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CAN THE AGE DISCREPANCIES OF NEUTRON STARS BE CIRCUMVENTED BY AN ACCRETION-ASSISTED TORQUE?

Y. Shi and R. X. Xu
School of Physics, Peking University, Beijing 100871, China; rxxu@bac.pku.edu.cn
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ABSTRACT

It is found that 1E 1207.4−5209 could be a low-mass bare strange star if its small radius or low-altitude cyclotron formation can be identified. The age problems of five sources could be solved by a fossil-disk–assisted torque. The magnetic dipole radiation dominates the evolution of PSR B1757−24 at present, and the others are in propeller (or tracking) phases.

Subject headings: pulsars: general — pulsars: individual (1E 1207.4−5209) — stars: neutron

1. INTRODUCTION

The age of a neutron star is an essential parameter, which is relevant to the physics of supernova explosions and, thereafter, the evolution of stars. However, it is still generally a big problem to determine its exact age (except for the Crab pulsar). A conventional and convenient way to obtain the age of rotation-powered neutron stars is by equalizing the energy-loss rate of spin-down to that of magnetodipole radiation, assuming that the inclination angle between magnetic and rotational axes is $\alpha = 90°$ (e.g., Manchester & Taylor 1977). This conclusion keeps quantitatively for any α, as long as the braking torques due to magnetodipole radiation and the unipolar generator are combined (Xu & Qiao 2001). The resultant age, the so-called characteristic age, is $T_c = P/(2\dot{P})$ if the initial period P_0 is much smaller than the present period P. The age, T_c, is generally considered as the true one for a neutron star with $P > 100$ ms since most newborn neutron stars could rotate initially at $P_0 \sim 20$–30 ms (e.g., Xu, Wang, & Qiao 2002).

It challenges the opinion above that the ages of a few supernova remnants (SNRs) are inconsistent with the T_c of their related isolated stars (Table 1), which implies that some additional torque mechanisms do contribute to star braking. Among the five stars, three of them have $T_c > 10T_{\rm SNR}$ (the age of the SNR), and other two $T_c \lesssim 2T_{\rm SNR}$. In addition, electron-cyclotron resonant lines are detected in two of the five neutron stars (1E 1207.4−5209: Bignami et al. 2003; 1E 2259+568: Iwasawa, Koyama, & Halpern 1992), but their inferred magnetic fields, $B_{\rm cyc}$, are significantly smaller than that in the magnetic dipole radiation model, B_d. The most prominent one in this age discrepancy issue is 1E 1207.4−5209, which has $T_c \gtrsim 30T_{\rm SNR}$ and $B_{\rm cyc} \lesssim B_d/30$.

One probable and popularly discussed way to solve the age problem is through an additional accretion torque (Marsden, Lingenfelter, & Rothschild 2001; Alpar, Ankay, & Yazgan 2001; Menou, Perna, & Hernquist 2001). In this Letter, whether or not an additional accretion torque can possibly solve the age discrepancy is investigated, including discussions about possible astrophysical implications.

2. THE CASE OF 1E 1207.4−5209

The key point in the age discrepancy of 1E 1207.4−5209 is how to spin down from $P_0 \sim 20$ to 424 ms in a short time of $T_{\rm SNR} \sim 7$ kyr if its true age is $T_{\rm SNR}$. Certainly the problem disappears if one assumes a long initial period $P_0 \sim 400$ ms or a large braking index $n \sim 50$ (Pavlov et al. 2002), but this is not of Occam's razor since it is generally believed that rotation-powered radio pulsars are born within ∼20 ms and brake with an index of $\lesssim 3$. Would an additional accretion torque help the spin-down? Actually, in an effort to reconcile B_d with $B_{\rm cyc}$, an accretion model for 1E 1207.4−5209 was proposed (Xu, Wang, & Qiao 2003). However, some of the difficulties with this model concern choosing a time-dependent accretion rate $\dot{M}_d(t)$ and determining the propeller torque with the rate $\dot{M}_d$.

Nevertheless, the propeller phase works in the centrifugal inhibition regime when $r_m > r_c$; for a star with mass M and magnetic moment μ, the corotation radius $r_c = [GM/(4\pi^2)]^{1/3}P^{2/3}$, and the magnetospheric radius $r_m = \{\mu^2/[\dot{M}_d(2GM)^{1/2}]\}^{2/7}$. To avoid the complex calculations of magnetohydrodynamics, the rotation energy loss due to the propeller torque could be simply introduced as $\dot{E}_a = -GM\dot{M}_d M/R_m$, based on the energy conservation law. This is unphysical but should be a limit for accretion braking. As r_m decreases ($\to r_c^+$), $\dot{M}_d$ increases, and $|\dot{E}_a|$ increases too. Therefore, the most efficient spin-down (MESD) takes place when $r_m \to r_c^+$.

