

# On the origins of part-time radio pulsars

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## ABSTRACT

Growing evidence suggests that some radio pulsars only act sporadically. These ‘part-time’ pulsars include long-term nulls, quasi-periodic radio flares in PSR B1931+24, as well as the so-called Rotating Radio Transients (RRATs). Based on the assumption that these objects are isolated neutron stars similar to conventional radio pulsars, we discuss two possible interpretations to the phenomenon. The first interpretation suggests that these objects are pulsars slightly below the radio emission ‘death line’, which become occasionally active only when the conditions for pair production and coherent emission are satisfied. The second interpretation invokes a radio emission direction reversal in conventional pulsars, as has been introduced to interpret the peculiar mode changing phenomenon in PSR B1822–09. In this picture, our line of sight misses the main radio emission beam of the pulsar but happens to sweep the emission beam when the radio emission direction is reversed. These part-time pulsars are therefore the other half of ‘nulling’ pulsars. We suggest that X-ray observations may provide clues to differentiate between these two possibilities.

**Key words:** stars: magnetic fields – stars: neutron – pulsars: general – radio continuum: stars – X-rays: stars.

## 1 INTRODUCTION

Recently, many interesting, peculiar radio-pulsar-like objects were discovered. It has been long known that old radio pulsars tend to ‘null’ occasionally, i.e. the radio emission ceases occasionally for one or more consecutive periods during the otherwise uninterrupted regular emission episodes (e.g. Ritchings 1976; Rankin 1986; Biggs 1992). Lewandowski et al. (2004) reported two pulsars with very long period of nulling. While PSR J1649+2533 exhibits pulse nulling for approximately 30 per cent of the time, another ‘bursting pulsar’, PSR J1752+2359, was found to have 70–80 per cent of the time in the ‘quasi-null’ state. The active and the null phases of these pulsars usually last for 100 s of periods. McLaughlin et al. (2006) reported the discovery of a new class of radio transients from the Parkes Multi-beam Pulsar Survey. The current sample includes 11 objects characterized by single, dispersed bursts of radio emission with durations ranging from 2 to 30 ms. Long-term monitoring of these objects led to the identifications of their spin periods ( $P$ ), ranging from 0.4 to 7 s. These fall into the range of the  $P$ -distribution of the conventional radio pulsars, although on the long end. The period derivatives ( $\dot{P}$ ) of three RRATs were measured, which are also typical for conventional pulsars. These objects have on average slightly higher brightness temperatures than the conventional pulsar population, but the small discrepancy is easily

accounted for by an observational selection effect (M. McLaughlin, private communication). McLaughlin et al. (2006) concluded that these objects represent a previously unknown population of rotation-powered neutron stars, which they call Rotating Radio Transients (RRATs). A serendipitous *Chandra* observation has detected one of the RRATs (RRAT J1819–1458; Reynolds et al. 2006) in X-rays, whose spectrum is dominated by a soft thermal component. Lately, Kramer et al. (2006) reported that a previously known pulsar, PSR B1931+24, when monitored long enough, shows a very long-term, quasi-periodic flaring behaviour. The ‘on’ state lasts for 5–10 d, while the ‘off’ state lasts for 25–35 d. More interestingly, the spin-down rate is different during the on and the off states, respectively. A further search for similar objects from the Parkes Multi-Beam Survey data revealed at least four more objects that share similar properties to PSR B1931+24 (Lyne 2006).

Understanding the physical origin of these ‘part-time’ radio pulsars as well as their relationship to the conventional radio pulsars is of great interest to understand the mechanisms of pulsar radio emission. Here, we discuss two possible interpretations to part-time pulsars by assuming that they are isolated neutron stars similar to conventional radio pulsars. We also discuss how X-ray data may be used to distinguish between these two possibilities.

