The Angular Momentum of Accreting Neutron Stars

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Abstract. I review the rotation measurements of accreting neutron stars. Many of the highly magnetic ($B > 10^{11}$ G) accreting X-ray pulsars have been continuously observed with the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-Ray Observatory (CGRO) since April 1991. These observations show that the accretion torque exerted on many disk-fed accreting X-ray pulsars changes sign on a monthly to yearly timescale. This results in alternating periods of spin-up and spin-down with nearly the same torques, leading to little net angular momentum gained by accretion. I also summarize recent discoveries with the Rossi X-Ray Timing Explorer (RXTE) of periodicities during Type I X-ray bursts. These seem to indicate that many of the rapidly accreting ($\dot{M} > 10^{-10} M_\odot \text{ yr}^{-1}$) and weakly magnetic ($B \ll 10^{11}$ G) neutron stars in our galaxy are rotating at frequencies $\gtrsim 250$ Hz. Most remarkable is that they all rotate within a rather narrow range of frequencies.

I INTRODUCTION

Since the discovery of neutron stars (NSs) over 30 years ago, there have been important open questions about the origin and evolution of their rotation. Measuring the NS rotation rates in the low-mass X-ray binaries has been a long-standing goal of X-ray astronomy and is motivated by the desire to find the progenitors of the millisecond radio pulsars.

There are now two methods of observing the spin in accreting NS. If the NS has a misaligned magnetic dipole, then the brightness asymmetry will be modulated by rotation. I will first review such observations for the accreting X-ray pulsars. Even if the star is not magnetic, modulations are possible during the rise (about one second) of a Type I X-ray burst, as it is then that the burning front is traveling around the star [1–4]. This has provided a new window on rotation for the weakly magnetic ($B \ll 10^{11}$ G) NS.

Before launching into a summary of the accreting NSs, let me briefly summarize their less degenerate counterparts, the accreting white dwarfs (WDs).
Spin periods are directly measured for those WDs sufficiently magnetized to channel the accretion flow onto their polar caps. The most rapid WD rotator known to be magnetic is AE Aqr ($P_s \approx 33$ s, see [5] for an overview), one of the large class of DQ Her-type magnetic WD’s that have accretion disks. The magnetospheres for these objects are not much larger than their radius and so their final spin periods are not all that different than the dwarf novae (see below). The WD moment of inertia is so large that measuring the accretion torque takes years, so that there is typically just one torque measurement for each object. At present, five are spinning up and two are spinning down [5]. Attempts to measure rotational broadening of photospheric absorption lines from isolated DA WDs have been unsuccessful for years, implying very slow rotation [6–8]. This agrees with the extremely slow rotation (5 hours to 2.5 days, [9]) measured from the frequency splitting of non-radial oscillations in the ZZ Ceti.\(^1\) Rapid rotation has recently been inferred for accreting WDs in dwarf novae systems, where presumably the magnetic field is low. Observations of dwarf novae after outburst have found that the WD is still hot for a time after the rapid accretion from the thermal disk instability has halted (see [11] for an overview). This has allowed the observers to see the WD photosphere in some detail and yielded direct measurements of rotational line broadening, where the largest value is for WZ Sagittae [12], where $v_{\text{rot}} \sin i = 1200^{+300}_{-100}$ km/s. The others are VW Hyi, with $v_{\text{rot}} \sin i \approx 600$ km/s [13] and U Gem with $v_{\text{rot}} \sin i \approx 100$ km/s [14]. These measurements imply WD rotation periods on the order of 30-300 seconds, much faster than the non-accreting WD’s.

The prolonged accretion of material is expected to drastically alter the angular momentum of the NS. The accretion torque depends on the amount of angular momentum brought in by the accreting matter. For example, if it always arrives with the specific angular momentum of a particle orbiting at the stellar radius ($R = 10$ km) it takes only $\approx 10^7$ yr of accretion at $\dot{M} \approx 10^{-9}M_\odot$ yr$^{-1}$ for a $M = 1.4M_\odot$ NS to reach $\nu_s \approx 50$ Hz from an initially low frequency. As we now discuss, other physics intervenes for the highly magnetic ($B > 10^{11}$ G) pulsars so spin frequencies this high are only seen in the weakly magnetic NSs.

