Transient Radio Neutron Stars

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Here I will review the high time resolution radio sky, focusing on millisecond scales. This is primarily occupied by neutron stars, the well-known radio pulsars and the recently identified group of transient sources known as Rotating RAdio Transients (RRATs). The RRATs appear to be abundant in the Galaxy, which at first glance may be difficult to reconcile with the observed supernova rate. However, as I will discuss, it seems that the RRATs can be explained as pulsars which are either extreme nullers, highly variable or weak/distant. I will re-cap some recent results including a re-analysis of the Parkes Multi-beam Pulsar Survey, which has identified several new sources, as well as the unusual timing behaviour of RRAT J1819−1458. This leads to an examination of where RRATs fit within the evolution of neutron stars post-supernova.

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1. Introduction

Short-timescale bursts, pulses or flickering at radio frequencies signal extreme astrophysical environments. A pulse of width W with a flux density S at an observing frequency ν which originates from a source at a distance D has a brightness temperature of

$$T_{\rm B} \geq 4.152 \times 10^{23}\, {\rm K} \left(\frac{{\rm SD}^2}{{\rm Jy.kpc}^2} \right) \left(\frac{{\rm GHz.ms}}{\nu.{\rm W}} \right)^2. \tag{1.1}$$

The minimum $T_{\rm B}$ in this expression is obtained when the emitting region is the maximum size of a causally connected region $cW = 300\,{\rm km}(W/1\,{\rm ms})$. Equation 1.1 is parameterised in units typical of Galactic millisecond bursts which we will discuss below. Thus observations of the transient radio sky probe compact objects and coherent non-thermal emission processes. If the dynamical time $t_{\rm dyn} = \sqrt{1/G\rho}$ dictates the scale on which we see changes then the millisecond radio sky consists mainly of neutron stars which have $t_{\rm dyn} \sim 0.1\,{\rm ms}$.

Neutron stars are the most populous member of 'transient phase space' [11] and it is on them that this work focuses. We will discuss the well known radio pulsars (see e.g. [39, 34]) which have been joined in recent times by the 'intermittent pulsars' [28] and the 'RRATs' (eRRATic radio sources, aka Rotating RAdio Transients, [43]). Together these sources exhibit variability on timescales spanning 16 orders of magnitude. Giant pulses of nanosecond duration have been observed in the Crab pulsar [21], whereas PSR B1931+24 has been seen to regularly switch on and off for ~ 5 and ~ 30 days respectively ($\sim 10^7$ s) [28]. The discovery of RRATs in particular has sparked much interest in radio transients. Their inferred population is large and a number of systematic searches of pulsar survey data have been performed [43, 22, 13, 25, 6], all of which have been successful in identifying new sources. In this paper we ask the question of whether RRATs are distinct from radio pulsars and the other manifestations of neutron stars with the aim of deciding where they fit in the 'neutron star zoo'. We begin by discussing in §2 the transient radio behaviour of the different neutron star classes. §3 then discusses the Galactic birthrates of neutron stars and how they compare to the observed core-collapse supernova rate in the Galaxy, in light of a recent re-processing of the Parkes Multi-beam Pulsar Survey (PMPS). We then, in §4, discuss the current state of knowledge regarding the evolution of neutron stars post-supernova, before concluding in §5.

2. Transient Neutron Stars

2.1 Basic Pulsar Model

The standard model of a pulsar is a rapidly spinning neutron star with a dipolar magnetic field emitting a coherent beam of radio emission along its magnetic poles powered by the loss of rotational energy [34]. If, as it rotates, the pulsar beam cuts our line of sight, a highly periodic source is detectable at the Earth. A typical pulsar has a period of $P \sim 0.5$ s and slows down at a rate of $\dot{P} \sim 10^{-15}$. Such sources are referred to as 'normal' or 'slow' pulsars and comprise the majority of the ~ 1800 presently known radio pulsars. In addition to these there are the millisecond pulsars (MSPs) which are the fastest rotators with typical periods of a few milliseconds.

We can derive some simple equations to quantify some pulsar parameters. The rate of rotational energy loss of a pulsar is simply $\dot{E} = d/dt[(1/2)I\Omega^2]$. Using canonical neutron star values for mass (1.4 $M_\odot$) and radius (10 km) we can take the moment of inertia to be that of a sphere to yield

$$\dot{E} = 3.95 \times 10^{31} \text{ ergs.s}^{-1} \left(\frac{\dot{P}}{10^{-15}} \right) \left(\frac{P}{\text{s}} \right)^{-3}. \qquad (2.1)$$

Equating this energy loss rate to the well known expression for the loss rate of a rotating magnetic dipole we can obtain an estimate for the 'characteristic magnetic field strength' which is

$$B = 1.0 \times 10^{12} \text{ G} \sqrt{ \left(\frac{\dot{P}}{10^{-15}} \right) \left(\frac{P}{\text{s}} \right) }. \qquad (2.2)$$

Assuming a spin-down law of the form $\dot{P} = KP^{2-n}$ we can determine an evolutionary timescale for pulsars by considering the case of a pulsar born spinning at a much faster rate than presently observed, i.e. $P_{\text{birth}} \ll P_{\text{now}}$. The 'spin-down' timescale is given by integrating the spin-down law to get

$$\tau = \frac{1}{(n-1)} \frac{P}{\dot{P}} \quad . \qquad (2.3)$$

For the dipolar case $n = 3$ which gives us the 'characteristic' timescale, $\tau_c = P/2\dot{P}$. This is commonly referred to as the pulsar's 'age' however we emphasise that τ_c is only a true representation of the pulsar age when the above assumptions are valid. Nevertheless τ_c does provide us with a representative timescale for pulsar evolution. Pulsars are typically classified using a $P - \dot{P}$ diagram as shown in Figure 1 and, using the above equations, lines of constant $\dot{E}$, B and τ_c are shown on this diagram.

