Spectral variation in the X-ray pulsar GX 1+4 during a low-flux episode

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ABSTRACT
The X-ray pulsar GX 1+4 was observed with the RXTE satellite for a total of 51 ks between 1996 July 19 and 21. During this period the flux decreased smoothly from an initial mean level of \( \approx 6 \times 10^{36} \) erg s\(^{-1} \) to a minimum of \( \approx 4 \times 10^{35} \) erg s\(^{-1} \) (2–60 keV, assuming a source distance of 10 kpc) before partially recovering towards the initial level at the end of the observation.

BATSE pulse timing measurements indicate that a torque reversal took place approximately 10 d after this observation. Both the mean pulse profile and the photon spectrum varied significantly. The observed variation in the source may provide important clues as to the mechanism of torque reversals.

The single best-fitting spectral model was based on a component originating from thermal photons with \( kT \approx 1 \) keV Comptonized by a plasma of temperature \( kT \approx 7 \) keV. Both the flux modulation with phase during the brightest interval and the evolution of the mean spectra over the course of the observation are consistent with variations in this model component; with, in addition, a doubling of the column density \( n_H \) contributing to the mean spectral change.

A strong flare of duration \( \approx 50 \) s was observed during the interval of minimum flux, with the peak flux \( \approx 20 \) times the mean level. Although beaming effects are likely to mask the true variation in \( M \) thought to give rise to the flare, the timing of a modest increase in flux prior to the flare is consistent with dual episodes of accretion resulting from successive orbits of a locally dense patch of matter in the accretion disc.

Key words: binaries: symbiotic – pulsars: individual: GX 1+4 – X-rays: stars.

1 INTRODUCTION
The study of X-ray pulsars has been an area of active research for almost 30 yr. In spite of this there remain some significant shortfalls in the understanding of these objects. An example is the persistent pulsar GX 1+4. At the time of its discovery (Lewin, Ricker & McClintock 1971) it was one of the brightest objects in the X-ray sky. The companion to the neutron star is an M6 giant (Davidsen, Malina & Bowyer 1977). GX 1+4 is the only known X-ray pulsar in a symbiotic system. Measurements of the average spin-up rate during the 1970s gave the largest value recorded for any pulsar (or in fact any astronomical object) at \( \approx 2 \) per cent per year. Inexplicably, the average spin-up trend reversed around 1983, switching to spin-down at approximately the same rate. Since that reversal, a number of changes in the sign of the torque (as inferred from the rate of change of the pulsar spin period) have been observed (Chakrabarty et al. 1997). Several estimates (Beurle et al. 1984; Dotani et al. 1989; Greenhill et al. 1993; Cui 1997) indicate a neutron star surface magnetic field strength of \( 2-3 \times 10^{13} \) G.

The X-ray flux from the source is extremely variable on time-scales of seconds to decades. Two principal flux states have been observed, a ‘high’ state that persisted during the spin-up period of the 1970s, and a ‘low’ state since. Although the mean flux has been increasing steadily during the current ‘low’ state it has not yet returned to the level of the 1970s. Superimposed on these long-term variations are smooth changes in the flux on time-scales of the order of hours to days. On the shortest time-scales the periodic variation resulting from the rotation period of the neutron star at around 2 min is observed.

Compared with other accretion-powered X-ray pulsars, GX 1+4 has an atypically hard spectrum extending out well past 100 keV (Frontera & Dal Fiume 1989). Historically the spectrum has been fitted with thermal bremsstrahlung or power-law models; more recent observations with improved spectral resolution generally favour a power-law model with exponential cut-off.

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Typical values for the cut-off power-law model parameters are photon index $\alpha = 1.1 - 2.5$; cut-off energy 5–18 keV; e-folding energy 11–26 keV. For any spectral model covering the range 1–10 keV, it is also necessary to include a Gaussian component representing iron-line emission at $\approx 6.4$ keV, and a term to account for the effects of photoelectric absorption by cold gas along the line of sight with hydrogen column density in the range $n_H = (4\pm 1) \times 10^{22}$ cm$^{-2}$. The source spectrum and in particular the column density $n_H$ have previously exhibited significant variability on time-scales as short as a day (Becker et al. 1976). Measurements of spectral variation with phase are few; one example of pulse-phase spectroscopy was undertaken with data from the Ginga satellite from 1987 and 1988 (Dotani et al. 1989). Only the column density and the iron-line centre energy were obtained from the EXOSAT experiment (Reynolds et al. 1996; Bildsten et al. 1997).

