Spin Clustering of Accreting X-ray Neutron Stars as Possible Evidence of Quark Matter

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Abstract. A neutron star in binary orbit with a low-mass non-degenerate companion becomes a source of x-rays with millisecond variability when mass accretion spins it up. Centrifugally driven changes in density profile may initiate a phase transition in a growing region of the core parallel to what may take place in an isolated millisecond pulsar, but in reverse. Such a star will spend a longer time in the spin frequency range over which the transition occurs than elsewhere because the change of phase, paced by the spinup rate, is accompanied by a growth in the moment of inertia. The population of accreters will exhibit a clustering in the critical frequency range. A phase change triggered by changing spin and the accompanying adjustment of moment of inertia has its analogue in rotating nuclei.

BACKGROUND

A neutron star, born with a non-degenerate companion, initially spins down because of the drag of the magnetic dipole torque. A wind from the hot surface of the companion disperses the pulsed signal and it is radio silent. Later in the companion's evolution when it overflows the Roche lobe, mass transfer commences to spin up the neutron star. It has begun what is believed to be its evolution from an old star with long period and fairly high magnetic field to a millisecond (ms) pulsar with low field [1, 2, 3, 4]. During the intermediate stage it emits x-rays because the surface and accretion ring are heated to high temperature.

Accreting canonical neutron stars would take only $\sim 10^8$ y at an accretion rate of $\dot{M} = 10^{-9} M_\odot$/y to attain a period of 2 ms (=500 Hz) and any asymmetry in the accretion pattern would cause millisecond variability in x-ray emission as was foreseen many years ago [5, 6]. This expectation has been realized in the last several years in numerous discoveries made with the Rossi X-ray Timing Explorer (RXTE). (See van der Klis for a critical review and discussion [7].) One of the big surprises is that most of the frequencies observed in these objects, generally interpreted as spin frequencies, seem to be clustered in a small band, or spike at ~ 300 Hz.

Several suggestions as to the origin of frequency clustering and much relevant research has been published. 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 [8]. Alternately, Rossby waves may be excited in the crust of the neutron star which trigger 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 [9]. We propose yet another mechanism—a natural extension of our earlier work—that could *temporarily* stall spinup for an epoch of 10^7 to 19^9 y and therefore lead to a frequency clustering in the population, while allowing a further evolution to the ms pulsar stage [10].

ROLE OF QUARK PHASE

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

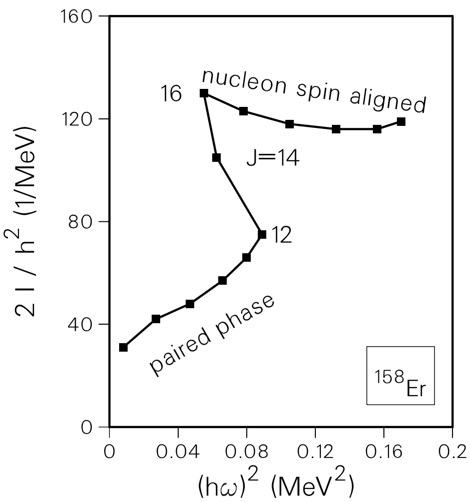


FIGURE 1. Backbending of moment of inertia in a radiating nucleus caused by a phase transition between a spin-aligned and BCS paired state.

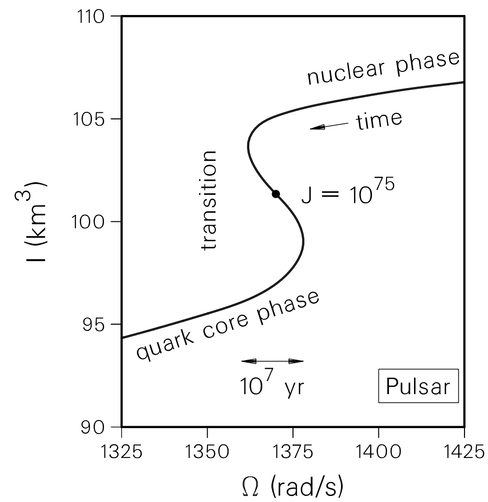


FIGURE 2. Backbending in a model neutron star caused by a phase transition between confined and deconfined matter. Depending on the stellar mass and equation of state, the transition may be less singular.

