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ABSTRACT

We observe glitches in the arrival times of x-ray pulses from GRO J1744–28 associated with the large x-ray bursts observed from this source. In early observations the pulse arrival time becomes delayed by 28ms (6% of the 467ms pulsar period) during bursts while the shape of the nearly sinusoidal light-curve is essentially unchanged. This arrival time lag decays exponentially over the next ~ 1000 seconds. In later observations, smaller phase lags were observed and, eventually, we observed bursts accompanied by a small phase advance. While explanations of these observations which rely on changes in the post-burst accretion flow are natural, our observations present some problems for these explanations. It may be that this behavior can be understood in analogy with glitches in spinning down radio pulsars though this explanation has its own problems. Explained as a glitch, the phase shift is the result of coupling of the neutron star crust to the crust super-fluid which is spun-up more slowly than the rest of the star and the recovery is due to coupling between the crust and the core of the neutron star.

Subject headings: binaries: general — pulsars: individual: GRO J1744–28 — X-rays: bursts

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1. Introduction

The newly observed source, GRO J1744–28, uniquely exhibits a combination of two common phenomena for which it earned designation as *the* bursting pulsar. It presents a rare opportunity to study the interaction of these two phenomena to better understand them both individually. That this rare opportunity coincided with the launch of the Rossi X-ray Timing Explorer (XTE) is extremely fortunate. The pulsar (Frequency = 2.14 Hz) is in a binary system with a low-mass companion and an orbital period of 11.8 days (Finger 1996). The persistent emission in the early observations was near the Eddington luminosity and the frequent bursts which have a much higher luminosity likely result from instabilities in the accretion disk around the neutron star (Daumerie et al. 1996). After the initial discovery of this source by the Burst and Transient Source Experiment (Kouveliotou et al. 1996) it was far enough from the Sun to be viewed by XTE on 1996 January 18 and has been observed by XTE regularly throughout the remainder of its visible lifetime with frequent short pointings. Details of the XTE program for observing GRO J1744–28 and of other of its characteristics as determined from the PCA data are presented by Giles et al. (1996).

A delay in the arrival time of the pulsar signal of GRO J1744–28 accompanying bursts has been observed by both the Oriented Scintillation Spectrometer Experiment (OSSE) on the Compton Gamma Ray Observatory (GRO) (Jung et al. 1996, Strickman et al. 1996) and the Proportional Counter Array (PCA) on XTE (Stark et al. 1996a,b). The analysis of the OSSE data presented by Strickman et al. (1996) concentrated on the study of the phase shift observed during the bursts. We observe a phase shift during the bursts which is similar to their report. We concentrate our study, however, on the pulse arrival time lag which persists after the burst emission has terminated.

2. Observations

Between 1996 January 18 and this writing XTE has been pointed at GRO J1744–28 on 48 occasions. Three of these observations (On 1996 January 18, January 27, and February 9) were for more than 12 hours while the remainder were for one or two hours. On each of the early occasions bursts were detected in the PCA. These observations have provided a large set of data to study the burst characteristics.

2.1. Phase Shift

In the early XTE observations of GRO J1744–28 each burst is accompanied by a lag in pulse arrival time. The onset of the lag associated with an individual burst can not be well described by these data beyond the determination that it occurs completely within the given burst. However, individual bursts are accompanied by a residual phase lag which decays exponentially over the interval between successive bursts. Figure 1 shows the light curve and the relative pulse phase for 4 hours of observation on 1996 February 9. Each point in Figure 1b is determined by folding 32 seconds of data on the pulse period which best describes the entire days data. Accompanying each of the bursts is a lag in the pulse arrival time of 25 ms which decays before the next burst.

In order to study the shift in the phase during the burst emission, the light curves for multiple bursts were added together. The onset of the bursts were aligned by eye and the alignment achieved in this way was refined so that the pulses from each data set would be correctly aligned before the burst. The average of the bursts aligned in this way on a single day was analyzed for a phase shift with high time resolution. Bursts observed on the same day have durations and persistent phase lags which are similar enough that they can be combined in this way. While the profiles of the bursts are similar, each burst does have individual characteristics which are lost in the averaging with the other bursts. Therefore, this technique will be more sensitive to universal behavior of the pulsar signal than to particular characteristics of individual bursts.

