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WHERE MAY ULTRAFAST ROTATING NEUTRON STARS BE HIDDEN?

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ABSTRACT

The existence of ultrafast rotating neutron stars (spin period $P \lesssim 1$ ms) is expected on the basis of current models for the secular evolution of interacting binaries, although they have not been detected yet. Their formation depends on the quantity of matter accreted by the neutron star which, in turn, is limited by the mechanism of mass ejection from the binary. An efficient mass ejection can avoid the formation of ultrafast pulsars or their accretion-induced collapse to a black hole. We propose that significant reductions of the mass transfer rate may cause the switch-on of a radio pulsar phase, whose radiation pressure may be capable of ejecting out of the system most of the matter transferred by the companion. This can prevent, *for long orbital periods and if a sufficiently fast spin has been reached*, any further accretion, even if the original transfer rate is restored, thus limiting the minimum spin period attainable by the neutron star. We show that close systems (orbital periods $P_{\rm orb} \sim 1$ hr) are the only possible hosts for ultrafast spinning neutron stars. This could explain why ultrafast radio pulsars have not been detected so far, as the detection of pulsars with very short spin periods in close systems is hampered, in current radio surveys, by strong Doppler modulation and computational limitations.

Subject headings: accretion, accretion disks — binaries: general — pulsars: general — stars: neutron — X-rays: general — X-rays: stars

1. INTRODUCTION

The shortest spin period ever observed for a rotating neutron star (NS), $P_{\rm min} = 1.56$ ms (Backer et al. 1982), is not a physical limit for the stability of spun-up NSs. In fact, the period $P_{\rm min}$ is longer than the limiting period, $P_{\rm lim}$, below which the star becomes unstable to mass shedding at its equator. Cook, Shapiro, & Teukolsky (1994) have shown that $P_{\rm lim} \sim 0.5$ ms for most equations of state (EOSs) adopted to describe the ultradense nuclear matter.

The reacceleration of an NS to ultrashort periods depends remarkably on the amount of mass (and hence of angular momentum) accreted. Typically $M_{1\,\rm ms} \sim 0.35\ M_\odot$ must be accreted to reach $P \sim 1$ ms (e.g., Burderi et al. 1999). Most donor stars in systems hosting recycled millisecond radio pulsars (MSPs) have certainly lost, during their interacting binary evolution, a mass greater than approximately $M_{1\,\rm ms}$. They now appear as white dwarfs of mass ∼0.15–0.30 $M_\odot$ (e.g., Taam, King, & Ritter 2000), whose progenitors are likely to have been stars of ∼1.0–2.0 $M_\odot$ (Webbink, Rappaport, & Savonije 1983; Burderi, King, & Wynn 1996; Tauris & Savonije 1999). Examples of possible evolutionary sequences, in which the assumption of *conservative* mass transfer is plausible, are computed in § 2. Hence, in order to explain the lack of ultrafast rotations, we have to find physical mechanisms able to prevent the accretion of a considerable fraction of the mass lost by the companion ($M_{\rm lost} = 0.8$–$1.7\ M_\odot$) onto the NS.

In this Letter, we propose a mass ejection mechanism based on the sweeping effects of the energy outflow from a rapidly spinning NS undergoing a radio pulsar phase. The sweeping effects of the energy outflow from a rapidly spinning NS have been firmly established since the early works of Shvartsman (1970) and Illarionov & Sunyaev (1975). Ruderman, Shaham, & Tavani (1989) and Shaham & Tavani (1991) discussed in particular the case of recycled pulsars in low-mass binary systems. As soon as the accreting plasma moves out beyond the light cylinder radius (where an object corotating with the NS attains the speed of light, $R_{\rm LC} = cP/2\pi$), the NS becomes generator of magnetodipole radiation and relativistic particles, whose pressure may expel the matter overflowing the Roche lobe (see also Campana et al. 1998). In the following, we determine the dependence of this mass ejection mechanism on the parameters of the system (§ 3) and show that it naturally provides both an explanation for the values of the mass and rotation of the observed MSPs (Thorsett & Chakrabarty 1999; Tauris & Savonije 1999) and an indication about where ultrafast spinning NSs could reside (§ 4), suggesting in turn why they could have been elusive up to now.