2.2 Pulsar Stability

Pulsars are commonly referred to as stable astrophysical clocks but this is true only when considering integrated pulse profiles (of 10^4 periods or more), especially those of the MSPs. Conversely, on a period-by-period basis the pulses we detect from pulsars are quite variable and exhibit much random as well as highly organised behaviour. Sub-pulse drifting is a phenomenon whereby the rotational phase where we see pulsar emission changes periodically (see Figure 2). Some pulsars also exhibit 'mode-changing' whereby they switch between two or more different stable emission profiles. Nulling can be seen as an extreme example of moding where one of the modes shows no radio emission, i.e. the radio emission ceases and the pulsar is 'off'. Typical nulling occurs for $1 - 10$ rotation periods but we must note that the observed selection of nulling pulsars is quite biased [55]. Pulsars with longer nulling fraction are less likely to be detected in a single survey pointing, and in a confirmation pointing, and hence may be discarded amongst the plethora of pulsar candidates produced in modern surveys[1]. Also, due to a lack of sufficient signal-to-noise ratio, weaker pulsars cannot be examined on shorter timescales. Thus there may well be nulling occurring either unnoticed or undetectable in many known pulsars.

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[1]The number of pulsar candidates produced in modern surveys has surpassed what can be inspected by humans in a reasonable time. This has led to the use of artificial neural networks to identify the best candidates [16].
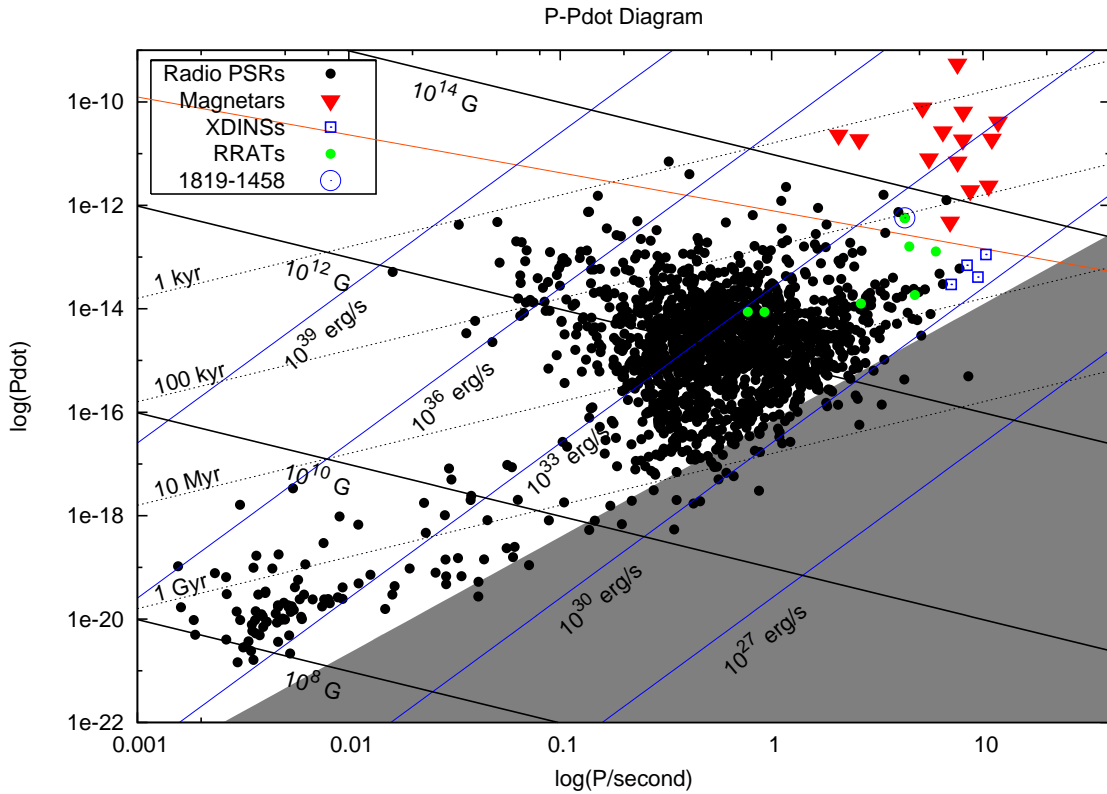
Figure 1: The pulsar $P - \dot{P}$ diagram. Shown are the radio pulsars, which can clearly be seen to consist of two classes — the 'slow' pulsars and the MSPs, as well as those RRATs (J1819−1458 is circled), XDINSs and magnetars with known period derivative. The shaded region in the bottom right denotes the canonical 'death valley' of [10] where we can see there is a distinct lack of sources. The radio loud-radio quiet boundary of [5] is also shown and we can see that only $\sim 1\%$ of sources are found above this line. Also plotted are lines of constant B, $\dot{E}$ and τ_c.

