Possible evidence of quark matter in neutron star X-ray binaries

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Abstract. We study the spin evolution of X-ray neutron stars in binary systems, which are being spun up by mass transfer from accretion disks. Our investigation reveals that a quark phase transition resulting from the changing central density induced by the changing spin, can lead to a pronounced peak in the frequency distribution of X-ray neutron stars. This finding provides one of several possible explanations available in the literature, or at least a contributor to part of the observed anomalous frequency distribution of neutron stars in low-mass X-ray binaries (LMXBs), which lie in a narrow band centered at about 300 Hz, as found by the Rossi Explorer (RXTE).

Key words: X-ray neutron stars: Frequency anomaly

1. Role of quark phase transition

The density and pressure in the interior of neutron stars is high in comparison with nuclear density by a factor of some 5 to 10 depending on the particular models used to estimate it. At such densities it is quite plausible that the quark constituents of hadrons loose their association with particular hadrons—the deconfined quark matter phase replaces the normal phase. In a nonrotating star, the radial boundaries between quark core, mixed phase, and normal hadronic phase would remain fixed. However in a rotating star, because of the centrifugal distortion of the density in the interior, these boundaries will change as the rotational frequency of the star changes with time.

A structural change occurs in such a star with changes in frequency (Glendenning, Pei & Weber 1997). If there were no change in the nature of matter, the stellar fluid would respond simply under the action of the centrifugal force. However, the compressibility of the normal nuclear matter phase and the deconfined and relatively free Fermi gas of the quark matter phase, are different. The former must be less compressible than the latter. When a ms pulsar spins down, its central density may rise above the critical phase transition density and the central core will then change phase to softer quark matter; it is compressed both by its own gravitational attraction, and by the weight of the overlying nuclear phase. The reverse will be true in spinup due to accretion. In either case, the distribution of mass, radius and moment of inertia are changed by a phase transition beyond those changes that would take place in an immutable fluid under the action of a changing centrifugal force.

These ideas were applied to the spin-down of a ms pulsar (Glendenning, Pei & Weber 1997, Glendenning 1998, Weber 1999). It was found that as the quark matter core grew in radial extent, the moment of inertia decreased anomalously, and could even introduce an era of spin-up lasting for ~10^7 years (Glendenning 1998). The response of the moment of inertia to changes in spin is very like the so-called “backbending” in nuclei predicted by Mottelson and Valatin (Mottelson & Valatin 1960) and discovered many years ago (Johnson, Ryde & Hjorth 1972, Stephens & Simon 1972).

Accreting X-ray neutron stars provide a very interesting contrast to the spin-down of isolated ms pulsars. The X-ray stars are being spun up by the accretion of matter from a low-mass, less-dense white dwarf companion. They are presumably the link between the canonical pulsars with mean period of 0.7 sec and the ms pulsars (Wijnands & van der Klis 1998, Chakrabarty & Morgan 1998).

If the critical deconfinement density falls within the range spanned by canonical pulsars, quark matter will already exist in them but may be “spun” out of X-ray stars as their frequency increases during accretion. We can anticipate that in a certain frequency range, the changing radial extent of the quark matter phase will actually inhibit changes in frequency because of the increase in moment of inertia occasioned by the gradual disappearance of the quark matter phase. Accreters will tend to spend a greater length of time in the critical frequencies than otherwise. There will be an anomalous number of accreters that appear at or near the same frequency. This is what was found recently with the Rossi X-ray Timing Explorer (RXTE) (van der Klis 2000).
Presumably, accretors commence their evolution near the death line of active canonical pulsars with frequencies of $\nu \sim 1$ Hz and end as ms pulsars with $\nu \sim 200$ to 600 Hz. The spinup evolution of an accreting star is a more complicated problem than that of the spindown of an isolated ms pulsar of constant baryon number. It is complicated by the accretion of matter ($M > 10^{-10} M_\odot$ yr$^{-1}$), a changing magnetic field strength (from $B \sim 10^{12}$ to $\sim 10^8$ G), and the interaction of the field with the accretion disk.

