THE ASTROPHYSICAL JOURNAL, 481:L101–L105, 1997 June 1

ON THE CORRELATION OF TORQUE AND LUMINOSITY IN GX 1+4

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Received 1996 December 26; accepted 1997 March 11

ABSTRACT

Over 5 years of daily hard X-ray (>20 keV) monitoring of the 2 minute accretion-powered pulsar GX 1+4 with the *Compton Gamma Ray Observatory*/BATSE large-area detectors has found nearly continuous rapid spin-down, interrupted by a bright 200 day spin-up episode. During spin-down, the torque becomes more negative as the luminosity increases (assuming that the 20–60 keV pulsed flux traces bolometric luminosity), the opposite of what is predicted by standard accretion torque theory. No changes in the shape of the 20–100 keV pulsed energy spectrum were detected, so that a very drastic change in the spectrum below 20 keV or the pulsed fraction would be required to make the 20–60 keV pulsed flux a poor luminosity tracer. These are the first observations that flatly contradict standard magnetic disk accretion theory, and they may have important implications for understanding the spin evolution of X-ray binaries, cataclysmic variables, and protostars. We briefly discuss the possibility that GX 1+4 may be accreting from a retrograde disk during spin-down, as previously suggested.

Subject headings: accretion, accretion disks — pulsars: individual (GX 1+4) — stars: neutron — X-rays: stars

1. INTRODUCTION

The torque exerted on a magnetic star by an accretion disk is of great interest in astrophysics, with relevance to binary evolution, star formation, neutron star structure, and the origin of millisecond radio pulsars. Accretion-powered pulsars are the ideal laboratory for the study of accretion torques, since the bolometric X-ray intensity is a tracer of the mass accretion rate, and the X-ray pulsations and the small moment of inertia of the neutron star permit torque measurements on short (of order days) timescales. For accretion from a prograde disk, the material torque will generally act to spin up the star until it reaches its equilibrium spin period, where steady accretion is halted by a centrifugal barrier (Pringle & Rees 1972; Lamb, Pethick, & Pines 1973; Illarionov & Sunyaev 1975). This shutoff occurs when the magnetospheric radius r_m (where the Keplerian kinetic stress is equal to the magnetic stress) is comparable to the corotation radius r_{co} (where the magnetic field lines move at the local Kepler velocity).

Early observations of disk-fed X-ray pulsars found that the simple model for steady spin-up sketched above is sometimes inadequate: some X-ray pulsars spin up at rates much smaller than predicted, or even spin down for extended intervals while continuing to accrete matter. This led to suggestions that additional magnetic spin-down torques must be present, capable of reducing or even dominating the material spin-up torque even while the star continues to accrete. These models invoke magnetic coupling of the accretion disk and the magnetosphere (Ghosh & Lamb 1979a, 1979b; Wang 1987, 1995) or loss of angular momentum through the expulsion of a centrifugally driven magnetohydrodynamic wind (Anzer & Börner 1980; Arons et al. 1984; Lovelace, Romanova, & Bisnovatyi-Kogan 1995). All of these near-equilibrium disk accretion scenarios predict that a higher mass accretion rate $\dot{M}$ should yield a smaller magnetospheric radius r_m and a larger spin-up torque. They likewise predict that a reduced $\dot{M}$ increases r_m and reduces the accretion torque until net spin-down occurs. For sufficiently low $\dot{M}$, this can eventually lead to centrifugal inhibition of accretion because of a "propeller" effect (cf. Illarionov & Sunyaev 1975).

Most of the sparse, intermittent observations of X-ray pulsars during the 1970s and 1980s were generally consistent with the near-equilibrium scenario (Nagase 1989 and references therein). However, more recent long-term monitoring of a large sample of accreting pulsars with the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* has found several systems whose behavior is difficult to explain in this context (Bildsten et al. 1997).