2. ACCRETION AND EJECTION DURING MASS TRANSFER

It is well known that an upper limit to the accretion rate is given by the Eddington limit. However, for typical initial masses $\lesssim 1.6\ M_\odot$ and initial orbital periods $P_{\rm orb} \lesssim 10$ days, the donor transfers mass at *sub*-Eddington rates, in principle making all $M_{\rm lost}$ available for the recycling of the NS. We explored the conservative mass transfer scenario computing the system evolution (with initial and final parameters listed in Table 1) with the ATON1.2 code (D'Antona, Mazzitelli, & Ritter 1989). The mass-loss rate is computed following the formulation by Ritter (1988), as an exponential function of the distance of the stellar radius to the Roche lobe, in units of the pressure scale height. This method also allows us to compute the first phases of mass transfer, during which the rate reaches values that can be much larger than the stationary values due to the thermal response of the star to mass loss. For systems having a mass donor of 1.2 $M_\odot$, we assumed either that the donor fills the

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TABLE 1
MASS EVOLUTION IN LOW-MASS BINARIES

System Type	Parameters	M_{NS} ($M_\odot$)	M_{donor} ($M_\odot$)	P_{orb} (hr)
1	Initial	1.40	1.20	10.46
	Final	2.58	0.02	1.42
2	Initial	1.40	1.20	30.55
	Final	2.35	0.25	338.1
3	Initial	1.40	1.40	33.95
	Final	2.54	0.26	483.8
4	Initial	1.40	1.60	34.00
	Final	2.67	0.33	346.0

Roche lobe while it is evolving toward the red giant branch (case B) or during the core hydrogen-burning phase (case A). Results are shown in Table 1.

In cases 2, 3, and 4, mass transfer is guided by the thermal and nuclear evolution of the secondary; in case 1 it is guided by magnetic braking. The latter evolution is expected to stop at $P_{orb} \simeq 2.5$ hr, when the star becomes fully convective. It may resume at a shorter period guided by gravitational wave loss of angular momentum, like in the cataclysmic binary systems, reaching a minimum period of ∼1.03 hr. For sequences 2, 3, and 4, the final period is in the range 90–150 hr; the final mass of the donor is in the range 0.21–0.33 $M_\odot$ (see Table 1), in agreement with the masses of the companion stars of MSPs, as inferred from accurate timing measures (e.g., Burderi, King, & Wynn 1998c). On the other hand, the assumption of conservative mass transfer leads to final NS masses in the range 2.3–2.7 $M_\odot$, much larger than the inferred masses of the NSs in these systems and dangerously close to (or even larger than) the maximum mass allowed for an NS in most of the proposed EOSs (Cook, Shapiro, & Teukolsky 1994). This suggests that either the mass transfer cannot be conservative or that the final NS must be very massive, implying that accretion-induced collapse to a black hole is a likely outcome for low-mass X-ray binaries (LMXBs). Indeed, the masses of a sample of radio pulsars in binary systems were estimated by Thorsett & Chakrabarty (1999). These are consistent with a remarkably narrow Gaussian distribution, with $M_{NS} = 1.35 \pm 0.04\ M_\odot$, although the sample is contaminated by five relativistic NS-NS binary systems, the progenitors of which are massive X-ray binaries. If the proposed value of the amount of mass accreted, less than 0.1 $M_\odot$, is representative of the MSP observed sample, this suggests that significant mass losses occur during the Roche lobe overflow phase.