2.3 RRATs

In 2006 eleven new sources, dubbed RRATs, were discovered in an archival search [43] of the PMPS [40]. These sources are characterised by detectable millisecond bursts of radio emission occurring as infrequently as every 3 hours to as often as every few minutes. The bursts have a duration of $\sim 1-30$ ms with peak flux densities (at 1.4 GHz) of $\sim 0.1-10$ Jy. In total this amounts to a mere 5 minutes of detectable radio emission per year for a typical RRAT, which illustrates the inherent difficulty in detecting such sources. As the RRATs are located at distances of a few kpc, Equation 1.1 tells us that the brightness temperatures are high at $10^{22} - 10^{23}$ K, which is within the range measured for radio pulsars. Observing a number of pulses from each source has enabled the determination of underlying periodicities using time differencing methods (see e.g. [25]) with periodicities in the range $0.7-7$ s for the original 11 sources. The most well studied source, J1819−1458, has been observed in the X-ray where a thermal spectrum at $kT \sim 140$ eV is seen [51, 44, 50]. All these characteristics point towards RRATs being neutron stars. Monitoring these sources reveals that their spin periods are slowing down, and we can measure period derivatives and
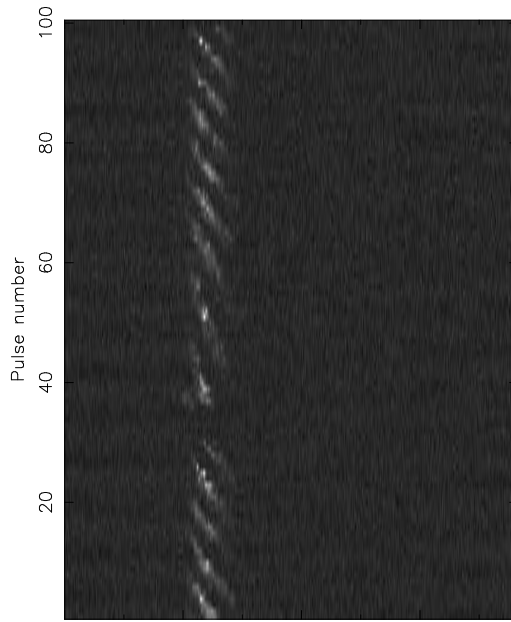
Figure 2: Plotted are a sequence of 100 pulses from PSR B0031−07 observed with the Westerboork Synthesis Radio Telescope. Periodic drifting of the pulse in pulse longitude is evident. This pulsar also exhibits nulls such as that visible between the fifth and sixth drift bands. (Image credit: M. Serylak).

place them in $P - \dot{P}$ space (Figure 1). Here we can see that they seem to occupy a region similar to the so-called high-B radio pulsars, i.e. between the main pulsar population and the magnetars. The arrival times of the pulses themselves seem to be random, not yet showing any highly significant quasi-periodicities on timescales up to 1000 days, although this is limited by the number of detected pulses [48]. Given the difficulty in detecting RRATs, we can estimate the selection effects and make a prediction of the Galactic population of RRATs. This yields $N_{\mathrm{RRAT}} = \gamma N_{\mathrm{PSR}}$ with $\gamma = 1 - 3$ [43, 25] but contains at least three built-in sources of uncertainty, namely the burst rate distribution, the fraction of RRATs obscured from detection due to the effects of radio frequency interference and the beaming fraction of RRATs. Of course, this estimate is also extrapolated from a very small sample population and there may be other unknown selection effects. Nonetheless, below we take this claim at face value and investigate the implications for the Galactic neutron star population. We also describe a re-analysis of the PMPS in search of more RRAT sources, conducted to better understand their phenomenology as well as improving the population estimate.

2.4 Intermittent Pulsars

2006 also saw the discovery of 'intermittent pulsars', sources which behave as normal radio pulsars for several days before switching off entirely for days to weeks. This switching occurs in a quasi-periodic fashion with the archetypal system PSR B1931+24 turning 'on' for $5 - 10$ days and 'off' for $25 - 35$ days [28]. These timescales allow the measurement of separate slow-down rates during the on and off states, $\dot{\nu}_{\mathrm{on}}$ and $\dot{\nu}_{\mathrm{off}}$. The difference in these rates is about 50% and reflects the extra energy loss due to the pulsar wind when there is radio emission. When off, the star slows down via dipole braking alone. When on, it has been seen to turn off in the space of a few seconds. This indicates a massive change in magnetospheric currents on a very short timescale to a new state

