A CESSATION OF X-RAY DIPPING ACTIVITY IN X1254—690

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Received 1999 June 1; accepted 1999 July 26

ABSTRACT

We present results from a campaign of simultaneous X-ray and optical observations of X1254—690 conducted using the Rossi X-Ray Timing Explorer and the CTIO 1.5 m telescope. We find that the usually observed deep X-ray dipping is not seen during the times of our observations, with an upper limit of \( \sim 2\% \) on any X-ray orbital variation, and that the mean optical variability has declined in amplitude from \( \Delta V = 0.40 \pm 0.02 \text{ mag} \) to \( 0.28 \pm 0.01 \text{ mag} \). These findings indicate that the vertical structure on the disk edge associated with the impact point of the accretion stream has decreased in angular size from \( 17^\circ–25^\circ \) to less than \( 10^\circ \), and support the suggestions of previous modeling work that the bulge provides 35%-40% of the contribution to the overall optical modulation. The average optical and X-ray brightnesses are comparable to their values during dipping episodes, indicating that the mean \( \dot{M} \) and disk radius remain unchanged.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (X1254—690) — stars: neutron — X-rays: stars

1. INTRODUCTION

In X-ray dipping sources, accretion disk structure extends vertically above the plane of the binary and periodically blocks the line of sight to the central compact object. This structure is believed to be a bulge in the disk edge, associated with the impact point of the accretion stream from the secondary star. Because of this azimuthal material, the X-ray light curves of these low-mass binaries contain deep, irregularly shaped dips associated with large increases in absorption, that recur on the orbital period of the system. Currently we know of \( \sim 10 \) X-ray dippers.

X1254—690 has an orbital period of 3.88 hr, and generally displays dips of up to 95% of the 1–10 keV flux lasting \( \sim 0.8 \text{ hr} \) per cycle (Courvoisier et al. 1986). Its counterpart, GR Mus, has a mean optical brightness of \( V = 19.0 \text{ mag} \), and shows a broad optical modulation probably due to the changing visibility of the heated face of the secondary star in the system, with an additional contribution from the X-ray-heated bulge (Motch et al. 1987, hereafter MEA). A short (5 hr) section of simultaneous X-ray and optical coverage showed that the optical minimum occurs 0.15 in phase after the center of the X-ray dips (MEA), supporting the system geometry described above.

Modeling of the observed variability leads to constraints on the source inclination of \( 65^\circ–73^\circ \), and on the distance of 8–15 kpc (MEA), and makes the prediction that the shape of the optical light curve should be correlated with the length of the X-ray dips, since both depend upon the angular extent of the accretion disk structure. In an attempt to confirm the linkage between the observed optical and X-ray characteristics in low-mass X-ray binaries (LMXB), we undertook a program of simultaneous observations of X1254—690 using the Rossi X-Ray Timing Explorer (RXTE) and the facilities at CTIO.

2. OBSERVATIONS

Observations of the optical counterpart of X1254—690 were performed at the CTIO 1.5 m telescope on 1997 April 28–May 1, using the Tek2k CCD with a pixel scale of 0.24 pixel\(^{-1}\). We obtained a total of 28 hr of CCD photometry, with typical exposure times of 600 s in \( V \) and 900 s in \( B \).

Over scan and bias corrections were made for each CCD image with the quadproc task at CTIO to deal with the 4-amplifier readout. The data were flat-fielded in the standard manner using IRAF, and photometry was performed by point-spread function fitting using DAOPHOT II (Stetson 1993). The instrumental magnitudes were transformed to the standard system through observations of several Landolt standard star fields (Landolt 1992). The systematic error (from the transformation to the standard system) in these optical magnitudes is \( \pm 0.10 \text{ mag} \), although the internal intrinsic \( 1 \sigma \) error in the relative photometry is estimated to be \( \pm 0.02 \text{ mag} \), based on the rms scatter in the light curves of comparison stars of similar brightness.

Simultaneous X-ray data from X1254—690 were obtained using the RXTE satellite. The data presented here were collected by the proportional counter array (PCA) instrument using the Standard 2 and Good Xenon configurations, with time resolutions of 16 s and less than 1 \( \mu \text{s} \), respectively, and full spectral resolution. The scheduling flexibility of RXTE enabled us to achieve an impressive degree of simultaneity with our ground-based observing program, with 70 ks of total coverage during our optical run. An additional section of X-ray data lasting 10 ks was obtained on 1997 May 5. Background subtraction was performed using modeling based on the instantaneous high-energy particle flux as measured by the six-fold anticoincidence counters in the PCA, along with minor contributions from activation during South Atlantic Anomaly (SAA) passages and the cosmic X-ray background.

