THE ASTROPHYSICAL JOURNAL, 547:L45–L48, 2001 January 20

DOES PULSAR B1757−24 HAVE A FALLBACK DISK?

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Received 2000 August 18; accepted 2000 November 2; published 2001 January 17

ABSTRACT

Radio pulsars are thought to spin down primarily as a result of torque from magnetic dipole radiation (MDR) emitted by the time-varying stellar magnetic field as the star rotates. This assumption yields a "characteristic age" for a pulsar, which has generally been assumed to be comparable to the actual age. Recent observational limits on the proper motion of pulsar B1757−24, however, revealed that the actual age (>39 kyr) of this pulsar is much greater than its MDR characteristic age (16 kyr), calling into question the assumption of pure MDR spin-down for this and other pulsars. To explore the possible cause of this discrepancy, we consider a scenario in which the pulsar acquired an accretion disk from supernova ejecta and the subsequent spin-down occurred under the combined action of MDR and accretion torques. A simplified model of the accretion torque involving a constant mass inflow rate at the pulsar magnetosphere can explain the age and period derivative of the pulsar for reasonable values of the pulsar magnetic field and inflow rate. We discuss testable predictions of this model.

Subject headings: pulsars: individual (PSR B1757−24) — stars: neutron — supernova remnants

1. INTRODUCTION

Isolated pulsars are spinning neutron stars whose observed spin rates gradually decrease with time. The age τ of a pulsar is usually assumed to be equal to the timing (or characteristic) age $\tau_{\rm MDR}$ derived by assuming pure magnetic dipole spin-down in vacuo, and the age is then given by $\tau_{\rm MDR} = -\Omega/2\dot{\Omega}$ (e.g., Manchester & Taylor 1977), where $\Omega = 2\pi/P$ and $\dot{\Omega} = -2\pi\dot{P}/P^2$ are the angular spin frequency and angular frequency derivative for a pulsar spin period P and period derivative $\dot{P}$. Under this same assumption of magnetic dipole radiation (MDR) spin-down, the magnetic field strength of the pulsar is given by the formula (Manchester & Taylor 1977)

$$B = 3.2 \times 10^{19} (P\dot{P})^{1/2}\ \mathrm{G}, \tag{1}$$

which is often assumed to be equal to the true field strength of the isolated pulsar (e.g., Taylor, Manchester, & Lyne 1993[2]).

PSR B1757−24 is a 0.125 s radio pulsar that appears to be associated with the supernova remnant G5.4−1.2 (Caswell et al. 1987). The pulsar is surrounded by a compact radio nebula having a cometary morphology with a tail extending back into the supernova remnant (Frail, Kassim, & Weiler 1994), strongly suggesting that the pulsar was formed in the supernova that produced G5.4−1.2 (Manchester et al. 1991). Given the temporal parameters of PSR B1757−24 ($P = 0.125$ s and $\dot{P} = 1.28 \times 10^{-13}$ s s^{-1}; Taylor et al. 1993), $\tau_{\rm MDR} = 16$ kyr and $B = 4 \times 10^{12}$ G for the pulsar. Assuming that $\tau_{\rm MDR}$ is similar to the pulsar's true age, the transverse velocity implied by the pulsar's displacement from the apparent center of G5.4−1.2 is greater than 1500 km s^{-1} (Gaensler & Frail 2000; Frail & Kulkarni 1991). Observations of PSR B1757−24 taken 6 yr apart, however, failed to detect the expected proper motion from the pulsar, yielding a distance-independent lower limit on the age of PSR B1757−24/G5.4−1.2 of 39 kyr (Gaensler & Frail 2000). This is more than a factor of 2 greater than the pulsar's MDR characteristic age.

The discrepancy between the proper-motion age and the MDR characteristic age of PSR B1757−24 suggests that the spin-down of the pulsar is not due purely to MDR but also has significant contributions from other sources of torque. Istomin (1994) considered a model for PSR B1757−24 in which the pulsar was interacting with dense plasma in the shell of G5.4−1.2, causing an increase in the torque at the light cylinder. Here we consider another possible source of extra torque on the neutron star—from a disk of material accreted from ejecta produced in the supernova explosion. These *fallback disks* may be roughly divided into two categories: "prompt" and "delayed." Prompt disks may be formed from ~0.001–0.1 $M_\odot$ (Michel 1988; Lin, Woosley, & Bodenheimer 1991) of ejecta material soon after the initial core collapse in a Type II supernova explosion (Woosley & Weaver 1995). Formation of such prompt disks is probably limited to more than 7 days after the core collapse because of heating of the ejecta by ^{56}Ni decays (Chevalier 1989). Delayed disks may form years after the explosion from ejecta decelerated by radiative cooling (Fryer, Colgate, & Pinto 1999) or by a strong reverse shock (Truelove & McKee 1999) caused by the primary supernova blast wave impinging on dense circumstellar material from the presupernova stellar wind (Gaensler 1999). Whether or not a neutron star accretion disk can form shortly after a supernova explosion depends on the opposing forces of the pulsar MDR wind and the pressure of the hot and turbulent environment shortly after the explosion. Since the latter is highly uncertain (Woosley & Weaver 1995), for the purposes of this Letter we assume that a disk can form around a neutron star under these conditions and explore the implications for PSR B1757−24.