For a model in which the propeller and electromagnetic torques are combined, in the MESD case, one can derive the period evolution

$$P < 1.1B_{12}^2 R_6^4 (M/M_\odot)^{-2}(t/{\rm yr}) + P_0 \ ({\rm ms}), \tag{1}$$

where $B_{12} = B/(10^{12}\ {\rm G})$ and $R_6 = R/(10^6\ {\rm cm})$. The right-hand side of equation (1) is an upper limit of P because (1) a realistic accretion rate may not be as high as that of the MESD and (2) the corresponding braking torque is not so effective. If 1E 1207.4−5209 is a conventional neutron star with a mass of $\sim 1\ M_\odot$ and a radius of $\sim 10^6$ cm, and if the line features are related to cyclotron absorptions near the surface (Xu et al. 2003; the polar magnetic field is thus 6×10^{10} G), one has $P < 3.8(t/{\rm kyr}) + P_0$ (ms).

Therefore, assuming 1E 1207.4−5209 has a true age $t \sim 7$ kyr and an initial period $P_0 \sim 20$ ms, the upper limit of the present period is ∼40 ms ($\ll P = 434$ ms), and then the age discrepancy cannot be solved in the conventional neutron star model. However, if 1E 1207.4−5209 is a strange star with a low mass, for instance, $R = 1$ km (and the mass is thus $\sim 10^{-3}\ M_\odot$ since low-mass strange stars have an almost homogenous density of $\sim 4 \times 10^{14}$ g cm^{-3}; Alcock, Farhi, & Olinto 1986), the upper limit is then $P \simeq 110B_{12}^2(t/{\rm yr}) + P_0$ (ms). In this case, 1E 1207.4−5209 could spin down to ∼2.8 s during ∼7 kyr if its polar magnetic field is 6×10^{10} G. In fact, the fitted radius of 1E 1207.4−5209

TABLE 1

List of Neutron Stars with Age Discrepancies

Stars	SNR	P (s)	$\dot P$ (10^{-13} s s^{-1})	T_c (10^3 yr)	$T_{\rm SNR}$ (10^3yr)	$B_{12,\,d}$[a]	$B_{12,\,{\rm cyc}}$[b]	References
1E 1207.4−5209	PKS 1209−51/52	0.424	0.07–0.3	200–900	~7	1.7–3.6	0.06	1, 2
1E 2259+586[c]	CTB 109	6.98	4.84	228	17	59	0.4–0.9	3, 4, 5
PSR B1757−24	G5.4−1.2	0.125	1.28	16	>39	4.0	...	6
PSR J1811−1925	G11.2−0.3	0.065	0.44	24	1.6	1.7	...	7
PSR J1846−0258	Kes 75	0.325	71	0.72	0.9–4.3	49	...	8

References.—(1) Pavlov et al. 2002; (2) Bignami et al. 2002; (3) Gavriil & Kaspi 2002; (4) Hughes, Harten, & van der Bergh 1981; (5) Iwasawa et al. 1992; (6) Marsden et al. 2001; (7) Torii et al. 1999; (8) Gotthelf et al. 2000.

[a] The magnetic fields in the magnetic dipole radiation model: $B_d = 3.2 \times 10^{19} (P\dot P)^{1/2}$ G, $B_{12,\,d} = B/(10^{12}$ G).

[b] The magnetic fields (in units of 10^{12} G) derived from spectral features as cyclotron resonant scattering. No gravitation redshift is included here.

[c] An AXP.

with a blackbody model is only ~1 km (Mereghetti, Bignami, & Caraveo 1996; Vasisht et al. 1997), although a lager radius is possible if a light-element atmosphere is applied (Zavlin, Pavlov, & Trümper 1998). The best-fit two-blackbody model of *XMM-Newton* data indicates an emitting radius of ~3 km for the soft component with a temperature of ~200 eV (Bignami et al. 2003). Combined with its nonatomic feature spectrum, we suggest that 1E 1207.4−5209 is a low-mass strange star with a bare quark surface (Xu 2002; Xu et al. 2003).

An alternative possibility is that 1E 1207.4−5209 is a conventional neutron star but that the cyclotron resonant absorption forms far away from the surface. The polar magnetic field is $\sim 6 \times 10^{10}[(R+h)/R]^3$ G if the resonant lines form at a height h. From equation (1), $424 < 1.1 \times 7 \times 10^3 B_{12}^2 + 20$, we estimate the low limit of the polar magnetic field to be $\sim 2.3 \times 10^{11}$ G. This implies that the resonant absorption region should be at a level of greater than 16 km height from the surface. Certainly, in case of no propeller torque [i.e., the polar magnetic field is $(1.7\text{–}3.6) \times 10^{12}$ G], the height of the resonant absorption region is 30–40 km.

