On the Nature of Part Time Radio Pulsars

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ABSTRACT

The recent discovery of rotating radio transients and the quasi-periodicity of pulsar activity in the radio pulsar PSR B1931+24 has challenged the conventional theory of radio pulsar emission. Here we suggest that these phenomena could be due to the interaction between the neutron star magnetosphere and the surrounding debris disk. The pattern of pulsar emission depends on whether the disk can penetrate the light cylinder and efficiently quench the processes of particle production and acceleration inside the magnetospheric gap. A precessing disk may naturally account for the switch-on/off behavior in PSR B1931+24.

Subject headings: stars: magnetic fields — stars: neutron – pulsars: individual: RRAT J1819−1458, GCRT J1745−3009, PSR B1931+24

1. Introduction

A small group of rotating radio transients (RRATs) were recently reported by McLaughlin et al. (2006). These objects are characterized by single, dispersed bursts of radio emission with durations between 2 and 30 ms. The average time intervals between bursts range from 4 minutes to 3 hours, with radio emission typically detectable for < 1 s per day. Periodicities in the range $0.4 - 7$ s for 10 of the 11 sources have been measured, suggesting that they are rotating neutron stars. Three of the sources have measured period derivatives, with one (RRAT J1819−1458) having a very high inferred magnetic field of 5×10^{13} G, if spin-down by magnetic dipole radiation is assumed.

A similar bursting radio source GCRT J1745−3009 was detected previously (Hyman et al. 2005), whose notable properties include "flares" approximately 1 Jy in magnitude lasting approximately 10 minutes each and occurring at apparently regular 77 minute intervals. GCRT J1745−3009 is located approximately $10'$ from the Galactic center, and just outside of the shell-type supernova remnant (SNR) G359.1−0.5 (Reich & Fürst 1984). If GCRT J1745−3009 and the SNR are related, then GCRT J1745−3009 would have the age of $\sim 10^5$

yr, comparable to RRAT J1819−1458. But the overall age distribution of RRATs is still not clear, although 5 out of 10 have spin periods $P > 4$ s.

Despite the small number of RRATs detected, McLaughlin et al. (2006) suggest that their ephemeral nature may point to a total Galactic population significantly exceeding that of the regularly pulsing radio pulsars. Investigation of the nature of RRATs will be of great interest on understanding pulsar formation, evolution and radiation mechanisms.

Several possible interpretations for the peculiar properties of RRATs as well as GCRT J1745−3009 have been examined. For the latter, models involving a precessing pulsar (Zhu & Xu 2006), binary neutron star (Turolla, Possenti, & Treves 2005), and transient white dwarf pulsar (Zhang & Gil 2005) have been suggested. More recently, Zhang, Gil & Dyks (2006) discuss two possible interpretations to RRATs: the first model suggests that these objects are pulsars slightly below the radio emission "death line", and become active occasionally when the conditions for pair production and coherent emission are satisfied; the second one invokes a radio emission direction reversal in normal pulsars due to some unknown reasons.

The re-activated dead pulsar model in Zhang et al. (2006) is particularly interesting, although the so-called "death line" is highly uncertain, because it depends not only on the magnetic field configuration, but significantly on the origin of gamma quanta, which are responsible for pair production. The outbursts of radio emission are assumed to be caused by internal magnetic field evolution in the neutron stars - when stronger multipole magnetic fields emerge to the polar cap region of the neutron star, the pair production condition could be satisfied and the neutron star behaves like a radio pulsar. A few lines of implications can be drawn from this idea. First, the large population of RRATs may be either due to higher birthrate of young pulsars than previously thought, or caused by a pile-up effect at large periods. This could be testified by future population synthesis of radio pulsars. Second, since reconnection typically occurs at a fraction of Alfv́en velocity $v_{\rm A}$, in the case where the instability is driven by the internal field, the growth time of the instability is (Thompson & Duncan 1995)

$$\Delta t \sim \frac{\Delta l}{v_{\rm A}} \sim 10 B_{*,12}^{-1} \rho_{15}^{1/2} (\frac{\Delta l}{0.1 R_*})\,{\rm s}, \tag{1}$$

where Δl is the displacement of the field lines, $B_* = 10^{12} B_{*,12}$ G, $\rho = 10^{15}\rho_{15}$ gcm^{-1}, and R_* the surface magnetic field strength, the core density, and the radius of the neutron star, respectively. To be compared to the measured RRAT burst duration of ~ 10 ms, one has to assume that the field readjustment should take place in the outer crust of the neutron star, where $\rho_{15} \sim 10^{-6}$.