2. SPIN-DOWN FROM ACCRETION TORQUES

An accretion disk around a magnetized neutron star can exert a spin-down torque on the star if the mass inflow rate is low and the magnetic field is strong. Quantitatively, this condition is met when the Keplerian corotation radius $R_c = 1.7 \times 10^8 P^{2/3}$ cm is less than the magnetospheric radius $R_M =$

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[2] See also http://pulsar.princeton.edu/pulsar/catalog.shtml.

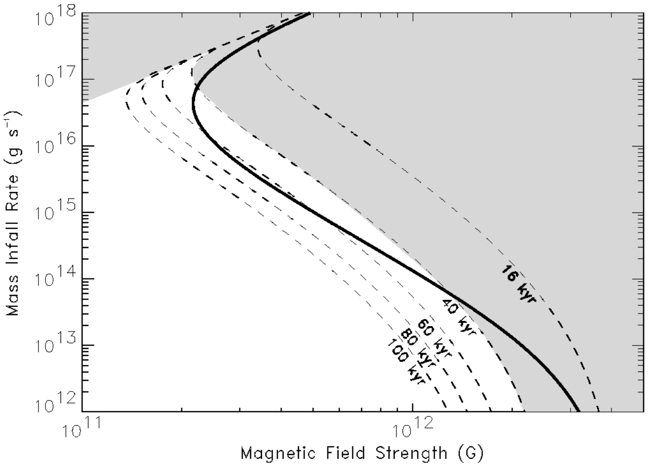

FIG. 1.—The discrepancy between the MDR age of 16 kyr and the proper-motion age of greater than 39 kyr for PSR B1757−24 may be resolved by the addition of "propeller" torque due to an accretion disk. This is shown by the plot of the calculated age (*dashed lines*) of pulsar B1757−24 vs. the neutron star magnetic field strength B and mass infall rate $\dot{m}$, assuming a combined spin-down torque due to both MDR and an accretion disk formed from supernova debris. The allowed combinations of B and $\dot{m}$ fall on portions of the thick solid line (corresponding to the observed period and spin-down rate of the pulsar) lying outside the shaded areas excluded by upper limits on the pulsar proper motion (Gaensler & Frail 2000) and the condition necessary for the propeller effect ($R_M > R_c$).

$4.6 \times 10^8 B_{12}^{4/7} \dot{m}_{15}^{-2/7}$ cm, where $\dot{m} = 10^{15}\dot{m}_{15}$ g s^{-1} is the mass inflow rate onto the magnetosphere and $B = 10^{12}B_{12}$ G is the strength of the neutron star dipole magnetic field (see, e.g., Frank, King, & Raine 1992). Here and elsewhere we assume a neutron star mass and radius of $M_* = 1.4\ M_\odot$ and $R_* = 10$ km, respectively. When $R_M > R_c$, infalling material is stopped at the magnetosphere by a centrifugal barrier that prevents accretion onto the neutron star surface. Instead, the infalling material may be accelerated away in a wind that carries away angular momentum from the magnetosphere and hence the neutron star itself. This "propeller effect" (Illarionov & Sunyaev 1975) spin-down mechanism has been invoked to explain the behavior of some Galactic accretion-powered X-ray pulsars (Cui 1997; Zhang, Yu, & Zhang 1998), the spin evolution of anomalous X-ray pulsars (AXPs; van Paradijs, Taam, & van den Heuvel 1995; Chatterjee, Hernquist, & Narayan 2000) and soft gamma-ray repeaters (Alpar 2000; Marsden et al. 2001), and the optical and infrared spectra of some radio pulsars (Perna, Hernquist, & Narayan 2000).