It is worth noting that 1E 1207.4−5209 could be a low-mass neutron star with a polar magnetic field $B_{12} = 0.06$. From equation (1) and the conditions of the MESD, one has $R_6^2 > 4(M/M_\odot)$ for $P_0 \sim 20$ ms. This implies a neutron star with a radius $R > 10$ km but a mass $M < M_\odot$ (e.g., Shapiro & Teukolsky 1983). This result may have difficulties in explaining (1) a nonatomic spectrum (Xu et al. 2003) and (2) a possibly small observed radius (Mereghetti et al. 1996; Vasisht et al. 1997; Bignami et al. 2003), and even the fitting result of a neutron star with 10 km and 1.4 $M_\odot$ (Zavlin et al. 1998).

3. OTHER SOURCES

If the other sources listed in Table 1 are neutron stars with $R_6 = 1$ and $M = M_\odot$, the low limits of the polar magnetic fields are 6.1×10^{11} G for 1E 2259+586, 4.9×10^{10} G for PSR B1757−24, 1.6×10^{11} G for PSR J1811−1925, and $(2.5\text{–}5.6) \times 10^{11}$ G for PSR J1846−0258. Among these sources, the only possible cyclotron absorption is found in 1E 2259+586, and the limit field is within the range of that inferred from the cyclotron line. This suggests that the cyclotron resonant absorption may take place just above the stellar surface.

How much mass could be accreted during the propeller phase in the case of the MESD? Certainly only a very small part of this matter can be accreted onto the stellar surface. When the MESD works, one obtains the accretion rate $\dot M_d \sim 2^{11/6} \times \pi^{7/3}\mu^2(GM)^{-5/3}P^{-7/3}$ from $r_m \simeq r_c$. If the quantities are rescaled ($m = M_d/M_\odot$, $\tau = t$/yr, and $p = P$/ms), one has $dm/d\tau \sim 0.24\mu_{30}^2(M/M_\odot)^{-5/3}p^{-7/3}$. Combining this with equation (1), one gets

$$m < \int_0^\infty \dot m \, d\tau = 0.16(M/M_\odot)^{-2/3} I_{45} p_0^{-4/3}, \qquad (2)$$

where $p_0 = P_0$/ms. Note that the upper limit of the accretion mass, M_d, on the right-hand side of equation (2) does not depend on the magnetic momentum. Typically, for $p_0 = 20$, the upper limit of the accretion mass is 2.95×10^{-3} $M_\odot$, which is reasonable since the amount of the fallback material after a supernova explosion could be as high as 0.1 $M_\odot$ (Lin, Woosley, & Bodenheimer 1991; Chevalier 1989). Due to r-mode instability, a nascent neutron star may lose its angular momentum rapidly through gravitational radiation if the initial period is less than ~3–5 ms (Andersson & Kokkotas 2001). The upper limit of the accretion mass in the case of the MESD is ~0.04 $M_\odot$ for $p_0 = 3$. These results indicate that the fallback matter is enough to brake the center stars by the propeller torque in the MESD case.

4. A MODEL WITH A SELF-SIMILAR ACCRETION RATE

Although the study of the MESD torque provides some useful information on the accretion model, including the appropriate magnetic field and the mass of the fallback disk around a neutron star, the accretion rate of the MESD torque is questionable in realistic cases. After a dynamical time, a fossil disk may form. For a viscosity-driven disk, the accretion could be in a self-similar way, with an accretion rate of (Cannizzo, Lee, & Goodman 1990)

$$\dot m = \dot m_0, \; 0 < t < T; \;\; \dot m = \dot m_0 (t/T)^{-\alpha}, \; t \geq T, \qquad (3)$$

where T is of order the dynamical time and $\dot m = dm/dt$. Assuming $T \sim 1$ ms, an initial disk mass of ~0.006 $M_\odot$, and an opacity dominated by electron scattering ($\alpha = 7/6$), Chatterjee, Hernquist, & Narayan (2000) developed the first detailed model of fossil-disk accretion for anomalous X-ray pulsars (AXPs). However, it is noted by Francischelli & Wijers (2002) that Kramers opacity may prevail in the fossil disk (i.e., $\alpha = 1.25$). In the regime of conventional neutron stars, we will calculate the accretion torque through the realistic accretion rate of equation (3), assuming $\alpha = 1.25$ and $T = 1$ ms, with