One of the most interesting tests of accretion torque theory has come from observations of the 2 minute X-ray pulsar GX 1+4. This long-period ($\gtrsim$200 days) symbiotic binary also contains the M6 III giant V2116 Oph and an accretion disk (Davidsen, Malina, & Bowyer 1977; Chakrabarty & Roche 1997). Throughout the 1970s, GX 1+4 was consistently bright ($\gtrsim$100 mcrab in the 2–10 keV band; see McClintock & Leventhal 1989 and references therein) and spinning up rapidly with a mean rate $\dot{\nu} \approx 6.0 \times 10^{-12}$ Hz s^{-1} (Nagase et 1989 and references therein). There were no observations of GX 1+4 between 1980 and 1983, but several observations by *EXOSAT* in 1983 and 1984 failed to detect it, indicating an X-ray flux decrease of at least 2 orders of magnitude ($\lesssim$0.5 mcrab in the 2–10 keV band; Hall & Davelaar 1983; Mukai 1988).

The pulsar reappeared with a reversed (spin-down) accretion torque and low luminosity in 1987 (3 mcrab in the 1–30 keV band; Makishima et al. 1988). During 1989–1991 it continued to spin down rapidly with a mean rate $\dot{\nu} \approx -3.7 \times 10^{-12}$ Hz s^{-1}, similar in magnitude to the previous spin-up rate. A surface dipole magnetic field of nearly 10^{14} G is required for this slow pulsar if its torque reversal is a sign of being near its

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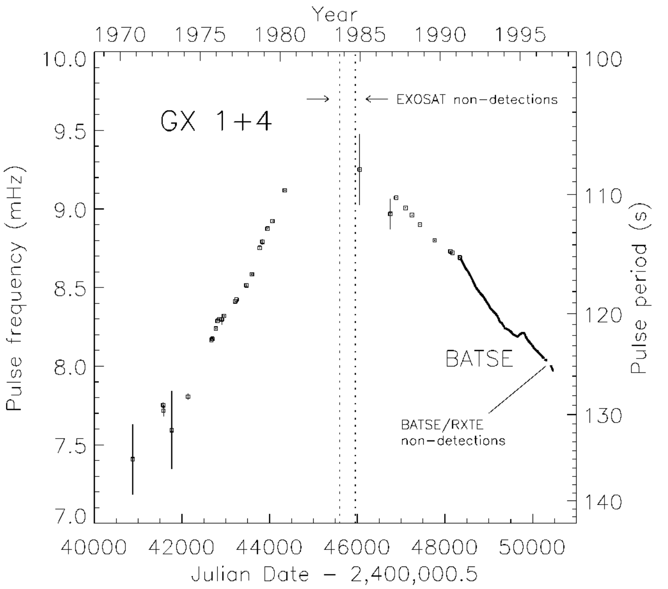

FIG. 1.—The long-term pulse frequency history of GX 1+4. The interval during which *EXOSAT* failed to detect the source is indicated by the dotted lines. The low state established by BATSE and *RXTE* nondetections is also indicated. The BATSE measurements comprise the solid line starting in 1991 and continuing after the late 1996 low state.

equilibrium spin period. GX 1+4 has the hardest X-ray spectrum among the persistent X-ray pulsars. Since some authors have suggested that the location of the high-energy break observed in X-ray pulsar spectra may be related to the magnetic field strength (e.g., Pravdo et al. 1978; Tanaka 1986), this might be evidence of a strong magnetic field in GX 1+4. Alternatively, Makishima et al. (1988) and Dotani et al. (1989) suggested that the spin-down may be due to accretion from a retrograde disk formed from the stellar wind of the red giant companion.

Long-term BATSE monitoring of GX 1+4 since 1991 has detected surprising changes in the apparent torque-luminosity relation that are not readily understood in terms of a near-equilibrium accretion torque model. In this Letter, we present the torque and flux data for GX 1+4. A preliminary account of this work was presented by Chakrabarty (1996).

2. OBSERVATIONS AND ANALYSIS

BATSE is a nearly continuous all-sky monitor of 20 keV–1.8 MeV hard X-ray/γ-ray flux (see Fishman et al. 1989 for a description). Our standard pulsed source detection and timing analysis uses the 20–60 keV channel of the 1.024 s DISCLA data (see Chakrabarty et al. 1993; Chakrabarty 1996). The barycentric pulse frequency history of GX 1+4 from 1991 April 16 to 1997 January 17 (MJD[7] 48,362–50,465) was determined by dividing the data into 5 day segments and searching the Fourier power spectrum of each segment for the strongest signal in the pulse period range 110 s $\lesssim P_{\rm pulse} \lesssim$ 130 s. Figure 1 shows the long-term pulse frequency history of GX 1+4, including pre-BATSE archival data. The overall BATSE pulse frequency history shows a significant quadratic trend toward smaller $\dot{\nu}$ magnitudes, with $|\dot{\nu}/\ddot{\nu}| \approx 10$ yr. There are also occasional oscillatory excursions about this quadratic trend in the pulse frequency. These are too large to be due to orbital Doppler shifts but might represent accretion torque variations.