The pulsar B1757−24 is in the propeller regime ($R_M > R_C$) for mass inflow rates of $\dot{m} < 5 \times 10^{17}$ g s^{-1} and a canonical (Manchester & Taylor 1977; Taylor et al. 1993) neutron star magnetic field of $\sim 10^{12}$ G. Since the characteristic age for an old (>10 kyr) pulsar depends only weakly on the initial spin period (Manchester & Taylor 1977), we neglect the different formation times of the delayed and prompt fallback disks and assume that the spin-down evolution of the pulsar at all times is determined by the combined torque from both the MDR and the accretion disk. The spin-down rate due to radiation from a rotating magnetic dipole is (Manchester & Taylor 1977)

$$\dot{\Omega}_M = -\frac{2B^2R_*^6\Omega^3}{3I_*c^3}, \qquad (2)$$

where $I_* = \frac{2}{5}M_*R_*^2$ is the neutron star moment of inertia. The spin-down rate due to the propeller torque vanishes gradually (Chatterjee et al. 2000; Alpar 2000) as the star approaches spin equilibrium ($R_M = R_c$) at a spin period $P_{\rm eq} = 4.7B_{12}^{6/7}\dot{m}_{15}^{-3/7}$ s. The spin-down rate due to the propeller torque is simply (Menou et al. 1999)

$$\dot{\Omega}_A = k\frac{\dot{m}R_M^2\Omega_{\rm eq}}{I_*}\left(1 - \frac{\Omega}{\Omega_{\rm eq}}\right), \qquad (3)$$

where k is a positive constant of order unity (Wang & Robertson 1985) and $\Omega_{\rm eq} = 2\pi/P_{\rm eq}$. Assuming a constant mass inflow rate and dipole magnetic field, the timing age for a final spin period $P = 2\pi/\Omega$ is given by

$$\tau_{\rm comb} = \int_{\Omega_0}^{\Omega} \frac{d\Omega}{\dot{\Omega}_M + \dot{\Omega}_A}, \qquad (4)$$

where Ω_0 is the initial angular frequency. A more realistic expression for the propeller torque would incorporate a time-dependent mass inflow rate (Cannizzo, Lee, & Goodman 1990) in equation (3), as $\dot{m}$ should decrease in time as the disk dissipates. For the model to be correct, however, a disk must still be present around the pulsar, because otherwise the MDR timing age would be greater than the true age. Therefore, the $\dot{m}$ used here may be thought of as a time-averaged value of the mass inflow rate. In addition, the effect of the propeller flow on the MDR torque (Roberts & Sturrock 1973) is not taken into account. We plan on incorporating both of these effects in future work.

A contour plot of the pulsar B1757−24 timing age $\tau_{\rm comb}$ for various values of the magnetic field strength B and mass inflow rate $\dot{m}$ is shown in Figure 1. The characteristic ages were calculated using equations (2)–(4) and assuming $P = 0.125$ s, $P_0 = 10$ ms, and $k = 1$. In this simple model, the allowed values of B and $\dot{m}$ for pulsar B1757−24 lie on the thick solid line corresponding to the observed P and $\dot{P}$. In addition, the shaded regions of parameter space in Figure 1 are excluded by the lower limit on the age (*right shaded region*; Gaensler & Frail 2000) and the necessary condition $R_M > R_c$ (*shaded region in upper left corner*). From Figure 1, we find that values of $2 \times 10^{11}\ {\rm G} < B < 1.4 \times 10^{12}$ G, 7×10^{13} g s$^{-1} < \dot{m} < 7 \times 10^{17}$ g s^{-1}, and 39 kyr $< \tau_{\rm comb} <$ 60 kyr are consistent with the lower limit on the true age of 39 kyr (Gaensler & Frail 2000) and the present-day spin-down rate of the pulsar.

3. DISCUSSION

In the context of this model, the required mass inflow rate for PSR B1757−24 overlaps the range of $\dot{m}$ inferred from accretion-powered neutron star systems (Bildsten et al. 1997). Radio pulsations are not seen from accretion-powered X-ray pulsars in binary systems (Fender et al. 1996), which implies that the emission mechanism responsible for radio pulsations may be quenched by matter near the polar caps of the pulsar. This is not a problem for the PSR B1757−24 model, however, because in propeller sources most of the matter is ejected before it has a chance to reach the polar cap and quench the radio emission. Radio emission may be suppressed for propeller sources closer to spin equilibrium than PSR B1757−24 (e.g., the AXPs; Chatterjee et al. 2000), however, because as equilibrium is approached more matter will be allowed to fall onto the neutron star surface. The total mass required to fuel the propeller spin-down over the lifetime (so far) of pulsar B1757−24 would be $\dot{m}\tau \sim 10^{-8}$ to $10^{-3}\ M_\odot$—a tiny fraction of the total amount of ejecta in a typical Type II supernova explosion (Woosley & Weaver 1995).

