Radio pulsar sub-populations (II): The mysterious RRATs

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Abstract. Several conjectures have been put forward to explain rotating radio transients (RRATs), the newest subclass of neutron stars, and their connections to other radio pulsars. This work discusses these conjectures in the context of the characteristic properties of the RRAT population. Contrary to expectations, it is seen that: (a) the RRAT population is statistically un-correlated with the nulling pulsars and (b) the RRAT phenomenon is unlikely to be related to old age or death-line proximity. It is perhaps more likely that the special emission property of RRATs is a signature of them being later evolutionary phases of other types of neutron stars which may have resulted in restructuring their magnetic fields.

Keywords. Radio pulsar—null—RRAT—statistics.

1. Introduction

Approximately 3500 neutron stars have been observed and investigated (in varying detail) since the serendipitous discovery of PSR B1919+21 in 1967 (Hewish et al. 1968). Most of these neutron stars are observed as radio pulsars, characterized by short spin-periods (∼10⁻³–10² s) and large inferred surface magnetic fields (∼10⁸–10¹⁵ G). These rotation powered pulsars (RPP) are mostly isolated, or are members of binaries, where active mass transfer is not currently taking place (Kaspi 2010; Konar 2013, 2017; Konar et al. 2016).

The main characteristic feature of a radio pulsar (RPSR) is the emission of highly coherent radiation (across a wide range of the electromagnetic frequency spectrum) observed as regular periodic pulses. However, the process of emission is seen to deviate from a regular pattern in a significant number of RPSRs. One such irregularity is the phenomenon of nulling, first detected by Backer (1970) and now seen in ∼200 pulsars, which refers to the abrupt cessation of pulsed emission for a number of (can vary from a few to hundreds or even thousands) pulse periods. In an earlier work, we have discussed the population of nulling pulsars (NPSRs) in detail (Konar & Deka 2019—paper-I hereafter).

However, the extreme case of irregular emission is displayed by a group of objects known as rotating radio transients (RRATs). In 2006, 11 new radio transient sources were discovered in the parkes multi-beam pulsar survey (McLaughlin et al. 2006). The duration of their radio bursts were ∼2–30 ms and the intervals between the bursts ranged from minutes to hours. None of these were detectable in periodicity searches and appeared only via single-pulse searches. The primary characteristic of these transients appeared to be sporadic single-pulse emissions at constant dispersion measures (DM); with underlying periodicities suggestive of a neutron star origin.

In this discovery paper, it was conjectured that the RRATs represented a distinct and previously unknown class of neutron stars and were defined to be radio pulsar which can only be detected through single-pulse searches. Alternatively, Burke-Spolaor & Bailes (2010) defined an RRAT as a pulsar which
predominantly emits isolated pulses. However, many argued that the RRAT behavior was only an extreme case of pulsar nulling/intermittency and required no separate identification. The justification for this argument comes from the fact that the log-normal pulse distributions and power-law frequency dependence of the mean flux are both consistent with those for the ordinary RPSRs (unlike magnetars or giant pulses from RPSRs). This is a clear indication of the RRATs being a subclass of RPSRs, whatever may be the reason for their unusual emission characteristics.

Nevertheless, with rapidly increasing number of RRAT detections, a clear-cut definition for these objects became essential. So, Keane & McLaughlin (2011) proposed the following—‘A RRAT is a repeating radio source, with underlying periodicity, which is more significantly detectable via its single pulses than in periodicity searches’. Clearly, this definition comes with a caveat. Because, a pulsar may appear RRAT-like in a certain observational set-up, but not in another. Notwithstanding the caveat, all detections identified as RRATs till then (McLaughlin et al. 2006; Hessels et al. 2008; Shitov et al. 2009; Keane et al. 2010; Burke-Spolaor & Bailes 2010; Burke-Spolaor et al. 2011; Keane et al. 2011) and later observational campaigns have used the same definition. Current public databases, like the ‘ATNF pulsar catalog’ or ‘the RRATalog’, also use this same criterion to classify objects as RRATs. In the present work, RRAT data has primarily been taken from these public databases. Therefore, here too RRAT has the same meaning as the definition above.

Assuming these to represent a distinct sub-population of neutron stars, McLaughlin et al. (2006) estimated that the RRATs are expected to be significantly more numerous (by a factor of 3 or 4) than ‘normal’ pulsars (typically detected through periodicity searches). Even if we accept this to be an over-estimate (given the uncertainties implicit in various factors), the implication is quite serious. On the basis of their estimates of the numbers and birthrates of galactic neutron stars, Keane & Kramer (2008) demonstrated that treating the normal pulsars, the RRATs, the X-ray dim isolated neutron stars (XDINS), the magnetars and the central compact objects (CCOs) as distinct sub-classes of neutron stars would not be consistent with the observed Galactic supernova rate (required to be greater than or equal to total neutron star birthrate). See Konar et al. (2016) and Konar (2017) for discussions on these observationally distinct sub-populations of neutron stars.

This inconsistency is suggestive of connections (evolutionary or otherwise) between distinct sub-populations of neutron stars. To explain the ‘RRAT phenomenon’ (specifically, the nature of their transient radio emission), a number of hypotheses have been suggested. Most of these hypotheses have direct bearings on the connection of RRATs with other neutron star sub-populations. For many of these hypotheses, there exist tentative observational support. But, as yet, none of them prove to be definitive.

Bearing all these in mind, we consider the characteristics of RRAT population as a whole and examine some of these hypotheses. The basic characteristics of the RRAT population are discussed in Section 2. In Section 3, we concentrate upon the question of the connection of the RRATs with the NPSRs, by comparing these two populations, in view of the results obtained in paper-I. In Section 4, we consider the question of the proximity of the RRATs and the NPSRs to the death-line. A few other hypotheses regarding the nature of RRATs are examined in Section 5 and we summarize our conclusions in Section 6.