which is apparently stable for $\sim 10^6$ periods before switching once more. The explanation as to why this switching is quasi-periodic is unknown. We note that the scenario of two slow-down rates should apply to RRATs also, if they are truly off (see §3 for a discussion of this). When on, a RRAT slows down at a rate $\dot{v}_{on}$. The slow-down rate of a RRAT is $\dot{v}_{RRAT} = \dot{v}_{on} f_{on} - \dot{v}_{off}(1 - f_{on})$ where f_{on} is the fraction of time the RRAT is on given by $f_{on} = gW/f_{beam}T_{obs}$. The factor g is the observed RRAT pulses/period, W is the pulse width, f_{beam} is the beaming fraction[2] (empirically found to be a function of period [54]) and T_{obs} is the range over which the observations were performed. A typical RRAT (see e.g. [25] for typical numbers) has $f_{on} \ll 1$ so that $\dot{v}_{RRAT} \approx \dot{v}_{off}$, i.e. measuring two slow-down rates is not possible for RRATs unlike in the case of intermittent pulsars where the timescales are more favourable.

2.5 Death Valley

Pulsar emission requires a supply of particles from the stellar surface which can be accelerated in the pulsar magnetosphere for pair production, $\gamma \rightarrow e^+ + e^-$, to ultimately lead to coherent radio emission. The strength of the electric potential ΔV depends on B and P, e.g. in the simple Goldreich-Julian case $\Delta V \propto B/P^2$ [19]. An electron accelerated in this potential will acquire a Lorentz factor of $e\Delta V/m_e c^2$. Depending on the emission mechanism (i.e. the dependence of ΔV on B and P) the minimum Lorentz factor sufficient for pair-production (the photon must have energy of at least $2m_e c^2$) defines a 'death-line', separating regions of $P - B$ space where radio pulsar emission is possible and regions where it is inhibited (the 'death valley'). Detailed considerations lead to different death-lines for different field configurations, e.g. on high curvature field lines [10], and death-lines for several emission mechanisms have been proposed (see e.g. [4, 49, 63]). We note however that the various death-lines do not satisfactorily explain the observed pulsar population and there is at least one pulsar which flouts the rules in the death valley, namely the 8.5-second PSR J2144$-$3933 whose detection as a radio pulsar poses serious challenges to pulsar emission theories [61].

3. RRATs: Recent Results

3.1 Too Many Neutron Stars?

As we have mentioned above, the projected Galactic population of RRATs is large, perhaps larger than the population of radio pulsars. With this in mind, and considering all the classes of neutron stars now known, it makes sense to revisit the question as to whether the numbers are consistent with the observed core-collapse supernova rate in the Galaxy. From measurements of Galactic γ-ray emission from radioactive aluminium this has been determined to be $\beta_{CCSN} = 1.9 \pm 1.1$ century^{-1} [14], and of course the birthrate of neutron stars cannot exceed this. If we make the assumption that all the known classes of neutron stars are independent populations then this condition becomes

$$\beta_{CCSN} \geq \beta_{PSR} + \beta_{XDINS} + \beta_{RRAT} + \beta_{magnetar} + \beta_{CCO}, \qquad (3.1)$$

where each rate β_X is the birthrate (per century) for neutron stars of type X. Equation 3.1 refers to different neutron star populations which we now quickly summarise.

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[2]The beaming fraction factor is necessary as we remember that the RRAT is 'on' also when pointed away from us.
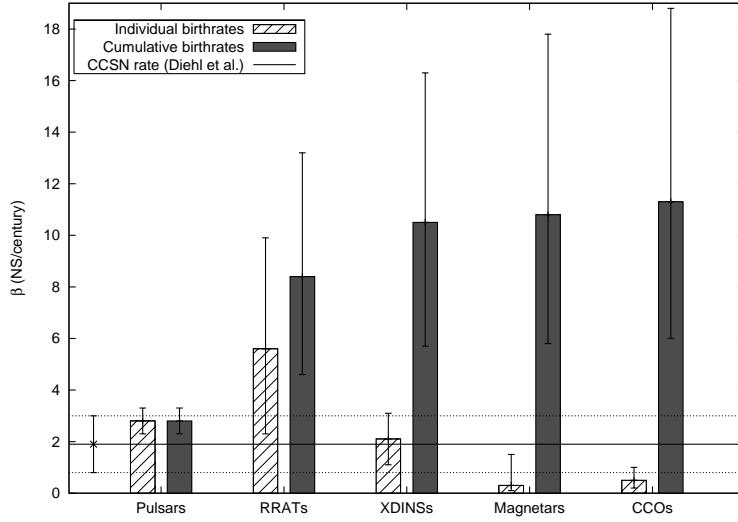
Figure 3: The estimates for individual neutron star birthrates for the different populations (hatched boxes), cumulative birthrate (solid boxes) and the core-collapse supernova rate (solid line). Adapted from a version in [24].

The (X-ray-Dim) Isolated Neutron Stars (XDINSs, aka INSs, see e.g. [23]) are a group of nearby neutron stars (sometimes referred to as "The Magnificent Seven") seen only via their thermal emission. There have been extensive searches for radio emission from XDINSs with no detection [27] and their X-ray spectra are well fit as blackbodies, without the need for a power-law component, which would be suggestive of an active magnetosphere.