## 2 MODEL I: RE-ACTIVATED DEAD PULSARS

It is believed that electron–positron pair production plays an essential role in pulsar coherent radio emission. The condition for the

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failure of pair production usually defines the pulsar radio emission ‘death line’ in the  $P - \dot{P}$  diagram of pulsars.<sup>1</sup> Although the death line issue has been re-investigated many times over the years (e.g. Ruderman & Sutherland 1975; Chen & Ruderman 1993; Arons 2000; Zhang, Harding & Muslimov 2000; Gil & Mitra 2001; Hirschman & Arons 2001; Harding & Muslimov 2002; Harding, Muslimov & Zhang 2002), it is very difficult and essentially impossible to define an exact line in the  $P - \dot{P}$  diagram. This is due to many uncertainties inherited to the death line problem (Zhang 2003), including the criterion to define pulsar death (whether the pair multiplicity is zero or only a small factor with respect to the primary particle number density, say, less than unity), the boundary condition of the inner ‘gap’ [a vacuum gap, a space-charge-limited flow (SCLF) or a partially screened gap], the gamma-ray emission mechanism [curvature radiation or inverse Compton scattering (IC)], the equation of state of the neutron star (or even strange quark star) and especially the unknown near-surface magnetic field configuration. What is relevant would be then a so-called ‘death valley’ in the  $P - \dot{P}$  diagram (named by Chen & Ruderman 1993). Pulsars in the valley could either be ‘alive’ or be ‘dead’ according to the properties of the individual pulsars.

Recently, the enigmatic radio bursting source in the direction of Galactic Centre GCRT J1745–3009 (Hyman et al. 2005) was interpreted by Zhang & Gil (2005) as a transient white dwarf pulsar with a rotation period of 77.13 min. Assuming a dipolar surface magnetic field  $\sim 10^9$  G, GCRT J1745–3009 is slightly below the white dwarf pulsar ‘death line’. Zhang & Gil (2005) then argued that if stronger multipole magnetic fields emerge to the polar cap region of the white dwarf, the pair production condition could be satisfied and the white dwarf could then behave like a neutron star radio pulsar. This corresponds to the observed five consecutive outbursts at 0.33 GHz with a 77.13-min period and a 10-min duration for each outburst recorded during 2002 Sept. 30 to 2002 Oct. The putative strong magnetic fields may not last long. This accounts for the cessation of the radio emission from the source. The reactivation of the source in 2003 (Hyman et al. 2006) corresponds to another episode of pair production in the white dwarf pulsar.

A natural inference from the above suggestion is that one would also expect similar situations for neutron star pulsars. Radio pulsars may not die abruptly at the end of their lives. Rather, they may experience a period of life during which the pair production processes could be maintained only sporadically. In other words, many pulsars not deep below the death line could jump out from the graveyard occasionally, if the pair production condition could be temporarily satisfied occasionally. One possibility is that strong sunspot-like magnetic fields emerge into their polar cap regions. Within such a scenario, part-time pulsars are simply these not-quite-dead (zombie) pulsars. The measured  $P$  for RRATs is typically long (five out of 10 have  $P > 4$  s; McLaughlin et al. 2006). This makes them more likely to locate in the death valley. For example, RRAT J1317 – 5759 ( $P = 2.64$  s,  $\dot{P} = 12.6 \times 10^{-15}$ ; McLaughlin et al. 2006) is below the curvature radiation death line for a pure star-centred dipolar field, i.e.  $\log \dot{P} = (11/4) \log P - 14.62$  for a vacuum gap and  $\log \dot{P} = (5/2) \log P - 14.56$  for a SCLF (Zhang et al. 2000). If the near-surface field configuration is nearly dipolar and if curvature radiation is the dominant mechanism to produce enough

pairs to power radio emission, RRAT J1317–5759 should be radio quiet most of the time since it is below the death line. If stronger sunspot-like fields emerge into the polar cap region, the pair production condition could be temporarily satisfied, so that a part-time pulsar could be temporarily re-activated.

