Transient radio bursts from rotating neutron stars

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The 'radio sky' is relatively unexplored for transient signals,[1] although the potential of radio-transient searches is high, as demonstrated recently by the discovery of a previously unknown type of source[2,3] which varies on timescales of minutes to hours. Here we report a new large-scale search for radio sources varying on much shorter timescales. This has revealed 11 objects characterized by single, dispersed bursts having durations between 2 and 30 ms. The average time intervals between bursts range from 4 minutes to 3 hours, with radio emission typically detectable for < 1 s per day. From an analysis of the burst arrival times, we have identified periodicities in the range 0.4–7 s for ten of the 11 sources, suggesting a rotating neutron star origin. Despite the small number of sources presently detected, their ephemeral nature implies a total Galactic population which significantly exceeds that of the regularly pulsing radio pulsars. Five of the ten sources have periods greater than 4 s, and period derivatives have been measured for three of the sources, with one having a very high inferred magnetic field of 5×10^{13} G, suggesting that this new population is related to other classes of isolated neutron stars observed at X-ray and gamma-ray wavelengths.[4]

The eleven sources were detected in a search for isolated bursts of radio emission in data recorded for the Parkes Multibeam Pulsar Survey between January 1998 and February 2002. Figure 1 and Figure 2 show example detections. All bursts from a given source have the same unique value of dispersion measure (DM), or integrated free-electron column density, incontrovertibly distinguishing them from impulsive terrestrial interference.

Since August 2003, all the sources have been reobserved at least nine times at intervals of between one and six months. All have shown multiple bursts, with between four and 229 events detected in total from each object (see Table 1). As far as we can tell from the limited statistics, the density of sources on the sky appears to be greater towards the Galactic plane, with eight of the 11 having $|b| < 2°$. Average rates of detected events range from one every three hours for J1911+00 to one every 4 minutes for J1819–1458. The 2 ms to 30 ms-long bursts have peak 1400-MHz flux densities which range from 0.1 to 3.6 Jy. These sources are therefore among the brightest radio sources in the Universe after the giant pulses detected from the Crab pulsar and the pulsar B1937+21.[5]

Periodicity searches that depend on a pulsar's time-averaged emission, including a standard Fourier analysis and a fast-folding algorithm,[6] have been carried out on all survey and follow-up observations, with no periodicities detected using these methods. However, for ten of the sources we have been able to identify a periodicity from the arrival times of the bursts themselves (see Table 2). The 0.4 to 7 s period range indicates that they are likely to be rotating neutron stars. Most of the periods are quite long; five of the 10 have periods exceeding four seconds, compared with only 1 in 200 of the known radio pulsar population. As shown in Table 2, for three of the sources we have been able to measure period derivatives using standard pulsar timing techniques[6] on the individual burst arrival times.

How is the bursting behaviour related to single-pulse behavior of normal radio pulsars? For most of the sources, the number of detected bursts is not yet sufficient to obtain reliable luminosity distributions. In Figure 3, we show the peak flux density distributions for four objects. For J1317–5759 and J1819–1458, the periodic sources with the greatest number of bursts detected, the non-detection in periodicity searches means that the average peak flux density must be less than 0.5% (for J1819–1458) and 0.8% (for J1317–5759) of the peak flux density of the strongest detected bursts. These objects show power-law tails to their burst amplitude distributions, as seen for giant pulses from the Crab pulsar and pulsar B1937+21 (e.g. ref. 5). However, all pulsars from which giant pulses have been detected appear to have high values of magnetic field strength at their light cylinder radii.[7] While the Crab pulsar has a magnetic field strength at the light cylinder of 9.3×10^5 G, this value ranges from only 3 to 30 G for these sources, suggesting that the bursts originate from a different emission mechanism.

We therefore conclude that these sources represent a previously unknown population of bursting neutron stars, which we call Rotating RAdio Transients (RRATs). In Figure 4, we show their relationship to other neutron star populations. The long periods of some of the RRATs are similar to the apparently radio-quiet X-ray populations of magnetars[4] and isolated neutron stars.[8] Additionally, the inferred surface dipole magnetic field of J1819–1458 of 5×10^{13} G is greater than the magnetic field of all but four of the 1600 known radio pulsars and is comparable to those of the magnetars.[9,4] This RRAT is young, with a characteristic age of 117 kyr, smaller than those of 94% of all currently known radio pulsars. The period and magnetic field of J1317–5759 are similar to those of J0720.4–3125, the only radio-quiet isolated neutron star with a measured period and period derivative.[10]

The RRATs for which we have measured period derivatives show no evidence for binary motion. Likewise, we detect no glitches or other timing abnormalities, although continued monitoring is necessary to gauge the regularity of spin-down rates. In the future, radio polarization data may enable us to constrain the emission mechanism. For the three RRATs with accurate positions, a search of high-energy archives[11] reveals no X-ray or gamma-ray counterparts.