The magnetars consist of the Soft Gamma Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs) [60]. These are thought to be isolated neutron stars with very strong magnetic fields of $10^{14} - 10^{15}$ G whose emission is powered by magnetic field decay. These magnetic fields exceed the 'quantum critical field' strength[3] $B_{QC} = 4.4 \times 10^{13}$ G so that higher order Quantum Electrodynamics effects play a role. For example, the amplitude for photon splitting, $\gamma \to \gamma + \gamma$, a third order effect, is proportional to $\alpha^3 (\hbar \omega / m_e c^2)^5 (B/B_{QC})^6$ [1] where α is the fine structure constant and $\hbar \omega$ is the photon energy. In magnetic fields $\gtrsim B_{QC}$ this dominates over photo-pair creation quenching the build-up of plasma and hence the radio emission [5]. For many years the known magnetars (radio-quiet) and the pulsars (radio-loud) were well separated into regions where this process was dominant or suppressed respectively. However, recently some magnetars have been found to be radio-loud [8, 9] and several radio pulsars with $B > B_{QC}$ have been identified (see Figure 1). So, although there is a dearth of sources in the $B \sim B_{QC}$ region, the fact that there are any at all implies that photon splitting may not always dominate over pair-creation, e.g. if single polarisation selection rules forbid it [56].

The Central Compact Objects (CCOs) are another small group of neutron stars which are isolated point sources associated with supernova remnants and are seen in thermal X-rays [20]. CCOs have no optical or radio counterparts and do not have associated pulsar wind nebulae. Recently the first measurement of a period derivative for a CCO has been performed for PSR J1852+0040,

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[3]The quantum critical value is that which makes the energy gap of electron cyclotron orbits ('Landau levels') equal the electron rest mass. In SI units $\Delta E = \hbar e B / m_e$ so that $B_{QC} = m^2 c^2 / q \hbar$.

associated with the SNR Kestevan 79, which has $\dot{P} = (8.68 \pm 0.09) \times 10^{-18}$ [20], implying, in the dipolar magnetic field scenario, the lowest magnetic field strength of any young neutron star of just $B = 3.1 \times 10^{10}$ G. An estimate of their birthrates was made by [18] to be $\beta_{CCO} \approx 0.5$ century^{-1}. Although excluded from the initial argument [24], we include the CCO birthrate in Figure 3 with the addition of an ad hoc uncertainty factor of 2.

One point of clarification is that β_{PSR} is the birthrate of 'normal' pulsars only, i.e. not the MSPs. This is because, according to the standard evolutionary picture [2], normal pulsars (in binary systems) are progenitors of MSPs. After $\sim 10^7$ yr, once a pulsar has slowed down and crossed the death line, it will no longer act as a radio pulsar. However, if this 'dead' pulsar has a binary companion it can experience a re-birth. Accretion from the companion re-heats areas of the neutron star surface and periodic X-ray emission will be visible from these hot spots. The system is now a low-mass X-ray binary (LMXB). In addition to mass transfer there is a transfer of angular momentum and the dead star is spun up to spin frequencies of hundreds of Hz and re-activated as a radio pulsar — an MSP. The transition from LMXB to MSP has been observed in PSR J1023+0038 over the last decade [3].

Using the best estimates for the various birthrates (see [24] and references therein), and assuming that the observed classes are distinct populations, we conclude that the supernova rate cannot keep pace with the necessary rate of neutron star production. This seems to point out that our assumption of distinct populations is invalid and has led naturally to the suggestion that the various classes are linked [24]. This link may be evolutionary in any of a few senses: (1) pulsars may evolve so as to increase nulling; (2) once a pulsar has evolved to particular areas of parameter space the selection effects may be changed so that the source appears more sporadic; (3) RRAT emission may be an extra 'mode' of emission in addition to the more steady (i.e. without nulling) emission seen in slow pulsars. Evolving beams would change the 'mode' in which we see the source during its lifetime. These possibilities are discussed in more detail in §4.

An alternative explanation to the 'birthrate problem' might simply be that the birthrate estimates are incorrect. This could allow the possibility of distinct populations (see §4 for a discussion of this). While this solution may seem less satisfactory, it can be directly investigated. The RRAT population estimate is the obvious target to try to improve: they make a large contribution to the putative birthrate problem and there is much survey data which has not been exhaustively searched for RRATs wherein many more may be discovered. With the discovery of many more RRATs an improved population estimate (and hopefully much other understanding) would follow.

3.2 PMSingle

With the goal of discovering more RRATs in the PMPS a complete reprocessing was recently performed, an analysis referred to as PMSingle [25]. This doubled the known PMPS RRATs to 22 with a few more confirmations soon to be reported [26]. Using radio frequency interference (RFI) removal techniques as described in [15] this search effectively set the fraction of sources missed by RFI to zero, thus removing this source of uncertainty [43] from the RRAT population estimate. The PMPS used a 13-beam receiver at 1.4 GHz where it is unlikely that a true astrophysical source would show up in more than a single beam, unless extremely bright (e.g. [32]). In addition to the RFI removal techniques, this re-analysis rejected multi-beam sources on this basis as well as expanding some of the parameter space searched (e.g. for wider pulses). Continued monitoring of

the newly identified RRATs will result in a determination of the RRAT burst rate distribution and efforts to this end are ongoing [26]. With this information we can perform a detailed population synthesis of RRATs but for now we can say that the new discoveries are consistent with the initial population estimate, i.e. there do seem to be about as many RRATs as radio pulsars in our Galaxy. However this statement must be interpreted carefully as described in §4. This effort to identify new RRATs is being helped by other searches which have also identified numerous sources, in surveys at GBT [22], Arecibo [13] and archival searches of higher latitude Parkes surveys [6].