A propeller effect (Illarionov & Sunyaev 1975) has been often invoked to explain this discrepancy. In the widely accepted scenario of accretion onto a magnetized NS (see, e.g., Hayakawa 1985 for a review) the accretion disk is truncated at the magnetospheric radius R_m, at which the magnetic field pressure equals the pressure of the matter in the disk. The value of R_m for a Shakura-Sunyaev accretion disk (e.g., Burderi et al. 1998a) is, in a first approximation, close to ∼0.5 times the Alfvén radius R_A: $R_m \simeq 0.5 R_A = 1.1 \times 10^6 \mu_{26}^{4/7} R_6^{-2/7} L_{37}^{-2/7} m^{1/7}$ cm, where L_{37} is the accretion luminosity in units of 10^{37} ergs s^{-1}, m is the NS mass in solar masses, R_6 is the NS radius in units of 10^6 cm, and μ_{26} is the magnetic moment of the NS in units of 10^{26} G cm^3 ($\mu = B_s R^3$, with R and B_s the NS radius and surface magnetic field along the magnetic axis, respectively). Accretion onto a spinning magnetized NS is centrifugally inhibited once R_m lies outside the corotation radius R_{co}, the radius at which the Keplerian angular frequency of the orbiting matter is equal to the NS spin: $R_{co} = 1.50 \times 10^6 m^{1/3} P_{-3}^{2/3}$ cm, where P_{-3} is the spin period in milliseconds. In this case, a significant fraction of the accreting matter could, in principle, be ejected from the system: this is called the propeller phase.

The virial theorem sets stringent limits on the fraction of matter that can be ejected in this phase. In fact, it states that, at any radius in the disk, the virialized matter has already liberated (via electromagnetic radiation) half of its available energy. Considering that $R_m \sim R_{NS}$ for MSPs, the matter at the magnetosphere has radiated ∼50% of the whole specific energy, $E_{acc} = GM/R_{NS}$, obtainable from accretion. To eject the same matter (close to the NS surface), $\sim\frac{1}{2}E_{acc}$ must be given back to it. As the only source of energy is that stored in the NS by the accretion process itself, the typical ejection efficiency is ∼50%. Actually, with a fine-tuned alternation of accretion and propeller phases of the right duration, the ejection efficiency can be higher than 50%, although a difficulty with this scenario is that, once the system has reached the spin equilibrium, no further spin-up takes place and the storage of accretion energy in a form that allows its subsequent reusage for ejection is impossible. Thus, the accreted mass is about half of the transferred mass, i.e., $\simeq 0.4$–$0.8\ M_\odot$. This has two main consequences: (1) even taking a propeller phase into account, NSs in MSPs will either be very massive or even collapse into black holes, and (2) as the amount of mass accreted is considerably larger than the minimum required to spin up the NSs to ultrashort periods, one has to invoke an ad hoc final, long-lasting propeller phase with a highly effective spin-down to form the observed population of moderately fast spinning MSPs.

An alternative viable hypothesis to explain the lack of ultrafast rotating NSs is that gravitational wave emission balances the torque due to accretion (see a review in Ushomirsky, Bildsten, & Cutler 2000). However, while these emission mechanisms, whose importance in LMXBs will be probably clarified in the near future by detectors such as LIGO II, might explain the observed spin periods of spun-up NSs, which seem to cluster between 260 and 590 Hz (see, e.g., van der Klis 2000), they cannot solve the problem of the large final masses of NSs.

The only way to overcome these difficulties is to obtain ejection efficiencies close to unity. This is indeed possible if the matter is ejected so far away from the NS surface that it has an almost negligible binding energy $GM/r \ll E_{acc}$. As the NS is spinning very fast, the switch-on of a radio pulsar is unavoidable once $R_m \geq R_{LC}$. The pressure exerted by the radiation field of the radio pulsar may overcome the pressure of the accretion disk, thus determining the ejection of matter from the system. Once the disk has been swept away, the radiation pressure stops the infalling matter as it overflows the inner Lagrangian point, where $E_{acc} \sim 0$.