The discovery of this new population results in substantially increased estimates of the total number of Galactic active radio-emitting neutron stars. We detect, on average, one burst for every three hours of observation for J1911+00. The chance of detection within the single 35-min discovery observation was therefore less than 20%, implying that there should be roughly five times the number of similar sources in the same searched volume. Applying a similar analysis to all of the RRATs shows that we expect there to be twice as many sources as we have detected at a similar sensitivity level and sky coverage as for the Parkes survey. This number may be a gross underestimate, however. Firstly, it is very difficult to identify such sources in observations which are contaminated with large amounts of impulsive interference. There may be at least twice as many RRATs that were missed due to this effect. Secondly, we are only extrapolating to the area covered by the Parkes survey, and the true distribution of these objects is unknown. In addition, because our sensitivity was diminished for burst durations greater than 32 ms, there may be more sources with longer bursts that fell below our detection threshold. Furthermore, previous surveys with observation times of a few minutes had little chance of detecting such events and most did not include searches for them.

With these caveats in mind, we have carried out a Monte Carlo simulation to provide a first-order estimate of the size of the Galactic RRAT population. The simulation assumes that their spatial distribution follows that derived for the pulsars detected in the Parkes survey,[12] that the burst-duration distribution is similar to that observed in the 11 found so far, and, as measured for the pulsar population,[13] that the differential radio luminosity function of an average burst is of the form $d \log N/d \log L = -1$, where N is the number of model sources above a given luminosity $L = Sd^2$, where S is the peak flux density and d is the distance. By calculating the threshold of our survey to model bursts, and generating Monte Carlo realizations, we find the simulations produce a good match to the observations, but are fairly insensitive to the minimum burst peak luminosity $L_{\rm min}$, which could plausibly lie in the range 1–100 mJy kpc^2. To be consistent with the detection of 11 sources reported here, the implied size of the Galactic population of RRATs $N \sim 4 \times 10^5 (L_{\rm min}/10\,{\rm mJy\ kpc}^2)^{-1} \times (0.5/f_{\rm on}) \times (0.5/f_{\rm int}) \times (0.1/f_b)$, where $f_{\rm on}$ is the fraction of sources with bursts visible within our 35-min observation, $f_{\rm int}$ is the fraction of bursts not missed due to interference and f_b is the fraction of RRATs whose bursts are beamed towards the Earth. The average beaming fraction for pulsars is roughly 10%, and decreases for longer period pulsars.[14] Given the small RRAT duty cycles (see Table 2), our adopted f_b is almost certainly a conservative overestimate. An $L_{\rm min}$ of 10 mJy kpc^2 is consistent with the lowest peak luminosities observed for the single pulses of known radio pulsars. Assuming that the total Galactic population of active radio pulsars is of order 10^5 (e.g. ref. 15), this discovery increases the current Galactic population estimates by at least several times. We therefore expect the emerging generation of wide-field radio telescopes to discover many more RRATs.

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Name	RA (J2000) h m s	Dec (J2000) ° ′ ″	l °	b °	DM pc cm^{-3}	D kpc	w_{50} ms	S_{1400} mJy	N_p/T_{obs} hr^{-1}	N_{det}/N_{obs}
J0848–43	08:48(1)	–43:16(7)	263.4	0.2	293(19)	5.5	30	100	27/19	9/28
J1317–5759	13:17:46.31(7)	–57:59:30.2(6)	306.4	4.7	145.4(3)	3.2	10	1100	108/24	23/24
J1443–60	14:43(1)	–60:32(7)	316.2	–0.6	369(8)	5.5	20	280	32/41	17/25
J1754–30	17:54(1)	–30:11(7)	359.9	–2.2	98(6)	2.2	16	160	18/30	10/20
J1819–1458	18:19:33.0(5)	–14:58:16(32)	16.0	0.1	196(3)	3.6	3	3600	229/13	24/24
J1826–14	18:26(1)	–14:27(7)	17.2	–1.0	159(1)	3.3	2	600	18/17	8/12
J1839–01	18:39(1)	–01:36(7)	30.1	2.0	307(10)	6.5	15	100	8/13	1/10
J1846–02	18:46(1)	–02:56(7)	29.7	–0.1	239(10)	5.2	16	250	11/10	5/9
J1848–12	18:48(1)	–12:47(7)	21.1	–5.0	88(2)	2.4	2	450	10/8	5/9
J1911+00	19:11(1)	+00:37(7)	35.7	–4.1	100(3)	3.3	5	250	4/13	4/11
J1913+1333	19:13:17.69(6)	+13:33:20.1(7)	47.5	1.4	175.8(3)	5.7	2	650	66/14	7/10