The situation for persistent pulsars is, however, less straightforward. The BATSE data have demonstrated that in general the torque is in fact uncorrelated with luminosity in these sources. The spin-up or spin-down rate can remain almost constant over intervals (referred to in this paper as a ‘constant torque state’ or just ‘torque state’) that are long compared with other characteristic time-scales of the system, even when the luminosity varies by several orders of magnitude over that time. Transitions between these states of constant torque can be abrupt, with time-scales of $<1d$ when the two torque values have the same sign; alternatively when switching from spin-up to spin-down (or vice-versa) the switch generally occurs smoothly over a period of 10–50 d.

It is possible that there remains some connection between the torque and luminosity, because at times the torque measured for GX 1 + 4 has been anticorrelated with luminosity (Chakrabarty et al. 1997). This behaviour has not been observed in other pulsars. One important caveat regarding the BATSE measurements is that the instrument can only measure pulsed flux. Systematic variations in pulse profiles or pulse fraction could introduce significant aliasing to the flux data, hence masking the true relationship between bolometric flux and torque. Given that pulse profile shape and torque state have shown evidence for correlation in GX 1 + 4 (Greenhill, Galloway & Storey 1998) this could potentially be an important effect.

In this paper we present results from spectral analysis of data obtained from GX 1 + 4 during 1996 using the Rossi X-ray Timing Explorer satellite (RXTE; Giles et al. 1995). A companion paper (Giles et al. 1999) contains detailed analysis of pulse arrival times and pulse profile changes.

## 2 OBSERVATIONS

The source was observed with RXTE between 1996 July 19 16:47 UT and 1996 July 21 02:39 UT. Several interruptions were made during that time as a consequence of previously scheduled monitoring of other sources. After screening the data to avoid periods contaminated by Earth occultations, the passage of the satellite through the South Atlantic Anomaly (SAA), and periods of unstable pointing, the total on-source duration was 51 ks. RXTE consists of three instruments, the proportional counter array (PCA) covering the energy range 2–60 keV, the high-energy X-ray timing experiment (HEXTE) covering 16–250 keV, and the all-sky monitor (ASM), which spans 2–10 keV. Pointed observations are performed using the PCA and HEXTE instruments, while the ASM regularly scans the entire visible sky.

The background-subtracted total PCA count rate for three of the five proportional counter units (PCUs) comprising the PCA is shown in Fig. 1(a). The other two PCUs were only active briefly at the beginning of the observation so those data are not included in the

Figure 1. (a) Background-subtracted PCA count rate for GX 1 + 4 over the course of the observation, showing the division between intervals 1, 2 and 3 (see text). The bin size is 16 s. (b) Mean PCA spectra between 2.2 and 40.0 keV during each interval. The data mode used is Standard-2, with 128 channels over the total range of the instrument. (c) Ratio of mean spectra in intervals 2 and 3 to that of interval 1, labelled 2/1 and 3/1, respectively. The dotted line indicates the energy of the Fe line. Spectra were obtained from the PCA except for the point covering the highest energy range, which was calculated using HEXTE data.

The phase-averaged PCA count rate was initially low at 
\( \approx 80 \text{ count s}^{-1} \). This corresponds to a flux of \( \approx 6 \times 10^{36} \text{ erg s}^{-1} \) in the 2–60 keV energy range, using the spectral model discussed in Section 3 and assuming a source distance of 10 kpc. Throughout this paper we shall use this value as the source distance unless otherwise specified; the actual distance is thought to be in the range 3–15 kpc (Chakrabarty & Roche 1997). During the course of the observation the count rate decreased to a minimum of \( \approx 5 \text{ count s}^{-1} \), corresponding to a flux of \( \approx 4 \times 10^{35} \text{ erg s}^{-1} \) before partially recovering towards the end. The count rates are unusually low for this source, with other observations giving significantly higher rates; for example \( \approx 320 \text{ count s}^{-1} \) and \( 230 \text{ count s}^{-1} \) (equivalent rates for three PCUs) in 1996 February and 1997 January, respectively. At times, the background-subtracted count rate during interval 2 drops significantly below zero. This is a consequence of the low-source-to-background-signal ratio (around 1:10) during this interval coupled with statistical variations in the binned count rate values.