2. RRAT population

So far, 162 RRATs (see Appendix) have been found through archival and direct pulsar surveys since their discovery (McLaughlin et al. 2006). Even though RRAT emission has an underlying periodicity, the interval between individual pulses can widely vary, depending upon the epoch. Because of this, the spin-period of an RRAT is determined by finding the greatest common denominator of the intervals between pulses. Clearly, this method is likely to yield a multiple of periods instead of the true one, unless more than a few pulses have been detected in an observation (Cui et al. 2017). This problem is usually taken care by detecting sufficiently large number of pulses from a particular RRAT to arrive at the true period of the neutron star.

To date, the population of RRATs has been seen to have the following ranges for the spin-period ($P_s$), the dipolar surface magnetic field ($B_s$) and the dispersion measure (DM):

- $P_s$: 41.5 ms–7.7 s;
- $B_s$: $1.67 \times 10^{11}$–4.96 $\times 10^{13}$ G;
- DM: 4.0–786.0 pc cm$^{-3}$.

Understandably, timing measurements are difficult and values for the spin-period or the period derivative (hence, estimates for the dipolar surface magnetic field) are not available for all of the known RRATs. In
developed by Chen & Ruderman (1993) are of importance for the RPSR population as a whole, and the NPSRs in particular.

Both of these death-lines are obtained assuming the pair productions ($\gamma + B \rightarrow e^- + e^+$, $\gamma$-photon, $e^-/e^+$-electron/positron, $B$-magnetic field) to occur predominantly near the polar cap of the neutron star (Ruderman & Sutherland 1975). It is also assumed that (a) the surface field is dipolar and (b) the radius of curvature for the magnetic field is approximately equal to the stellar radius. These death-lines, numbered as [2] and [4a] in paper-I are as follows:

\begin{align}
[2]: \quad 4 \log B_s - 6.5 \log P_s &= 45.7, \\
[4a]: \quad 4 \log B_s - 6 \log P_s &= 43.8, 
\end{align}

where $P_s$ is in seconds and $B_s$ is in Gauss. Death-line [2] corresponds to the case of very curved field lines, whereas [4a] is obtained for extremely twisted field lines. It is clearly seen from Figure 1 that the region beyond death-line [4a] is almost empty. However, the RRATs and the NPSRs are almost entirely bounded below by the death-line [2], suggesting similarities/connections between these two populations.

3. RRAT–NPSR connection

Because of their intermittent nature, it has been natural to look for similarities and/or connections between the RRATs and the NPSRs. Burke–Spolaor & Bailes (2010) considered this issue in detail and concluded that RRATs are likely to be ‘extreme’ cases of NPSRs. They found that PSR J0941–5907, known to have many different modes of emission—a strong mode with a broad profile with nulls, a weak mode with a narrow profile that has occasional bursts of up to a few clearly detectable pulses at a time, and a low-level underlying emission. It has been argued that this source would look like an RRAT for most of the time, if placed at a larger
distance (Young et al. 2014). A very similar conjecture has also been made about another NPSR (B0656+14/J0659+1414) that it would have appeared RRAT-like, if located at a greater distance (Weltevrede et al. 2006). J1107—5907 also exhibits different NFs in different emission modes, similar to that observed in B0826—34 (J0828—3417) and J0941—39, both of which appear to switch between an RRAT-like and a more typical ‘pulsar-like’ phases (Burke-Spolaor & Bailes 2010; Burke-Spolaor et al. 2012; Esamdin et al. 2012).

Then again, the weak emission mode of B0826—34 is liable to be confused with nulling phases, if the signal is not integrated over a sufficiently long interval of time. This has been suggested to be indicative of an evolutionary progression towards the death-line; and that all (or most) pulsars likely start off as continuous emitters, gradually begin to null and then increase their NF to become RRATs, ultimately crossing the death-line to end the active radio emission phase (Burke-Spolaor & Bailes 2010). In fact, both J1107—5907 and B0826—34 are quite close to the death line. However, there also exist a large number of NPSRs that are close to the death-line, but are not known to exhibit any RRAT-like behavior. Similarly, quite a few RRATs are found far away from the death-line (Figure 1). Therefore, death-line proximity does not immediately imply a certain nature of pulsar emission. We discuss this issue in detail in Section 3.

Even though the picture is not yet clear, it is evident that there exist certain connections between the RRATs and NPSRs. Clear nulling segments were also exhibited recently by another RRAT (J1913+1330) in a FAST observation (Lu et al. 2019). At this point, some other objects have also been observed to exhibit such RRAT–NPSR ‘dual’ nature (Table 4). To understand this connection better, we look at the statistical nature of the RRAT and NPSR populations below.

Table 1 summarizes the average values of relevant physical quantities of the RRAT and NPSR populations. Clearly, the RRATs have larger average spin-periods and larger average surface magnetic fields, as has already been remarked upon. Consequently, NPSRs have larger characteristic ages \( \tau_c \) compared to the RRATs \( (B_s \sim \sqrt{P_s \cdot P_s}, \quad \tau_c \sim P_s / P_s) \). We must remember that the estimate of characteristic age is crucially dependent on the assumption of a constant magnetic field, which may or may not be applicable to RRATs. However, RRATs clearly have lower average DM, indicating that they are not necessarily located farther away compared to the NPSRs. Therefore, the conjecture that a distant NPSR might appear to be RRAT-like is unlikely to explain the majority of objects, even if such a situation is realized for a small number of RRATs.

Figures 2–4 show the distribution histograms of these parameters. To quantify the nature of the distributions, we perform 1-sample Kolmogorov–Smirnov (von Mises 1980) tests on each set of data. The results are summarized in Table 2. It is seen that \( P_{KS} \), the probability of error for rejecting the hypothesis that the data is normally distributed, is very high for \( \log(P_s) \) and \( \log(B_s) \) but tiny for DM for both RRAT and NPSR populations (\( P_s \) in units of second and \( B_s \) in units of Gauss). Clearly, \( \log(P_s) \) and \( \log(B_s) \) are expected to be normally distributed. In other words, \( P_s \)
and $B_s$ are log-normally distributed for both the populations, though with somewhat different degree of normality. We also perform the 2-population Kolmogorov–Smirnov tests on the parameter values to compare the RRAT and NPSR populations. The bottom panel of Table 3 show the results. It is obvious that the statistical distributions of $P_s$, $B_s$ for RRATs and NPSRs are completely dissimilar.