Not all part-time pulsars are below the star-centred dipolar death line. For example, RRATs J1819 – 1458 ( $P = 4.26$  s,  $\dot{P} = 576 \times 10^{-15}$ ) and J1913 + 1333 ( $P = 0.92$  s,  $\dot{P} = 7.87 \times 10^{-15}$ ) (McLaughlin et al. 2006) are both somewhat above the star-centred dipolar death line. The spin parameters of PSR J1752 + 2359 ( $P = 0.41$  s,  $\dot{P} = 0.64 \times 10^{15}$ ; Lewandowski et al. 2004) and PSR B1931 + 24 ( $P = 0.81$  s,  $\dot{P} = 8.11 \times 10^{15}$ ; Kramer et al. 2006) also place them slightly above these death lines. In order to interpret them as re-activated pulsars, one needs to argue that in general the near-surface magnetic field strengths of these objects are overestimated. This could be simply due to the inaccuracy of the estimates introduced by a crude dipole spin-down model. Alternatively, this could be caused by an off-centre (but still axisymmetric) dipolar magnetic field configuration of the neutron star (e.g. Arons 2000). In such a picture, the ‘near-end’ polar cap has a stronger magnetic field than the case of a star-centred dipole, while the ‘far-end’ polar cap has a weaker field. While some active pulsars deep below the star-centred dipolar death line may be those cases we see the near-end polar caps, part-time pulsars would be those we see the far-end polar caps. Within such a scenario, the part-time pulsars are not systematically older than other pulsars in the death valley; their peculiar behaviour is caused by their unfavourable viewing geometry, i.e. one sees the far-end off-centre dipole where the local magnetic fields are systematically weaker than their brethren. For example, the thermal X-ray emission RRAT J1819–1458 is bright (Reynolds et al. 2006), which is consistent with being a young pulsar. The pair production condition could, however, not be satisfied most of the time, if our line of sight sweeps a far-end dipole where the near-surface magnetic field is too weak.

Another source of gamma-rays to trigger pair production is IC (e.g. Zhang & Qiao 1996). For star-centred dipoles, some RRATs are above the death line of resonant-IC-controlled gaps (both vacuum gaps and SCLFs; Zhang et al. 2000), and all part-time pulsars are above the death line of non-resonant-IC-controlled SCLFs (Harding et al. 2002). However, detailed modelling suggests that pair multiplicity could be much lower in IC-controlled SCLFs than in CR-controlled SCLFs for a star-centred dipole (Harding & Muslimov 2002; Harding et al. 2002). It is unclear whether the resulting low pair multiplicity could be sufficient to trigger strong coherent radio emission in these pulsars. Since there is no abrupt change of radio emission properties for pulsars across the star-centred CR death lines, one could speculate that there might not be two distinct types of pulsars controlled by CR and IC, respectively. The reactivation model relies on the conjecture that pulsar pair cascades are induced by curvature radiation only.

The existence of multipole magnetic fields near pulsar polar caps has been required by the earliest pulsar models (e.g. Ruderman & Sutherland 1975). Theoretically strong spot-like magnetic fields could be generated from the subsurface toroidal magnetic field component through Hall-drift induced instability (Geppert, Rheinhardt & Gil 2003) or through small-scale turbulent dynamo actions (Urpin & Gil 2004). During the spin-down of a pulsar, the magnetic flux is expected to move as a consequence of the interaction between neutron and proton superfluid vortices (Ruderman 1991; Ruderman et al. 1998; Jones 2006). The dynamical evolution of the field configuration may be slow. The pair production condition, on the other hand, has a threshold (Ruderman & Sutherland 1975), i.e.

<sup>1</sup> The real condition for pulsar coherent radio emission may be more stringent than this, since it invokes additional criteria on how coherence is generated and maintained. So the pair production condition is only a necessary but not a sufficient condition for pulsar radio emission.

$(E_{\text{ph}}/2m_e c^2)(B_{\perp}/B_q) \sim 0.1$  (Ruderman & Sutherland 1975), where  $E_{\text{ph}}$  is the photon energy,  $B_{\perp}$  is the perpendicular magnetic field encountered by the photon and  $B_q = 4.414 \times 10^{13}$  G is the critical magnetic field. A pair production cascade is abruptly developed as soon as the threshold condition is met. The dynamical time-scale of the inner gap ( $\sim h_{\text{gap}}/c \sim 10^{-6}$  to  $10^{-4}$  s, where  $h_{\text{gap}}$  is the height of the gap) is much shorter than the rotation period  $P$ . So the time-scale to turn on the pulsar radio emission is typically much shorter than  $P$ . The time-scale during which the pair condition is satisfied is hard to derive from the first principles. From the data, it seems that this time-scale varies in a wide range. Most RRATs have one single pulse in each burst, with one having multiple periods within a single burst (M. McLaughlin, private communication). Long-term nulling pulsars (e.g. PSR J1752+2359; Lewandowski et al. 2004) sustain the radio emission for 100 s of periods, while PSR B1931+24's on-state lasts for 5–10 d (Kramer et al. 2006). The strength of the evolving multipole fields is not constrained, but should be around  $10^{12}$  G or higher in order to make the model work. The dynamical evolution of the fields should occur throughout the neutron star's lifetime. However, in young pulsars with small  $P$ , the contribution of these evolving fields may not be significant since the stable field lines have a large enough curvature to facilitate pair production. Only in slow pulsars, whose stable  $B_{\perp}$  component is small enough, do the evolving components dominate the pair production process. This is consistent with the fact that part-time pulsars tend to have long periods.