The observation is divided into three intervals on the basis of the mean flux (Fig. 1a). Interval 1 covers the start of the observation to just before the flux minimum, during which the flux was approximately the mean flux (Fig. 1a). Interval 2 spans the period of minimum flux, during which time the flux was significantly below zero. This is a consequence of the low-source-to-background-signal ratio (around 1:10) during this interval coupled with statistical variations in the binned count rate values.

Accompanying the changes in flux were significant variations in pulse profile and spectral shape. Historically GX 1+4 has shown evidence of a correlation between torque state and pulse profile shape (Greenhill, Galloway & Storey 1998). Throughout the period of spin-up during the 1970s pulse profiles were typically brighter at the trailing edge with respect to the primary minimum; e.g. Doty, Hoffman & Lewin (1981). Since then, measured pulse profiles have typically been leading-edge bright, with less pronounced asymmetry; e.g. Greenhill et al. (1993). During interval 1 the pulse profile was observed to be leading-edge bright, similar to other observations since the 1980s. Pulsaions all but ceased during interval 2, and in interval 3 the shape of the profile had changed dramatically and resembled the trailing-edge bright profiles typically observed during the 1970s (Giles et al. 1999).

The count rate spectra taken during each interval are shown in Fig. 1(b). The overall spectral shape changed significantly over the course of the observation, with the spectrum becoming harder in intervals 2 and 3 compared with interval 1. The iron fluorescence line at around 6.4 keV appears more prominent in the second and third intervals. Iron-line enhancement during intervals 2 and 3 is also apparent in the spectral ratios, Fig. 1(c). These ratios were calculated by subtracting the background spectrum (including a component to account for the emission from the galactic plane; see Section 3) from the source spectrum for each interval and dividing the resulting spectra for intervals 2 and 3 by that of interval 1. Because the count rate drops off steeply above 10 keV, the spectral bins must be made correspondingly larger to achieve a reliable ratio. The data point in the highest energy band for each curve was obtained from HEXTE data, while the lower energy ratios are calculated from PCA data. The decrease in flux observed from interval 1 to 2 and 3 becomes more pronounced at energies below 6 keV. Above 15 keV the spectral ratios are almost constant with energy.

### Table 1. Fitting parameters for intervals 1 and 3 using the best-fitting model based on Comptonization of soft photons by hot plasma. \( kT_s \) is the temperature of the thermal input spectrum, \( kT_i \) and \( \tau_p \) are the temperature and optical depth, respectively, of the scattering plasma, and \( A_e \) is the normalization parameter for the Comptonized model component. The model also incorporates a Gaussian component representing iron-line emission, with \( E_{Fe} \) the line centre energy, \( \sigma \) the line width, \( A_{Fe} \) the normalization and EW the equivalent width. Both these components are attenuated by photoelectric absorption by cold matter along the line of sight, with column density \( n_H \). Data used is from PCA mode Standard-2. Confidence intervals are 90 per cent; fit statistic is reduced \( \chi^2 \) (\( \chi^2_r \)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Interval 1</th>
<th>Interval 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_H ) ( \times 10^{22} \text{ cm}^{-2} )</td>
<td>13.6 ± 1.4</td>
<td>28.8 ± 2.3</td>
</tr>
<tr>
<td>( kT_s ) (keV)</td>
<td>1.18 ± 0.21</td>
<td>1.00 ± 0.13</td>
</tr>
<tr>
<td>( kT_i ) (keV)</td>
<td>7.7 ± 0.53</td>
<td>8.6 ± 0.81</td>
</tr>
<tr>
<td>( \tau_p )</td>
<td>3.2 ± 0.24</td>
<td>2.9 ± 0.21</td>
</tr>
<tr>
<td>( A_e ) (photons cm(^{-2} \text{ s}^{-1} \text{ keV}^{-1} ))</td>
<td>(5.14 ± 0.25) ( \times 10^{-3} )</td>
<td>(4.42 ± 0.20) ( \times 10^{-3} )</td>
</tr>
<tr>
<td>( E_{Fe} ) (keV)</td>
<td>6.406 ± 0.357</td>
<td>6.37 ± 0.20</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.3 ± 0.023</td>
<td>0.37 ± 0.02</td>
</tr>
<tr>
<td>( A_{Fe} ) (photons cm(^{-2} \text{ s}^{-1} \text{ keV}^{-1} ))</td>
<td>(4.23 ± 0.22) ( \times 10^{-4} )</td>
<td>(5.0 ± 0.36) ( \times 10^{-4} )</td>
</tr>
<tr>
<td>EW (keV)</td>
<td>0.18 ± 0.016</td>
<td>0.24 ± 0.019</td>
</tr>
</tbody>
</table>

