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PHASE TRANSITION AND SPIN CLUSTERING OF NEUTRON STARS IN X-RAY BINARIES

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ABSTRACT

The spins of X-ray neutron star accretors in low-mass binaries are found to cluster at about 300 Hz with the exception of a few higher frequency objects. We find that a postulated phase transition induced by the centrifugally driven dilution in the density profile of the star can produce a similar feature. It takes from 10^7 to 10^9 yr, depending on the mass accretion rate, to expel the high-density phase from the core. The corresponding *growth* in the moment of inertia retards spin-up during this epoch. Normal mass accretion–driven spin-up resumes at its completion. A phase change triggered by the changing spin and the accompanying evolution of the moment of inertia has its analog in rotating nuclei as was discovered in the 1970s.

Subject headings: accretion, accretion disks — binaries: close — dense matter — stars: neutron — stars: rotation — X-rays: stars

1. INTRODUCTION

Many observations taken over the last several years with the *Rossi X-Ray Timing Explorer* (*RXTE*) seem to suggest that most neutron stars that are being spun up by accretion from low-mass X-ray binaries (LMXBs) are clustered in a small spin-frequency band, with several stars having higher frequency, close to the fastest millisecond (ms) pulsars (see the review of van der Klis 2000 and Fig. 1 of this Letter). Several suggestions as to the cause of the clustering have been advanced. In one scenario, a small quadrupole distortion provided by a thermally induced density asymmetry creates gravitational waves whose torque balances that applied by accreting matter at the observed critical frequencies (Bildsten 1998; Ushomirsky, Cutler, & Bildsten 2000). Alternately, Rossby waves may be excited in the crust of the neutron star; this excitation triggers a thermal runaway of the *r*-mode, reducing the spin below the excitation frequency, at which time accretion may again spin up the star. This cycle may be repeated several times before the donor star is consumed (Anderson et al. 2000).

We propose yet another mechanism—a natural extension of our earlier work—that could *temporarily* stall spin-up, and therefore lead to a frequency clustering in the population, while allowing a subsequent evolution to the ms pulsar stage (Glendenning, Pei, & Weber 1997; Glendenning & Weber 2000). The mechanism is a phase transition in the core of the star between an interior high-density phase and the surrounding normal nuclear-matter phase. The radial location of the phase boundary is propelled inward as the density profile of the star falls because of the growth of the centrifugal force during spin-up. The moment of inertia grows as the relatively incompressible nuclear-matter phase replaces the compressible high-density phase and acts as a governor, resisting accretion-driven spin-up during the phase transition epoch. This epoch is calculated to last for 10^7–10^9 yr, depending on the accretion rate. Thus, the above process will cause a clustering of neutron star accretors in the frequency range that corresponds to the spinout of the high-density phase. When the high-density phase is entirely expelled from the stellar core, normal accretion-driven spin-up resumes until the donor star is consumed or conditions otherwise alter to halt accretion. The distribution in spin of X-ray neutron stars in LMXBs should therefore appear as a peak above a rather smooth distribution up to the short millisecond spins of very fast pulsars.

2. ROBUSTNESS

The inverse of the above mechanism for the response of a complex object to changes in spin actually occurs in another physical system—a rotating deformed nucleus. In this case, the phase transition is from a nucleon spin-aligned phase at high spin (at which the Coriolis force quenches the Cooper pairing of nucleon spins) to a spin-paired phase at slow rotation. Such a phenomenon, referred to as backbending (because of the behavior of the moment of inertia with spin; see Fig. 2), was predicted by Mottelson & Valatin (1960) and discovered in the 1970s (Johnson, Ryde, & Hjorth 1972; Stephens & Simon 1972). The analog of backbending in certain rotating deformed nuclei that are radiating angular momentum can possibly occur in isolated ms pulsars that are spinning down because of magnetic dipole radiation (Glendenning et al. 1997). It is interesting that a similar response to a phase transition in spinning objects at extremes of size and baryon number—in the one case in a quantal system, in the other classical—may and theoretically can occur.

Because of the occurrence in another physical system of the inverse of the mechanism that we describe here for stars, the physics is robust. That does not mean that the clustering that we predict in our scenario occurs for a broad range of parameters describing the nuclear, quark, and stellar physics. Rather, it occurs in a restricted space as discussed further in § 7.

3. ASSUMPTIONS

The density in the interior of neutron stars is a few times the nuclear density. At such densities, it is quite plausible, and we *assume* that quarks lose their association with particular hadrons—the more compressible deconfined quark matter phase replaces the normal phase in the core of the star.