Table 1. Measured and derived parameters for the 11 sources. For each, we give the Right Ascension, Declination, Galactic longitude, Galactic latitude, DM, inferred distance, average burst duration at 50% of the maximum, peak 1400-MHz flux density of brightest detected burst, ratio of the total number of bursts detected to the total observation time, and the ratio of the number of observations in which at least one burst was detected to the total number of observations. Estimated 1-σ errors are given in parentheses where relevant and refer to the last quoted digit. The mean latitudes and longitudes are comparable to those of the pulsars detected in the Parkes survey. The distances are inferred from their DMs, positions and a model for the Galactic free electron density.[16] The mean distance of 4.2 kpc is comparable to that of 5.8 kpc for the pulsars detected in the Parkes survey. The extremely sporadic nature of the bursts makes localization difficult, with most positions known only to within the 1400-MHz 14-arcminute beam of the Parkes Telescope. For the three sources for which we have measured period derivatives, more accurate positions have been derived through radio timing. Burst durations for each source remain constant, within the uncertainties, and are all much larger than those measured for pulsar giant pulses (e.g. refs. 17, 18).

Name	P	w_{50}/P	Epoch	$\dot{P}$	B	τ_c	$\dot{E}$
	s	%	MJD	10^{-15} s s^{-1}	10^{12} G	Myr	10^{31} erg s^{-1}
J0848–43	5.97748(2)	0.50	53492	–	–	–	–
J1317–5759	2.6421979742(3)	0.38	53346	12.6(7)	5.83(2)	3.33(2)	2.69(1)
J1443–60	4.758565(5)	0.42	53410	–	–	–	–
J1754–30	0.422617(4)	3.79	53189	–	–	–	–
J1819–1458	4.263159894(6)	0.07	53265	576(1)	50.16(6)	0.1172(3)	24.94(5)
J1826–14	0.7706187(3)	0.26	53587	–	–	–	–
J1839–01	0.93190(1)	1.61	51038	–	–	–	–
J1846–02	4.476739(3)	0.36	53492	–	–	–	–
J1848–12	6.7953(5)	0.03	53158	–	–	–	–
J1913+1333	0.9233885242(1)	0.22	53264	7.87(2)	2.727(4)	1.860(6)	39.4(1)

Table 2. Measured and derived parameters of the 10 sources with measured periods. For each, we give the period, average duty cycle (i.e. w_{50}/P), the epoch of the period and, if measurable, the period derivative and derived parameters. Periods are derived by calculating the largest common denominator of the differences between the burst arrival times at a given epoch. Given the number of pulses detected per epoch, and the number of epochs for which a periodicity can be measured, we may calculate the probability that the listed period is an integer multiple of the true period. Because of the small number of bursts detected per epoch for J1754–30 and J1848–12, there is a 32% and 16% chance, respectively, that the listed period is actually an integer multiple of the true period. For J1839–01 and J1846–02, this probability is less than 1% and for all others, the probability is less than 0.1%. Assuming that they are rotating neutron stars, the inferred surface dipole magnetic field is calculated as $B \equiv 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G, the characteristic age as $\tau_c \equiv P/2\dot{P}$ and the spin-down luminosity as $\dot{E} \equiv 4\pi^2 I\dot{P}P^{-3}$, where I, the neutron star moment of inertia, is assumed to be 10^{45} g cm^2 (see ref. 6). The duty cycles are generally smaller than those of radio pulsars with similar periods.