3. THE EFFECT OF THE PULSAR ENERGY OUTFLOW

The push on the accretion flow exerted by the (assumed dipolar) magnetic field of the NS can be described in terms of an outward pressure (we use the expressions *outward* or *inward pressures* to indicate the direction of the force with respect to the radial direction): $P_{mag} = B^2/4\pi = 7.96 \times 10^{14} \mu_{26}^2 r_6^{-6}$ dyn cm^{-2}, where r_6 is the distance from the NS center in units of 10^6 cm. If the disk terminates outside R_{LC}, the outward pressure is the radiation pressure of the rotating magnetic dipole, which, assuming isotropic emission, is $P_{PSR} = 2.04 \times 10^{12} P_{-3}^{-4} \mu_{26}^2 r_6^{-2}$ dyn cm^{-2}. In Figure 1, the two outward pressures (P_{mag} and P_{PSR}) are shown as thick lines for typical values of the parameters (see figure caption).

The flow, in turn, exerts an inward pressure on the field. For a Shakura-Sunyaev accretion disk (see, e.g., Frank, King, & Raine 1992): $P_{disk} = 1.02 \times 10^{16} \alpha^{-9/10} n_{0.615}^{-1} L_{37}^{17/20} m^{1/40} R_6^{17/20}\ \times$

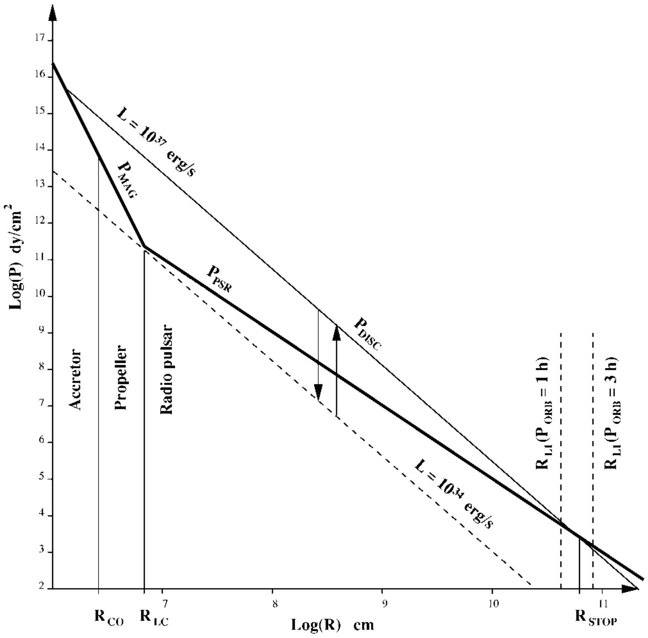

FIG. 1.—Radial dependence of the pressures relevant for the evolution of accreting NSs and recycled pulsars. The parameters adopted are $\mu_{26} = 5$, $P_{-3} = 1.5$, $\alpha = 1$, $n_{0.615} = 1$, $R_6 = 1$, $m = 1.4$, and $f = 1$.

$f^{17/5} r_6^{-21/8}$ dyn cm^{-2}, where α is the Shakura-Sunyaev viscosity parameter, $n_{0.615} = n/0.615 \sim 1$ for a gas with solar abundances (where n is the mean particle mass in units of the proton mass), and $f = [1 - (R_6/r_6)^{1/2}]^{1/4} \leq 1$. As before, we measure $\dot{M}$ in units of L_{37}, supposing that all the matter reaches the NS surface. Note that this equation is valid in zone C of the disk, that is, at radii larger than 3.45×10^7 cm for a luminosity of 10^{37} ergs s^{-1} (Burderi, King, & Szuszkiewicz 1998b). In Figure 1, the inward disk pressure for a luminosity $L_{\max}$, corresponding to a high accretion rate, is shown as a thin solid line. The disk pressure line, which intersects $P_{\rm mag}$ at $R_{\rm LC}$, defines a critical mass transfer rate $\dot{M}_{\rm switch}$ (i.e., a critical luminosity $L_{\rm switch}$, shown as a dashed line in Fig. 1) at which the radio pulsar switches on.