Such a quark matter core does not endow the hybrid star itself with any remarkable property aside from reducing the

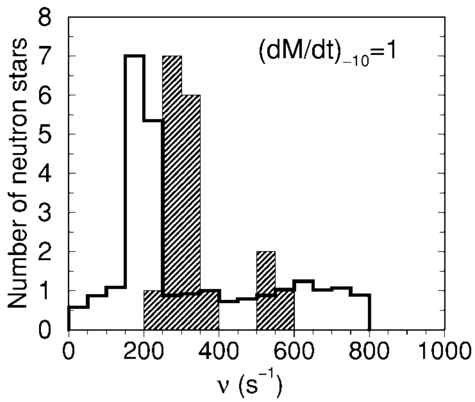

FIG. 1.—Recent data compiled by van der Klis (2000) from the *RXTE* experiments (*shaded histogram*) indicating a clustering in the frequency of the population of neutron stars in LMXBs. The calculated spin distribution is averaged over donor masses of X-ray neutron stars in case of a phase transition (*open histogram*). If there is no phase transition, the calculated distribution is smooth with no peak.

limiting mass, generally to values $\lesssim 1.5\ M_\odot$, which is small compared with models of neutron stars that are made purely of neutrons but which is quite in agreement with observed masses (Thorsett & Chakrabarty 1999). Moreover, there are grounds to believe, and we *assume* that neutron star masses do in fact fall in a very small interval, bounded from below by the Chandrasekhar limit on the iron core mass in the presupernova star and from above by the neutron star mass that is limited by any one of three possible phase transitions: hyperionization, quark deconfinement, and kaon condensation (Glendenning & Moszkowski 1991; Glendenning 1992; Brown & Bethe 1994).

We shall *assume* therefore that canonical pulsars—like the Crab and more slowly rotating ones—have a quark matter core essentially from birth and that neutron stars fall in a narrow mass range.

4. STELLAR MODEL

The theory and parameters used to describe our model neutron star are precisely those used in our previous publication on the effect of a phase transition on the pulse timing of ms pulsars (Glendenning et al. 1997). The initial stellar mass is $M = 1.42\ M_\odot$, close to the nonrotating mass limit. The critical mass at breakup frequency is $1.66\ M_\odot$. The confined hadronic phase is described by a generalization of a relativistic nuclear field theory solved at the mean field level in which members of the baryon octet are coupled to scalar, vector, and vector-isovector mesons (Glendenning 1985, 2000). The parameters (Glendenning & Moszkowski 1991; Glendenning et al. 1997) of the nuclear Lagrangian were chosen so that symmetric nuclear matter has the following properties: a binding energy $B/A = -16.3$ MeV, a saturation density $\rho = 0.153\ \mathrm{fm}^{-3}$, a compression modulus $K = 300$ MeV, a symmetry energy coefficient $a_{\rm sym} = 32.5$ MeV, and a nucleon effective mass at saturation $m^\star_{\rm sat} = 0.7m$. These, together with the ratio of hyperon to nucleon couplings of the three mesons ($x_\sigma = 0.6$, $x_\omega = 0.653 = x_\rho$), yield the correct Λ binding in nuclear matter (Glendenning & Moszkowski 1991).

Quark matter is treated in a version of the MIT bag model with the three light flavor quarks ($m_u = m_d = 0$, $m_s = 150$ MeV) as described in Farhi & Jaffe (1984). A value of the bag constant $B^{1/4} = 180$ MeV is employed, as in Glendenning et al. (1997). The transition between these two phases of a medium with two independent conserved charges (baryon and electric) is described in Glendenning (1992).

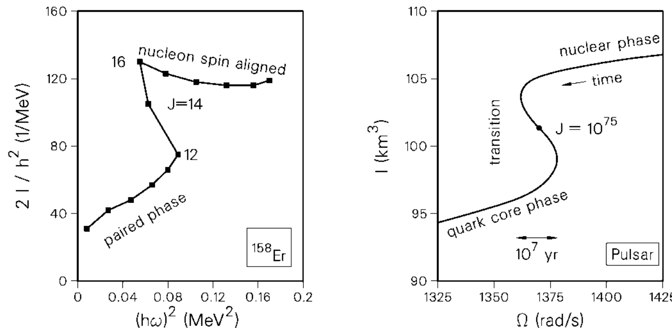

FIG. 2.—Backbending of the moment of inertia in a *deformed rotating* and radiating nucleus and ms pulsar caused by a phase transition. This behavior causes the accretion-induced spin-up in neutron stars to stall for an epoch of 10^7–10^9 yr (adapted from Glendenning et al. 1997 and Glendenning 1998).