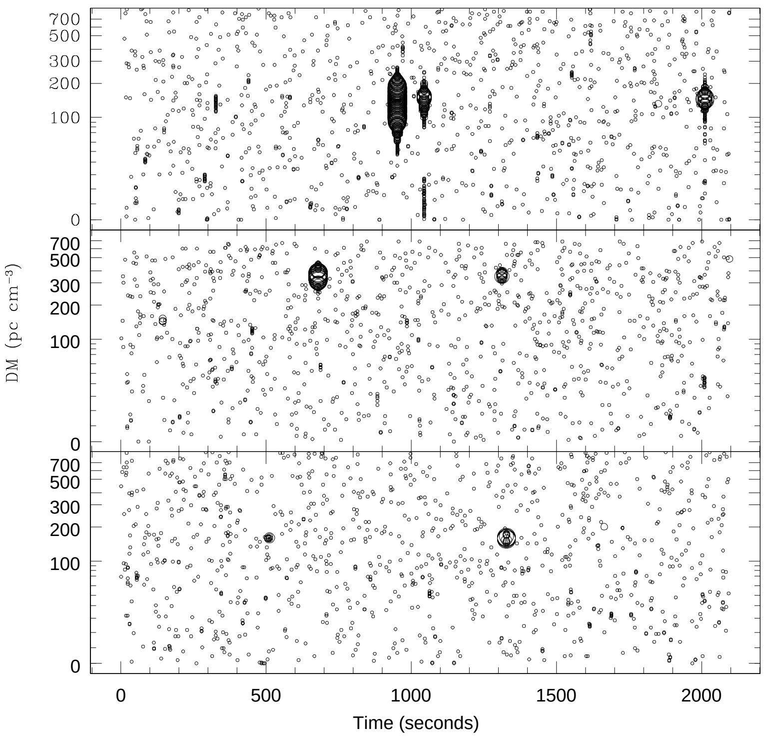

Figure 1. The observational signatures of the new radio transient sources. From top to bottom, we show the original detections of J1317–5759, J1443–60 and J1826–14 in the Parkes Multibeam Survey data. The Parkes survey, which has discovered over 750 radio pulsars,[19] used a 13-beam 1400-MHz cryogenic receiver and covered 1500 deg^2 within 5° of the Galactic plane, for longitudes $260° < l < 50°$ with 250-μs sampling of a multi-channel receiver and 35-min dwell-times on each position.[20] Approximately 30% of all pulsars that were detected in the survey using standard periodicity-seeking Fourier techniques were also detected in the burst search. Since radio waves are dispersed by ionised gas in the interstellar medium, the effects of such dispersion have to be removed, and we have therefore used search techniques similar to those described in ref. 21. In short, the 35-minute time series were dedispersed for a number of trial values of DM. The time series were smoothed by convolution with boxcars of various widths to increase sensitivity to broadened pulses, with a maximum boxcar width of 32 ms. Because the optimal sensitivity is achieved when the smoothing window width equals the burst width, our sensitivity is lower for burst durations greater than 32 ms. Each of these time series was then searched for any bursts above a threshold of five standard deviations, computed by calculating a running mean and root-mean-square deviation of the noisy time series. All bursts detected above a 5-σ threshold are plotted as circles, with size proportional to the signal-to-noise ratio of the detected burst. The abcissa shows arrival time while the ordinate shows the DM. Because of their finite width, intense bursts are detected at multiple DMs and result in vertical broadening of the features. Bursts which are strongest at zero DM and therefore likely to be impulsive terrestrial interference are not shown. In general these were easily identified by their detection in multiple beams of the 13-beam receiver.

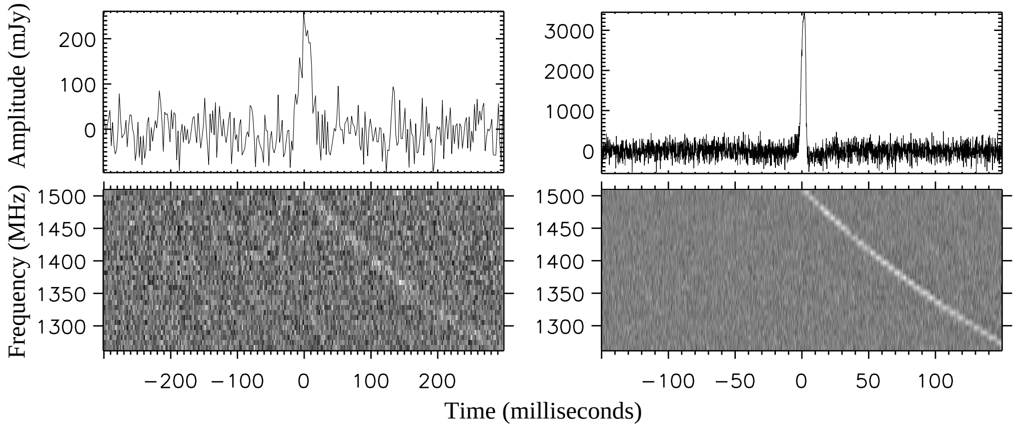

Figure 2. Burst observational signatures in frequency and time. The brightest single dispersed bursts detected from (left) J1443–60 and (right) J1819–1458. The lower panel shows the dispersed nature of the bursts detected in the individual frequency channels. The dispersion sweep is that expected for the radiation from a celestial source after passing through the ionised gas of the interstellar medium. The upper panel shows the dedispersed time series, obtained by summing outputs of the individual receiver channels at the optimum value of the DM.