2. Spin-evolution of accreting X-ray neutron stars

The change in moment of inertia as a function of rotational frequency caused by accretion of matter is similar to that described by [Ghosh, Lamb & Pethick 1977, Lipunov 1992] for spindown of a ms pulsar because of magnetic dipole radiation. However, there are additional phenomena as just mentioned. Generally, a canonical pulsar will have evolved from birth with moderate rotational frequency to the deathline. At that time, the usual drag of the dipole radiation will be eclipsed by the accretion phenomena. The spin-up torque of the accreting matter causes a change in the star’s angular momentum according to the relation [Elsner & Lamb 1977, Ghosh, Lamb & Pethick 1977, Lipunov 1992]

$$ \frac{d J}{dt} = \dot{M}(r_m) - N(r_c). \tag{1} $$

This can be rewritten as a time evolution equation for the angular velocity $\Omega$ of the accreting star ($\equiv J/I$),

$$ I(t) \frac{d\Omega(t)}{dt} = \dot{M}(t) - \Omega(t) \frac{d I(t)}{dt} - \kappa \mu^2 r_c(t)^{-3}, \tag{2} $$

with the following definitions: The accretion rate is denoted by $\dot{M}$ ($G = c = 1$) and

$$ \bar{l}(r_m) = \sqrt{M r_m} \tag{3} $$

is the angular momentum added to the star per unit mass of accreted matter. The quantity $N$ stands for the magnetic plus viscous torque term ($\kappa \sim 0.1$),

$$ N(r_c) = \kappa \mu^2 r_c^{-3}, \tag{4} $$

with $\mu \equiv R^3 B$ the star’s magnetic moment. The quantities $r_m$ and $r_c$ denote the radius of the inner edge of the accretion disk and the co-rotating radius, respectively, and are given by ($\xi \sim 1$)

$$ r_m = \xi r_A, \tag{5} $$

and

$$ r_c = (M \Omega^{-2})^{1/3}. \tag{6} $$

Accretion will be inhibited by a centrifugal barrier if the neutron star’s magnetosphere rotates faster than the Kepler frequency at the magnetosphere. Hence $r_m < r_c$, otherwise accretion onto the star will cease. The Alfén radius $r_A$, where the magnetic energy density equals the total kinetic energy of the accreting matter, in Eq. (5) is defined by

$$ r_A = \left( \frac{\mu^4}{2 M M^2} \right)^{1/7}. \tag{7} $$

We assume that the magnetic field evolves according to

$$ B(t) = B(\infty) + (B(0) - B(\infty)) e^{-t/t_d} \tag{8} $$

with $t = 0$ at the start of accretion, and where $B(0) = 10^{12}$ 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 1999].

It has previously been assumed that the moment of inertia in Eq. (2) does not respond to changes in the centrifugal force, and in that case, the above formula yields a well-known estimate of the period to which a star can be spun up [Bhattacharya & van den Heuvel 1993]. The approximation is true for slow rotation. However, the response of the star to rotation becomes important as the star is spun up by accretion. Not only do changes in the distribution of matter occur but internal changes in composition occur also because of changes induced in the central density by centrifugal dilution [Glendenning, Pei & Weber 1997]; both changes effect the moment of inertia and hence the response of the star to accretion. In this Letter we wish to follow the spin-evolution of the star, and so, must take such refinements into account.

![Fig. 1. Moment of inertia of neutron stars with (solid curves) and without (dashed curves) quark deconfinement assuming 0.4$M_\odot$ is accreted.]

The moment of inertia of ms pulsars or of neutron star accretors has to be computed in GR without making the usual assumption of slow rotation [Hartle 1967].
Fortunately, we have previously obtained an expression for the moment of inertia of a rotating star (Glendenning & Weber 1992). The expression is too cumbersome to reproduce here. Stars that are spun up to high frequencies close to the breakup limit (Kepler frequency) undergo dramatic interior changes; the central density may change by a factor of four or so over that of a slowly rotating star if a phase change occurs during spin-up (Glendenning 1998, Weber 1999).

Figure 2 shows how the moment of inertia changes for neutron stars in binary systems that are spun up by mass accretion according to Eq. (2) until $0.4 M_\odot$ has been accreted. The neutron star models are fully described in (Glendenning, Pei & Weber 1997) and references therein, and the initial mass of the star in our examples is $1.42 M_\odot$. Confined nuclear matter is described by a covariant Lagrangian describing the interaction of the members of the baryon octet with scalar, vector and vector-isovector mesons and solved in the meanfield approximation. Quark matter is described by the MIT bag model. In one case, it is assumed that a phase transition to quark 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 accretion rates are assumed, which range from $M_{-10} = 1$ to 100. These rates are in accord with observations made on low-mass X-ray binaries (LMXBs) observed with the Rossi X-ray Timing Explorer (van der Klis 2000). The observed objects, which are divided into Z sources and A(toll) sources, appear to accrete at rates of $M_{-10} \sim 200$ and $M_{-10} \sim 2$, respectively.

Figure 2 shows the spin evolution of accreting neutron stars as determined by the changing moment of inertia and the spin evolution equation (3). Neutron stars without quark matter in their centers are spun up along the dashed lines to equilibrium frequencies between about 600 Hz and 850 Hz, depending on accretion rate and magnetic field. The $dI/dt$ term for these sequences manifests itself only insofar as it limits the equilibrium periods to values smaller than the Kepler frequency, $\nu_K$. In both Figs. 1 and 2 we assume that $0.4 M_\odot$ is accreted. Otherwise the maximum frequency attained is less.