\( \chi^2_r \) = 1.105 (64 dof) 0.7251 (64 dof)
Fitting this model to the interval 2 mean spectra resulted in an acceptable $\chi^2$-fit statistic of 0.7943, but with very wide confidence limits for the fit parameters. No improvement in the confidence intervals is obtained by freezing selected parameters to the mean values for the entire observation (e.g. $T_0$). The fit parameters are effectively unconstrained and as such cannot be relied upon as a measure of the source conditions. Additionally, the interval 2 spectra alone do not permit an unambiguous choice of spectral model. We cannot distinguish between cut-off power-law, broken power-law, and Comptonization spectral models during this interval on the basis of $\chi^2$. A comparable fit can even be obtained using a model consisting of two blackbody emission components, with fitted temperatures $1.4^{+1.5}_{-0.5}$ keV and $6.0^{+7.5}_{-4.5}$ keV ($\chi^2 = 0.81$; see Section 5). Consequently we restrict the discussion of the mean-spectral-fitting results to those from intervals 1 and 3.

The Comptonization model implementation in XSPEC offers a geometry switch that affects the fitted value of the optical depth $\tau_P$. The switch can be set to model either disc or spherical geometries. As we will argue in Section 6, neither of these are strictly appropriate for the present situation. Consequently, we performed all the fitting using the disc geometry, but note that fitted values of $\tau_P$ with the spherical geometry will be approximately twice as large. The fitted values of $\tau_P$ should be an adequate comparative measure of the degree of Comptonisation between different spectra.

The increase in line-of-sight absorption following interval 1, suggested initially by the spectral ratios (Fig. 1c), is further supported by the model fits. The fitted column density $n_H$ more than doubles between interval 1 and 3. Spectral fits to each uninterrupted ‘burst’ of data (see Fig. 1a) indicate that the increase took place smoothly over approximately 10 h, although significant variations in the fitted $n_H$ values are observed on time-scales as short as 2 h. BeppoSAX satellite observations indicate that $n_H$ may have persisted at the level measured at the end of interval 3 at least until August 19 (Israel et al. 1998).

The input spectral temperature $kT_0$ is consistent with a constant value of $\approx 1$ keV during the entire observation. The decrease in flux following interval 1 is associated with a marginally significant decrease in the fitted values of the scattering optical depth $\tau_P$ and the Comptonised component normalisation parameter $A_C$.

The model parameters associated with the Gaussian component, representing fluorescence from iron in the circumstellar matter, are consistent with constant values over the course of the observation. The line-centre energy is consistent with emission from cool matter, with no significant change in the centre energy found between intervals. The iron-line equivalent width (EW) increases with marginal significance following interval 1.

## 4 PULSE-PHASE SPECTROSCOPY

The data from interval 1 were divided into 10 equal phase bins, and a spectrum obtained for each phase range. The ephemeris is that of Giles et al. (1999), with best-fitting constant-hyacentre-corrected period $P = 124.36568 \pm 0.00020$ s. The primary minimum is defined as phase zero. Data from interval 1 alone were used, for two reasons. First, the count rate was at its highest during that time, making the signal-to-noise ratio optimal compared with the other intervals. It was not possible to fit models reliably to pulse-phase spectra from interval 2 (owing to the low count rate) or interval 3 (owing to its short duration). Secondly, because the evidence of the pulse profiles suggests conditions in the source may be rather different between intervals 1, 2 and 3, this seems a better choice than simply combining all the data.