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 limiting mass, generally to values $\leq 1.5 M_{\odot}$—small compared to models of neutron stars that are made purely of neutrons—but quite in agreement with observed masses [11]. Moreover, there are grounds to believe 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 pre-supernova star, and above by the neutron star mass which is limited by any one of three possible phase transitions, hyperonization, kaon condensation and quark deconfinement [12, 13, 14]. 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.

By comparison, millisecond pulsars are centrifugally flattened in the equatorial plane and the density is diluted in the interior. We shall suppose that the critical phase transition density lies between the diluted density of ms pulsars and the density at the center of canonical pulsars. Then as a ms pulsar spins down, or as a canonical neutron star at some stage begins accreting matter from a companion and is spun up, a change in density distribution paced by the changing centrifugal force will, in some critical frequency range, cause a change of phase of matter in an expanding region of the core. In the case of spindown of an isolated ms pulsar, self-gravity and the weight of the surrounding part of the star will squeeze the more compressible high-density phase that is forming in the interior. Conversely, an accreting neutron star that is being spun up, will, over time, spin out the already present quark phase. In either case, the moment of inertia will progressively alter with the change of phase of matter and therefore the star's spin rate will adjust to conserve angular momentum that is not being carried off by radiation or supplied by accreted matter fast enough. For this reason, a spin anomaly should occur in both types of objects, ms pulsars and x-ray neutron stars in binaries, if it occurs in either. The phase change manifests itself as a temporary governer on spin causing changes in rotational frequency to stall in about the same range in the two types of objects. The population of x-ray accreters should exhibit more objects in the critical frequency range than in neighboring ones. This appears to be the meaning of recent discoveries made with the RXTE [7]. The effect of a phase transition on the population of ms pulsars is less direct since it involves a convolution of our results for x-ray accreters.

Previously, it was found for ms pulsars that the mixed phase in a model star converts to pure quark matter, first at the center and then in an expanding region, paced by the slow loss of angular momentum to radiation [15, 16, 17, 18]. The consequent decrease in the moment of inertia could even introduce an era of *spinup* lasting for $\sim 2 \times 10^7$ years or $\sim 1/50$ of the spindown time [16]. The anomalous spinup of our model star occurred in a small frequency band around 220 Hz [15]. Such a response of the moment of inertia to a change of phase occasioned by changing spin is very like the so-called "backbending" in rotating nuclei caused by coriolis quenching of BCS nucleon spin pairing predicted by Mottelson and Valatin [19] and discovered in the 1970s [20, 21]. (Compare Figs. 1 and 2.)

[b]

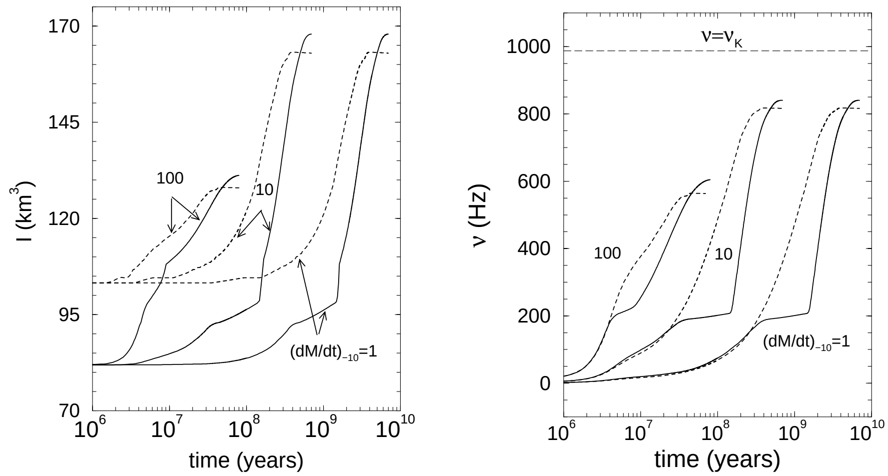


FIGURE 3. Moment of inertia of neutron stars with (solid curves) and without (dashed curves) quark phase transition assuming $0.4M_\odot$ is accreted. Results for three *average* accretion rates are shown.