The intersections of the $P_{\rm disk}$ line corresponding to $L_{\max}$ with each of the outward pressure lines define equilibrium points between the inward and outward pressures. The equilibrium is *stable* at $r = R_m$ and *unstable* at $r = R_{\rm stop}$, which can be derived equating $P_{\rm PSR}$ and $P_{\rm disk}$:

$$R_{\rm stop} \sim 8 \times 10^{11} \alpha^{-36/25} n_{0.615}^{-8/5} R_6^{34/25} \times f^{136/25} L_{37}^{34/25} m^{1/25} \mu_{26}^{-16/5} P_{-3}^{32/5} \text{ cm}. \tag{1}$$

In fact, as $P_{\rm mag}$ is steeper than $P_{\rm disk}$, if a small fluctuation forces the inner rim of the disk inward (outward), in a region where the magnetic pressure is greater (smaller) than the disk pressure, this results in a net force that pushes the disk back to its original location R_m. As $P_{\rm PSR}$ is flatter than $P_{\rm disk}$, with the same argument is easy to see that no stable equilibrium is possible at $R_{\rm stop}$ and the disk is swept away by the radiation pressure. This means that, for $r > R_{\rm stop}$, no disk can exist for any luminosity less than approximately $L_{\max}$.

It is convenient to divide the systems into "compact" and "wide," depending on whether the primary Roche lobe radius ($R_{\rm L1}$) lies inward or outward from $R_{\rm stop}$, as they behave very differently in response to significant variations of the mass transfer rate. The dependence of $R_{\rm L1}$ on the orbital parameters is given by

$$R_{\rm L1} = 3.5 \times 10^{10} P_h^{2/3} (m + m_2)^{1/3} \times \left[1 - 0.462 \left(\frac{m_2}{m + m_2}\right)^{1/3}\right] \text{ cm}$$

using the approximation given by Paczyński (1971), where P_h is the orbital period in hours and m, m_2 are the NS and the companion masses in solar masses, respectively. Therefore, the $P_{\rm orb}$ that separates compact and wide systems can be obtained by imposing $R_{\rm stop}/R_{\rm L1} = 1$ and solving for $P_{\rm orb}$:

$$P_{\rm crit} = 1.05 (\alpha^{-36} n_{0.615}^{-40} R_6^{34})^{3/50} L_{36}^{51/25} m^{1/10} \mu_{26}^{-24/5} P_{-3}^{48/5} \times \left[1 - 0.462 \left(\frac{m_2}{m + m_2}\right)^{1/3}\right]^{-3/2} (m + m_2)^{-1/2} \text{ hr}, \tag{2}$$

where L_{36} is $L_{\max}$ in units of 10^{36} ergs s^{-1}. (In the following, always keep in mind that the separation between compact and wide systems depends on $P_{-3}^{48/5}$ and has no "absolute" meaning).

When the luminosity alternates between its maximum value $L_{\max}$ and a minimum luminosity $L_{\min} < L_{\rm switch}$, the behavior of a compact system is cyclic. During the high state, the magnetospheric radius is smaller than both the corotation and the light cylinder radius and the NS will normally accrete matter and angular momentum, thus increasing its spin (accretion phase). The sudden drop in the mass transfer rate to $L_{\min}$ initiates a phase, which we termed "radio ejection," in which the mechanism that drives *mass overflow* through L1 is still active, while the pulsar radiation pressure prevents mass accretion. As the matter released from the companion cannot accrete, it is now ejected as soon as it enters the Roche lobe of the primary. When the system goes back to the high state, the disk might form again and the accretion can resume.

The response of a wide system to the same variations of the accretion rate is quite different. When the mass transfer rate recovers the value corresponding to the high state, the cyclic behavior is lost. Indeed, since in this case $R_{\rm L1}$ is located beyond $R_{\rm stop}$, $P_{\rm disk} < P_{\rm PSR}$ at $R_{\rm L1}$ even in the high state and the accretion cannot resume. This means that for a wide system, once a drop of the mass transfer rate has started the radio ejection, a subsequent restoration of the original mass transfer rate is unable to quench the ejection process (as already pointed out by Ruderman et al. 1989).