5. ACCRETION INDUCED SPIN-UP

The critical density at which the phase transition occurs is solely a property of hadronic matter. That density moves radially through the core of the star, either outward or inward, depending on whether the star is losing angular momentum by radiation or gaining it by accretion. Aside from the small effect of added mass, the formation or expulsion of the quark matter core should occur in the same frequency range for ms pulsars as for accreting neutron stars. We therefore use a simple schematic model of accretion in which the spin-up torque of the accreting matter causes a change in the star's angular momentum J according to the relation (Elsner & Lamb 1977; Ghosh, Lamb, & Pethick 1977; Lipunov 1992)

$$\frac{dJ}{dt} = \dot{M}\sqrt{Mr_m} - \kappa\mu^2 r_c^{-3}$$

($G = c = 1$; $\kappa \sim 0.1$). The first term represents the torque applied by the accreting matter and the second by the magnetic field of the neutron star and the viscosity of matter in the accretion ring. The star's magnetic moment is denoted by $\mu \equiv R^3B$, the corotating radius by $r_c = (M/\Omega^2)^{1/3}$, the inner edge of the accretion ring by $r_m = \xi r_{\rm A}$, ($\xi \sim 1$), and the Alfvén radius at which the magnetic energy density equals the total kinetic energy density of the accreting matter by $r_{\rm A} = [\mu^4/(2M\dot{M}^2)]^{1/7}$.

The above equation can be written as a time evolution equation for the angular velocity Ω of the accreting star:

$$I(t)\frac{d\Omega(t)}{dt} = \dot{M}\sqrt{M(t)r_m(t)} - \Omega(t)\frac{dI(t)}{dt} - \kappa\mu(t)^2 r_c(t)^{-3}.$$

The moment of inertia I of ms pulsars or of neutron star accretors has to be computed in general relativity without making the usual assumption of slow rotation. We use a previously obtained expression for the moment of inertia of a rotating star (Glendenning & Weber 1992). The results for three accretion rates for stars with and without a quark matter core are shown in Figure 3.

The magnetic field B is believed to decay only weakly because of ohmic resistance in canonical pulsars but very significantly while accreting matter from a companion. This era

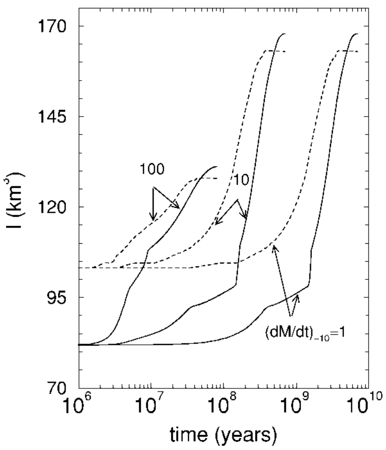

FIG. 3.—Neutron star moments of inertia as a function of time during accretion-driven spin-up for stars with and without quark phase transition (*solid and dashed curves, respectively*). Three accretion rates (in units of 10^{-10} $M_\odot$ yr^{-1}) are illustrated.

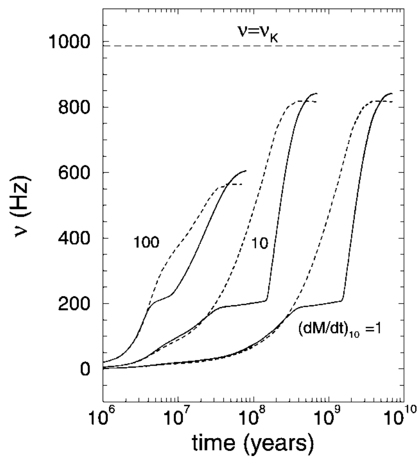

FIG. 4.—Spin of neutron stars as a function of time during the accretion for a star with (*solid curves*) and without (*dotted curves*) quark phase transition. Three accretion rates (in units of 10^{-10} $M_\odot$ yr^{-1}) are illustrated. Note that the plateaus, which cause the peak in spin of the accreting neutron stars, occur at ≈200 Hz for each rate.

can last up to 10^9 yr and cause field decay by several orders of magnitude. For a review of the literature and several evolutionary scenarios, see Konar & Bhattacharya (1999a, 1999b), Urpin & Geppert (1996), Urpin & Konenkov (1997), and Urpin, Geppert, & Konenkov (1998). Although there is no consensus concerning the magnetic field decay, observationally, we know that canonical pulsars have fields of $\sim 10^{11}$–10^{13} G, while ms pulsars have fields that lie in the range of $\sim 10^8$–10^9 G. We shall rely on this observational fact and assume that the field decays according to $B(t) = B(\infty) + [B(0) - B(\infty)]e^{-t/t_d}$ with $t = 0$ at the start of accretion, $B(0) = 10^{12}$ G, $B(\infty) = 10^8$ G, and $t_d = 10^6$ yr. Such a decay to an asymptotic value seems to be a feature of some treatments of the magnetic field evolution (Konar & Bhattacharya 1999a, 1999b). The frequency attained after a few million years of accretion will be independent of the initial value. We take $\nu(0) = 1$ Hz for definiteness. The evolution of spin for two cases, with and without a phase transition, are shown in Figure 4.