Each of the 10 spectra were then fitted with the model described in Section 3. Initially, all fitting parameters (barring those of the galactic ridge component) were left free to vary. Fitted values of the column density $n_H$, input spectrum temperature $kT_0$, and the iron-line-component parameters were all found to be consistent with those for the mean interval 1 spectrum. Confidence limits for the scattering plasma temperature $kT$ were very large within some phase ranges, while significant variations with phase were observed only in the normalization parameter $A_C$ and scattering optical depth $\tau_P$. To improve the confidence intervals for the latter three parameters a second fit was performed with all other parameters frozen at the fitted values for the mean interval 1 spectrum. The resulting fit values are shown in Fig. 2.

Around the phase of primary minimum ($\phi = 0.0-0.1$) the fitted value of $\tau_P$ is significantly higher than the mean value, while $kT$ is lower. The normalization $A_C$ is also significantly lower than the mean value at $\phi = 0.0$, but in the phase bin immediately following is above the confidence limits for the mean. There is little evidence for strong spectral variation from the mean at other phases, however, we do notice an almost monotonic decrease in the normalization $A_C$ from $\phi = 0.1$ and throughout the pulse cycle.

## 5 FLARE SPECTRA

During the period of lowest flux (interval 2) a strong flare was observed, with the peak flux rising to almost 20 times the mean level during this interval (Fig. 3a). The flare was preceded by a modest brightening of the source, which began $\approx 150$ s before the flare itself and lasted $\approx 60$ s; a second pre-flare brightening began $\approx 50$ s before the main flare, lasting $\approx 30$ s. Both the flare and the pre-flare activity occurred within the extent of two pulse periods. From the ephemeris determined for the full data set (Giles et al. 1999), a primary minimum would have occurred between the first and second pre-flares had the source been pulsing as was observed during intervals 1 and 3. The instantaneous flux during the flare peaked at $\approx 105$ count s$^{-1}$, compared with the mean rate during interval 2 of $\approx 5$ count s$^{-1}$. No comparable events occurred at other times during interval 2. During intervals 1 and 3, the significant variations between successive pulse profiles make it difficult to rule out flares with peaks having similar heights above the mean level. Certainly no flares with the same proportional increase in flux compared to the mean occurred over the course of the observation.

The count rate during this interval was too low to obtain useful full-resolution spectra. Instead, low-resolution spectra at various times were extracted from the uninterrupted portion of data within which the flare was observed. The PHA ratios obtained by dividing the various spectra are shown in Fig. 3(b). The top panel shows the ratio of the mean spectrum following the flare to that preceding it (excluding the flare itself). Mean flux decreased by around 50 per cent following the flare, with no strong evidence of spectral variation. The second and third plots show the ratios of the pre-flare (interval A on Fig. 3a) and flare (intervals B and C)
Spectral variation in GX 1+4

In each case there is no evidence of spectral variation; each ratio is consistent with constant PHA ratio in the range 3±20 keV. The pre-flare exhibits only a modest increase in flux of around 50 per cent, while during the 58-s window encompassing the flare itself the mean flux increased by 4±5 times.

The bottom panel shows the PHA ratio between the falling and rising parts of the main flare (intervals C and B respectively). The ratio is constant barring a broad dip between 6 and 12 keV. Examination of the spectra indicate that this dip is not due to any global change in the spectral shape, but rather a localised decrease in flux within that energy range as the flare developed. Modelling the spectra from the rising and falling parts using the two-temperature model described in Section 3, we find that the variation can be fitted best by a decrease in the temperature of the cooler component ($\chi^2 = 1.6$) although the change in temperature is not statistically significant.

**Figure 2.** (a) Spectral-model fitting parameters with pulse phase during interval 1. The top panel shows the scattering plasma temperature $kT$; the middle panel the optical depth for scattering $\tau_P$; while the bottom panel shows the model component normalization $A_C$. The error bars show the 90 per cent confidence limits. The fitted parameter values for the mean interval 1 spectra are shown by the solid lines; 90 per cent confidence intervals as dotted lines. (b) Pulse profile from background-subtracted event-mode PCA data. Two full pulse periods are shown for clarity.

**Figure 3.** (a) Event-mode PCA light curve (averaged over 1-s bins) during interval 2 showing the flare. Thick lines show the predicted times of primary minima from the ephemeris of Giles et al. (1999). The three intervals of interest are labelled A, B and C, for the pre-flare brightening, flare rise, and flare fall, respectively. (b) The top panel shows the ratio of the mean post-flare to the mean pre-flare spectrum (excluding the flare itself). The second panel shows the ratio of the spectrum during the pre-flare increase (interval A in Fig. 3a) to the mean spectrum (excluding the flare). The third panel shows the ratio of the flare spectra (intervals B and C) to the mean (excluding the flare). The fourth panel shows the ratio of the spectrum during the flare decrease (C) to that during the flare increase (B).