The combined distributions, for both of these parameters, are also log-normally distributed with a degree of normality in between the RRAT and NPSR distributions. This could be due to the fact that the size of the NPSR population is much bigger (twice for $P_s$ and five times for $B_s$ values) than the RRAT population and the behavior of the combined population is basically dictated by that of the NPSRs. It might be tempting to conclude that the NPSRs and RRATs come from two different segments of the same underlying population, which is Gaussian in nature.

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Table 2. Kolmogorov–Smirnov test statistics: $P_{KS}(N)$ is the probability of error for rejecting the null hypothesis that the sample is normally distributed and $D_{KS}(N)$ is the magnitude of the difference between the sample distribution and the normal distribution. The tests are performed on log($P_s$), log($B_s$) and DM. $P_{KS(R-N)}$ and $D_{KS(R-N)}$ are the corresponding quantities for null hypothesis that both the RRATs and NPSRs are drawn from the same underlying population. Data: (a) RRAT—Appendix and (b) NPSR—Null Catalog.

|       | $P_{KS}$ | $D_{KS}$ | $N$ |
|-------|----------|----------|-----|
| RRAT  | 0.36     | 0.93     | <10$^{-5}$ |
|       | 0.08     | 0.07     | 0.23 |
|       | 109      | 44       | 162 |
| NPSR  | 0.70     | 0.55     | <10$^{-5}$ |
|       | 0.05     | 0.05     | 0.17 |
|       | 222      | 215      | 222 |
| All   | 0.47     | 0.63     | <10$^{-5}$ |
|       | 0.05     | 0.05     | 0.19 |
|       | 331      | 259      | 384 |
| KS2: RRAT vs. NPSR | $P_{KS}$ | $D_{KS}$ | $N$ |
|       | <10$^{-3}$ | <10$^{-3}$ | $\sim$ 10$^{-2}$ |
|       | 0.25     | 0.33     | 0.17 |
|       | 109,222  | 44,215   | 162,222 |

Table 3. The average values of $P_D$ and $\epsilon$ (see text for definitions) for the RRAT, NPSR and the combined populations. Kolmogorov–Smirnov test statistics, $P_{KS}(N)$ and $D_{KS}(N)$, to check whether $P_D$ is normally distributed (this test is not performed on $\epsilon$ as it is clearly an asymmetric and skewed distribution). $P_{KS(R-N)}$ and $D_{KS(R-N)}$ are corresponding quantities for the null hypothesis that both the RRATs and NPSRs are drawn from the same underlying population. Data: (a) RRAT—Appendix and (b) NPSR—Null catalog.

|       | $P_D$ | $P_{KS}$ | $D_{KS}$ | $\epsilon$ |
|-------|-------|----------|----------|-------------|
| RRAT  | 6.44s | 0.93     | 0.08     | 0.96        |
| NPSR  | 3.52s | 0.57     | 0.05     | 0.96        |
| All   | 4.01s | 0.61     | 0.05     | 0.96        |
| KS2(R–N) | $P_D$ | $P_D$ | $\epsilon$ | $\epsilon$ |
|       | $P_{KS}$ | $D_{KS}$ | $P_{KS}$ | $D_{KS}$ |
|       | <10$^{-3}$ | 0.36     | 0.90     | 0.09        |

But the fact that both the RRAT and NPSR parameters also tend to be separately Gaussian, contradicts such a conclusion.

As expected, the nature of the DM distribution is very different. Given that the dispersion measure can...
be considered to be a proxy for distance (with certain caveats), a normal distribution is not really expected. Because every detection is limited by the inherent sensitivity of the particular observation and nearer sources are expected to be detected with a higher probability. But it is surprising to note that the DM distributions of the NPSRs and the RRATs are totally dissimilar $(P_{KS}(R-N) < 10^{-2})$. As both the RRATs and NPSRs are being detected by same/similar observational instruments, we can interpret this result in two ways: either, (a) the single pulse searches (detecting RRATs) are more sensitive at low DM compared to the periodicity searches (detecting regular pulsars), or (b) for any given detection sensitivity, only RRATs located at shorter distances are detected. The second possibility, suggestive of a scenario where the ‘RRAT phenomenon’ is observed only for nearby neutron stars, is problematic as it exacerbates the ‘birthrate problem’ discussed earlier.

In summary, the current populations of the RRATs and NPSRs cannot be said to belong to the same sub-class of RPSRs. Therefore, while the observations clearly suggest that they have certain inherent connections, it would perhaps not be accurate to treat the RRAT emission simply as an extreme form of nulling behavior.

4. Death-line proximity

It has been suggested that the RRATs could be RPSRs close to the pulsar death line in the $P_s-B_s$ plane. These systems might be emitting weak and continuous radio pulses, which have not been detected yet, in addition to the observed short radio bursts (Weltevrede et al. 2006).

To check if the RRAT phenomenon is connected to a proximity to the death-line, we define a proximity parameter, $\epsilon$, given by

$$\epsilon = \frac{\tau_D - \tau_c}{\tau_D},$$

where $\tau_c$ is the current (characteristic) age of a pulsar given by $P_s/2\dot{P}_s$. This definition of $\tau_c$ inherently assumes that: (a) the pulsar has $P_s \sim 0$ at birth and (b) $B_s$ does not evolve significantly over the active lifetime of a pulsar. This constant surface magnetic field of a pulsar is obtained using the measured values of $P_s$ and $\dot{P}_s$ from the relation:

$$B_s = 3.2 \times 10^{19} \sqrt{P_s \dot{P}_s} \ G,$$

where $P_s$ is in seconds and $\dot{P}_s$ is in $s^{-1}$, assuming a purely dipolar field.

Under the same assumptions mentioned above, $\tau_D$ is defined to be the total time taken by a pulsar to reach the death line, such that

$$\tau_D = \frac{P_D}{2\dot{P}_D},$$

where $P_D$ is the spin-period at death line and $\dot{P}_D$ is the period derivative at the death-line. Clearly, the definition of $\tau_D$ depends on a particular choice of the death-line. In this work, we adopt death-line [2], given by Equation (1). This gives us the following expressions for $P_D$ and $\dot{P}_D$:

$$\log P_D = 0.62 \log B_s - 7.03,$$

$$\dot{P}_D = 9.76 \times 10^{-39} P_D^{-1} B_s^2,$$

where $P_D$ is in seconds, $\dot{P}_D$ is in $s^{-1}$ and $B_s$ is in G. The distribution histograms of $P_D$ and $\epsilon$, for the corresponding populations are shown in Figures 5–7.