6. POPULATION CLUSTERING IN SPIN

The plateau regions evident in the spin evolutions shown in Figure 4 mark the epochs during which the quark phase is being spun out of the stellar core as a consequence of which the moment of inertia increases anomalously. The timing and duration of these epochs depend of course on the mass accretion rate. To illustrate spin clustering, we assume that neutron stars begin their accretion evolution at the rate of one every million years. For one initial accretor mass of 1.42 $M_\odot$, for one accretion rate, and for an average over four donor masses from 0.1 to 0.4 $M_\odot$, the result is shown in Figure 1. The calculated distribution of objects above about 400 Hz is unstable and will actually collapse to black holes, and in doing so it will reach an even much higher spin. Donors of all masses in the range just mentioned contribute to neutron star spins of up to 400 Hz.

Figure 1 is only illustrative of the phenomenon of the anomalous growth or decline of the moment of inertia induced by a change of phase in the spinning object. A complete account of the spin-frequency distribution of neutron star accretors, in particular the peak position and the relative number of stars in the peak as compared with the background, depends on several unknown factors both with regard to the equation of state of dense hadronic matter and with regard to accretion. We need to know (1) the initial mass distribution of accretors, (2) the distribution of accretion rates, and (3) the distribution of donor masses. What is clear is that accretors of lower initial mass (<1.3 $M_\odot$) in orbit with higher mass donors (0.3–0.4) will provide a high-frequency tail. The peak receives its contribution from higher mass accretors (near the mass limit) and lower mass donors. The peak position is not effected by the accretion rate, but its width is. The data are too sparse as yet to permit a deduction with regard to the unknowns enumerated above, although clearly the ratio of objects in the peak compared with the background contains such information.

7. DISCUSSION

Theoretically, a phase transition can (but not necessarily does) cause a distinct clustering in the frequency of X-ray accretors, which is independent of the details of accretion, such as the rate, or the particular description of the accretion mechanism. As emphasized, the position of the peak is an intrinsic property of our model star. But the transition can also occur unheralded by any remarkable signal (Glendenning 1998). Of the three nuclear-matter equations of state that were shown elsewhere to bracket acceptable nuclear-matter and hypernuclear properties (Glendenning & Moszkowski 1991), only one is found here to produce the backbending shown in Figure 2, so that there is specificity with respect to the equation of state. Therefore, if our mechanism can be brought into agreement with the observed spin clustering and is confirmed by observation of the inverse process in an isolated ms pulsar (Glendenning et al. 1997; Glendenning 1998; Heiselberg & Hjorth-Jensen 1998; Chubarian et al. 2000), then we may learn rather precise information about the equation of state of neutron star matter and of the narrowness of the window in which neutron stars exist, quite apart from the discovery of an abnormal high-density phase in slowly rotating neutron stars.

The apparent frequency clustering of X-ray neutron stars is about 100 Hz higher than we calculate. This discrepancy should not be surprising in view of our ignorance of the equation of state above the saturation density of nuclear matter and the necessarily crude representation of hadronic matter in the two phases in the absence of relevant solutions to the fundamental QCD theory of strong interactions. But however crude any model of hadronic matter may be, the physics underlying the effect of a phase transition on spin evolution is robust, as cited in § 2, although not inevitable.

The data in Figure 1 are gathered from Tables 2–4 of the review article by van der Klis (2000) concerning discoveries made with the *RXTE*. The interpretation of millisecond oscillations in the X-ray emission found in bursts or of the difference between twin quasi-periodic oscillations in X-ray brightness is ambiguous in some cases. For example, some of the burst data near 600 Hz may actually represent twice the rotational frequency of the star. For this and other caveats, see the review article by van der Klis (2000).

Nevertheless, the basic feature will probably survive—a clustering of X-ray neutron stars at moderate spin and a high spin tail. Certainly there are high spin *pulsars*. A histogram of ms pulsar frequencies shows a concentration around 200 Hz and a tail extending to ∼600 Hz. So the (sparse) data on X-ray objects and on ms pulsars seem to agree on a peak in the number of stars at moderate spin and on the attenuation at high spin. (For ms pulsars, the attenuation may be partly a selection effect due to the interstellar dispersion of the radio signal.)

8. SUMMARY

We suggest that the apparent clustering in the rotation frequency of accreting X-ray neutron stars in low-mass binaries may be caused by the progressive conversion of quark matter in the core to confined hadronic matter, paced by the slow spin-up due to mass accretion. When conversion is completed, normal accretion-driven spin-up resumes. To distinguish this conjecture from others, one would have to discover the inverse phenomenon—a spin anomaly near the same frequency range in an isolated ms pulsar (Glendenning et al. 1997). If such a discovery were made and the apparent clustering of X-ray accretors is confirmed, we would have some degree of confidence in the hypothesis that a phase of matter such as existed in the very early universe is reformed in a cold state during the birth of neutron stars.

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