10} < W/t_{\rm samp} \leq 2^{12}$, the width of a broad-band signal is comparable to or larger than the dispersion delay across the entire band, $t_{\rm DM} \approx 131.2\,(DM/100\,{\rm pc\,cm^{-3}})$ ms. It is equivalent to note that the 'DM width' becomes much wider than the entire DM range searched (see Cordes & McLaughlin 2003, equation 4). A number of such pulses were detected, but none with the frequency–time signature or broad range in detected DM values one would expect from an astrophysical signal. Wider pulses are ever less distinguishable from zero-DM (i.e. terrestrial) signals, especially at the detection threshold. As expected, the number of detections for each boxcar width is approximately constant up to 2^{10}, then increases for the widest boxcars when wide zero-DM signals become detected at essentially all DM values. Also as expected, there are excess events detected, at all DM values and in all beams, for the width corresponding to the 50-Hz mains signal. A conservative 10σ limit on burst events can be calculated using the well-known radiometer equation (Lorimer & Kramer 2005). This yields $S_{{\rm SP},10\sigma} = 120\,/\sqrt{W/10\,{\rm ms}}$ mJy, where W is the pulse width. This corresponds to a radio pseudo-luminosity of <0.051 Jy kpc^2 $= 4.8 \times 10^{11}$ W Hz^{-1}. This is an order of magnitude fainter than the lowest luminosities detected in coherent radio bursts from the sporadically emitting long-period NSs (Keane et al. 2010), and thus a very constraining limit suggesting that a similar burst mechanism is not present in RX J0648.0−4418.

3.2 Periodicity search

The rotation period of RX J0648.0−4418 is known to high precision (Mereghetti et al. 2013). Nonetheless, we performed a search in period, in the range 13.0–13.4 s, far in excess of the period uncertainty. This search used the fast folding algorithm, which is superior to Fourier transform searches for periodicities $\gtrsim$1 s (Kondratiev et al. 2009), and considered a duty cycle range of ∼0.01 – ∼8 per cent. The same DM trials as per Section 3.1 were used. Our number of statistical trials is $\sim 1.6 \times 10^9$, less than for the single pulse search. Thus, there is an expectation of ∼1 signal with S/N $\gtrsim$6 simply by chance. However, due to both chance time alignments of imperfectly excised RFI events at integer multiples of our trial periods and the red noise seen in the data (the latter having no influence on the single pulse search), 8 is a more realistic threshold. No signals with S/N > 8 with the expected signatures of a genuine astrophysical signal were observed. Matching our conservative approach from Section 3.1, we place a flux density limit on periodic emission of $S_{\rm fold,\,10\sigma} = 29\,\mu$Jy, for an indicative duty cycle, δ, of 1 per cent; the sensitivity scales as $\sqrt{\delta/(1-\delta)}$. This flux density limit is at the level of the deepest limits on unidentified *Fermi* objects (Barr et al. 2013). The corresponding radio pseudo-luminosity limit is 1.2×10^{-5} Jy kpc^2 $= 1.2 \times 10^8$ W Hz^{-1}.

3.3 Fast radio burst search

RX J0648.0−4418 is quite far off the Galactic plane ($l = 253\overset{\circ}{.}7065$, $b = -19\overset{\circ}{.}1409$) and the product of observing time and field of view for our observations is reasonably large at 5.4 h deg^2. The FRB rate is approximately 1 per 200 h in the intergalactic volume probed by the High Time Resolution Universe (HTRU) survey (Thornton et al. 2013).[2] The HTRU search probed events up to a DM of 2000 pc cm^{-3}. We searched our data to a DM of 10 000 pc cm^{-3}. Subtracting a reasonable estimate for the combined Milky Way plus host galaxy DM contributions of 500 pc cm^{-3} from both searches, and using the DM–z relation of (Ioka 2003) we deduce the relative volumes probed. If FRBs were standard candles visible to (say) $z \sim 3$ then we might expect ∼1 event during our observations. If FRBs have a wide luminosity distribution then our high-DM search probes even more volume. We did not detect any FRBs in our search. This implies either (i) we have been unlucky as we are dealing with small number statistics and a highly uncertain rate estimate, (ii) FRBs are standard candles but with luminosities such that they

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[1] http://sourceforge.net/projects/heimdall-astro/

[2] We note however that the error on this number is very large. With 95 per cent error bars the four events detected in Thornton et al. (2013) should be taken as $4^{+5.1}_{-2.6}$ (Gehrels 1986).

are not detectable out to $z \sim 3$, or (iii) FRBs have a wide luminosity distribution such that some are detectable to high redshift, but have a much lower rate than estimated. We speculate that a combination of the first two possibilities seems most likely.

4 DISCUSSION AND CONCLUSION

Is RX J0648.0−4418 an NS? It does not show any periodic or bursting radio emission down to quite stringent limits. It seems that such mechanisms are not in operation, or that the beaming geometry of such emission is unfavourable, although, as there are no pulsar beaming fraction measurements for $P \gtrsim 3$ s (Tauris & Manchester 1998), it is difficult to make an estimate of this beaming fraction. The possibility remains that it is a slow pulsar whose radio emission mechanism is just extremely intermittent. Our observations limit the emission of any detectable burst to no more often than once every $\sim 10^5$ rotation periods. For its 'characteristic age' of $P/(2\dot{P}) \gtrsim$ 35 Myr, its temperature is too hot to be explained by standard NS cooling (Keane et al. 2013) but is easily explained by accretion. The mass, at 1.28(5) $\mathrm{M}_{\odot}$, is on the light side of the observed NS mass distribution, when corrections for the system binding energy and any accreted mass are considered. Thus, any formation scenario may need to invoke an electron capture supernova (Patterson 2004) in identifying a viable formation scenario. The inferred NS magnetic field strength of $\lesssim 10^{13}$ G is sufficiently high that X-ray absorption lines might be expected, but none are reported.

Is RX J0648.0−4418 a WD? Mereghetti et al. (2009) argue that, based on the X-ray spectrum, a WD is a better fit, but that an NS is not ruled out. Our observations probe coherent, non-thermal radio emission only, so cannot limit the actual temperature of the star but only the brightness temperature; our pseudo-luminosity limit corresponds to a brightness temperature limit of $\lesssim 10^{20}$ K ($\lesssim 10^{16}$ K) for single pulse (periodic) emission. However, if the fractional radio energy loss rate is the same in WDs as it is for NSs, our WD luminosity limit is thus $\sim 10^6$ times more constraining. The inferred WD magnetic field strength is $\lesssim 10^7$ G, which would have no impact on the X-ray spectrum. We note that if radio-emitting magnetars are in fact WDs, and RX J0648.0−4418 were similar, we would expect it to be visible in the frequency range we observed.

ACKNOWLEDGEMENTS

EFK thanks Mark Purver, Willem van Straten, Matthew Bailes and the anonymous referee, for helpful comments which have improved the quality of this paper. This work used the gSTAR national facility which is funded by Swinburne and the Australian Government's Education Investment Fund. The Parkes Radio Telescope is part of the Australia Telescope National Facility, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. EFK acknowledges the support of the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project number CE110001020.

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