It is to be noted that $P_D$ or $\tau_D$ and hence the proximity parameter, $\epsilon$, can only be calculated where the current value of $\dot{P}_s$ has been measured. Hence, such a calculation can be done only for a small number of RRATs, even though it is possible to obtain $\epsilon$ for almost the entire population of NPSRs. Moreover, for any given choice of death-line, there exist a few objects, which fall on the right of the line (in the $P_s-B_s$ plane). This happens because every theoretical

![Figure 5](image-url)
death-line makes certain simplifying assumptions which may or may not be applicable for a given pulsar. So, these ‘beyond death-line’ pulsars have also been excluded from the $C_15$ calculation. The average values of $\dot{P}_D$ and $\dot{P}_D$ are shown in Table 3. For the NPSRs, it can be seen from Figure 6 that $P_D$ has a very clear log-normal distribution with the peak at $\sim 2.5$ s. Though it is not as obvious for the RRATs, the $P_D$ distribution is again nearly log-normal albeit with a higher peak value of $\sim 5$ s. Surprisingly, contrary to expectation, the proximity parameter for both the RRATs and NPSRs have rather similar behavior. Even though close to the death-line, both types of objects have larger fractions of their life-time to go through yet. This likely rules out the possibility that nulling or RRAT behavior can be treated simply as an ‘old age’ characteristic appearing in a particular evolutionary phase. However, as mentioned above, such a conclusion crucially depends on the assumption of constant surface magnetic fields, which may or may not be true for the objects under consideration.

Therefore, it is important to consider other evolutionary connections for the RRATs. In the next section, we discuss a few important conjectures of that nature.

5. Other connections

Initially, the RRAT phenomenon was considered to be a manifestation of certain selection bias and/or the sensitivity of a telescope. For example, they were thought to be giant pulses from weak pulsars (Knight et al. 2006); or to be pulsars with special emission behavior, being far away (as discussed in Section 3). But there appears to be far more to the RRATs than simple observational effects.

 Besides the NPSRs, regular non-nulling RPSRs have also been observed to behave like RRATs, like J0828$-$3417 or J1119$-$6127. While J0828$-$3417 is an ordinary pulsar with a low DM, J1119$-$6127 is a high-magnetic field pulsar with a rather high value of DM (Table 4). In fact, J1119$-$6127 has been observed to exhibit different types of radio behavior at different epochs with RRAT-like events typically preceded by large spin-period glitches. Weltevrede et al. (2011) argued that the glitches could be responsible for reconfiguration of the magnetic field giving rise to such changed emission behavior, and this likely indicates the existence of a group of neutron stars that become visible for a brief, while only in the immediate aftermath of glitch activity. It has also been suggested that RRATs likely to have evolutionary links with magnetars (McLaughlin et al. 2009) or XDINS (Popov et al. 2006). Observation of RRATs in X-ray would help confirming such links. Unfortunately, only two RRATs, J1819$-$1458 (McLaughlin et al. 2007) and J1119$-$6127 (Archibald et al. 2017), have been observed in X-rays with upper limits for the X-ray luminosity estimated for another two RRATs (J0847$-$4316, J1846$-$0257). Most probably, the main reason for X-ray non-detection of RRATs is the uncertainties in source positions (Kaplan et al. 2009). The post-glitch recovery of the
frequency derivatives (decrease in the average spin-down rate instead of an increase), as well as the X-ray outbursts of J1819−1458 and J1119−6127 have been observed to be clearly magnetar-like (Lyne et al. 2009; Rea et al. 2010; Archibald et al. 2017; Bhat-tacharyya 2018). Given the unusual change in _P_s, it has been suggested that J1819−1458 is actually transitioning from being a magnetar to an RRAT (Lyne et al. 2009). The view that the RRATs could be an evolutionary stage rather than a separate class of neutron stars is indeed strengthened by such observations.

On the other hand, Gencali & Ertan (2018) have argued for a case of accretion-induced revival of a pulsar, that has evolved beyond the death-line, in their fallback-disc model to explain the behavior of J1819−1458. This model, while reproducing the observed values of _P_s, _P_dot and the X-ray luminosity, obtains a dipolar field strength of _ ~ 5 × 10^{11} G at the polar cap. This value of the magnetic field combined with the measured _P_s implies a ‘dead’ pulsar, located beyond the death-line in the _P_s−B_s plane. If this indeed is the case, then only accretion can explain the X-ray activity. It is therefore argued that J1819−1458 is evolving towards becoming an XDINS, reinforcing an earlier suggestion of the connection between RRATs with such objects. One needs to remember that the magnetic field obtained in this model is much smaller than the field inferred from the dipole torque formula (quoted in Table 4). However, an absorption line at _ ~ 1 keV has been detected in the X-ray spectrum of J1819−1458 (Rea et al. 2009). If this happens to be a cyclotron absorption line, then, the required field strengths would be _ ~ 2 × 10^{14} G and _ ~ 10^{11} G for protons and electrons, respectively (Miller et al. 2013).

It is also interesting to consider J1107−5907, which arguably could have appeared to be an RRAT had it been located at a larger distance, in the light of this suggestion. It is an old, isolated RPSR and in the _P_s−B_s plane located in the region between those of normal and recycled pulsars. There exists a possibility that such pulsars are mildly recycled in high-mass X-ray binaries (HMXB) (Konar & Bhattacharya 1999; Konar 2017). If so, then RRAT phenomenon could indeed be related to accretion-induced changes in the magnetic field structure.