II TORQUES ON THE X-RAY PULSARS

The small moment of inertia and large torques allow for repeated measurements of the accretion torques on X-ray pulsars. Indeed, BATSE’s continuous observations have provided a monitor of the torque exerted during magnetic accretion [15]. These observations have found that spin-up and spin-down are nearly equally prevalent in these systems [15,16], contrary to the picture in the 1970’s, when most accreting pulsars were thought to be spinning up steadily

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\(^1\) Unfortunately it is still the case that no positive identification of a non-radial pulsation on an accreting NS has been made (see [10] for a brief summary).
(see Figure 5 in [17]). BATSE has also tested theories of accretion torque and magnetospheric QPO generation on timescales of days [18], which we will not review here.

Let’s start with some simple estimates that set the stage for the discussion of the observations for the magnetic X-ray pulsars. In these objects, the magnetic field cannot be ignored. The accreting pulsar will experience a spin-up torque

\[ N \approx \dot{M}(GMr_m)^{1/2}, \]

assuming the gas deposits its angular momentum at the magnetospheric boundary, and that field lines transport all of this angular momentum to the star [19,20]. The variable \( r_m = \xi r_A \) is the magnetospheric radius with

\[ r_A \equiv \left( \frac{\mu^2}{2GM^2} \right)^{1/7} = 6.8 \times 10^8 \text{ cm} \left( \frac{\mu}{10^{30} \text{ G cm}^3} \right)^{4/7} \left( \frac{10^{-10} \text{ M}_\odot \text{ yr}^{-1}}{\dot{M}} \right)^{2/7}, \]

being a characteristic length found by equating magnetic and fluid stresses for a NS with magnetic dipole moment \( \mu \). Estimates for the dimensionless number \( \xi \) range from \( \approx 0.52 \) [21] to \( \approx 1 \) [22–24]. The detailed physics by which material at this magnetospheric boundary loses its orbital angular momentum, becomes entrained on the magnetic field lines, and makes its way to the magnetic polar caps on the star is beyond this review.

Accretion will be inhibited by a centrifugal barrier if the pulsar magnetosphere rotates faster than the Kepler frequency at the magnetosphere, \( r_m \). For accretion to continue, the magnetospheric radius must lie inside the corotation radius defined by the NS spin period, \( P_s \),

\[ r_{co} = \left( \frac{GM P_s^2}{4 \pi^2} \right)^{1/3} = 1.7 \times 10^8 \left( \frac{P_s}{\text{s}} \right)^{2/3} \text{ cm}, \]

so that if we demand that \( r_m < r_{co} \) there is a characteristic torque,

\[ N_o \equiv \dot{M}(GMr_{co})^{1/2}, \]

which is convenient to use as it only depends on the NS spin period, \( P_s \), and \( \dot{M} \). A pulsar subject to the torque in equation (1) will spin-up at a rate

\[ \dot{\nu} = \frac{N}{2\pi I} = 1.6 \times 10^{-13} \text{s}^{-2} \left( \frac{\dot{M}}{10^{-10} \text{ M}_\odot \text{ yr}^{-1}} \right) \left( \frac{P_s}{\text{s}} \right)^{1/3} \left( \frac{r_m}{r_{co}} \right)^{1/2}, \]

where \( I \approx 0.4MR^2 \) is the NS’s moment of inertia. The timescale for spinning up the NS is then

\[ t_{spin-up} \equiv -\frac{\dot{\nu}}{\nu} \simeq 2 \times 10^5 \text{ yr} \left( \frac{10^{-10} \text{ M}_\odot \text{ yr}^{-1}}{\dot{M}} \right) \left( \frac{s}{P_s} \right)^{4/3} \left( \frac{r_{co}}{r_m} \right)^{1/2}, \]
FIGURE 1. The intrinsic spin frequency history of the accreting X-ray pulsar Cen X-3 from BATSE observations [15]. The orbit has been subtracted so that these frequencies are the NS spin frequency. The negligible error bars are omitted. The data gap near day 8700 is from a tape recorder error, the other gaps are real non-detections of the pulsar due to low luminosities.

much shorter than the ages of most X-ray binaries [25]. Hence in this simple picture the NS gets spun up until the spin frequency matches the Kepler frequency at the magnetosphere (or where \( r_m \approx r_{co} \))

\[
P_{s,eq} \approx 8 \, \xi^{3/2} \left( \frac{10^{-10} M_\odot \, \text{yr}^{-1}}{M} \right)^{3/7} \left( \frac{\mu}{10^{30} \, \text{G cm}^3} \right)^{6/7}.
\] (7)

Presumably, NSs with \( P_s < P_{s,eq} \) cannot easily accrete and may experience a strong spin-down torque via the propeller effect [26]. Hence, none of the high field objects are rapidly rotating. If it is true that the X-ray pulsars are at \( P_s \sim P_{s,eq} \), then one infers magnetic field strengths in the range \( 10^{11} - 10^{14} \, \text{G} \).