In this *Letter* we present an alternative interpretation to RRATs. We propose that some of them may be isolated neutron stars surrounded by a debris disk, which originate either from the supernovae that produced the neutron stars or from the captured interstellar medium. The neutron stars act as a propeller when the disk penetrates inside the light cylinder, and the outflow or wind from the disk may quench the pair production processes in the pulsar magnetosphere with only transient radio emission allowed. The interaction between a processing debris disk with the neutron star magnetic field may also be responsible for the quasi-periodic switch-on/off transition in PSR B1931+24 recently reported by Kramer et al. (2006).

2. RRATs

In the standard model for radio pulsars, the rotationally induced electric field of a rotating, magnetized neutron star pulls the plasma off the surface and eject it beyond the light cylinder to form a relativistic wind (Goldreich & Julian 1969). Pulsar emission is then associated with the acceleration of particles to maintain this wind, which appears by the avalanche process of ($e^{\pm}$) pair production (Ruderman & Sutherland 1975). In the polar-cap models, the acceleration and radiation occur near the magnetic poles in the inner magnetosphere, while in the outer-gap models, these processes occur in the outer magnetosphere (see Kaspi, Roberts, & Harding for a review). The flow of the plasma along open field lines results in some plasma void regionsin the vicinity of null-charge surfaces. In such charge-deficient regions (or "gaps") electric field parallel the magnetic field lines $E_{||} \neq 0$ is sustained, electrons and positrons can be accelerated to relativistic energies.

It is interesting to see whether the conditions for pulsar emission will be satisfied if there is a disk surrounding the neutron star. Michel & Dessler (1981, 1983; see also Michel 1988) argued that radio pulsars and X-ray pulsars differ mainly in the fact that the former are surrounded by a supernova fallback disk with negligible accretion, while the latter are surrounded by an accretion disk. Alternatively, the debris disks around isolated neutron stars may result from the captured interstellar medium (e.g. Popov et al. 2000). The fallback disk model was recently adopted to account for the observational characteristics of anomalous X-ray pulsars (Yusifov et al. 1995; Chattterjee, Hernquist, & Narayan 2000; Alpar 2001). Such disks can also influence pulsar braking indices and timing ages. Menou, Perna, & Hernquist (2001) have explored a disk model for the spin-down of young radio pulsars, in which the neutron star loses rotational energy not only by emitting magnetic dipole radiation, but also by torquing a supernova fallback disk. Marsden, Lingenfelter, & Rothschild (2001) considered a similar model to explain the discrepancies between a pulsar's true age and its characteristic age. Recent X-ray observations also show that some young pulsars, such as the Crab and Vela pulsars, may have the jet configuration, which suggests the existence of a disk surrounding the neutron star (Blackman & Perna 2004, and references therein). The strongest constraints on the presence of a disk is given by its optical and longer wavelength emission. Perna & Hernquist (2000) have examined the reprocessing of beamed pulsar emission by the debris disks. They found that, since the reradiated flux gives the dominant contribution at long wavelengths produced in the bulk of the disk, whereas the optical emission is generated in its innermost part, the optical rather the longer wavelength emission would be highly suppressed, if the inner edge of the disk were truncated at a radius larger than the magnetospheric radius. Most recently, Wang, Chakrabarty, & Kaplan (2006) report the discovery of mid-infrared emission from a cool disk around the isolated young X-ray pulsar 4U 0142+61, presenting the first direct evidence for supernova fallback.

In the original picture of Sturrock (1971) and Michel & Dessler (1981) the debris disk is magnetically coupled with the neutron star with no accretion. This may be true for cold disks with extremely low viscosity. However, it is conventionally thought that the pulsar emission will quenched if the disk wind plasma penetrating into the light cylinder.

Most of the neutron stars with a surrounding disk should have experienced the accretor and propeller regimes (Illarionov & Sunyave 1975). The existence of a disk inside the light cylinder may significantly influence the pulsar radiation processes. Magnetocentrifugally driven outflows from the disks has been discussed by a number of authors during the propeller phase (e.g. Camenzind 1990; Königl 1991; Lovelace et al. 1995; Agapitou & Papaloizou 2000; Ustyugova et al. 2006). The disk wind itself may also be strong enough to influence the structure of pulsar winds (Blackman & Perna 2004). It has already been shown that the $\sim 10^{12}$ V potential difference across the magnetospheric gap and the outward-directed electric field required by the Ruderman-Sutherland model for the generation of radio waves will be negated, if the number density of matter at the Alfv́en surface is greater than $\sim 7.2 \times 10^7$ cm^{-3} (Wang 1983), a condition satisfied by most neutron stars with a debris disk where there is significant wind or outflow from the disk. The density of the outflow plasma, if similar to that in the disk, can be estimated to be