A direct consequence of the reactivation model is that the global pulsar current is turned on only during the re-activated phase. A clear change of spin-down torque in PSR B1931+24 during the 'on' and 'off' phases (Kramer et al. 2006) lends strong support to this scenario.

### 3 MODEL II: NULLING PULSARS VIEWED AT THE OPPOSITE DIRECTION

The measured spin parameters of the three RRATs (J1317–5759, J1819–1458 and J1913+1333; McLaughlin et al. 2006) and other part-time pulsars (PSR J1752+2359; Lewandowski et al. 2004 and PSR B1931+32; Kramer et al. 2006) do not differ significantly from those of conventional pulsars. This raises the possibility that these objects are intrinsically similar to conventional pulsars but appear differently because of certain geometrical reasons. One possible picture is the emission direction reversal mechanism recently proposed by Dyks, Zhang & Gil (2005a) to interpret the peculiar mode-changing behaviour of PSR B1822–09 (Gil et al. 1994).

Fig. 4(b) from Gil et al. (1994) displays an interesting mode switching phenomenon for PSR B1822–09. There are three emission components located at phases  $17^\circ$ ,  $33^\circ$  and  $215^\circ$ , respectively. The first two peaks are termed as the main pulse, and the third one is called the interpulse. While the second peak of the main pulse appears all the time, there is an apparent switching on/off anti-correlation between the first peak of the main pulse and the interpulse, i.e. the first peak is on whenever the interpulse is off, and vice versa. Such a phenomenon has been difficult to interpret within the traditional pulsar models. Dyks et al. (2005a) proposed that pulsar radio emission may occasionally reverse direction. According to this hypothesis, PSR B1822–09 is a special case in which our line of sight happens to sweep the emission beams of both the traditional outward emission and the inward emission during the reversal phase.

A natural inference from the reversal hypothesis is that in most geometric configurations, the line of sight can only sweep one emis-

sion beam, either the outward main beam or the inward one. Dyks et al. (2005a,b) proposed that pulsar 'nulling' is caused by reversal, and that the conventional nulling pulsars are those pulsars whose outward main pulse is swept by the line of sight. Within this picture, there should also be cases when only the reversed inward component is seen. These objects would be identified as part-time pulsars. As a result, part-time pulsars are the 'opposite' population of nulling pulsars.

The origin of the emission direction is unknown. One possibility may be the large-amplitude oscillation of the current far above the surface (Levinson et al. 2005). This is preferably achieved for a charge-starving initial condition (Levinson et al. 2005), which tends to happen below the curvature emission death line if the near surface magnetic field is nearly dipolar (Harding & Muslimov 2002). This would be consistent with that part-time pulsars tend to concentrate in the death valley. According to this picture, not only is the pulsar death associated with the inability of producing pairs, but the processes such as current oscillations may also be relevant. In the case of PSR B1822–09 (Gil et al. 1994), a sequence of pulses appear at the interpulse phase when the proposed reversal occurs. This would be consistent with the bursting pulsar PSR J1752+2359 (Lewandowski et al. 2004). RRATs usually show one pulse during each burst. On the other hand, many nulling pulsars only miss one pulse during each null.

Since the reversal model interprets nulls and bursts of radio emission via a geometric effect, no significant spin-down torque change is expected during the 'on' and 'off' states. This model is therefore ruled out at least for PSR B1931+32 (Kramer et al. 2006).