3.3 Unusual Glitches

The original RRAT sources have now been monitored for several years. This has led to co-herent timing solutions and in the case of J1819−1458 the detection of glitches. Glitches are step changes in spin frequency ν and its derivative $\dot{\nu}$ of the form

$$\nu(t) \rightarrow \nu(t) + \Delta\nu_{\mathrm{p}} + \Delta\dot{\nu}_{\mathrm{p}}t + \Delta\nu_{\mathrm{d}}e^{-t/\tau_{\mathrm{d}}} \tag{3.2}$$

$$\dot{\nu}(t) \rightarrow \dot{\nu}(t) + \Delta\dot{\nu}_{\mathrm{p}} + \Delta\dot{\nu}_{\mathrm{d}}e^{-t/\tau_{\mathrm{d}}} \tag{3.3}$$

where the permanent steps are labelled with a 'p' and the steps labelled 'd' decay on a timescale of τ_{d} [53]. The glitches detected in J1819−1458 have fractional sizes of $\Delta\nu/\nu = 0.6 \times 10^{-6}$ and 0.1×10^{-6}, similar in size to those seen in young pulsars [36]. The noteworthy point however is that the net effect of the glitches is to decrease the slow-down rate of the star's rotation, i.e. the magnitude of $\dot{\nu}$ decreased. This is completely anomalous and unlike all radio pulsars glitches ever detected (see Figure 4). When contemplating the significance of this effect we might consider that the effect of the glitches in $P - \dot{P}$ space is to move J1819−1458 (labelled in Figure 1) downwards. If we were to propose that such glitches were typical in this source then it would suggest that J1819−1458 previously occupied the region of $P - \dot{P}$ space where the magnetars are. The importance of such effects must be considered when we consider pulsar (and magnetar) spin evolution in the $P - \dot{P}$ diagram.

4. RRATs: Special or Not?

There has been some debate about what exactly a RRAT is and if in fact they are 'special' or not. Here we investigate these questions. Firstly we invoke the (effective) definition implemented for RRATs discovered in the PMPS [43, 25]: a RRAT is a source identified in a single pulse (SP) search rather than a periodicity (FFT) search. If we let r denote the ratio of the SP and FFT search signal-to-noise ratios, i.e. $r = (S/N)_{\mathrm{SP}}/(S/N)_{\mathrm{FFT}}$, then RRATs are sources with $r > 1$. We see immediately that this definition depends on observing time as well as being at the mercy of the (a priori unknown) pulse amplitude distributions of RRATs. The definition is a detection classification only, i.e. sources identified as "RRATs" ($r > 1$) in one survey may well be identified as "pulsars" ($r < 1$) in another survey with longer pointings. Are the group of RRATs, so defined, in any way special?

To answer this we consider what this definition means as far as selection effects are concerned. If we take a source which emits pulses a fraction g of the time and nulls a fraction $1 - g$ of the time then we can derive the condition for $r > 1$ to be $N^{-1} < g < 2N^{-1/2}$ where N is the number of pulse
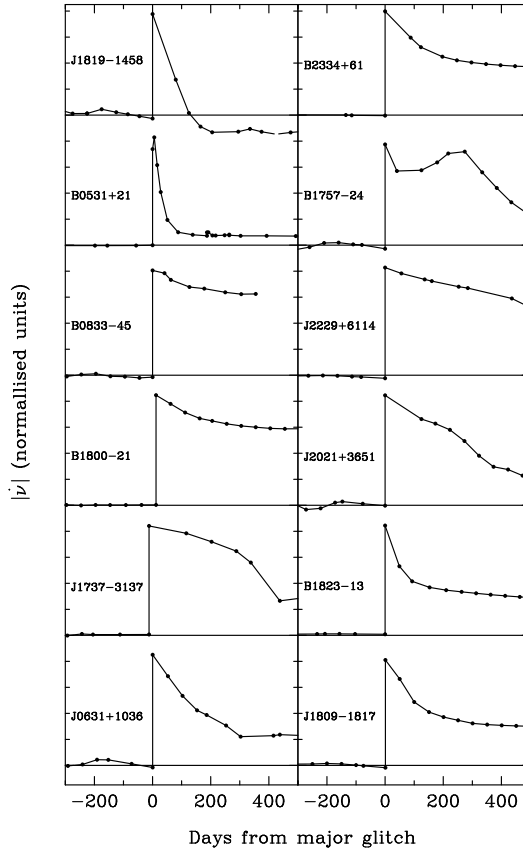
Figure 4: The relative change in the magnitude of $\dot{\nu}$ due to glitches, in J1819$-$1458 and a sample of glitches in other pulsars [36].