### 6 DISCUSSION

Re-analysed BATSE data confirm that GX 1+4 underwent a torque reversal from spin-down to spin-up around 1996 August 2, approximately 10 days after the RXTE observation (Giles et al. 1999). Since contributions to the net torque on the neutron star may come from both accreted material and magnetic stresses within the disc, it seems reasonable to suggest that changes in the magnetosphere or disc structure that cause the torque reversal may occur some time before a measurable effect is seen on the star itself. We therefore suggest that the spectral and pulse profile changes measured during our observation are related to the (presently unknown) phenomenon that causes torque reversals. Additional support for this connection is provided by the observation of dramatic pulse profile shape changes during the RXTE observation coupled with the previously noted correlation between pulse profile shape and torque state (Greenhill, Galloway & Storey 1998). Until an observation can be made that encompasses the precise time a torque reversal is occurring, it may be impossible to determine more about the process.

Comptonization models have been used to fit spectra for this source from past observations, e.g. Staubert et al. (1995); however, it has not previously been possible to eliminate all other candidate models on the basis of the $\chi^2$ fit parameter. The particular model used for the spectral fitting simulates Comptonization in an unmagnetized plasma (Titarchuk 1994), and since the available evidence points towards a strong magnetic field in GX 1+4 (although this awaits confirmation by more direct measurements...
such as a cyclotron resonance line) the model-fitting parameters may not be an accurate measure of the source conditions. It is likely that the principal effect of the magnetic field will be to make the spectral parameters dependent on the emission angle. Hence the model-fitting parameters obtained from the mean spectra are expected to be a reasonable approximation of the actual values (L. Titarchuk, private communication).

Assuming that the majority of the X-ray emission originates from a blackbody at most the size of the neutron star \(R_\star\approx10\text{ km}\), we expect a temperature \(kT_0\gg0.5\text{ keV}\). The temperature of the input spectrum \(kT_0\approx1\text{ keV}\) obtained from the model fits is consistent with this calculation. Rough estimates of the accretion column density can be made based on the mass transfer rate derived from the luminosity, and assuming a simple column geometry. The accretion luminosity \(L_{\text{acc}}=GM\dot{M}/R_\star\) and hence during interval 1 \(\dot{M}=2\times10^{16}\text{ g s}^{-1}\). Assuming that the accretion column radius \(R_c\) is some fraction \(f\) of the neutron-star radius \(R_\star\), and the column plasma is moving at approximately the free-fall velocity \(v_f=0.5c\), the estimated optical depth for Thompson scattering is \(\tau_\text{opt}=0.17/f\). In general, \(f\) is subject to considerable uncertainties particularly given the over-simplistic geometry adopted here, but we estimate \(f=4\times10^{-2}\) (e.g. Frank, King & Raine 1992) and thus the optical depth \(\tau=5\), close to the model-fitting values.

The pulse-phase-spectroscopy results also show that \(\tau_{\text{ph}}\) and \(A_C\) are significantly modulated at the pulsar rotation period. Consequently we propose that the Comptonization model provides a realistic picture of spectral formation in this source, with scattering taking place in the accretion column. Thus the \(kT\) parameter can be interpreted as the mean temperature of the scattering plasma. The model normalization parameter \(A_C\) is somewhat more difficult to relate to a physically measurable quantity, because both the \(kT\) and \(\tau_{\text{ph}}\) parameters can affect the total flux from the model component.

The spectral ratios (Fig. 1c) and the spectral-fitting parameters strongly suggest that the variations in the mean spectra during the course of the observation are due to two factors. The decrease in flux, which is essentially independent of energy, is presumably a result of decreased rate of mass transfer to the neutron star \(\dot{M}\). This is accompanied by a strong increase in absorption by cold material causing the flux decrease below 6 keV.