This hypothesis can be tested by multiwavelength observations. In this model, the total emission from the pulsar would be due to the propeller wind, MDR, and thermal emission from the accretion disk. Wang & Robertson (1985) calculated the angle-integrated thermal bremsstrahlung emissivity j_B from the heated plasma in a propeller flow. Using their scalings, the X-ray luminosity and temperature are given by $L_X \sim 4\pi R_m^2 \delta j_B \sim 4.0 \times 10^{33} B_{12}^{1/2} \dot{m}_{15}^{3/4}$ ergs s^{-1} and $kT \sim 50 \dot{m}_{15}^{1/2} B_{12}^{1/3}$ keV, respectively, where δ is the width of the magnetospheric boundary layer where the plasma is heated by the magnetic field. This assumes spherical symmetry, so the luminosity will probably be $\sim 10^{33}$ ergs s^{-1} or less for the case of a disk geometry. If PSR 1757$-$24 is not a propeller source, we would expect the nonthermal X-ray emission that is characteristic of young rotation-powered pulsars (Seward & Wang 1988)—e.g., a power-law emission spectrum with a photon index $\Gamma \sim 2$ and an X-ray luminosity given by the empirical relation $L_X \propto (\Omega\dot{\Omega})^{1.39} \sim 1.2 \times 10^{34}$ ergs s^{-1}. At a distance of 5 kpc (Gaensler & Frail 2000), the flux from the nonthermal, nonpropeller emission would be 4×10^{-12} ergs cm^{-2} s^{-1}, which would be easily detectable by *XMM* or *Chandra*. The detection of dimmer, thermal X-ray emission instead of the brighter nonthermal emission would be evidence in support of the propeller model.

Cooler disk blackbody emission could also be visible at optical and infrared wavelengths from the accretion disk. The spectrum of propeller disks depend on B, $\dot{m}$, and the disk orientation with respect to the line of sight (e.g., Perna et al. 2000), but we can place an upper limit on the optical emission from a PSR B1757$-$24 disk in the following manner. Assuming that the majority of the optical disk emission originates at the innermost disk radii (Perna et al. 2000), the upper limit on the optical luminosity is $L_o < GM_* \dot{m}/R_m \sim 0.11 \dot{m}_{15}^{9/7} B_{12}^{-4/7} L_\odot$. This estimate ignores heating of the disk by irradiation from the pulsar, which dominates the heating only for pulsar luminosities $L_X > 10^{34}$ ergs s^{-1} (Perna et al. 2000). Assuming $B_{12} = 1$, $\dot{m} = 1$, and an apparent visual magnitude of -26.78 for the Sun (Lang 1980, p. 559), the apparent magnitude of the disk at 5 kpc (uncorrected for extinction) is $m_v > 20.7$. The extinction A_V can be estimated from the formula $N_{\rm H} = 1.79 \times 10^{21} A_V$ mag cm^{-2} (Predehl & Schmitt 1995), where $N_{\rm H}$ is the H I column density along the line of sight. At a distance of 5 kpc, $N_{\rm H} \sim 10^{22}$ cm^{-2} in the Galactic plane (as can be seen from the AXP spectral data in Perna et al. 2000), which yields an extinction of $A_V \sim 5.6$ mag and a lower limit on the disk magnitude of $m_V > 26$. This is comparable to the estimated magnitudes of propeller disks around AXPs as calculated by Perna et al. (2000).

If PSR B1757$-$24 is indeed surrounded by an accretion disk, then fossil accretion disks and propeller spin-down may be present, or may have been present at one time, in a significant fraction of isolated pulsars. This would affect the distributions of pulsar ages, magnetic field strengths, and space velocities inferred using the pulsar's P and $\dot{P}$ values and the MDR formulae discussed in § 1. Magnetic field strengths estimated using equation (1), for example, would overestimate the true field strengths for both pulsars currently undergoing propeller spin-down. The effect on the distribution of radio pulsar ages—and hence the distribution of pulsar velocities inferred from their angular positions (e.g., Cordes & Chernoff 1998)—depends on whether each pulsar is currently undergoing propeller spin-down or not. If a pulsar is currently undergoing propeller spin-down, then the MDR timing age $\tau_{\rm MDR}$ is an *underestimate* of the true age (as exemplified by PSR B1757$-$24). If a pulsar had a propeller disk that then dissipated, its present-day MDR age would be an *overestimate* of its true age, since the pulsar had undergone a period of increased spin-down rate (over the MDR spin-down rate) in the past. The latter scenario is probably more prevalent in the observed population of radio pulsars, since radio pulsations may be scattered and quenched in neutron stars with strong propeller flows (e.g., Alpar 2000; Fender et al. 1996), and therefore one might expect a systematic overestimation of radio pulsar ages due to fossil disks and propeller spin-down. Curiously, such a systematic overestimation of pulsar ages using MDR has been inferred from some pulsar population studies (Cordes & Chernoff 1998).