Mean pulsed energy spectra were measured by folding long segments of the BATSE CONT data (16 energy channels at 2.048 s resolution) using a pulse timing model derived from the pulse frequency history. A single-harmonic pulse model was employed to measure the pulsed count rates in the resulting pulse profiles (see Chakrabarty et al. 1995). The spectrum was measured during three different source states: a relatively quiescent spin-down interval during 1993 January 23–April 23 (MJD 49,010–49,100), a portion of a bright spin-down flare during 1993 September 9–21 (MJD 49,239–49,251), and the bright spin-up interval during 1994 October 13–1995 March 22 (MJD 49,638–49,798). All three intervals were adequately fitted by a thermal bremsstrahlung model (including Gaunt factor) with $kT \approx 45$ keV. During the bright spin-up interval, pulsations were clearly detected at photon energies as high as 160 keV.

We obtained a 20–60 keV pulsed flux history by folding 5 day intervals of the DISCLA data using the pulse periods determined from Fourier analysis, measuring the phase-averaged pulsed count rate by fitting the pulse profiles with a sinusoidal template (Chakrabarty et al. 1995) and correcting the resulting pulsed count rates for the instrumental response assuming a fixed source spectrum. Because GX 1+4 is faint relative to the background and the BATSE detectors are uncollimated, this analysis technique is only sensitive to the pulsed component of the 20–60 keV emission. Because of its faintness and source confusion problems near the Galactic center, BATSE monitoring measurements of GX 1+4 using Earth occultation techniques (Harmon et al. 1992) are not available, so that its unpulsed component is indistinguishable from the background. Figure 2 (*top*) shows the hard X-ray pulsed flux history measured since 1991. The detection threshold of these 5 day integrations is approximately 1.5×10^{-10} ergs cm^{-2} s^{-1} $\approx$ 15 mcrab (20–60 keV). Some of the points in the flux history are upper limits with this approximate value.

To compute the torque history of GX 1+4, we calculated a running three-point numerical derivative of the pulse frequency history. For those intervals prior to 1996 August during which the pulsar was not detected, the mean pulse frequency derivative was estimated using a linear interpolation of the nearest pulse frequency measurements adjacent to the undetected interval. We did not attempt to interpolate over the long undetected interval during 1996 August–December. The resulting pulse frequency derivatives $\dot{\nu}$ (which are proportional to the net torque on the neutron star) are shown in Figure 2 (*bottom*).

3. TORQUE AND LUMINOSITY BEHAVIOR

Our observations of GX 1+4 divide naturally into five states. During MJD 48,362–49,613 (1991 April 16–1994 September 18), we observed continued spin-down, with relatively steady, persistent 20–60 keV pulsed emission of $\approx 2 \times 10^{-10}$ ergs cm^{-2} s^{-1} interrupted by intermittent bright flares of about a 20 day duration. The cross-correlation function (e.g., Bendat & Piersol 1986) of the flux and torque histories over this interval has a very strong negative peak at zero lag with a correlation coefficient of −0.85. This indicates a strong anticorrelation (negative correlation) of the two quantities, rather than the positive correlation predicted by standard disk accretion torque theory. This anticorrelation is clearly evident in Figure 2 from the enhanced spin-down episodes accompanying most of the intensity flares in this interval (MJD 48,393, 48,546, 48,998, and 49,238). However, two of the weaker flares (MJD

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[7] Modified Julian Date = JD −2,400,000.5.