The instantaneous \( \dot{M} \) and torques can be much different than their long-term averages, however, so one only obtains a rough indication of \( B \) this way.

The early picture of long-term pulsar spin evolution was based on sparse measurements of \( \sim 10 \) objects [21,17]. In particular, the spin behavior of Cen X-3 and Her X-1 suggested that the simple spin-up torque estimate in equation (1) was sometimes inadequate. These pulsars were apparently spinning up on a timescale much longer than predicted by equation (4). Moreover, both sources also underwent short episodes of spin-down, indicating that angular momentum was actually being lost by the pulsar while it continued to accrete.

Figure 1 is the frequency history of the 4.8 s pulsar Cen X-3 from BATSE [15]. This is an example where BATSE observations reveal a strikingly different picture of pulsar spin behavior than previously known [16]. Prior to 1991, the long-term frequency evolution was described as secular spin-up at
\[ \dot{\nu} = 8 \times 10^{-13} \text{Hz s}^{-1}, \] a factor of 10-20 slower than predicted by equation (5) for the roughly known accretion rate of \( \dot{M} \approx (3 - 6) \times 10^{-9} M_\odot \text{yr}^{-1} \). In contrast, the BATSE data show that Cen X-3 exhibits 10–100 d intervals of steady spin up and spin down at a much larger rate consistent with the simple estimate of equation (4). The torques have a bimodal distribution, with the average spin up torque \( (7 \times 10^{-12} \text{Hz s}^{-1}) \), larger than the average spin down torque \( (3 \times 10^{-12} \text{Hz s}^{-1}) \) [16]. Transitions between spin up and spin down occur on a time scale more rapid than BATSE can resolve (less than a day). More significantly, the long-term spin-up rate inferred from the pre-BATSE data is not representative of the instantaneous torque; its small value is a consequence of the frequent torque transitions of roughly \( \pm N_o \).

We now know that this switching behavior is common. In 1991, the 7.6s pulsar 4U 1626–67 underwent a reversal to spin down at a rate \( \dot{\nu} = -7 \times 10^{-13} \text{Hz s}^{-1} \) after 20 years of spin up with \( \dot{\nu} = +8.5 \times 10^{-13} \text{Hz s}^{-1} \) [27]. The final torque is nearly equal in magnitude but opposite in sign and the magnitude is comparable to \( N_o \). The pulsar GX 1+4 underwent a similar transition to spin-down in 1988 [28] after more than a decade of steady spin up. Again, the spin down rate is close in magnitude to the spin up rate [29] and of order \( N_o \). The 38s pulsar OAO 1657–415 has torque episodes similar to those seen in Cen X-3 [30].

There are at least two classes of models that might explain instantaneous spin-down in disk-fed pulsars, and both involve the interaction between the accretion disk and the stellar magnetosphere. Ghosh and Lamb (1979) [21] argued that Her X-1 and Cen X-3 must be near equilibrium and found that additional negative torques would then act on the NS. Stars sufficiently close to equilibrium might then spin-down while continuing to accrete. Other theories explain spin-down via the loss of angular momentum in an MHD outflow [31–33]. Outflowing material moves along rigid magnetic field lines like beads on a wire, gaining angular momentum as it is forced to corotate. This can result in a spin-down torque on the star if the matter leaving is somehow tied to field lines that eventually connect to the star. This connection remains a challenge.

The BATSE observations pose difficulties for all these theories. To produce the bimodal torque behavior, all near-equilibrium models require delicate changes in \( \dot{M} \). The transitions in Cen X-3 always alternate between torques of opposite sign. Why should this occur? The situation is even more challenging for 4U 1626–67, where \( \dot{M} \) is most likely set by the loss of orbital angular momentum via gravitational radiation. Having the companion switch to such a finely-tuned mass transfer rate so that the spin-down torque would have nearly the same magnitude as the previous spin-up torque seems difficult. These difficulties (as well as the anti-correlation of torque and flux in GX 1+4 [29]) led Nelson et al. (1997) [16] to hypothesize that the accretion disks were alternating their sense of rotation, becoming retrograde at times. Though a radical hypothesis, it just might be what is needed.
III WEAKLY MAGNETIC NEUTRON STARS

The launch of the Rossi X-Ray Timing Explorer (RXTE) has allowed for the discovery of fast quasi-periodic variability from many rapidly accreting ($\dot{M} > 10^{-10} M_\odot$ yr$^{-1}$) and weakly magnetic ($B < 10^{11}$ G) NSs in low-mass X-ray binaries [34]. These observations strongly suggest that these NSs are rapidly rotating, as predicted by those scenarios connecting the millisecond radio pulsars to this accreting population [35]. Discoveries have occurred on two different fronts: (1) kHz QPO’s in the persistent emission [34] and, (2) periodicities during Type I bursts. I will summarize the latter here.