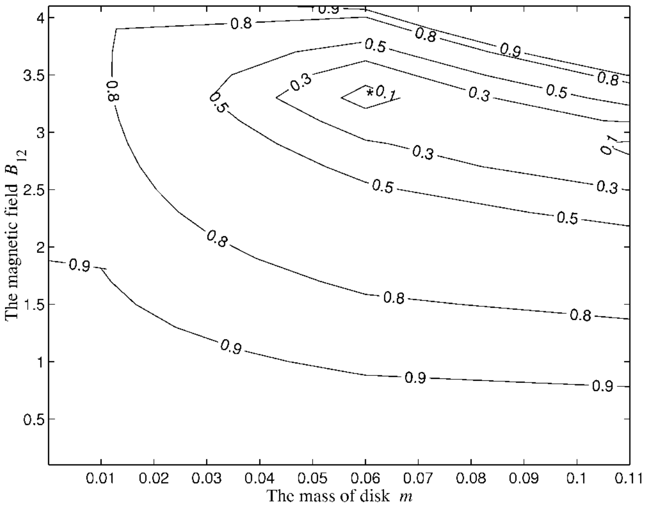

FIG. 1.—Contour of the relative error of period for 1E1207.4−5209 in a model with self-similar accretion. The star sign indicates the parametric position we choose for a reasonable neutron star and the fossil disk around it. The disk mass m is in units of solar mass, and the polar magnetic field B_{12} is in units of 10^{12} G.

the inclusion of magnetic dipole radiation. The spin-up/spin-down torque proposed by Menou et al. (1999),

$$\dot{J} = 2\dot{M}_d r_m^2 \Omega_{\rm K}(r_m)[1 - \Omega/\Omega_{\rm K}(r_m)], \tag{4}$$

is applied for the action of the fossil disk in the model, where $\Omega = 2\pi/P$ and $\Omega_{\rm K}(r_m)$ is the Keplerian angular velocity at the magnetospheric boundary.

One may compute the accretion rate, $\dot{m}$, as well as the spin evolution, $P(t)$. The total disk mass could be $m = \int_0^\infty \dot{m}\, dt$. It is worth noting that the disk mass obtained in this way could be much larger than that in the MESD case because of the inclusion of the high accretion in the initial period.

We think that the accretion rate characterized by equation (3) is, in a sense, average. The period derivative, $\dot{P}$, may be affected by dynamical instabilities or some stochastic processes, whereas the period, P, is of the integration over a very long time. We therefore calculate $P(T_{\rm SNR})$ for any disk mass, m, and polar magnetic field, B_{12}, of neutron stars. For 1E 1207.4−5209, the calculated contour of the relative error of the period, $|P(T_{\rm SNR}) - P|/P$ ($P = 0.424$ s for 1E 1207.4-5209), is shown in Figure 1. A reasonable parameter set (disk mass m and polar magnetic field B_{12}) is chosen if the following criteria are met: (1) the relative error of the period is smaller; (2) $m < 0.1$; and (3) $B_{12,\,\rm cyc} < B_{12} < B_{12,\,d}$ (Table 1). We then have $m = 0.054$ and $B_{12} = 3.55$. The parameter sets for other sources can also be obtained in this way, and these are listed in Figure 2 (except for PSR J1811−1925). The period evolution curves, with these parameters, are drawn in Figure 2. Note that these curves do not change significantly if the parameter sets shift in a reasonable manner.

The heights, h, of cyclotron resonant scattering regions can be obtained based on the differences of the parametric magnetic field, B_{12}, and the field inferred from absorption features, $B_{12,\,\rm cyc}$. It is found that $h \sim 29$ km and ~8.8–15 km for 1E 1207.4−5209 and 1E 2259+586, respectively, in the model.