In conclusion, while the evolution without a radio ejection phase implies that a large fraction of the transferred mass is accreted onto the NS (because of the constraints imposed by the virial theorem), we have demonstrated that the switch-on of a radio pulsar (associated to a significant drop in mass transfer) could determine ejection efficiencies close to 100%, as the matter is ejected before it falls into the deep gravitational potential well of the primary. For compact systems, we have shown that radio ejection is swiftly quenched by a resumption of the original mass transfer rate, leading to the prediction that the amount of mass accreted is substantial. On the other hand, if a radio ejection starts in a wide system, this implies that the accretion is inhibited in the subsequent evolution.

4. WHERE TO SEARCH FOR ULTRAFAST SPINNING NSs

A statistical analysis based on the current samples of detected MSPs (Cordes & Chernoff 1997) proved that, using different hypotheses for the period distributions of these sources, there is always a nonnegligible probability for periods $P < P_{\rm min}$. Possenti et al. (1998, 1999) performed population synthesis calculations including propeller and randomly choosing the mass accreted onto the NS in the interval 0.01–0.4 $M_\odot$ (this corresponds to efficiency of ejection between 60% and 99%). They confirmed that the process of recycling in low-mass binaries can produce a significant amount of ultrarapidly rotating objects, under different assumptions for the evolution of the mass transfer and the magnetic field. However, despite the large efforts devoted in the last years (D'Amico 2000; Crawford, Kaspi, & Bell 2000; Edwards, van Straten, & Bailes 2001), no pulsar with $P < P_{\rm min}$ has been observed so far.

The more rapid the NS spins, the smaller is the drop of $\dot{M}$ needed to switch the pulsar on and expel the accretion disk (see § 3). Once this occurs, a new phase of accretion is possible only if the orbital period is short enough. Equation (2) predicts that spinning an NS up to $P \lesssim 1$ ms requires very close ($P_{\rm orb} \lesssim 1.5$ hr) binary systems.

The orbital Doppler shift on the pulsar signal can provide a natural observational bias against the detection of ultrarapidly spinning pulsars. All the codes for searching for pulsations from a source in a close binary system are a compromise between computational capability and sensitivity: on each data set, they must perform a two-dimensional search in the space of the unknown parameters' dispersion measure (DM; related to the distance of the object) and acceleration (resulting from binary motion). Short data sets reduce the Doppler period shifts during the observation and relax the computational requests, but at the price of limiting the sensitivity (see, e.g., Camilo et al. 2000). As a consequence, up to now orbital periods shorter than ∼90 minutes have been poorly searched, even in the more favorable case of targeted searches (as those pointing to globular clusters), where one of the two parameters (DM) is known. This observational bias could be enhanced in the presence of eclipses (favored in very close binary pulsar systems; Nice, Arzoumanian, & Thorsett 2000) or in case of a large duty cycle of the pulsar signal, a low radio luminosity, and a strong interstellar scintillation, already suggested for the elusiveness of ultrafast rotating pulsars (Possenti 2000, p. 159).

Even in the favorable case $P_{\rm orb} < P_{\rm crit}$, a steady accretion during all the Roche lobe overflow phase (i.e., no ejection episodes) could prevent the formation of an ultrafast-spinning NS; in fact, if the EOS is soft, the NS could undergo a collapse to a black hole. Actually, Cook et al. (1994) showed that (because of the centrifugal pull determined by the rapid NS rotation) an NS can accrete matter even beyond the limit at which the black hole collapse takes place. However, when the accretion halts and the fast-spinning NS loses rotational energy via magnetodipole emission, a radial instability can set in, leading to the formation of a black hole (see Stella & Vietri 1999).

In summary, we have shown the following: (1) For very fast rotating NSs, if variabilities in the matter flow trigger an extended radio pulsar phase, accretion onto an NS cannot recover unless also the orbital period is quite short. Thus, extremely compact binary systems are strongly favored for harboring ultrafast rotating pulsars. (2) If the EOS for the nuclear matter is soft enough, binary evolution with a steady accretion rate would often lead to black hole formation via accretion-induced collapse.

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