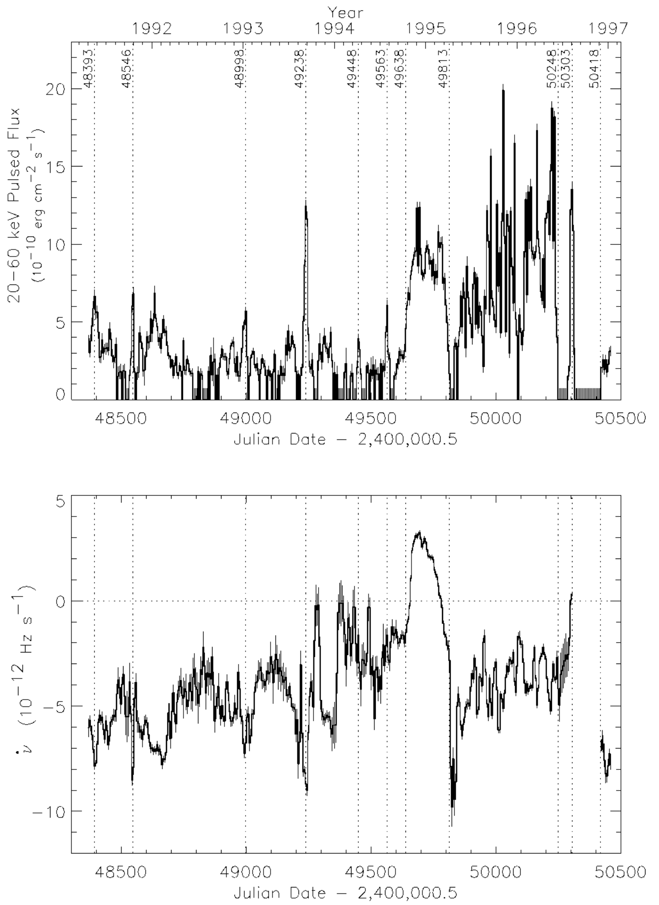

FIG. 2.—*Top*: BATSE 20–60 keV pulsed flux history for GX 1+4, averaged at 5 day intervals. The detection threshold is 1.5×10^{-10} ergs cm^{-2} s^{-1}. Points whose error bars intersect zero flux are upper limits. *Bottom*: Pulse frequency derivative ($\dot{\nu}$) history for GX 1+4. The gap during MJD 50,313–50,418 corresponds to the BATSE and *RXTE* nondetections. The epochs of flares and other interesting events discussed in the text are marked by the vertical dotted lines in both panels.

49,448 and 49,563) do not show an obvious anticorrelation, and indeed seem to be accompanied by *reduced* spin-down.

We examined the torque-luminosity relation during this first spin-down state by assuming $-\dot{\nu} \propto F_x^{\beta}$ and fitting the data to this model using a doubly weighted regression (Feigelson & Babu 1992; Press et al. 1992). Excluding nondetections ($F_x \lesssim 1.5 \times 10^{-10}$ ergs cm^{-2} s^{-1}) and points where the torque was consistent with zero, the best-fit power-law index is $\beta = 0.48 \pm 0.01$. The data and best-fit model are shown in Figure 3. The scatter for points with $-\dot{\nu} < 4 \times 10^{-12}$ Hz s^{-1} is very large, with no clear correlation present. The data from the weak flares on MJD 49,448 and 49,563 form the extremely discrepant group of points in the bottom right portion of Figure 3. Excluding all of the points with $-\dot{\nu} < 4 \times 10^{-12}$ Hz s^{-1} does not significantly alter the best-fit β.

The second state began around MJD 49,638 (1994 October 12), when GX 1+4 entered a prolonged (~200 days) bright period. During this bright state, the pulsar underwent a smooth torque reversal to spin-up. When the pulsar began to fade, it also resumed rapid spin-down. The cross-correlation function of the flux and torque histories during MJD 49,638–49,813 (1994 October 12–1995 April 6) contains a strong positive peak at zero lag, with a correlation coefficient of +0.56. Because the spin-up episode spans only a factor of 2 in flux, it was not possible to characterize the functional form of the torque-luminosity relation. The abrupt large spin-down torque accompanying the low flux level around MJD 49,825 (1995 April 18) is suggestive of "propeller" spin-down due to the centrifugal inhibition of accretion.