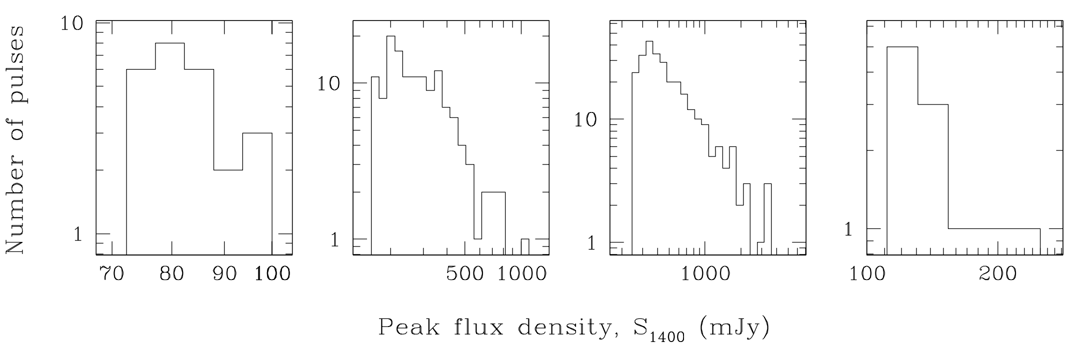

Figure 3. Typical burst intensities. Histograms of the peak flux densities for (from left to right): J0848–43, J1317–5759, J1819–1458 and J1846–02. The lower bound of all histograms corresponds to a threshold of 6σ. The minimum detectable flux density varies due to the different burst widths. The pulse amplitude distributions are described by power laws of index ~ 1, less steep than the indices of $2-3$ measured for giant pulsing pulsars (e.g. refs. 21, 22).

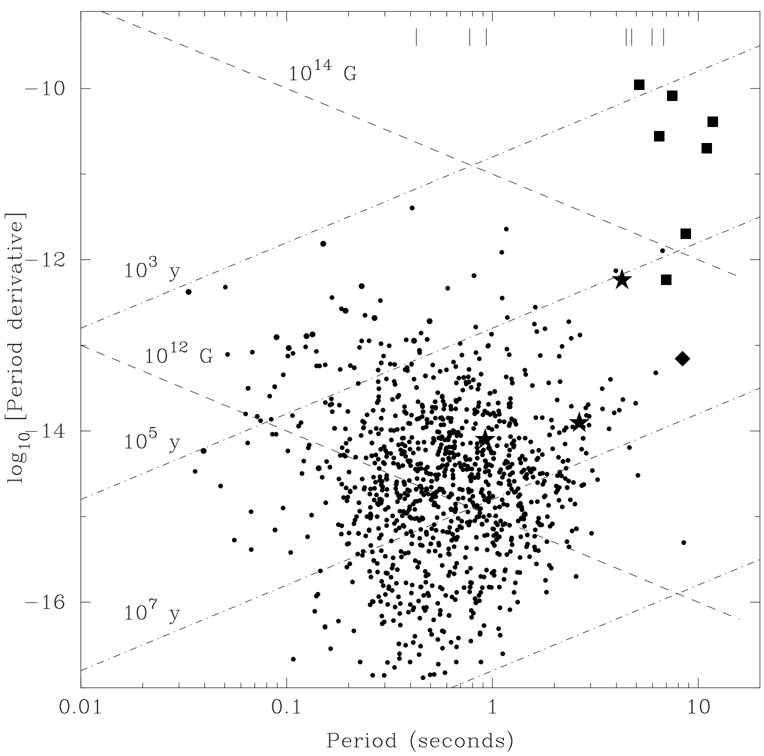

Figure 4. The rotational properties of neutron stars summarised in a $P-\dot{P}$ diagram. The rotational period derivative is plotted against period for pulsars (dots), magnetars (squares), the one radio-quiet isolated neutron star with a measured period and period derivative (diamond), and the three RRATs having measured periods and period derivatives (stars). The vertical lines at the top of the plot mark the periods of the other seven sources in Table 2. Dashed lines indicate the loci of constant values of characteristic age and inferred surface dipole magnetic field strength.