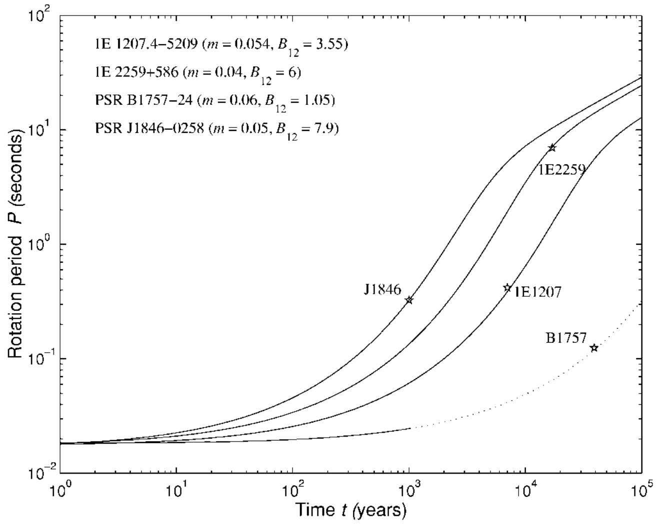

FIG. 2.—Period evolution in a model with self-similar accretion for the four pulsars labeled. The parameter sets used to calculate the curves are also listed. The solid curves (and the solid part of the curve of PSR B1757−24) indicate that the accretion torque works (i.e., the magnetospheric radius is smaller than that of light cylinder, $r_m < r_L$), while the dotted part of the curve of PSR B1757−24 means that the pulsar and the fossil disk could evolve independently (i.e., $r_m > r_L$).

Whether the disk will influence the spin-down of the neutron star or suppress the radio emission will depend on the location of r_m relative to the light-cylinder radius, r_L, and the corotation radius, r_c (Chatterjee et al. 2000). Magnetic dipole radiation dominates, and the disk and the star will effectively evolve independently if $r_m > r_L$; but in other cases, accretion onto the star will lead to accretion-induced X-ray emission that is radio-quiet. We see from Figure 2 that the condition of $r_m > r_L$ is satisfied only for PSR B1757−24 when it is older than ~10^3 yr. We are therefore not surprised that PSR B1757−24 is now radio-loud, whereas the others (1E 1207.4−5209, 1E 2259+586, and PSR J1846−0258) are radio-quiet. The AXP 1E 2259+586 is in a tracking phase, and we expect that the other two (1E 1207.4−5209 and PSR J1846−0258) will evolve to be AXPs when they are in tracking phases as well.

PSR J1811−1925 is an interesting exception among the five sources; its age is certain if it has a physical association with the remnant of a supernova recorded in A.D. 386. In its calculated contour, we can only choose $\{B_{12} = 2.6, m = 0.1\}$ or $\{B_{12} = 1.6, m = 2.2\}$; both parameter sets are not reasonable (i.e., they cannot meet the above three criteria). This may imply that the accretion of PSR J1811−1925 is not self-similar. Recalling that the low limit of polar field is only 1.6×10^{11} G if in the MESD case, we could suggest that PSR J1811−1925 has a field within (1.6–17) $\times\ 10^{11}$ G, with an accretion stronger than that of equation (3) but weaker than that in the MESD case. This result hints that PSR J1811−1925 is radio-quiet (Crawford et al. 1998). In addition, the parametric field, $B_{12} = 3.55$, chosen for 1E 1207.4−5209, which is close to $B_{12,\,d} = 3.6$, would also indicate that the real accretion is not described by equation (3). In fact, the accretion of equation (3) is for the capture of material by black holes where the magnetic field is not important, which could differ from that for neutron stars with strong fields.

5. CONCLUSIONS AND DISCUSSIONS

The possibility of solving the age discrepancy by an accretion-assisted torque is discussed. We find the following: (1) 1E 1207.4−5209 is not a neutron star, but rather a low-mass bare strange star, if the cyclotron resonant region is near the polar cap with a magnetic field of 6×10^{10} G, whereas it could be a conventional neutron star if the cyclotron lines form at a height of 16–40 km. An identification of a smaller radius or a low-altitude cyclotron formation favors a low-mass bare strange star model for 1E 1207.4−5209. (2) Among the five sources with age problems, the magnetic dipole radiation dominates the evolution of PSR B1757−24 at present, and the others are in propeller (or tracking) phases. (3) The real accretion around these sources may differ from a self-similar one (eq. [3]), at least for PSR J1811−1925. (4) By a calculation with self-similar accretion, it is suggested that PSR J1846−0258 and 1E 1207.4−5209 (and probably PSR J1811−1925) would evolve to be AXPs in the future.

The debris disks formed following supernova explosions are also currently being studied as a way of interpreting other astrophysical phenomena, e.g., AXPs and soft γ-ray repeaters. Factually, these disks around the sources could be bright in a wide spectral range. Recent discoveries of possible optical and near-infrared emission from a few AXPs may hint at such kinds of fallback accretion disks (1E 2259+586: Hulleman et al. 2001; 1RXS J170849−400910: Israel et al. 2003; 1E 1048.1−5937: Wang & Chakrabarty 2002). Although a comparison of optical and near-infrared observations with theoretical predictions of spectra of disks around neutron stars (Perna, Hernquist, & Narayan 2000) has helped to rule out the presence of disks in some cases, more detailed studies in this area are still necessary and may be an effective way to test the fossil-disk model for young neutron stars.

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