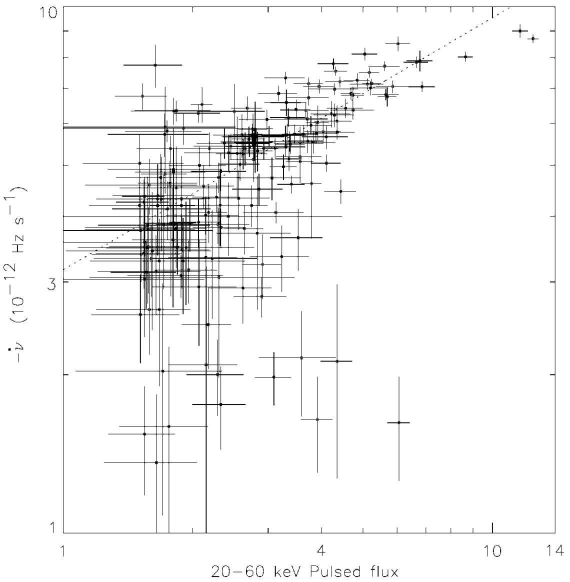

FIG. 3.—Torque-luminosity anticorrelation of GX 1+4 during the 1991–1995 (MJD 48,362–49,613) spin-down interval. The negative pulse frequency derivative is plotted as a function of the 20–60 keV pulsed flux (in units of 10^{-10} ergs cm^{-2} s^{-1}). Nondetections ($F_x \lesssim 1.5 \times 10^{-10}$ ergs cm^{-2} s^{-1}) and points with torque consistent with zero are omitted. The dotted line indicates the best-fit power-law model for the torque-luminosity relation, $-\dot{\nu} \propto F_x^{0.48}$. The data for smaller torques ($-\dot{\nu} < 4 \times 10^{-12}$ Hz s^{-1}) are very scattered and show no clear correlation with flux.

The third state began after the end of the bright spin-up episode. During MJD 49,848–50,243 (1995 May 11–1996 June 9), the pulsed hard X-ray emission varied erratically, although the pulsar continued to spin down at a relatively steady rate. The wildly fluctuating flux history suggests that the flux was varying on a timescale much shorter than our 5 day measurements. The cross-correlation function of the torque and flux histories during this interval contains a weak negative peak at zero lag, with a correlation coefficient of −0.87. The erratic flux behavior was abruptly ended around MJD 50,243 by a quiet interval of about a month in duration, during which the pulsar was usually below the BATSE detection threshold but evidently continued to spin down.

GX 1+4 reappeared briefly with a bright flare peaking on MJD 50,303 (1996 August 8), during which the pulsar made a transition to spin-up. It then rapidly dropped below our detection threshold again on MJD 50,313 (1996 August 18), remaining undetected until MJD 50,418 (1996 December 1). The drop in flux was too rapid to allow us to determine the torque state of the pulsar at the end of the flare. This was the longest undetected interval for GX 1+4 since the start of BATSE monitoring in 1991. During this BATSE low state, a series of 2–60 keV observations with the *Rossi X-Ray Timing Explorer (RXTE)* also failed to detect pulsations, establishing an upper limit (≲0.2 mcrab; Cui & Chakrabarty 1996) comparable to the 1983/1984 *EXOSAT* low state. Since MJD 50,418, the pulsar has been continuously detected by BATSE as of MJD 50,465 (1997 January 17) and is spinning down rapidly at a rate of -7.5×10^{-12} Hz s^{-1}.

4. DISCUSSION

According to standard accretion torque models, the spin-down of a pulsar accreting from a prograde disk requires that the neutron star is rotating very near its equilibrium spin period, where $r_m \approx r_{\rm co}$. The primary evidence in favor of this explanation is that, on average, the flux from GX 1+4 measured by BATSE is higher during spin-up than during spin-down, as the standard models predict. The precise torque-luminosity relationship for the pre-BATSE data is not known, because those observations did not have a sufficient time baseline to measure the instantaneous torque accurately. Still, on average, the flux during the 1970s spin-up era was significantly higher than during the 1980s spin-down era (e.g., McClintock & Leventhal 1989), also supporting the equilibrium spin explanation for GX 1+4. If this explanation is correct, then GX 1+4 must have the strongest known magnetic field of any neutron star.