periods during our observation and we have ignored some pulse shape factors of order unity [41]. If we observe for a time $T = NP$ then we can convert this to a constraint on $g - P$ space which is $Tg^2/4 < P < Tg$ [42]. For a given g, the low period limit defines the $r = 1$ condition so that at lower periods an FFT search is more effective. For higher periods than Tg there is unlikely to be even one pulse during the observation. Thus RRATs are those sources detected in the hatched region in $g - P$ space in Figure 5. Clearly this definition depends on the observing time T, and the boundaries shown in Figure 5 are for the 35-minute pointings of the PMPS [40]. Different surveys will have different 'RRAT-PSR' boundaries, e.g. the higher-latitude Parkes surveys [6] had shorter pointings and hence different boundaries which are over-plotted on Figure 5. Thus the "RRAT" J1647$-$36 detected in the high-latitude surveys would have been detected as a "pulsar" if it were surveyed in the PMPS. We note that in reality the g values we measure represent the *apparent* nulling fraction, i.e. the intrinsic values of g may be higher depending on the pulse-to-pulse modulation and distance to the source [59, 6].

So the definition of a RRAT is arbitrary, survey-dependent and makes a selection in $g - P$ space. FFT searches also make a selection in $g - P$ space but, in comparison, single pulse searches are sensitive to higher period sources (up to several seconds) with moderate nulling fraction down to very short period pulsars with large nulling fractions. It seems unfair to compare period dis-

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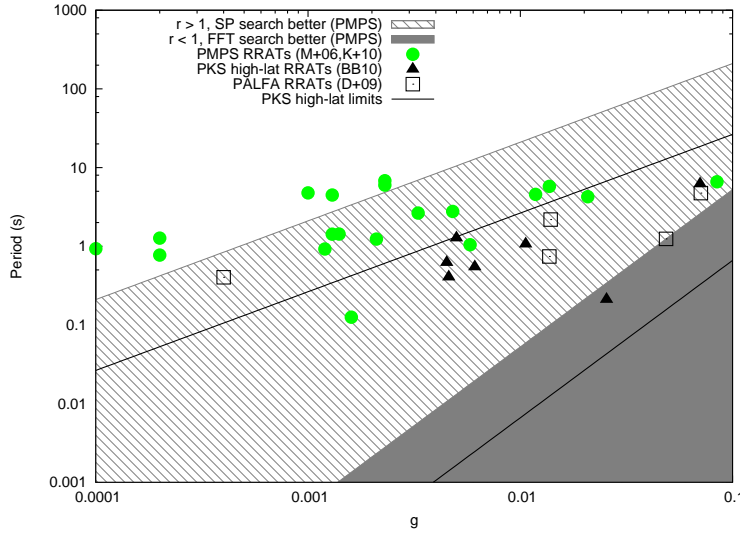
Figure 5: Plotted here is $g - P$ space with the regions where SP searches (hatched) and FFT searches (shaded) are more effective for the PMPS [40], which define the "RRAT" and "pulsar" regions. Over-plotted are the PMPS RRATs with measured periods as reported in [43, 25] (M+06 and K+10 in the figure). Also plotted are the "RRAT" and "pulsar" boundaries for the Parkes high-latitude surveys and the sources discovered therein which have known P and g [6] (BB10 in the figure). For J1654−23 we use the correct period as recently determined, not that published in BB10 [26]. We also plot the sources reported in [13] (D+09 in the figure). J1854+03 is plotted with the PMPS sources, although it was also identified in PALFA. We note that the boundaries for the inner-Galaxy PALFA pointings are the same as for the Parkes high-latitude surveys if we assume no difference in sensitivity. This is of course incorrect, and due to this extra difference (the Parkes surveys have the same sensitivity as each other) the D+09 sources are plotted simply for illustration.

tributions of sources selected in this way, but we do note that the periods of many PMPS RRATs are well above (more than an order of magnitude) the minimum periods where they would still be classified as RRATs, i.e. for a given g the PMPS was sensitive to low-period RRATs (e.g. $P \lesssim 1.0$ s and $g \lesssim 0.001$) but these were not detected. This is also true for most of the high-latitude survey sources and boundaries. Monitoring RRATs over some time reveals their slow-down rate $\dot{P}$ which is not subject to any selection effect. This has shown that RRATs have high spin-down rates compared to the normal radio pulsars [43, 42, 26] and this implies stronger magnetic fields according to Equation 2.2. This suggests the question of whether long period and/or high B sources have higher nulling fractions or modulation indices (i.e. low observed g values). Here we reach a dead end because, as discussed in § 2.2, the nulling properties of pulsars, i.e. the $g - P$ distribution of FFT-selected sources, is unknown. A project to determine the nulling characteristics of a large population of pulsars may shed some light on how g depends on pulsar parameters like P and B. A weak correlation of modulation index with B has been suggested in [57].