$$\rho_{\mathrm{w}} = \frac{\dot{M}}{2\pi R H v_{\mathrm{r}} m_{\mathrm{H}}} \simeq 2.2 \times 10^{15} (\frac{\dot{M}}{10^{14}\mathrm{gs}^{-1}})(\frac{\alpha}{0.01})^{-1}(\frac{H/R}{0.1})^{-3}(\frac{R}{10^9\,\mathrm{cm}})^{-3/2}\,\mathrm{cm}^{-3}, \tag{2}$$

where $\dot{M}$ is the mass inflow rate in the disk, H the half thickness, v_{r} the radial velocity, R the inner radius of the disk, α the viscosity parameter, and m_{H} the proton mass, respectively. It can be much larger than the Goldreich-Julian density ρ_{GJ} for typical values of the adopted parameters, if one assumes that the electron-positron pairs in the gap are close to saturation,

$$\rho_{\mathrm{GJ}} = \frac{\Omega B}{2\pi c e} = 7 \times 10^{10} B_{*,12} P^{-1} (\frac{R_*}{R})^{-3}\,\mathrm{cm}^{-3}, \tag{3}$$

where P is the neutron star spin period. Failure of pulsar emission may also partly result from the fact that coherent radiowaves with a wavelength longer than 75 cm can be absorbed effectively in the wind plasma (Illarionov & Sunyave 1975).

The flow in the inner part of the accretion disk is expected to have density fluctuations ("clumps") produced by a variety of mechanisms, such as thermal instability, Kelvin-Helmholtz instability, and magnetoturbulence (see Lamb et al. 1985; Shibazaki & Lamb 1987). The clumpy wind density would be much higher than the averaged value estimated above. They may also leave short, sporadic "transparent" time for the development of particle acceleration in the gap and generation of pulsar emission. If we assume that the typical clump separation is less than the disk height $H_{\rm in}$ at the inner edge $R_{\rm in}$ of the disk, the duration of successful pulsar emission should be less than

$$\tau \sim H_{\rm in}/v_{\rm esc}, \tag{4}$$

where $v_{\rm esc}$ is the escape velocity at $R_{\rm in}$. If $R_{\rm c} < R_{\rm in} < R_{\rm lc}$ and $H/R \lesssim 0.1$, we have $11P$ ms $< \tau < 1.7P^{3/2}$ s. Here $R_{\rm c} \equiv (GMP^2/4\pi)^2$ is the corotation radius and $R_{\rm lc} \equiv cP/2\pi$ is the light cylinder radius, respectively. As pointed out by Zhang et al. (2006), the dynamical time scale of the inner gap ($\sim h_{\rm gap}/c \sim 10^{-6} - 10^{-4}$ s, where $\sim h_{\rm gap}$ is the height of the gap) is much smaller than the rotation period P. So the time scale to develop a pair cascade is much shorter than τ. Its magnitude seems compatible with the burst durations measured so far.

The debris disk may be popular in relatively young neutron stars. Jiang & Li (2005) performed Monte-Carlo simulation of pulsar evolution, assuming that all neutron stars are born with a surrounding supernova fallback disk with the initial masses of the disk ranging from $10^{-6}\,M_\odot$ to $10^{-2}\,M_\odot$. They found that the emerging proportion of disk-fed neutron stars (i.e. with the disk extending inside the light cylinder) is $\sim 20\% - 50\%$ at age of 10^3 years, and $\sim 10\% - 25\%$ at age of 10^4 years. Obviously these numbers are sensitive to the assumptions for the initial parameters, e.g., the distributions of the initial disk masses, of the neutron star spin periods, magnetic fields, and most importantly, the mechanisms of the propeller spin-down. However, it clearly demonstrates that a considerable fraction of isolated neutron stars could harbor a debris disk with sufficiently long time (Popov et al. (2000) suggested that a fraction of $0.1\% - 0.2\%$ of all isolated neutron stars may be presently in the propeller stage due interaction with the interstellar medium). It was also found that the ratio of the characteristic age $t_{\rm c} = P/2\dot{P}$ and the true age t distributes within a relatively wide range from ~ 0.1 to ~ 10, indicating that $t_{\rm c}$ and the magnetic field strength estimated from magnetic dipole radiation may considerably deviate from the actual values for these neutron stars. The disk-assisted spin-down may also explain why RRATs have relatively long spin periods compared with normal isolated radio pulsars.