### 4 X-RAYS AS POSSIBLE DIFFERENTIATOR

The two models suggested in this paper are plausible ways of interpreting the available radio emission data of part-time pulsars. It would be interesting to find some criteria to differentiate between the two mechanisms. We suggest that X-ray data may provide important clues.

In general, the X-ray emission of a neutron star consists of three possible components, although not all the three components are detectable in every pulsar: (i) a pulsed, non-thermal component originating from the magnetosphere, (ii) a thermal component from the bulk of the star due to neutron star cooling and (iii) a hot thermal component from a small area on the neutron star surface, possibly due to enhanced heating at the polar cap. Although the cooling component is determined by age only and, hence, cannot be used to differentiate between the two scenarios, the other two emission components are potentially useful to put constraints on the above-mentioned two scenarios.

In the first (reactivation) model, no significant X-ray emission from these two components is expected in the quiescent state, during which the magnetosphere is charge-starved. There could still be a primary particle outflow, but the radiated energy is likely in the gamma-ray band (e.g. Muslimov & Harding 2004). One therefore does not expect a strong non-thermal X-ray component of magnetospheric origin during the quiescent state. For the same reason, one does not expect a strong active returning particle flow, and hence, a significantly heated polar cap. Potentially during the reactivation phase, the resumed magnetospheric activities would lead to both non-thermal X-ray emission and polar-cap heating. A coordinated simultaneous observation in both X-ray and radio bands is therefore desirable to test this scenario. Because the 'duty cycles' of RRATs' activity are very short (McLaughlin et al. 2006), the enhancement of X-ray emission during the active phase of RRATs may be too

small to be observed with the current X-ray telescopes. The bursting pulsar PSR J1752+2359 and the flaring pulsar PSR B1931+32, on the other hand, could be ideal sources to perform such a test.

The second (reversal) model interprets part-time pulsars as nulling radio pulsars viewed at the opposite direction so that the reversed emission beam is detected. Nulling pulsars are usually middle-aged to old pulsars (e.g. table 4 of Rankin 1986). A growing sample of pulsars in this age group have been observed by X-ray observatories (*Chandra* and *XMM-Newton*; e.g. Becker et al. 2004, 2005; Zavlin & Pavlov 2004; De Luca et al. 2005; Zhang, Sanwal & Pavlov 2005; Tepedelenliolu & Ögelman 2005; Kargaltsev et al. 2006). These observations indicate that the emission of these pulsars likely has multiple emission components, including a non-thermal magnetospheric component and sometimes a hotspot thermal emission component. The latter has been claimed to be discovered in several nulling pulsars in table 4 of Rankin (1986), including PSR 0628–28 (Tepedelenliolu & Ögelman 2005), PSR 0656+14 (De Luca et al. 2005) and PSR 1133+16 (Kargaltsev et al. 2006). This component is likely produced by the returning particle flow that precipitates and heats the polar cap region (see e.g. Zhang et al. 2005 and Gil, Melikidze & Zhang 2006 for more discussion).

Generally, part-time pulsars would display the similar X-ray emission properties to the nulling pulsars within the reversal model, since the underlying pulsars are supposed to be active. The observed X-ray spectrum should then generally include a magnetospheric component and/or a hotspot component. There may be exceptions from this rule because the significance of these spectral components depends on the viewing geometry. For example, the projected area and luminosity of the hotspot would be diminished if the reversed viewing direction is far off the magnetic poles. The direction of non-thermal X-rays in the magnetosphere [either outwards (Zhang & Harding 2000) or inwards (Cheng, Gil & Zhang 1998; Wang et al. 1998)] is unknown, so that the detectability and significance of this component in the reversed geometry are uncertain. None the less, detecting either the hotspot component or the magnetospheric component would be a strong support to the reversal scenario.

To summarize, detailed X-ray observations should shed light on to the nature of part-time pulsars. If a strong non-thermal emission component and/or a distinct ‘hotspot’ thermal component are detected during the ‘off’ mode of radio emission, the reactivation model (Model 1) is essentially rejected, and the reversal model (Model 2) is generally supported. Non-detections, on the other hand, would be consistent with the reactivation model and disfavour the reversal model, although more detailed modelling is needed to tell whether the model is completely ruled out.