Figure 2 shows the relative pulse phase for the average burst on a much shorter time scale than in Figure 1. Figure 2a shows the phase lag determined from folding on one second intervals the count of *good xenon* events in the PCA which are events which were detected on only a single anode in a proportional counter unit's detector volume. The count of *good xenon* events excludes events with coincident detection on more than one of the anodes since, in general, such events are more likely to be due to charged particles passing through the detector than x-rays from the source. During the bursts, however, the rate of coincident detection of multiple x-rays on different anodes of the detector became significant. These multiple-anode events *are* counted but their number is reported only every 125 ms which makes analy-

sis on short time scales during the bursts impossible until the behavior of the PCA under these extreme conditions is better understood. Under the assumption that the rate of coincident multiple-anode events is dominated by the coincident detection of two real x-rays we can combine the multiple-anode rate with the *good xenon* rate to estimate the actual number of detected x-rays. Figure 2b shows the phase lag for the average of the 16 bursts on 1996 February 9 including these events. The phase shift determined from analysis of these events is less well determined because of the poorer time resolution but it is more consistent with the observation reported by Strickman et al. (1996). The maximum phase shift implied by the PCA data during these 16 bursts is 50 ± 20 ms.

From the first XTE observation until early February, each burst is accompanied by a persistent phase lag with an average magnitude of ~ 28 ms. Starting in mid-February the average magnitude of the phase lag declines and a number of bursts are accompanied by no phase lag or by a phase advance. By early April the bursts are accompanied by a phase advance of, on average ~ 10 ms.

2.2. Recovery

Following the average burst on 1996 February 9, Figure 2 shows that there is a phase lag of 30 ms which persists after the burst emission has ceased. Figure 1 shows that the phase lag of some of the individual bursts which were combined to make the average burst described by Figures 2 and 3 decays exponentially over the next several hundred seconds. Observations of the source are regularly interrupted by Earth occultation which has limited our ability to study in detail the entire recovery after many bursts. As a result, we have observed a complete recovery for only a handful of the many bursts observed by XTE. An example of such a recovery is plotted in Figure 4b in which the phase lag has an exponential decay time of 720 ± 20 seconds. Typically, the phase lag has a decay time of several hundred seconds. It appears that the phase lag usually completely recovers after one burst before the next burst occurs although this may not always be the case.

Swank et al. (1996) reported the observation of deficits in the persistent flux following each burst. This deficit appears shortly after the burst (See Figure 1a) and the flux recovers to its pre-burst level exponentially over several hundred seconds. The flux deficit recovery corresponding to the burst producing

the phase shift in Figure 4b is plotted in Figure 4a. The exponential recovery time in this case is significantly shorter for the flux deficit than for the phase lag. For the vast majority of the bursts that have been examined carefully, the flux deficit recovers significantly more quickly than the phase lag, though for some cases there is an insignificant difference or the flux deficit recovers more slowly.

2.3. Pulse Shape

Except during the bursts, where because of dead-time we can not make strong conclusions about pulse shape, we see no evidence of significant deviation in the pulse shape from a perfect sinusoid. The power of the first harmonic frequency is a few percent of the power of the fundamental 2.14 Hz frequency before and after the burst. There is no increase in the power of any harmonic frequencies at any time after the burst. Not only is there no evidence for a change in the pulse shape associated with the bursts but the pulse shape appears not to change over the visible lifetime of the source, appearing as a perfect sinusoid even in the most recent data.

3. Discussion

In developing an understanding of the physics of the observed pulse phase lag, we divide the discussion into two categories: an interpretation which involves only changes in the configuration of the accretion flow onto the neutron star and one which involves a rotational change in some component of the neutron star. Both interpretations have features which make them attractive in explaining the observed phenomena and both of them have features which make them unattractive. In the discussion that follows we present a brief summary of these two interpretations as they relate to our observations.