FIGURE 4. Evolution of spin frequencies of accreting neutron stars with (solid curves) and without (dashed curves) quark deconfinement if $0.4M_\odot$ is accreted. The spin plateau around 200 Hz signals the ongoing process of quark confinement in the stellar centers. Spin equilibrium is eventually reached.

ACCRETION INDUCED SPINUP

It is clear from the foregoing discussion that in our model, the particular details of the accretion process do not determine in what range the spinup stalls for a time. 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 [22, 23, 24]

$$\frac{dJ}{dt} = \dot{M}\sqrt{Mr_{\rm m}} - \kappa\mu^2 r_{\rm c}^{-3} \tag{1}$$

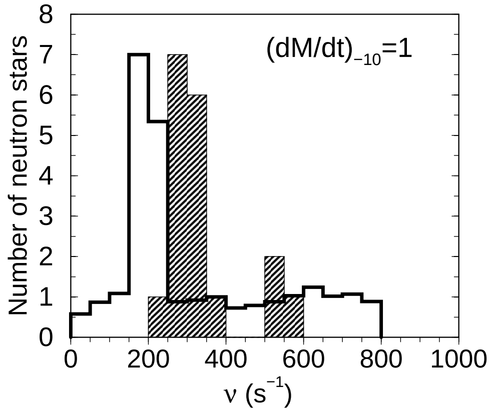
$(G = c = 1)$ $(\kappa \sim 0.1)$. The first term represents the torque applied by the accreting matter and the second by the magnetic field of the neutron star and the viscosity of matter in the accretion ring. The star's magnetic moment is denoted by $\mu \equiv R^3 B$, the co-rotating radius by $r_{\rm c} = (M/\Omega^2)^{1/3}$, the inner edge of the accretion ring by $r_{\rm m} = \xi r_{\rm A}$, $(\xi \sim 1)$ and the Alfén 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;

$$I(t)\frac{d\Omega(t)}{dt} = \dot{M}\sqrt{M(t)r_{\rm m}(t)} - \Omega(t)\frac{dI(t)}{dt} - \kappa\mu(t)^2 r_{\rm c}(t)^{-3}\,. \tag{2}$$

The moment of inertia I of ms pulsars or of neutron star accreters has to be computed in GR without making the usual assumption of slow rotation. We use a previously obtained expression for the moment of inertia of a rotating star [25].

The magnetic field B is believed to decay only weakly due to ohmic resistance in canonical pulsars, but very significantly while accreting matter from a companion. This era can last up to 10^9 y and cause field decay by several orders of magnitude. For a review of the literature and several evolutionary scenarios, see Ref. [26]. Although there is no consensus concerning the magnetic field decay, observationally, we know that canonical pulsars have fields of $\sim 10^{11}$ to $10^{13} G$, while ms pulsars have fields that lie in the range $\sim 10^8$ to $10^9 G$. We shall rely on this observational fact, and assume that the field decays according to $B(t) = B(\infty) + [B(0) - B(\infty)]e^{-t/t_{\rm d}}$ with $t = 0$ at the start of accretion, $B(0) = 10^{12}$ G, $B(\infty) = 10^8$ G, and $t_{\rm d} = 10^6$ yr. Such a decay to an asymptotic value seems to be a feature of some treatments of the magnetic field evolution [26]. The frequency attained after a few million years of accretion will be independent of the initial value. We take $\nu(0) = 1$ Hz.



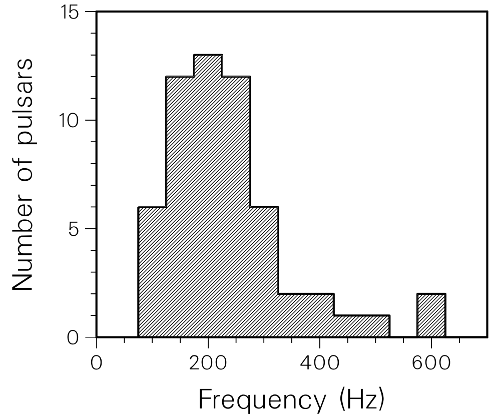


FIGURE 5. Calculated spin distribution of the underlying population of x-ray neutron stars for one accretion rate (open histogram) is normalized to the number of observed objects (18) at the peak. Data on 18 neutron stars in LMXBs (shaded histogram) is from Ref. [7]. The spike in the calculated distribution corresponds to the spinout of the quark matter phase. Otherwise the spike would be absent.