Figure 8 shows the possible import of the connections discussed above. Not only RRATs and NPSRs, but magnetars along with RPSRs exhibiting magnetar characteristics have been shown here. Clearly, high-

**Table 4.** RRATs are also occasionally show up as other kinds of neutron stars (indicated in the last column). Here, RPSR means radio pulsars not known to show any nulling behavior.

| RRAT J-name | _P_s (s) | _B_s (10^{12} G) | DM (pc cm^{−3}) | Other
|-------------|---------|-----------------|-----------------|-------|
| J0828−3417  | 1.85    | 1.37            | 52.20           | RPSR |
| J0941−39    | 0.59    | –               | 78.20           | NPSR |
| J1119−6127  | 0.41    | 41.00           | 704.80          | RPSR |
| J1647−3607  | 0.21    | 0.17            | 224.00          | NPSR |
| J1819−1458  | 4.26    | 49.60           | 196.00          | Magnetar |
| J1840−1419  | 6.60    | 6.55            | 19.40           | NPSR |
| J1854−1557  | 3.45    | 4.00            | 150.00          | NPSR |
| J1913+1330  | 0.92    | 2.86            | 175.64          | NPSR |
| J2033+0042  | 5.01    | 7.05            | 37.84           | NPSR |

**Figure 8.** Distribution of RRATs (red triangles), NPSRs (circled dots in blue) and magnetars (circled stars in orange) in the _P_s−B_s plane. Green circled stars represent either magnetars exhibiting RPSR characteristics or RPSRs exhibiting magnetar characteristics. The red dashed-lines are evolutionary tracks of RRATs to the theoretical death-line ‘(2)’ (grey dashed-line) with constant _B_s. See text for the significance of the named pulsars. Data: (a) RRAT: Appendix, (b) NPSR: Null catalog and (c) magnetar: magnetar catalog (http://www.physics.mcgill.ca/~pulsar/magnetar/main.html).
magnetic field RRATs inhabit the same region of the $P_s - B_s$ space as the magnetars. Now, magnetars are understood to be powered by the decay of their magnetic fields. Considering the relative locations, it is quite conceivable that the magnetars may end up as RRATs in the course of their evolution. J1107−5907, J0828−3417, J1119−6127 and J1819−1458 have been individually marked in Figure 8 to highlight their special characteristics. It is seen that J1107−5907, an NPSR and likely to have RRAT-like behavior if located at a larger distance, is somewhat far away from both the majority of RRATs as well as NPSRs. Though, we must remember that only about 25% of the known RRATs are seen in this diagram as the rest do not have a $B_s$ estimate. On the other hand, J0828−3417, a similar object is seen right in the middle of the NPSR as well as the RRAT population. Of the two magnetar-like objects, while J1819−1458 is in the magnetar region, J1119−6127 is quite far away from all three (RRAT, NPSR, magnetar) groups. One possibility is that these objects (J1107−5907, J1119−6127) really are the missing links, transitioning from one class to another and are caught at the regions of transition. Another interesting object is J0835−4510, also shown in Figure 8, is a known NPSR, which sometimes show magnetar-like behavior. These objects clearly demonstrate the intertwining connections between many distinct observational classes of neutron stars.

We have also shown the trajectories of RRATs, from their present location to the death-line, in Figure 8 assuming a constant surface dipolar magnetic field. It is obvious from these tracks that unless they are intrinsically different, the RRATs and NPSRs would be part of the same underlying population. In Section 3, we have noted that they are not. Therefore, it is likely that the assumption of an RRAT having a constant magnetic field is incorrect, even it is true for regular RPSRs inclusive of NPSRs (Bhattacharya et al. 1992; Konar & Bhattacharya 1997).

Random, sporadic processes have also been considered to explain the RRAT phenomenon. For example, the quasi-periodic activity of B1931+24 (J1933+2421) has been thought to arise from the interactions between the neutron star magnetosphere and the precessing debris disk surrounding it (Li 2006), or because of the migration of asteroids (formed from supernova fallback material) into pulsar light-cylinder region disrupting the emission process (Cordes & Shannon 2008). It has also been suggested that pulsars can have radiation belts, similar to those in planetary magnetosphere, and sporadic release of plasma trapped therein can interfere with pulsar emission processes giving rise to RRAT-like behavior (Luo & Melrose 2007). Moreover, some of the single pulse events initially thought to be RRATs have now been tagged as potentially mislabeled FRBs (Keane 2016). Quite clearly, even if such explanations hold good for certain specific RRATs, the majority of objects demand a more general scenario.

6. Conclusions

The RRATs, one of the latest observational sub-classes, comprise a tiny (<5%) subset of the known neutron stars. As yet, there is no clear understanding of the nature of their sporadic emission. In this work, we have considered the population of RRATs and discussed some of the prominent hypotheses (offered to explain the RRAT phenomenon) in the light of the general properties of this population.

First of all, considering the population characteristics, we come to the conclusion that the RRAT behavior can neither be explained as special observational effects or as a result of certain random processes.

One of the main trains of thought, regarding the RRATs, has been about their connection with the NPSRs. Comparing the two populations, we find that:

- The RRATs are bounded by death-line [2], like NPSRs.
- RRATs have, on an average, higher $P_s$ and $B_s$ than NPSRs.
- RRATs tend to have smaller DM compared to the NPSRs.
- $P_s$ and $B_s$ of RRATs and NPSRs as well as the combined population appear to have log-normal distribution.
- The statistical distributions of $P_s$, $B_s$ and DM for RRATs and NPSRs do not appear to come from the same underlying distribution.

Thus, we conclude that the RRATs and NPSRs, even if connected through evolution, do not come directly from the same underlying population, and RRAT behavior is unlikely to be a manifestation of extreme nulling.

Another important conjecture has been to attribute the RRAT behavior to the proximity of these neutron stars to the death-line. We have considered this assertion by quantifying the death-line nearness through the proximity parameter, $e$. We find that the RRATs appear to have a significant part of their active life left before they would reach the death-line. Even though this finding crucially depends on the assumption of a constant magnetic field, if true, this indicates that the RRAT behavior is not a direct consequence of old age.
However, we find two very different and intriguing conjectures to hold some promise. First, the RRAT phenomenon could be associated with re-structuring of magnetic fields. This could either be accretion-induced, through the revival of ‘dead’ pulsars. Or it could be glitch-induced. Second, the RRATs could be later evolutionary stages of other varieties of neutron stars like magnetars (Konar 2012). Even though a recent work suggests that magnetars are likely to evolve into XDINS (Jawor & Tauris 2022), in an independent work (Chowhan et al. 2022), we find that even though majority of magnetars are likely to evolve into XDINS, some of the magnetars as well as most of the high magnetic radio pulsars are likely to evolve into RRATs.