This began with the detection of nearly coherent $\nu_B = 363$ Hz oscillations during type I X-ray bursts from the low accretion rate ($\dot{M} < 10^{-9} M_\odot$ yr$^{-1}$) NS 4U 1728-34 [36]. Pulsations with amplitudes of 2.5 – 10% were detected in six of the eight bursts analyzed at that time. In addition, two separate high frequency quasi-periodic oscillations (QPOs) were found in the persistent emission. These changed with accretion rate, but maintained a fixed difference frequency of $\nu_d \approx 363$ Hz, identical to the period seen during the bursts. The detection of two drifting QPO’s (in the persistent emission) separated by a fixed frequency identical to that seen in the bursts naturally leads to beat frequency models [36,37]. The difference frequency is presumed to be the NS spin frequency, $\nu_s = 1/P_s$, whereas the upper frequency has different origins in different models (see [34] for a summary). Most importantly, we expect to see the spin during the burst rise, as it is during this time that the nuclear burning front is engulfing the whole star, leading to a temporarily large brightness asymmetry on the star [1–4]. The temporal behavior of the periodic oscillation during the rise of the bursts is consistent with this explanation [38].

There are presently six NSs with measured periodicities during Type I X-ray bursts. The burst frequencies, $\nu_B$ and kHz QPO difference frequencies, $\nu_d$, are as follows: 4U 1702-429 ($\nu_B = 330$ Hz, [39]), 4U 1728-34 ($\nu_B = \nu_d = 363$ Hz, [36]), KS 1731-260 ($\nu_B = 524$ Hz, $\nu_d = 260 \pm 10$ Hz, [40,41]), Aql X-1 ($\nu_B = 549$ Hz, [42]), 4U 1636-53 ($\nu_B = 581$ Hz, $\nu_d = 276 \pm 10$ Hz, [43,44]), MXB 1743-29 ($\nu_B = 589$ Hz [45]). Clearly, both the difference frequencies and the measured frequencies in the Type I bursts are in a rather narrow range, from 260 to 589 Hz. Indeed, if some of the frequencies seen during the Type I bursts are doubled due to, for example weak dipolar fields, then the inferred spin frequencies are all within an even narrower range (262-363 Hz). There are also many NSs that accrete at higher rates and are not regular Type I X-ray bursters. Many of these objects, notably the “Z” sources, also show drifting QPO’s at fixed separation, again with a similarly narrow frequency range (250-350 Hz). Beat-frequency like models are also applied to these observations so as to infer $\nu_s$.2

2) The applicability of such a model is less clear when the difference frequency is not constant, as in Sco X-1 [46] and 4U 1608-52 [47].
The frequency observed in the cooling tail of bursts from MXB 1743-29 [45], 4U 1728-34 [38] and Aql X-1 [42] increased by a few Hz as the flux decreased. There is no torque large enough to change the neutron star spin this rapidly, so Strohmayer et al. (1997) [45] argued that the observed periodicity is the rotation rate of the burning shell alone. They noted that the slight \((\Delta r \ll R)\) hydrostatic expansion during the burning can explain the observations if the shell conserves angular momentum. In that case, the change in thickness (roughly \(\Delta r \approx 20\) meters, [4]) will lead to a frequency change of the burning material by an amount \(\Delta \nu \approx \nu_s (\Delta r / R) \approx 2 \times 10^{-3} \nu_s\), or a change of 1 Hz for a 500 Hz rotation. This is close to what is observed. It is presumed that the neutron star spin frequency is the higher value and is unchanging throughout the burst. Indeed, well separated observations of 4U 1728-34 find the same asymptotic frequency [36,38].

Why is the observed frequency evolution always from low to high during the cooling tail? It is most likely because the atmospheric scale height decreases during the cooling phase [45]. The atmosphere expanded and spun-down at the onset of the thermonuclear instability. However the radiative layer on the neutron star delays the information about the burst. Hence, the small amount of hydrostatic expansion and spin-down has already occurred by the time the observer sees the burst. Observing the spin-down will be difficult.