Reynolds et al. (2006) recently report the discovery of the X-ray counterpart to RRAT

J1819−1458. While their data are insufficient for fitting to more detailed neutron star atmosphere models, they suggest that the emission from RRAT J1819−1458 is consistent with a cooling neutron star of age $\sim 10^4 - 10^5$ yr, at a distance $\lesssim 2$ kpc. This seems to be in contradiction with our scenario since thermal, soft radiation is not expected from a propeller, in which nonthermal magnetospheric emission should dominate (e.g. Popov, Turolla, & Possenti 2006). From the work of Cannizzo, Lee, & Goodman (1990) and Mineshige et al. (1997) for supernova fallback, we can roughly estimate the mass inflow rate in the disk as

$$\dot{M} \simeq 1.8 \times 10^{14} (\frac{M}{1M_\odot})(\frac{\Delta M}{10^{-5} M_\odot})(\frac{\alpha}{0.01})(\frac{t}{10^5\,\mathrm{yr}})^{-1.35}\,\mathrm{gs^{-1}}, \tag{5}$$

where ΔM is the amount of fallback material. With Eq. (5) the maximum luminosity released by the propeller process is

$$L_{\mathrm{prop}} = \frac{GM\dot{M}}{R_{\mathrm{m}}} \simeq 2.4 \times 10^{30} (\frac{M}{1M_\odot})^2 (\frac{\Delta M}{10^{-5} M_\odot})(\frac{R_{\mathrm{m}}}{0.5 R_{\mathrm{lc}}})^{-1}(\frac{\alpha}{0.01})(\frac{t}{10^5\,\mathrm{yr}})^{-1.35}\,\mathrm{ergs^{-1}}, \tag{6}$$

for RRAT J1819−1458, which is much smaller than the measured luminosity $\sim 10^{33}\,\mathrm{ergs^{-1}}$, implying that neutron star cooling could still dominate X-ray emission in this object. But we mention that a neutron star undergoing propeller spindown could be a weak point source of γ-ray radiation during the (radio-)quiescent state (Wang & Robertson 1985).

3. PSR B1931+24

More recently Kramer et al. (2006) report the quasi-periodical pattern in the radio pulsar PSR B1931+24: the radio emission switches off in less than 10 seconds after the active phases of $\sim 5 - 10$ days, and remains undetectable for the next $\sim 25 - 35$ days when it switches on again. More remarkably, the pulsar rotation slows down 50% faster when it is on than when it is off, indicating an increase in magnetospheric currents when the pulsar switches on. As pointed out by Kramer et al. (2006), the discovery of PSR B1931+24's behaviour suggests that many more such objects exist in the Galaxy, and the bursting radio source GCRT J1745−3009 may turn out to be a short-timescale version of PSR B1931+24 and hence to be a radio pulsar.

The 35 day period is not likely to be attributed to free precession of the neutron star, because no evidence of expected profile changes is found (Kramer et al. 2006). However, it might be accounted for in our pulsar + debris disk model. Here we suggest that the 35 day period is the precession period of the debris disk. It is well known that the neutron star receives a kick during the supernova explosion, and it is likely that there is misalignment between the angular momenta of the fallback disk and the neutron star, leading to free precession of the disk (Katz 1973; Roberts 1974). The disk precession can also be induced by the radiation or magnetic torques generated from the neutron star (e.g. Petterson 1977; Pringle 1996; Lai 1999). There is extensive evidence for a warped, precessing disk in X-ray binaries and active galactic nuclei (e.g. Ogilvie & Dubus 2001, and references therein).

The quasi-periodicity in PSR B1931+24 may be explained in the following picture. We assume that the inner edge of the debris disk is close to the pulsar's light cylinder. It is known that the horizontal distance of the disk from the spin axis of the neutron star always changes during the precession. As soon as the disk penetrates inside the light cylinder, the propeller process commences along with outflows from the disk, particle acceleration processes in the magnetospheric gap are then quenched and the coherent radio emission cuts off. The neutron star slows down only by magnetic dipole radiation. The pulsar radiation switches on when the disk moves outside the light cylinder. In this case both magnetic dipole radiation and pulsar wind brake the neutron star, so that the pulsar slows down faster than during the off phase. This scenario also suggests that PSR B1931+24 may appear as a RRAT during the off phase. The recent detection of transient pulsed radio emission from the anomalous X-ray pulsar XTE J1810−197 (Camilo et al. 2006) could be an example of this transition.

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