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Appendix. The RRATs

Table 5 lists the known RRATs, detected till date, which we have used for our calculations in this work. Majority of the sources are obtained from the RRATalog site maintained by Bingyi Cui and Maura McLaughlin. For the rest, discovery papers have been referred. The parameter values for spin period ($P_s$), dispersion measure (DM), characteristic age ($\tau$), and surface dipolar field ($B_s$) are taken from the ATNF pulsar catalog (Manchester & Hobbs 2005), except where the objects are not yet included in the ATNF list. Parameter values for these second set of objects are taken from the discovery papers and the references are marked with a -P. For some sources, different names have been used by different groups. We have primarily used the ATNF names and indicated the alternative names in the ‘Other-Name’ column. The references cited in the tables with numbers ranging from 1 to 9 correspond to the following:

(1) RRATalog (last update September 2016);
(2) Weltevrede et al. (2011);
(3) Esamdin et al. (2012);
(4) Deneva et al. (2013);
(5) Cui et al. (2017);
(6) Tyul’bashev et al. (2018);
(7) Good (2021);
(8) Logvinenko et al. (2020);
(9) Tyul’bashev et al. (2021).

RRATalog: http://astro.phys.wvu.edu/rratalog/
ATNF: http://www.atnf.csiro.au/research/pulsar/psrcat/

| B-name J-name | Other-name | $P_s$ (s) | DM (Pfc cm$^{-3}$) | $\tau$ (yr) | $B_s$ (G) |
|---------------|------------|----------|---------------------|-------------|-----------|
| J0054+66      | J0054+66   | 1.39     | 15.00               |             |           |
| J0054+69      | J0054+69   |          | 90.30               |             |           |
| J0103+54      | J0103+54   | 0.35     | 55.60               |             |           |
| J0121+53      | J0121+53   | 2.72     | 91.38               |             |           |
| J0139+3336    | J0139+3336 | 1.25     | 21.23               | 9.58e+06    | 1.62e+12  |
| J0156+04      | J0156+04   |          | 27.50               |             |           |
| J0318+1341    | J0318+1341 | 1.97     | 12.05               |             |           |
| J0201+7005    | J0201+7005 | 1.35     | 21.03               | 3.88e+06    | 2.76e+12  |
| J0302+2252    | J0302+2252 | J0301+20 | 1.21     | 18.99               | 2.32e+08   | 3.19e+11  |
| J0305+4001    | J0305+4001 |          | 24.00               |             |           |
| J0332+79      | J0332+79   | 2.06     | 16.67               |             |           |
| J0410-31      | J0410-31   | 1.88     | 9.20                |             |           |
| J0441-04      | J0441-04   |          | 20.00               |             |           |
| J0447-04      | J0447-04   | 2.19     | 29.83               |             |           |
| J0452+1651    | J0452+1651 |          | 19.00               |             |           |
| J0513-04      | J0513-04   |          | 18.50               |             |           |
| J0534+34      | J0534+34   | J0534+3407 |          | 24.50               |           |
| J0544+20      | J0544+20   | J0544+20 | 56.90               |             |           |
Table 5. Continued.

| B-name    | J-name    | Other-name | $P_s$ (s) | DM (Pcf cm$^{-3}$) | $\tau$ (yr) | $B_s$ (G) |
|-----------|-----------|------------|-----------|-------------------|-------------|-----------|
| 019       | J0545−03  | J0545−03   | 1.07      | 67.20             | (1)         |           |
| 020       | J0550+09  | J0550+09   | 1.75      | 86.60             | (1)         |           |
| 021       | J0609+1635| J0609+1635 |           | 85.00             | (6)         |           |
| 022       | J0614−03  | J0614−03   | 0.14      | 17.90             | (1-P)       |           |
| 023       | J0621−55  | J0621−55   |           | 22.00             | (1)         |           |
| 024       | J0625+1730| J0625+1730 |           | 58.00             | (6)         |           |
| 025       | J0627+16  | J0627+16   | 2.18      | 113.00            | (1)         |           |
| 026       | J0628+0909| J0628+0909 | 1.24      | 88.30             | 3.59e+07    | 8.35e+11  |
| 027       | J0640+0744| J0640+0744 |           | 52.00             | (6)         |           |
| 028       | J0736−6304| J0736−6304 | 4.86      | 19.40             | 5.07e+05    | 2.75e+13  |
| 029       | J0803+34  | J0803+34   | 34.00     |                   | (1-P)       |           |
| 030       | J0812+8626| J0812+8626 |           | 40.25             | (9)         |           |
| 031       | J0826−34  | J0828−3417 | 1.85      | 52.20             | 2.94e+07    | 1.37e+12  |
| 032       | J0937−24  | J0937−24   |           | 142.80            | (1)         |           |
| 033       | J0845−36  | J0845−36   | 0.21      | 29.00             | 2.61e+07    | 1.67e+11  |
| 034       | J0847−4316| J0847−4316 | 5.98      | 292.50            | 7.90e+05    | 2.71e+13  |
| 035       | J0912−3851| J0912−3851 | 1.53      | 71.50             | 6.74e+06    | 2.37e+12  |
| 036       | J0923−31  | J0923−31   |           | 72.00             | (1)         |           |
| 037       | J0941+1621| J0941+1621 |           | 23.00             | (6)         |           |
| 038       | J0941−39  | J0941−39   | 0.59      | 78.20             | (1)         |           |
| 039       | J0957−06  | J0957−06   | 1.72      | 26.95             | (1)         |           |
| 040       | J1005+30  | J1005+30   |           | 17.50             | (6)         |           |
| 041       | J1010+15  | J1010+15   |           | 42.00             | (4)         |           |
| 042       | J1014−48  | J1014−48   | 1.51      | 87.00             | (1)         |           |
| 043       | J1048−5838| J1048−5838 | 1.23      | 70.70             | 1.60e+06    | 3.92e+12  |
| 044       | J1059−01  | J1059−01   |           | 18.70             | (1)         |           |
| 045       | J1111−55  | J1111−55   |           | 235.00            | (1)         |           |
| 046       | J1119−6127| J1119−6127 | 0.41      | 704.80            | 1.61e+03    | 4.10e+13  |
| 047       | J1126−27  | J1126−27   | 0.36      | 26.86             | (1)         |           |
| 048       | J1129−53  | J1129−53   | 1.06      | 77.00             | (1)         |           |
| 049       | J1132+0921| J1132+0921 |           | 22.00             | (6)         |           |
| 050       | J1132+25  | J1132+25   | J1132+2515| 1.00              | 23.00       | (6)         |
| 051       | J1135−49  | J1135−49   |           | 114.00            | (1)         |           |
| 052       | J1153−21  | J1153−21   | 2.34      | 34.80             | (1)         |           |
| 053       | J1216−50  | J1216−50   | 6.35      | 110.00            | (1)         |           |
| 054       | J1226−3223| J1226−3223 | 6.19      | 36.70             | 1.39e+07    | 6.69e+12  |
| 055       | J1252+53  | J1252+53   | 0.22      | 20.70             | (7)         |           |
| 056       | J1307−67  | J1307−67   | J1308−67  | 3.65              | 44.00       | (1)         |
| 057       | J1311−59  | J1311−59   |           | 152.00            | (1)         |           |
| 058       | J1317−5759| J1317−5759 | 2.64      | 145.30            | 3.33e+06    | 5.83e+12  |
| 059       | J1326+33  | J1326+33   | 0.04      | 4.00              | (6)         |           |
| 060       | J1329+13  | J1329+13   | J1329+1349| 12.00             | (6)         |           |
| 061       | J1332−03  | J1332−03   | 1.11      | 27.10             | (1)         |           |
| 062       | J1336−20  | J1336−20   | 0.18      | 19.30             | (1-P)       |           |
| 063       | J1336+33  | J1336+33   | J1336+3346| 3.01              | 8.50        | (6)         |
| 064       | J1346+0622| J1346+0622 |          | 8.00              | (6)         |           |
| 065       | J1354+24  | J1354+24   |          | 20.00             | (1)         |           |
| 066       | J1400+21  | J1400+21   | J1400+2127| 10.50             | (6)         |           |
| 067       | J1404+1210| J1404+1210 | 2.65      | 17.05             | (6-P)       |           |
| 068       | J1404−58  | J1404−58   |          | 229.00            | (1)         |           |
| 069       | J1424−56  | J1424−56   | J1423−56  | 1.43              | 32.90       | (1)         |
| 070       | J1433+00  | J1433+00   |          | 23.50             | (1)         |           |
Table 5. Continued.