Allowing the burning shell to have its own rotation rate leads to matter wrapping around the star many times during the instability, possibly leading to a different spreading speed in the longitudinal direction at fixed latitudes. If true, one might hope to see a different form of burst rise depending on the rotation rate. Such shear layers can be unstable to the Kelvin-Helmholtz instability. However, the buoyancy due to the mean molecular weight contrast or even thermal effects can easily stabilize this shear as the Richardson number \(Ri = N_{BV}^2/(\partial v_{rot}/\partial z)^2 \gg 1/4\), where \(N_{BV} > 10\) kHz is the local Brunt-Väisälä buoyant frequency [48]. The shear might thus persist for the few seconds required. Further theoretical studies need to be carried out to fully understand the repercussions of this result. Problems that immediately come to mind are the role of any magnetic field and more importantly, the possibility of longer timescale rotational instabilities.

**IV CONCLUSIONS AND OPEN QUESTIONS**

So, where do things stand? Figure 2 displays the spin periods and orbital periods for all accreting NS where both have been measured. As is evident, the X-ray pulsars (all objects with \(P_s > 10\) ms on this plot) have a large range of spin periods, presumably due to the large range of magnetic field strengths and accretion rates. The outliers are identified by name. Clearly the most rapidly rotating X-ray pulsar A 0538-67 needs to be confirmed. What is most striking about this figure is the narrow range of frequencies where the
FIGURE 2. The NS spin period versus the binary orbital period (the “Corbet” diagram, [51]). The X-ray pulsar data are from Table 1 of [15]. The symbols for the X-ray pulsars are: Be-type binaries (filled circles), wind-fed massive binaries (open circles), Roche-lobe overflow fed massive binaries (open triangles), unknown companion (filled triangles), Roche-lobe fed low-mass binaries (open squares). The filled squares are the four LMXB’s (Sco X-1, Cyg X-2, 4U 1636-53 & Aql X-1) for which the kHz QPO inferred spin period [34] and orbital period [52] are known. The two solid horizontal lines show the range of inferred spin frequencies from the kHz QPO’s alone [34] (i.e. $\nu_d$). This would be the range of inferred $\nu_s$ if there is frequency doubling during Type I bursts. If the burst frequencies are $\nu_s$, then the dashed line represents the shortest period yet seen in an accreting NS (1.69 ms [45]).

LMXB’s reside (see caption for details). It is remarkable that these stars are all rotating at nearly the same rate. White and Zhang (1997) [49] argued that this similarity arises because these weakly magnetic ($B \sim 10^8 - 10^9$ G) NSs have reached an equilibrium where the magnetospheric radius equals the co-rotation radius. The NSs must then have an intrinsic relation between their magnetic fields and accretion rates so that they all reach a rotational equilibrium of roughly the same frequency. The mapping of this onto the NS parameters is a bit uncertain for magnetospheres this close to the NS. Naively applying the standard scalings would imply that $\mu \propto \dot{M}^{1/2}$ for this to be true. Clearly, nothing like this is seen for the highly magnetic X-ray pulsars. The similarities in spin frequencies remains to be explained and is also motivated by Backer’s [50] recent claim of a similarly narrow range of spin periods at birth for the millisecond radio pulsars.

What about the magnetic X-ray pulsars? The BATSE observations suggest that the disk-accreting pulsars are always subject to instantaneous torques
of magnitude $\approx N_0 \equiv \dot{M}(GM_{\text{crit}})^{1/2}$ and only differentiate themselves by the timescale for reversals of sign. We see some (e.g. Cen X-3, Her X-1, OAO 1657-415) that switch within $\sim 10 - 90$ days, whereas others (e.g. 4U 1626-67 and GX 1+4) switch once in 10-20 years. The primary theoretical issues are then identifying the physics that sets this timescale and understanding why the magnitudes of the spin-up and spin-down torques are the same. Whether this is because these objects are at, or near, the equilibrium spin period is still an open question.

It is intriguing to apply this picture of the long-term evolution of disk-fed pulsars to those that are not monitored by BATSE. First, it makes it more plausible that one of the class of the “6 second” pulsars which are spinning down (1E 2259+586, 1E 1048.1-5937, 4U 0142+61, [53]) might eventually switch to spin-up. The pulsar 1E 1048.1-5937 has the shortest spin-down time amongst these ($t_{sd} = 10^4$ yr) and might be the most likely one to undergo a torque reversal. There is already some evidence for a brief torque reversal in 1E 2259+586 [54]. In addition, the long-term torque inferred for LMC X-4 is nearly a factor of 100 lower than $N_0$, suggesting that this pulsar may be undergoing rapid switching like Cen X-3. Repeated torque measurements of this object should bear this out.

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