3.1. Accretion

If the bursts are due to accretion at an accelerated rate, triggered by an instability outside the interface between the neutron star magnetosphere and an accretion disk (Daumerie et al. 1996), the inner radius is expected to depend on the mass flow through it (Ghosh & Lamb 1991). Assuming that the disk is never too far from equilibrium, the inner radius of the disk during the bursts should be smaller than before the bursts and during the dips following bursts the inner radius should be larger. Large changes in

the inner radius translate to only a few degrees in the angle at which the accreting matter encounters the neutron star surface. If the flow is symmetric about the magnetic axis, for the observed single peaked, sinusoidal pulsation there would be no change in phase. In order to produce a phase shift the angle at which the pulsar emission leaves the emission region must change azimuthally about the rotation axis of the neutron star. A change in the mass accretion rate implies a change in the accretion torque which implies such an azimuthal change in the angle at which accreting matter encounters the emission region. Tilting the emission region with a change in the accretion torque will produce a phase shift without producing a change in the pulse shape. For a decrease in the torque, the tilt corresponds to a phase lag though it does not appear that the theory of angular momentum transport through the magnetosphere (Ghosh, Lamb, & Pethick 1977) allows the 20° observed phase change. Miller (1996) has considered the flow to be asymmetric such that the emission region forms an arc partially surrounding the the magnetic pole of the neutron star. Changes in the inner radius of the disk produce rotation of this emission region about the pole which could produce a significant phase shift in the pulsar.

If the field and flow configuration followed the flow rate exactly, the phase change after the burst should be of the opposite sign to that during the burst and track the time scales of the dips. In fact there are several differences between the phase and flux behavior, as can be seen in Figure 4. After a burst, the flux returns to its pre-burst level and then decreases to its minimum post-burst value in 100–200 seconds, whereas the phase shift is at its maximum value immediately following the burst emission. Also the time constant for the flux recovery can be significantly different from the time constant which best describes the recovery of the phase shift. A gradual relaxation of the phase lag is observed over a time which can be 3 times as long as that of the flux recovery. It may be, however, that the observed flux deficit does not track the accretion configuration very well for this non-equilibrium situation. Additionally, we observe that the phase shift during the burst has the *same* sign as the persistent phase shift after the burst (see Figure 2). We have little evidence that the pulse shape doesn't change *during* the bursts so it may be that the burst emitting region is physically offset from persistent emitting region as suggested by Strickman et al. (1996).

3.2. Pulsar Glitches

While we could expect phase distortion from accretion flow changes of magnitudes comparable to those observed, the dominant changes may have a different origin. Because the phase change observed associated with the burst is a lag, it does not suggest interpretation in terms of an increase in angular momentum of the neutron star. After the burst, if the phase relaxation is interpreted as a measure of the angular velocity, the pulsar has additional angular momentum which decays away. This decay could be interpreted as the sharing of the angular momentum in the crust of the star to which it was initially imparted by the burst with the core of the star. The observed time scale for the relaxation is consistent with this interpretation. To explain the phase lag which appears during the burst, however, we must invoke other processes.

Interpreted as an angular velocity (Ω) change the phase lags correspond to initial spin-down with $\Delta\Omega/\Omega \sim 10^{-3}$ (Stark et al. 1996a) and subsequent spin-up with a relaxation time scale ~ 720 sec. In radio pulsars which are spinning down due to electromagnetic dipole radiation, glitches appear as a sudden spin-up in rotation rate with magnitudes $\Delta\Omega/\Omega \sim 10^{-9}$ – 10^{-6} (Lyne 1993), considerably less than that observed here. According to the vortex creep theory (Pines & Alpar 1985), sudden outward motion (unpinning) of the superfluid vortex cores which are pinned on the crust nuclei transfers angular momentum to the neutron star crust, resulting in its spin-up. On the glitch time scale it is expected that the neutron star superfluid core and solid outer crust are effectively decoupled. The core recouples to the crust on the dynamical crust-core coupling time scale which is $\tau = 100(m/\delta m)^2 P \sim 10^2$ – $10^4 P$, where P is the rotation period of the neutron star, and δm is the change in mass of protons as a result of their coupling with neutrons (Alpar & Sauls 1988). The net change of angular velocity $\Delta\Omega$ actually reflects the total angular momentum transferred to the crust at the time of glitch. It is possible to see a high fractional change in the angular velocity ($\Delta\Omega/\Omega \sim 10^{-3}$), if an observation could be made before the crust shares its excess angular momentum with the core. Observations of radio pulsars have not explored this regime, however. For example, one of the Vela pulsar ($P = 0.089$ sec) glitches was resolved with regular relaxation 2 minutes after the glitch. This constrained the crust-core coupling time as $\tau < 1350P$ for the Vela pulsar (Chau

et al. 1993).