As discussed in [6], there are three credible explanations for the nature of RRATs: (1) a distinct population with high nulling fraction; (2) a distinct evolutionary phase with high nulling fraction (dubbed "true RRATs"); (3) weak/distant pulsars with a high modulation index. There seems to be no reason to consider RRATs as a distinct population. In fact, as discussed in § 3.1, this leads to inconsistencies [24]. Solutions (2) and (3) are both consistent with high observed nulling fractions,

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i.e. low values of g. The question of the "RRAT emission mechanism", for which there have been many proposed explanations [30, 62, 35, 12, 47], might then more accurately be re-phrased as a question of what causes nulling of the pulsar emission mechanism and how this might occur on long ($\sim 10 - 10^4$ period) timescales. The high projected population of RRATs also becomes less if some sources are covered by solution (3). Such sources will have low-luminosity[4] periodic emission. The pulsar population is estimated only above some threshold luminosity $L_{min} \sim 0.1$ Jy.kpc^2 (for periodic emission), so that if these sources are above L_{min} they are already accounted for within low-luminosity selection effect scaling factors in estimates of the pulsar population (see e.g. [33]). If the underlying periodic emission were below L_{min} then these sources would contribute to a birthrate problem by increasing the pulsar population estimate, and indeed the required low-luminosity turn-over[5] is not yet seen, which is why artificial cut-offs are usually applied in population syntheses (see e.g. [17]). Extreme modulation can account for all but two RRATs, according to the analysis of [6] (but notably not J1819−1458, which agrees with [46]), but the true number may be larger as it assumes analogues of the extreme source PSR B0656+14 to be common in the Galaxy. RRAT pulse amplitude distributions will shed more light on these matters [46]. Another recently discovered phenomenon is sources switching between RRAT-like and pulsar-like modes like PSR J0941−39 [6], consistent with the suggestion that nulling is a type of moding [55], although it is unknown how this correlates with pulsar parameters such as age, P or B. This also leads to the suggestion that nulling fraction may increase in steps rather than gradually as a pulsar evolves.

5. Conclusion

The transient radio sky at millisecond scales contains thousands of neutron stars. Searches for isolated bursts (rather than FFT searches for periodic emission) have revealed sources which appear to null on various timescales. Much recent interest has focused on the RRATs. These sporadically emitting sources are abundant in the Galaxy so that it seems necessary to absorb the RRATs within the known neutron star populations [24], either as a distinct evolutionary stage or as pulsars with extreme pulse amplitude variability. As the RRATs have longer periods than might be expected (given the selection effects) and higher B values than the normal radio pulsars, this suggests that long P and/or high-B sources may have increased nulling fractions and/or increased pulse-to-pulse modulation, in comparison to the general (FFT-selected) pulsar population. Of the RRATs which do not seem to fit the mould of highly modulated pulsars, J1819−1458 is the best studied source (and the source with the strongest B). It has been seen to undergo anomalous glitches. These have been proposed to have had an evolutionary impact so that J1819−1458 may be an exhausted magnetar [36], although the importance of this unique glitch behaviour is still uncertain. Recently sources have been identified which alternate between RRAT-like and pulsar-like behaviour, perhaps transitionary objects. The class of intermittent pulsars has lengthy nulls of several days which are quasi-periodic. It is difficult to understand these periodicities which are apparently absent from the RRATs [48]. More information on nulling phenomenology, such as the 'periodic nulls' in

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[4]Here 'luminosity' is used to refer to the quantity $L = SD^2$ which has units of Jy.kpc^2 or alternatively $W.Hz^{-1}$.

[5]There must be a low-luminosity turn-over so that the integral $\int N(L)dL$ does not diverge at the low end. Here $N = N(L)$ denotes the number of pulsars with luminosity between L and $L + dL$.

PSR J1920+1040 and the 'component nulls' in PSR J1326−6700 reported by [55], is needed to relate these transient behaviours to one another.

These discoveries also highlight our lack of knowledge of neutron star evolution post-supernova. The XDINSs and magnetars must also be accommodated into any evolutionary paradigm. It is important to point out that the beaming fraction of long period sources is small. If we extrapolate the empirical pulsar beaming fraction [54], which was derived from measurements of low-period ($P < 2$ s) pulsars, to RRATs and XDINSs (periods up to 11 s), we get very small values of $f_{\text{beam}} \approx 0.03$. Thus the chance of missing any beamed radio emission from the 7 well studied XDINS is high at $\sim (0.97)^7 \approx 0.8$ and we should not dismiss large beaming effects for these long-period sources. We also wish to explain the origin of magnetars. The standard pulsar spin-down model presented in § 2 with dipole braking, i.e. $n = 3$, is not realised in the handful of sources with known braking indices. In fact the measured values of n range from -1.5 to 2.9 [38, 37, 7, 45, 31], telling us that τ_c is an unreliable age estimate. Unfortunately alternative age estimates, such as cooling ages, kinematic ages or supernova remnant associations, are known only for a small number of sources. The low braking indices also imply increasing surface magnetic fields strengths (clear from combining the spin-down law with Equation 2.2) and there is also some evidence for magnetic field alignment with the rotation axis [58]. While these effects are poorly understood they must be considered (see e.g. [52]) to determine a full picture of neutron star evolution.

Further progress in pursuit of these questions will be made with the identification of many more sources. New radio transients, like those described here, are expected to be detected in abundance with next generation instruments like LOFAR, the ATA, FAST, the SKA pathfinders, and, in a decade or so, with the SKA itself (see [29] and references therein).

Acknowledgements

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