ACCRETION COLUMN DISRUPTION IN GX 1+4

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ABSTRACT

Daily observations of the binary X-ray pulsar GX 1+4 were made with the Rossi X-Ray Timing Explorer (RXTE) satellite between 1997 May 16 and 20 as part of a 4 month monitoring program. On May 17, the sharp dips normally observed in the light curve were all but absent, resulting in a pulse fraction \( f_p \approx 0.5 \) instead of the more typical value of \( \approx 0.8 \) measured before and after. A dramatic hardening of the 2–40 keV phase-averaged spectrum was also observed. The power-law photon index was \( 1.16 \pm 0.02 \), whereas values of 1.6–2.0 are more typical. In terms of a Comptonization continuum component, the optical depth for scattering was \( \tau \approx 19 \), with 4–6 the usual range for RXTE spectra. Pulse-phase spectroscopy indicates that \( \tau \) is decreased relative to the phase-averaged value around the primary minimum where an increase is normally observed. The reduced depth of the dip is interpreted as disruption of the accretion column, and the accompanying spectral variation suggests a substantially different accretion regime than is usual for this source.

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

1. INTRODUCTION

The X-ray pulsar GX 1+4 is unusual in several respects. It is the only confirmed neutron star in a symbiotic binary (Belczynski et al. 2000) that appears to be accreting from the giant companions’ stellar wind. The neutron star spin period evolution is the only confirmed neutron star in a symbiotic binary (Belczynski et al. 2000) that appears to be accreting from the giant companions’ stellar wind. The neutron star spin period evolution.

Historically, X-ray pulsar spectra have generally been fitted with variations on a power law, which is well known to be a signature of unsaturated Comptonization (e.g., Pozdnyakov, Sobel, & Sunyaev 1983). Model fitting to the available archival Rossi X-Ray Timing Explorer (RXTE) data shows that the spectra of GX 1+4 are broadly consistent with an analytic approximation to a Comptonization continuum component combined with a Gaussian component to represent iron line emission, both attenuated by neutral absorption with variable column density (Galloway 2000).

The archival RXTE data, which span 2 orders of magnitude in flux for the source, has also revealed that the X-ray light curves and mean pulse profiles of all but one of the observations exhibit sharp dips spanning \( \Delta \phi \approx 0.1–0.2 \) in phase. During 1996 July, the count rate dropped to \( \approx 10 \) counts \( \text{s}^{-1} \) over \( \approx 6 \) hr; sharp dips were observed in the mean pulse profiles even then (Giles et al. 2000). Similar dips are observed in only two other X-ray pulsars, RX J0812.4–3114 (Reig & Roche 1999) and A0535+262 (Čemeljic & Bulik 1998). A recent analytic and modeling study suggests that the sharp dips are signatures of eclipses of the emitting region by the accretion column (D. K. Galloway et al. 2000, in preparation).

Pulse-phase spectroscopy using a continuum spectral model that simulates thermal Comptonization of both GX 1+4 and RX J0812.4–3114 shows a significant increase in the fitted optical depth \( \tau \) coincident with the dip phase. If the inclination angle \( i \) of these systems is roughly equal to their magnetic colatitude \( \beta \), such an increase may result when one of the accretion columns approaches alignment with the line of sight once each rotation period. At the phase of closest alignment, photons emitted from the polar cap must propagate a greater distance through the column to escape and ultimately reach the observer. Numerical modeling using a simplified column geometry confirms that the resulting increase in optical depth will have just the effect observed in GX 1+4 and RX J0812.4–3114 (Galloway & Wu 2000).

2. OBSERVATIONS AND DATA ANALYSIS

RXTE consists of three instruments: (1) the proportional counter array (PCA), which is sensitive to photons in the energy range of 2–60 keV; (2) the high-energy X-ray timing experiment, covering 16–250 keV; and (3) the all-sky monitor, which spans 2–10 keV (Giles et al. 1995). The analysis of RXTE data presented in this Letter was carried out using LHEASOFT 5.0, released in 2000 February 23 by the RXTE Guest Observer Facility. The data were first screened to ensure that the pointing offset was less than 0.02 and that the source was greater than 10° from the Sun. This introduces additional gaps to the data. Instrumental background from cosmic-ray interactions and as a result of satellite passages close to the South Atlantic Anomaly are estimated using the PCACBACKEST software, which is included in the LHEASOFT package. The “bright” source background models from the 2000 February 23 release were used, and these are appropriate when the net source count rate is \( \approx 60 \) counts \( \text{s}^{-1} \). Spectral fitting was undertaken using the XSPEC spectral-fitting package version 11 (Arnaud 1996). For more details of the spectral analysis, see Galloway (2000).