It is possible to expect an analogous spin-down glitch if the neutron star is spinning-up due to the external accretion torque rather than spinning down. The external spin-up torque or heat generated during a burst might trigger inward motion of pinned vortices and subsequent crust spin-down. However, in GRO J1744–28, the angular velocity change has three important components. The ~ 700 sec exponential spin-up must be preceded by two successive glitches which represent the transition to and from the significant spin-down during the burst. The situation is not entirely analogous to the radio pulsar glitches because an additional unpinning event and outward vortex motion is required to explain both the post-burst angular velocity and the in-burst angular velocity required to create the observed post-burst phase shift.

The observed recovery time scale, expressed in terms of the rotation period, is on the order of the coupling time scale between the neutron star superfluid core and the crust. The large glitches in pulse arrival times may be interpreted either as a starting point of an ordinary glitch event or as a sudden movement of neutron star crustal plates of the type described by Ruderman (1991). The relative motion of such crustal plates may provide a mechanism for the multiple glitches suggested by our observations. We are studying for the first time the pulse arrival times during a glitch in the dynamical range of crust-core coupling time scales which has not been observed before by x-ray missions or by radio observatories.

REFERENCES

- Alpar, M. A. & Sauls, J. A. 1988, *ApJ*, 327, 723
- Chau, H. F., McCulloch, P. M., Nandkumar, R., & Pines, D. 1993, *ApJ*, 413, L113
- Daumerie, P., Kalogera, V., Lamb, F. K., & Psaltis, D. 1996, *Nature*, in press
- Finger, M. 1996, private communication
- Ghosh, P. & Lamb, F. K. 1991, *Neutron Stars: Theory and Observation*, Vol. 344, NATO ASI Series C, ed. Ventura, J. & Pines, D. (Dordrecht, Netherlands: Kluwer), 363
- Ghosh, P., Lamb, F. K., & Pethick, C. J. 1977, *ApJ*, 217, 578
- Giles, A. B., Swank, J. H., Jahoda, K., Zhang, W., Strohmayer, T., Stark, M. J., & Morgan, E. H. 1996, *ApJ*, submitted
- Jung, G. V., Philips, B. F., Kurfess, J. D., Grove, J. E., Strickman, M. S., Johnson, W. N., Dermer, C. D., & Share, G. H. 1996, *IAU Circ.* 6321
- Kouveliotou, C., van Paradijs, J., Fishman, G. J., Briggs, M. S., Kommers, J., Harmon, B. A., Meegan, C. A., & Lewin, W. H. G. 1996, *Nature*, 379, 799
- Lyne, A. G. 1993, *The Lives of the Neutron Stars*, Vol. 450, NATO ASI Series C, ed. Alpar, M. A., Kızıloğlu, Ü., & van Paradijs, J. (Dordrecht, Netherlands: Kluwer), 167
- Miller, G. S. 1996, *ApJ*, submitted
- Pines, D. & Alpar, M. A. 1985, *ApJ*, 316, 27
- Ruderman, M. 1991, *ApJ*, 382, 587
- Stark, M. J., Baykal, A., Strohmayer, T., & Swank, J. H. 1996a, *IAU Circ.* 6324
- Stark, M. J., Baykal, A., Strohmayer, T., & Swank, J. H. 1996b, *IAU Circ.* 6334
- Strickman, M. S. et al. 1996, *ApJ*, submitted
- Swank, J. et al. 1996, *IAU Circ.* 6291

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Fig. 1.— Light curve (a) and pulse phase lag (b) for part of the observation on 1996 Feb 9.

Fig. 2.— Average phase lag for 16 bursts observed on 1996 Feb 9 from (a) *Good Xenon* events with 16 ms time resolution and (b) including two-photon events rejected in plot (a) which are counted with a time resolution of 125 ms.

Fig. 3.— Average burst profile (a) for 16 bursts observed on 1996 Feb 9 for energies ≥ 12.5 keV. Also the pulsed component (b) with the burst profile removed. The dotted lines correspond to the expected pulse arrival times extrapolated from pre-burst data. The pulse shape changes are indicative of saturation of the detector rather than changes in the source.

Fig. 4.— Recovery of the post-burst flux deficit (a) and the pulse arrival time lag (b) in the 6th burst observed by XTE on 1996 Jan 27. The best-fit exponential recovery has a characteristic time of 450 ± 10 s (a) and 720 ± 20 s (b).