Variations in the column density \(n_H\) on time-scales of \(\approx 2\text{ h}\) have not previously been observed in this source. The iron-line energy and the relationship between equivalent width and \(n_H\) are consistent with the spherical distribution of matter suggested by Kotani et al. (1999), however, the variation is much too rapid to be attributable to the negative feedback effect that those authors suggest regulates mass transfer to the neutron star in the long term.

The rapid variation may be an indication of significant inhomogeneities in the circumstellar matter, or alternatively that the giant wind velocity is much faster than 10\text{ km s}^{-1} as suggested by infrared observations of the companion (Chakrabarty, van Kerkwijk & Larkin 1998).

Variation in the spectral-fitting parameters with pulse phase may provide clues to the distribution of matter in the accretion column. The sharp dip in the pulse profiles is associated with a significant increase in the scattering optical depth \(\tau_{\text{ph}}\) and decrease in the Comptonization-component normalization parameter \(A_C\) (Fig. 2). Such an effect may be observed if the accretion column is viewed almost directly along the magnetic axis, resulting in a much greater path length for photons propagating through the relatively dense matter of the column; essentially an ‘eclipse’ of the neutron-star pole by the accretion column. Preliminary Monte Carlo modelling based on Comptonization as the source of high-energy photons supports this as a possible mechanism (Galloway, in preparation). Accretion-column eclipses have previously been postulated to explain dips in pulse profiles from A 0535+262 (Cemeljic & Bulik 1998) and RX J0812.4−3114 (Reig & Roche 1999). That the plasma temperature \(kT\) is also low around the phase of primary minimum may be related to the bulk motion of the column plasma, because the relative velocity of the plasma in the observer’s frame will depend on orientation (and hence pulse phase). The velocity of bulk motion is likely to be many orders of magnitude above the thermal velocity (in the plasma rest frame) and so may result in observable variation of this fitting parameter with pulse phase. The asymmetry of the normalization \(A_C\) with respect to the primary minimum furthermore points to significant asymmetry of the emission on the ‘leading’ and ‘trailing’ side of the pole. Such asymmetry may originate from a non-zero relative velocity between the disc and column plasma where the disc plasma becomes bound to the magnetic field lines and enters the magnetosphere (Wang & Welter 1981). The additional observation that the width of the dip decreases with increasing energy may point towards a role for resonant absorption (Giles et al. 1999).

The observation of a short-duration flare during the minimum flux period provides a further example of previously unseen behaviour in this source. With the peak flux during the flare rising to almost 20 times the mean level, and with no other comparable events observed during interval 2, it is likely that the flare was due to a short-lived episode of enhanced accretion. The mean accretion rate during interval 2 can be estimated to be \(\approx2.5\times10^{15}\text{ g s}^{-1}\) (Frank et al. 1992); the increased luminosity observed during the flare thus implies additional accretion of at least \(5\times10^{17}\text{ g}\). In order to measure the instantaneous \(\dot{M}\) throughout the flare it would be necessary to correct for the effects of anisotropic emission from the neutron star surface as well as changing observation angle with the rotation of the star. Because the geometry is essentially unknown, and beam patterns rather model-dependent, this is not yet possible.

We do, however, note that the delay between the start of the pre-flare increase (‘A’ in Fig. 3) and the flare itself is \(\approx 150\text{ s}\). The relative angular velocities of the disc plasma and the neutron-star magnetic-field lines at the inner disc radius imply a periodicity significantly different from that resulting from the rotation of the neutron star. From the mean interval 2 luminosity and the estimated surface magnetic field strength for GX 1+4 of \(3\times10^{15}\text{ G}\) we estimate the inner disc radius as \(2.7\times10^3\text{ m}\). A locally dense patch of plasma rotating with Keplerian velocity in the disc would pass close to the region where plasma enters the accretion column originating from each pole every \(150\text{ s}\) or so. Thus it is conceivable that these two events represent successive passages of the same patch through the column uptake zone in the disc. After the second passage, the patch is presumably completely transmitted to the star and so no further flaring behaviour is seen.

If \(\dot{M}\) variations are a significant factor in the evolution of the flare, we might see other indications in the flare shape. If the polar region cools much more slowly than the flare time-scale an asymmetric flare might be observed. Spectral-model fits might also indicate cooling of the emission component originating from the pole. However, the flare appears almost completely symmetric, and spectral fits to the rising and falling parts of the flare do not exhibit cooling at any statistically significant level.
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