RRAT J1819–1458 was serendipitously detected with *Chandra* by Reynolds et al. (2006, see also Gaensler et al. 2006). The spectrum of the X-ray counterpart is similar to that of a radio pulsar of comparable age, which is dominated by a soft thermal component due to neutron star cooling. Neither the strong non-thermal magnetospheric emission nor a hotspot thermal emission was identified. The data are therefore consistent with the reactivation pulsar model, and the reversal model is disfavoured with the present quality of the X-ray spectrum.

## 5 CONCLUSIONS AND DISCUSSION

We have suggested two possible interpretations to the recently identified part-time pulsars. One is that these objects are re-activated dead pulsars slightly below the conventional radio emission (pair

production) death line. The other is that they are simply the other half of nulling pulsars for which our line of sight misses the outward-directed main radio emission beam but happens to sweep the reversed inward-directed emission beam.

Since the predicted X-ray emission properties differ significantly from each other in the two scenarios, we suggest an X-ray diagnostic to differentiate between the two possible interpretations. In particular, a coordinated X-ray and radio observational campaign would be essential to unravel the nature of these part-time pulsars. If a strong non-thermal magnetospheric emission component and/or a hotspot thermal emission component are identified from their X-ray spectra, these objects are then very likely similar to conventional pulsars. The emission direction reversal and a preferred viewing geometry are likely the agents to make a part-time pulsar. Such an identification would lend support to the inward emission proposal for radio pulsars (Dyks et al. 2005a,b). Alternatively, if after deep searches no strong magnetosphere-related X-ray emission components (non-thermal or hotspot thermal) are detected from any of these objects, part-time pulsars are then very likely not-quite-dead pulsars before disappearing in the graveyard. This would suggest that the microscopic condition near the pulsar polar cap region is much more complicated than usually imagined. This allows us to directly study the dynamical evolution of the magnetic fields near the polar cap region. In any case, either possibility would provide profound implications for understanding the poorly known pulsar radio emission mechanism.

So far, the available data seem to be consistent with the reactivation model, while the reversal model is disfavoured for at least PSR B1931+24 and RRAT J1819–1458. A systematic search for X-ray counterparts of RRATs and other part-time pulsars is desirable to draw a firmer conclusion.

Several other suggestions have been proposed recently to interpret part-time pulsars.

(i) Popov et al. (2006) suggest that RRATs may be related to X-ray dim isolated neutron stars (XDINSs) based on comparisons of the birth rate and X-ray property of the two populations. The reactivation model discussed here would offer a mechanism to generate part-time pulses from these objects. If it turns out that all RRATs are X-ray dim, the reversal model would be disfavoured since it predicts bright non-thermal and hotspot thermal emission components. The discoveries of these components, on the other hand, would disfavour the suggestion that RRATs are related to XDINSs.

(ii) Cordes & Shannon (2006) and Li (2006) independently suggest that part-time pulsars are modulated by sporadic accretion into the neutron star magnetosphere that quenches the coherent radio emission. An earlier suggestion along the same line has been made by Wright (1979). In these scenarios, there is another X-ray emission component due to accretion. However, a proper adjustment of parameters (e.g. Li 2006) would make the model satisfy the X-ray constraint from RRAT J1819–1458 (Reynolds et al. 2005). Based on X-ray data alone, it is not easy to differentiate these models from the ones we propose.

(iii) Weltevrede et al. (2006) argue that bright pulses detected in pulsars such as PSR B0656+14, if the pulsar is far away enough, would mimic RRATs’ emission. In view of the fact that the X-ray spectrum of RRAT J1819–1458 (dominated by a cooling thermal component; Reynolds et al. 2006) is not fully consistent with that of PSR B0656+14 (with the existence of another ‘hotspot’ thermal component and possibly a non-thermal component besides the cooling thermal component; e.g. Marshall & Schulz 2002; De Luca et al. 2005), this suggestion may not be conclusive. Even if RRATs

are B0656+14-like objects, some other part-time pulsars still call for other interpretations including the ones suggested in this paper.

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