However, the apparent anticorrelation of torque and luminosity observed by BATSE during spin-down is inconsistent with the near-equilibrium accretion torque models. Moreover, the flux during the bright spin-down flare centered at MJD 49,238 reached intensities similar to the bright spin-up interval near MJD 49,700 without triggering a similar torque reversal, even though the duration of the spin-down flares was much longer than the viscous timescale (of order hours) required for the inner disk to adjust to a higher $\dot{M}$. Since BATSE only detects the pulsed hard X-ray emission from GX 1+4, it is possible that our flux measurements are a poor tracer of bolometric luminosity (which should be proportional to the mass accretion rate). The observed changes in flux might actually be due to changes in the spectral shape and/or pulsed fraction. However, since 20–100 keV pulsed spectra measured during three different states show no significant difference in shape, any such spectral changes must only occur below 20 keV. Moreover, such changes would have to be quite drastic in order to offset the factor of 7 increase in BATSE flux measured during the MJD 49,238 spin-down flare. Multiple observations with wide-bandpass missions like *RXTE* and the European *Beppo-SAX* will eventually resolve this question.

Another puzzling observation is that the spin-up and spin-down torques in GX 1+4 are quite similar in magnitude, and the transition between the two states is relatively abrupt. Similar behavior has been observed in several other accreting pulsars (4U 1626−67, Chakrabarty et al. 1997; Cen X-3, Finger, Wilson, & Fishman 1994; and OAO 1657−415, Chakrabarty et al. 1993), spanning a wide range in binary parameters and companion types. The near-equilibrium accretion torque models do not explain why a particular torque magnitude should be preferred in both spin-up and spin-down. They would require a sudden and finely tuned transition in $\dot{M}$.

Based on the apparent torque-luminosity anticorrelation in GX 1+4 and the similarity of spin-up/spin-down torque magnitudes in several systems, Nelson et al. (1997) have revived an earlier suggestion (Makishima et al. 1988; Dotani et al. 1989) that the observed spin-down episodes may simply be due to the formation of a retrograde accretion disk, with material rotating with the opposite sense as the pulsar. As long as the magnetosphere is far inside the corotation radius ($r_m \ll r_{\rm co}$), a reversed disk should produce a spin-down torque of similar magnitude to the spin-up torque from a prograde disk. The torque magnitude in both cases would increase with the accretion rate. For this explanation to be viable, the switching of the accretion disk probably must occur on timescales shorter than the time required to reach spin equilibrium, since otherwise the spin-up and spin-down torque magnitudes need not be similar.

In the particular case of GX 1+4, the retrograde disk scenario for spin-down would eliminate the need for an unusually strong magnetic field, since the pulsar would necessarily be far from its equilibrium spin period. The chief question is how a retrograde disk could form and remain stable over the long timescales of months or years over which spin-down is observed. For systems in Roche lobe overflow, the accretion stream carries high specific angular momentum with the same sense as the orbit, so formation of a stable retrograde disk seems implausible. However, GX 1+4 has several attributes that set it apart from the other systems: a mass ratio near unity, a long (of order years) binary period, and a mass donor that may not be in Roche lobe overflow and probably has a relatively dense, slow wind (Chakrabarty & Roche 1997). Under these conditions, formation of a retrograde accretion disk may be possible.

We thank an anonymous referee for helpful comments. This work was funded in part by NASA grants NAG 5-1458 and NAGW-4517. D. C. was supported at Caltech by a NASA GSRP Graduate Fellowship under grant NGT-51184. The NASA Compton Postdoctoral Fellowship program supported D. C. (NAG 5-3109), L. B. (NAG 5-2666), and R. W. N. (NAG 5-3119). L. B. was also supported by Caltech's Lee A. DuBridge Fellowship, funded by the Weingart Foundation, and by the Alfred P. Sloan Foundation.

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Note added in proof.—B. Paul, A. R. Rao, & K. P. Singh (1997, A&A, 320, L9) have reanalyzed a subset of the BATSE spin-down data presented here and claim that the spin-down torque lags the flux by 5.6 ± 1.2 days. We found no evidence for this effect in the analysis presented here.