Between 1997 May 16 and 20, GX 1+4 was observed daily for \( \approx 12 \) minutes. The phase-averaged background-subtracted count rate varied from day to day, from \( \approx 100 \) counts \( \text{s}^{-1} \) (with all five proportional counter units operating) on May 17 to \( \approx 500 \)
counts s$^{-1}$ on May 18 and 20 (Fig. 1). For four of the five observations, the sharp dips that form the primary minimum in the pulse profile were clearly observed in the background-subtracted PCA count rate. The pulse fraction is defined as

$$f_p = \frac{F_{\text{max}} - F_{\text{min}}}{F_{\text{max}}},$$

where

$$F_{\text{min}} < F(\phi_i) < F_{\text{max}} \forall i \in 1, \ldots, n$$

and where $F(\phi_i)$ is the mean pulse profile calculated over $n$ bins. On May 16 and 18–20, $f_p \approx 0.8$, as is typical for the source. On May 17, however, the sharp dips in the pulse profile were weaker or absent, resulting in a pulse fraction $f_p \approx 0.5$ (Fig. 1, second panel from top). The minima are instead broad and irregular, lacking the consistency over successive cycles observed on other days.

Spectral model fitting of the standard-2 mode spectra averaged over each daily observation was undertaken with the Comptonization continuum model (COMPTT in XSPEC; Tashchuk 1994) following Galloway (2000). Note that it was not possible to obtain a background spectrum for the May 20 observation because of problems with the filter file; the background spectrum from the previous days’ observation was used instead. Several of the spectral fit parameters show significant variability (Table 1). The column density $n_H$ varied between $\approx 10^{23}$ and $\approx 3.2 \times 10^{23}$ cm$^{-2}$. The source spectrum temperature $T_s$ was somewhat higher than is typical on May 16 but decreased to a more typical 1.2–1.3 keV by May 18. For two of the spectra, the scattering plasma temperature $T_s$ similarly could not be constrained by the fitting algorithm and instead was fixed at 10 keV. For the other 3 days, $T_s$ varied between $\approx 6.5$–7 and $\approx 10$ keV. The most dramatic variation was in the fitted optical depth $\tau$, which was 3.6–4 on May 16 and 18–20 but $\approx 19$ on May 17. The equivalent width of the Fe Gaussian component was also unusually high for this spectrum, at more than 1.8 keV. These variations occurred as the luminosity varied between 1.5 and $3.6 \times 10^{37}$ ergs s$^{-1}$, assuming a source distance of 10 kpc. The actual distance of the source is thought to be in the range of 3–15 kpc (Chakrabarty & Roche 1997).

The $\chi^2$ values indicate good fits for each spectrum except on May 17. The spectrum obtained on this day does not resemble any of the other $\approx 50$ spectra extracted over the course of the RXTE observations between 1996 and 1997. The model fit was problematic in several respects. Initial fits with all parameters free to vary resulted in a fit value for the $T_{\text{max}}$ parameter (associated with the Xe absorption edge at 4.83 keV) an order of magnitude greater than the maximum for all the other spectra. Thus, the value for this parameter was instead fixed (“frozen”) at the fit value for the spectrum extracted over the whole of the 1997 May observation. The fitted $T_{\text{bar}}$ value, when free to vary, also became much larger than was consistent for the other spectra and so was fixed at 1.3 keV. This value is typical for the source at other times (Galloway 2000). While the resulting fit statistic $\chi^2 \approx 2.60$ indicates an unacceptable fit, no improvement was found using alternative continuum models, including a power law, a power law with exponential cutoff, and a broken power law. A comparable fit was obtained with a blackbody component, resulting in $\chi^2 \approx 2.74$ with a fitted $T_{\text{bb}} = 6.65_{-0.65}^{+0.76}$ keV in rough agreement with $T_s$ for the COMPTT fit of 6.51_{-0.60}^{+0.67}$ keV.

The data from each of the observations on May 16–20 were divided into 10 phase bins based on the pulse period $P = 126.4319(0) \pm 0.0005(5)$ s estimated from regular BATSE monitoring of the source. The ephemeris for each day was chosen arbitrarily so that the first phase bin was centered on the primary minimum, defined as phase 0.0. Each of the resulting phase-selected spectra were fitted with the usual spectral model with at most $T_s$, $\tau$, and the COMPTT and Gaussian component normalizations free to vary. The other parameters were fixed at the fit values for the phase-averaged spectrum on the same day. This approach is essentially identical to that of Galloway et al. (2000). For the May 16 and 19 observations, $T_s$ was also fixed at the same value as for the phase-averaged spectrum (see Table 1). Variation of $T_s$ and $\tau$ with phase is small, except close to the primary minimum. The fitted $\tau$ around phase 0.0 on May 16 and 18–20 was significantly greater than the value for the phase-averaged spectrum, by 20%–60%. For the May 17 observation, at the much shallower primary minimum, $\tau$ is instead marginally lower than the phase-averaged fit values, while $T_s$ is somewhat higher (Fig. 2).