The spin-up scenario is dramatically different for neutron stars in which quark deconfinement occurs. In this case, as known from Fig. 1, the temporal conversion of quark matter into its mixed phase of quarks and confined hadrons is accompanied by a pronounced increase of the stellar moment of inertia. This increase contributes so significantly to the torque term $N(r_c)$ in Eq. (2) that the spin-up rate $d\Omega/dt$ is driven to saturation around those frequencies at which the pure quark matter core in the center of the neutron star gives way to the mixed phase of confined hadronic matter and quark matter. The star resumes ordinary spin-up if this transition is completed. The epoch during which the spin rates are saturated is determined by attributes like the accretion rate, magnetic field, and its assumed decay time. The epoch lasts between $\sim 10^7$ and $10^9$ yr depending on the accretion rate at the values taken for the other factors.

We can translate the information in Fig. 2 into a frequency distribution of X-ray stars 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, but will not change the basic form of the distribution. The result is shown in Fig. 3. The result is striking. Spinout of the quark matter core as the neutron star spins up is signalled by a spike in the frequency distribution. The concentration in frequency is centered around 200 Hz, about 100 Hz lower than the observed spinup anomaly. This discrepancy is not surprising given the crude representation of confinement by the MIT bag model while the physics underlying the effect of a phase transition on spin rate is robust.

We address now the bump in the histogram at high frequencies. Certainly there are high frequency pulsars. However, if a histogram of ms pulsar frequencies is made from Ref. (Princeton data base), a spike is found near 300 Hz, and a strong attenuation in number of high frequency pulsars above the spike. So both the (sparse) data on X-ray objects and on ms pulsars agree on a spike and on attenuation at high frequency. Why the high frequency bump (containing about 9 X-ray objects) in our Fig. 3? The actual white dwarf masses in these low-mass binaries is believed to be 0.1 to $0.4 M_\odot$. We computed the fre-
Fig. 3. Frequency distribution of X-ray neutron stars. Calculated distribution is normalized to the number of observed objects (14). (The normalization causes a fractional number to appear in many bins.) Data on neutron stars in LMXBs (A=Atoll sources, Z=Z sources) is from Ref. [van der Klis 2000]. The spike in the calculated distribution corresponds to the spinout of the quark matter phase and the corresponding growth of the moment of inertia. Otherwise the spike would be absent.

frequency distribution for donor masses in this range in steps of 0.1$M_\odot$ and until all mass has been transferred at the chosen rate. (The result has little sensitivity to the accretion rate.) Since we do not know the mass distribution of donors, we averaged the results. The highest frequencies are attributable to the 0.4$M_\odot$ mass donors. These presumably account for the high frequency tail of the ms pulsar distribution. Of course it is only an assumption that the mass distribution of donors is flat and that the donor is entirely consumed. Each binary represents a unique combination of neutron star and companion masses, magnetic fields, and accretion rates, but with unknown weight for these differences. We simply do not know how the high frequency end is attenuated, but it surely is, as observation tells us, though not so severely as the few data on LMXBs would suggest, inasmuch as they are believed to be the pathway to ms pulsars, several of which have frequencies as high as $\sim 650$ Hz.

3. Summary

We have traced the time evolution of the moment of inertia and rotational frequency for a neutron star accreting matter from a low-mass companion, under various assumptions about the accretion rate and for two stellar models, one an ordinary neutron star populated by nucleons, hyperons and leptons, and one in which phase equilibrium between ordinary and quark deconfined matter occurs within the density range found in canonical pulsars. In the second case the computed frequency distribution of X-ray neutron stars shows a spike, much as is observed in a recent compilation of data [van der Klis 2000]. There are various suggestions as to the cause of the spike, several of which we cite (c.f. Bildsten 1998, Andersson et al 2000, Levin 1999). A possible contributing mechanism which causes some accretors of suitable mass to resist spinup for a lengthy era is that discussed in this paper—the ongoing reduction of quark matter cores in the centers of neutron stars as they are spun up. This occurs because, with increasing spin, the density of the inner region is centrifugally diluted until it falls below the threshold density at which quark matter can exist, first in the center, and then in an expanding region. As explained in the introduction, the conversion of quark matter to confined hadronic matter manifests itself in an expansion of the star and a significant increase in its moment of inertia. As a consequence, the angular momentum added to a neutron star during this phase of evolution is then consumed by the star’s expansion, inhibiting a further spin-up until the quark matter has been converted into a mixed phase of matter made up of hadrons and quarks.

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