FIGURE 6. Data on the frequency distribution of 60 millisecond pulsars ($1 \leq P < 10$ ms). The frequency bins are 50 Hz wide.

The theory and parameters used to describe our model neutron star are precisely those used in previous publications [15]. Its initial mass is $M = 1.42M_\odot$, close to the mass limit of the rotating star of $1.66M_\odot$. 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 Ref. [27]. A value of the bag constant $B^{1/4} = 180$ MeV is employed, as in [15]. The transition between these two phases of a medium with two independent conserved charges (baryon and electric) is described in Ref. [13].

Figure 3 shows how the moment of inertia changes for a neutron star in a binary system that is spun up by mass accretion according to Eq. (2). In one case we assume that a phase transition between quark matter and confined hadronic matter occurs, and in the other that it does not. This accounts for the different initial moments of inertia, and also, as we see, the response to spinup. Three *average* accretion rates are assumed, $\dot{M}_{-10} = 1$, 10 and 100 (where $\dot{M}_{-10}$ is in units of $10^{-10}M_\odot$/y). The corresponding spin evolution of accreting neutron stars as determined by the changing moment of inertia and the evolution equation (2) is shown in Fig. 4. In both Figs. 3 and 4 we assume that $0.4M_\odot$ is accreted. Otherwise the maximum frequency attained is less.

We compute a frequency distribution of x-ray stars in low-mass binaries (LMXBs) from Fig. 4, for *one* accretion rate, by assuming that neutron stars begin their accretion evolution at the average rate of one per million years. A different rate will only shift some neutron stars from one bin to an adjacent one. The donor masses in the binaries are believed to range between 0.1 and $0.4M_\odot$ and we assume a uniform distribution in this range. The resulting frequency distribution of x-ray neutron stars is shown in Fig. 5; it is striking. Spinout of the quark matter core as the neutron star spins up is signalled by a spike in the distribution which would be absent if there were no phase transition in our model of the neutron star. The position of the spike depends only on the stellar model. But the weight of the spike as compared to the high frequency tail depends sensitively on the weight with which the donor masses are assigned, the initial mass function of the accreting neutron stars (for which we have taken only one mass), and to a minor degree on the accretion rate. A donor of mass $0.1M_\odot$ contributes only to the spike, while all greater masses contribute to the spike and to higher frequency x-ray stars. Objects above about 400 Hz are unstable to collapse to very high-spin black holes. Accretors of lower initial mass than we assume would contribute to the long high-frequency tail as well, possibly, to the spike.

DISCUSSION AND SUMMARY

Theoretically, a phase transition can (but not necessarily does) cause a distinct clustering in frequency of x-ray accreters, which is independent of details of accretion, such as rate, mass accreted so long as it exceeds a small minimum value ($\sim 0.1M_\odot$), or indeed to the particular description of accretion mechanism that we employ. 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 [16].

The apparent frequency clustering of x-ray neutron stars is about 100 Hz higher than calculated. This discrepancy should not be surprising in view of our ignorance of the equation of state above 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 rate is robust, although not inevitable. We have cited an analogous phenomenon discovered in rotating nuclei [19, 20, 21].

The data in Fig. 5 is gathered from Tables 2–4 of the review article of van der Klis concerning discoveries made with the Rossi X-ray Timing Explorer [7]. The interpretation of millisecond oscillations in the x-ray emission, either that 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 [7].

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 $\sim$ 600 Hz as shown in Fig. 6. So both 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 attenuation at high spin. For ms pulsars the attenuation may be partly a selection effect due to interstellar dispersion of the radio signal.

To summarize, we suggest that the apparent clustering in 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 spinup due to mass accretion. When conversion is completed, normal accretion driven spinup resumes. To distinguish this conjecture from others, one would have to discover the inverse phenomenon—a spin anomaly near the same frequency in an isolated ms pulsar [15]. If such a discovery were made, and the apparent clustering of x-ray accreters 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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