| B-name | J-name | Other-name | $P_\star$ (s) | DM (Pfc cm$^{-3}$) | $\tau$ (yr) | $B_{\star}$ (G) |
|--------|--------|------------|---------------|---------------------|------------|----------------|
| 071    | J1439+76 | J1439+76 | 0.95          | 22.29               |            | (1)            |
| 072    | J1444–6026 | J1444–6026 | 4.76          | 367.70              | 4.07e+06   | 9.51e+12       |
| 073    | J1502+28 | J1502+28 | J1502+2813   | 3.78          | 14.00      | (6)            |
| 074    | J1513–5946 | J1513–5946 | 1.05          | 171.70              | 1.94e+06   | 3.02e+12       |
| 075    | J1534–46 | J1534–46 | 0.36          | 64.40               | (1)        |
| 076    | J1538+2345 | J1538+2345 | 3.45          | 14.91               | 7.93e+06   | 4.93e+12       |
| 077    | J1541–42 | J1541–42 | 60.00         |                     | (1)        |
| 078    | J1549–57 | J1549–57 | 0.74          | 17.70               | (1)        |
| 079    | J1550+0943 | J1550+0943 | 21.00         |                     | (8)        |
| 080    | J1554+18 | J1554+18 | 24.00         |                     | (1)        |
| 081    | J1554–5209 | J1554–5209 | 0.13          | 130.80              | 8.65e+05   | 5.42e+11       |
| 082    | J1555+01 | J1555+01 | J1555+0108   | 18.50         |            | (6)            |
| 083    | J1603+18 | J1603+18 | 0.50          | 29.70               | (1)        |
| 084    | J1610–17 | J1610–17 | 1.30          | 52.50               | (1-P)      |
| 085    | J1611–01 | J1611–01 | 1.30          | 27.21               | (1)        |
| 086    | J1623–0841 | J1623–0841 | 0.50         | 59.79               | 4.08e+06   | 1.00e+12       |
| 087    | J1647–3607 | J1647–3607 | 0.21         | 224.00              | 2.61e+07   | 1.67e+11       |
| 088    | J1649–4653 | J1649–4653 | 0.56         | 331.00              | 1.78e+05   | 5.32e+12       |
| 089    | J1652–4406 | J1652–4406 | 7.71         | 786.00              | 1.29e+07   | 8.66e+12       |
| 090    | J1654–23 | J1654–23 | J1653–2330   | 0.55          | 74.50      | 6.31e+05 1.62e+12 |
| 091    | J1703–38 | J1703–38 | 6.44          | 375.00              | (1)        |
| 092    | J1705–04 | J1705–04 | 0.24          | 42.95               | (1)        |
| 093    | J1707–4417 | J1707–4417 | 5.76         | 380.00              | 7.84e+06   | 8.29e+12       |
| 094    | J1709–43 | J1709–43 | 228.00        |                     | (1)        |
| 095    | J1717–03 | J1717–03 | 3.90          | 25.60               | (1)        |
| 096    | J1720–00 | J1720–00 | 3.36          | 46.20               | (1)        |
| 097    | J1724–35 | J1724–35 | 1.42          | 554.90              | (1)        |
| 098    | J1727–29 | J1727–29 | 93.00         |                     | (1)        |
| 099    | J1732+2700 | J1732+2700 | 36.50        |                     | (1)        |
| 100    | J1739–2521 | J1739–2521 | 1.82         | 186.40              | 1.20e+08   | 6.69e+11       |
| 101    | J1753–12 | J1753–12 | 0.40          | 73.20               | (1)        |
| 102    | J1753–38 | J1753–38 | 0.67          | 168.00              | (1)        |
| 103    | J1754–3014 | J1754–3014 | 1.32         | 89.70               | 4.72e+06   | 2.45e+12       |
| 104    | J1807–2557 | J1807–2557 | 2.76         | 385.00              | 8.77e+06   | 3.76e+12       |
| 105    | J1819–1458 | J1819–1458 | 4.26         | 196.00              | 1.20e+05   | 4.96e+13       |
| 106    | J1825–33 | J1825–33 | 1.27          | 43.20               | (1)        |
| 107    | J1826–1419 | J1826–1419 | 0.77         | 160.00              | 1.39e+06   | 2.63e+12       |
| 108    | J1838+50 | J1838+50 | 2.58          | 21.81               | (7)        |
| 109    | J1839–0141 | J1839–0141 | 0.93         | 293.20              | 2.49e+06   | 2.38e+12       |
| 110    | J1840–1419 | J1840–1419 | 6.59         | 19.40               | 1.65e+07   | 6.55e+12       |
| 111    | J1841–04 | J1841–04 | J1841–0448   | 29.00         |            | (6)            |
| 112    | J1843+01 | J1843+01 | 1.27          | 251.90              | (1)        |
| 113    | J1846–0257 | J1846–0257 | 4.48         | 237.00              | 4.42e+05   | 2.71e+13       |
| 114    | J1848–1243 | J1848–1243 | 0.42         | 91.96               | 1.49e+07   | 4.32e+11       |
| 115    | J1848+1516 | J1848+1516 | 2.24         | 77.44               | 2.11e+07   | 1.96e+12       |
| 116    | J1849+0112 | J1849+0112 | 1.83         | 217.20              | 1.59e+06   | 5.01e+12       |
| 117    | J1850+15 | J1850+15 | 1.38          | 24.70               | (1)        |
| 118    | J1853+04 | J1853+04 | 1.32          | 549.30              | (1)        |
| 119    | J1854+0306 | J1854+0306 | 4.56         | 192.40              | 4.98e+05   | 2.60e+13       |
| 120    | J1854–1557 | J1854–1557 | 3.45         | 150.00              | 1.21e+07   | 4.00e+12       |
| 121    | J1856+09 | J1856+09 | 2.17          | 193.40              | (1)        |
Table 5. Continued.