4. SUMMARY

We have shown that the addition of torques from an accretion disk can explain the discrepancy between the MDR timing age of PSR B1757$-$24 and its true age. This model can be tested through X-ray and optical observations of this pulsar. The accretion disk model for pulsar B1757$-$24 leaves open the question of whether or not pulsar B1757$-$24 is an unusual and rare object or if it instead reflects a generic feature in the evolution of neutron stars. If the former is true, the accretion model removes the need (Gaensler & Frail 2000) to revise our current understanding of the physics and astrophysics of neutron stars because of this single pulsar. If the latter is true, however, the distributions of pulsar magnetic field strengths, ages, and velocities will have to be reconsidered to take into account the effects of increased spin-down due to accretion disk torques. Observations of young pulsars associated with supernova remnants may hold the key toward resolving this question, because the pulsar ages can be constrained independently of the pulsar temporal parameters.

We thank the referee for helpful comments. This work was performed while one of the authors (D. M.) held a National Research Council–GSFC Research Associateship. R. E. R. acknowledges support by NASA contract NAS5-30720, and R. E. L. support from the Astrophysical Theory Program.

REFERENCES

Alpar, M. A. 2000, ApJ, submitted (astro-ph/0005211)
Bildsten, L., et al. 1997, ApJS, 113, 367
Cannizzo, J. K., Lee, H. M., & Goodman, J. 1990, ApJ, 351, 38
Caswell, J. L., et al. 1987, MNRAS, 225, 329
Chatterjee, P., Hernquist, L., & Narayan, R. 2000, ApJ, 534, 373
Chevalier, R. A. 1989, ApJ, 346, 847
Cordes, J. M., & Chernoff, D. F. 1998, ApJ, 505, 315
Cui, W. 1997, ApJ, 482, L163
Fender, R. P., et al. 1996, in Proc. Second Integral Workshop: The Transparent Universe, ed. C. Winkler, T. J.-L. Courvoisier, & P. Durouchoux (ESA SP-82; Noordwijk: ESA), 303
Frail, D. A., Kassim, N. E., & Weiler, K. W. 1994, AJ, 107, 1120
Frail, D. A., & Kulkarni, S. R. 1991, Nature, 352, 785
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Fryer, C. L., Colgate, S. A., & Pinto, P. A. 1999, ApJ, 511, 885
Gaensler, B. M. 1999, in ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport (San Francisco: ASP), 449
Gaensler, B. M., & Frail, D. A. 2000, Nature, 406, 158
Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185
Istomin, Ya. N. 1994, A&A, 283, 85
Lang, K. R. 1980, Astrophysical Formulae (Berlin: Springer)
Lin, D. N. C., Woosley, S. E., & Bodenheimer, P. H. 1991, Nature, 353, 827

Manchester, R. N., Kaspi, V. M., Johnston, S., Lyne, A. G., & D'Amico, N. A. 1991, MNRAS, 253, P7

Manchester, R. N., & Taylor, J. H. 1977, Pulsars (San Francisco: Freeman)

Marsden, D., Lingenfelter, R. E., Rothschild, R. E., & Higdon, J. C. 2001, ApJ, in press (astro-ph/9912207)

Menou, K., et al. 1999, ApJ, 520, 276

Michel, F. C. 1988, Nature, 333, 644

Perna, R., Hernquist, L., & Narayan, R. 2000, ApJ, 541, 344

Predehl, P., & Schmitt, J. M. H. H. 1995, A&A, 293, 889

Roberts, D. H., & Sturrock, P. A. 1973, ApJ, 181, 161

Seward, F. D., & Wang, Z.-R. 1988, ApJ, 332, 199

Taylor, J. H., Manchester, R. N., & Lyne, A. G. 1993, ApJS, 88, 529

Truelove, J. K., & McKee, C. F. 1999, ApJS, 120, 299

van Paradijs, J., Taam, R. E., & van den Heuvel, E. P. J. 1995, A&A, 299, L41

Wang, Y.-M., & Robertson, J. A. 1985, A&A, 151, 361

Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181

Zhang, S. N., Yu, W., & Zhang, W. 1998, ApJ, 494, L71