3. DISCUSSION

For sources with $i \approx \beta$, assuming that $i$, $\beta$, and the footpoints of the accretion column on the neutron star do not change, dips
due to column eclipses must always be observed while accretion continues through the columns. The apparent disappearance of the dip during the 1997 May 17 observations clearly challenges this picture. The flux at this time is more than an order of magnitude larger than the lowest level measured by RXTE; complete cessation of accretion seems unlikely. Another possibility is that the geometry of the system is changing such that the accretion column drops out of alignment briefly. The inclination angle $i$ may vary because of the geodetic precession of the pulsar, as is suggested for some radio pulsars (e.g., Kramer 1998). Alternatively, the magnetic colatitude $\beta$ may change because of the evolution of the neutron star magnetic field. Variations due to the former effect, however, are only expected on timescales of years. And while the latter possibility cannot be discounted because of the lack of knowledge regarding such evolution, it seems much more likely that each of these mechanisms would cause a much longer lasting, if not permanent, cessation of eclipses rather than what is observed in GX 1+4.

Variations in the position of the column itself are much more plausible. As the accretion rate $M$ (and hence the luminosity $L_X$) decreases, the balance of magnetic and gas pressures at the inner edge of the accretion disk means that the disk will be truncated farther out from the neutron star (Ghosh & Lamb 1979a, 1979b). Field lines threading the boundary region where disk material decelerates and becomes bound to the accretion column will thus meet the neutron star at progressively higher latitudes on the star. In principle at least, this mechanism may cause the column to move in and out of alignment, in which case eclipses (and dips) would be expected over only a finite range of $L_X$. Instead, what appears to be the case for GX 1+4 is that dips are normally observed at the full range of luminosities at which the source was observed by RXTE and that they are perhaps absent at a particular flux level only within that range. Observations at flux levels comparable to that of 1997 May 17, however, do generally exhibit sharp dips. If the accretion column has indeed been disrupted rather than moved, accretion must be occurring over a much larger region of the neutron stars’ magnetosphere in order to give the observed X-ray flux. That material can enter the magnetosphere of the star without being channeled along the field lines suggests either that the magnetic field strength is in actual fact low for an X-ray pulsar or that some global magnetohydrodynamic instability is operating that can completely disrupt the flow.

The unique phase-averaged RXTE spectrum that is observed coincident with the unusually low pulse fraction underlines the significance of this event. That the optical depth has increased fivefold compared with values obtained before and after suggests that the source has been “smothered” by hot accreting material, which presumably also contributes to the unusually strong Fe line emission. Such a large $\tau$ suggests that the photon spectrum will approach thermalization with the scattering material; the close agreement of the fitted blackbody temperature and the scattering plasma temperature provides corroboration for the COMPTT component fits during this interval. The
pulse-phase spectral variation was also different from that normally observed in the source. Typically, $\tau$ is significantly greater than the mean value around the primary minimum; this is the case for previously published results (e.g., Galloway et al. 2000) as well as for the observations on May 16 and 18–20. On May 17, $\tau$ was instead somewhat less than the phase-averaged value around the primary minimum. These results are strongly suggestive of a substantially different distribution of matter around the source. The increase in the equivalent width also observed on May 17 was not accompanied by the usual increase in the neutral column density (Kotani et al. 1999; Galloway 2000), further indicating varying conditions close to the star rather than in the outer circumstellar matter.

At least one similar event has been observed previously from this source. On 1993 December 11, a pulse fraction of $\approx 35\%$ (20–100 keV) was measured using balloon-borne instruments, along with an unusually hard spectrum with a power-law energy index of $0.54 \pm 0.18$ (Rao et al. 1994). For comparison, a power-law fit was made to RXTE spectra from May 17 in the energy band of 20–40 keV only. The resulting photon index of $1.15_{-0.18}^{+1.28}$ is consistent with the fit value for the full PCA energy range and represents a significantly harder spectrum than on 1993 December 11. Flux measurements by the BATSE aboard the Compton Gamma Ray Observatory satellite indicate that following that observation, the source entered a hard X-ray low state with $L_X \leq 0.1$ keV cm$^{-2}$ s$^{-1}$ (20–60 keV) that persisted (with brief interruptions) for the next 250 days. In contrast, the May 17 observation was made during a flare lasting 20 days in which the flux peaked at 0.2 keV cm$^{-2}$ s$^{-1}$. The other spectra from 1997 May give fitted $\tau$-values at intermediate levels between the two distinct spectral states that were suggested by the analysis of the archival RXTE observations (Galloway 2000). It is possible that the disruption of the accretion column is also related to a transition between these states.

This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center, and also the BATSE pulsar group home page.$^2$

$^2$ Available at http://www.batse.msfc.nasa.gov.

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