| B-name J-name Other-name | $P_\nu$ (s) | DM (Pc cm$^{-3}$) | $\tau$ (yr) | $B_s$ (G) |
|---------------------------|------------|-------------------|-------------|-----------|
| J1859+07                  |            | 303.00            | (1)         |
| J1901+11                  | 0.41       | 268.90            | (1)         |
| J1905+0414                |            | 383.00            | (1)         |
| J1905+0902 J1905+09       | 0.22       | 433.40            | 9.88e+05    | 8.84e+11  | (1) |
| J1906+03                  | 1.26       | 212.00            | (1-P)       |
| J1909+0641 J1909+06       | 0.74       | 36.70             | 3.65e+06    | 1.56e+12  | (1) |
| J1911+00                  | 6.94       | 100.00            | (1)         |
| J1912+08                  |            | 96.00             | (1)         |
| J1913+1330 J1913+1330    | 0.92       | 175.64            | 1.69e+06    | 2.86e+12  | (1) |
| J1915+06                  | 0.64       | 214.50            | (1)         |
| J1915+11                  | 2.18       | 91.06             | (1)         |
| J1917+11                  | 5.06       | 319.00            | (6-P)       |
| J1917+1723                |            | 38.00             | (6)         |
| J1919+1745 J1919+1745 J1919+17 | 2.08 | 142.30 | 1.93e+07 | 1.91e+12 | (1) |
| J1925+16                  | 3.89       | 88.00             | (1)         |
| J1927+1725 J1927+1725 J1928+17 | 0.29 | 136.00 | 1.26e+07 | 3.16e+11 | (1-P) |
| J1928+15                  | 0.40       | 242.00            | (1)         |
| J1929+11                  | 3.22       | 80.00             | (1-P)       |
| J1930+0104 J1930+0104     |            | 42.00             | (6)         |
| J1931+42                  |            | 50.90             | (7)         |
| J1944+10 J1944+10         | 0.41       | 31.01             | (1)         |
| J1946+24 J1946+24         | 4.73       | 96.00             | (1)         |
| J1952+30 J1952+30         | 1.67       | 188.60            | (1)         |
| J1956+28 J1956+28         | 0.26       | 45.69             | (1)         |
| J1958+30 J1958+30         | 1.10       | 199.30            | (1)         |
| J2000+29 J2000+29         | 3.07       | 132.50            | (1)         |
| J2007+20 J2007+20         | 4.63       | 67.00             | (1)         |
| J2033+0042 J2033+0042 J2033+00 | 5.01 | 37.84 | 8.20e+06 | 7.05e+12 | (1) |
| J2047+1259 J2047+1259     |            | 36.00             | (8)         |
| J2052+1308 J2052+1308     |            | 42.00             | (6)         |
| J2105+19 J2105+19 J2105+1917 | 2.30 | 50.75 | 7.00e+06 | 3.51e+12 | (1) |
| J2105+6223 J2105+6223     |            | 33.00             | (6)         |
| J2107+2606 J2107+2606     |            | 10.50             | (6)         |
| J2135+3032 J2135+3032     |            | 63.00             | (6)         |
| J2146+2148 J2146+2148     |            | 43.00             | (6)         |
| J2202+21 J2202+21 J2202+21 | 0.4       | 7.00             | (6)         |
| J2205+2244 J2205+2244     |            | 22.00             | (6)         |
| J2210+2118 J2210+2118     |            | 45.00             | (6)         |
| J2225+35 J2225+35         | 0.94       | 51.80             | (1)         |
| J2311+67 J2311+67         | 1.94       | 97.10             | (1-P)       |
| J2325+0530 J2325+0530     | 0.87       | 14.97             | 1.34e+07    | 9.57e+11  | (1) |

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