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FIG. 1.—The optical (V) and X-ray (2–10 keV) light curves of
X1254–690, as observed using the RXTE PCA and the CTIO 1.5 m
Telescope on 1997 April 28–May 1. The X-ray data are plotted with a
time resolution of 16 s. The tick marks in the upper panel indicate the
times of optical minima; the ticks in the lower panel were generated by
subtracting 0.15 × Porb and represent the expected times of X-ray dip
centers, assuming the standard system geometry.

The optical and X-ray light curves for these observations are shown in Figure 1. Tick marks are plotted in the upper panel, indicating the expected times of optical minimum throughout the observation, based on a folding analysis of the data and an orbital period of P orb = 0.163890 day. (The ephemeris of MEA is not precise enough to extrapolate into the epoch of the RXTE observations.) The ticks in the lower panel were generated by subtracting 0.15 × P orb from the times of optical minimum, and represent the expected times of X-ray dip centers based on the standard LMXB system geometry. Below, we follow the usual convention and define phase zero as the time of optical minimum.

3. RESULTS

The X-ray light curve presented in Figure 1 bears little resemblance to the previous behavior of the source (e.g., Courvoisier et al. 1986, Fig. 1). In the 2–10 keV energy range chosen for this figure, the observed reduction in flux during dips is generally 20%–95%, with a dip duration of 20% of the total cycle (Courvoisier et al. 1986); no such dramatic activity is seen in Figure 1, even though we have good coverage of the expected times of all or part of five separate dips.

Small variations are seen in the X-ray light curve, particularly at JD 2,450,567.6. However, as we demonstrate in Figure 2, the X-ray hardness ratio is strongly correlated with intensity during these episodes. This indicates that the flux reductions observed are due to intrinsic variations in the intensity of the central source, rather than absorption events caused by obscuration of the flux by accretion disk material. True dipping events are associated with an increase in low-energy absorption, and therefore an inverse correlation between hardness and intensity (e.g., Courvoisier et al. 1986; Smale et al. 1988). The 1997 May 5 data (not shown here) include an interval spanning a sixth expected X-ray dip, but are similarly featureless. We conclude that there is no evidence for dipping activity during our RXTE observations.

Our spectral fitting bears out this conclusion. Fitting short sections of data accumulated before, during, and after the apparent flux reduction episode at JD 2,450,567.6 seen in the first night of RXTE observing (Fig. 1), we find that the 2–15 keV spectra can be well fitted with a cutoff power law with photon index of α = 0.6 ± 0.1 and cut-off energy Ecutoff = 4.3 ± 0.3 keV. We find a mean equivalent hydrogen column density of NH = 4.8 × 10^21 cm^-2, and can set an 90% upper limit on the increase of this NH during the flux reduction episode of 4 × 10^21 cm^-2, two orders of magnitude less than the NH ≈ 5 × 10^23 cm^-2 measured during the deep dips of Courvoisier et al. (1986).

In Figure 3 we present the folded optical and X-ray light curves for our observations. The optical light curves both show quasi-sinusoidal variability on the 3.88 hr period, with full amplitudes of modulation of 0.28 ± 0.01 mag in V and 0.30 ± 0.01 mag in B. By contrast, we can place an upper limit of 2% on the presence of a significant X-ray orbital modulation.

We find no significant correlations between the X-ray and optical light curves on timescales of 10^2–10^5 s, using the
period (50 minute) source X1916

binaries are well known. In the extreme case of the short-

0.28

sinusoidal variability on the 3.88 hr period with full amplitudes of

with the folded X-ray light curve. The optical curves both show quasi-

B

X-ray ñux. Binning up the folded light curves, and no signiñcant autocorrelations in the

(1997). We also detect no signiñcant lag between the

z

and

V

B

light curves in

95% dipping is generally observed centered on phase 0.85.) The data

from each observing night were renormalized to a common mean before

performing the folds.

Fig. 3. The folded V and B optical light curves for X1254 — 690, along

with the folded X-ray light curve. The optical curves both show quasi-
sinusoidal variability on the 3.88 hr period with full amplitudes of

0.28 ± 0.01 and 0.30 ± 0.01 magnitudes, respectively. The folded X-ray

light curve shows no evidence for the usual pronounced dipping activity,

and we can place an upper limit of 2% on the presence of a signiñcant

X-ray orbital modulation. (During "normal" dipping episodes, deep

∼95% dipping is generally observed centered on phase 0.85.) The data

from each observing night were renormalized to a common mean before

performing the folds.

z-transformed discrete correlation function of Alexander

(1997). We also detect no signiñcant lag between the V and

B light curves, and no signiñcant autocorrelations in the

X-ray ñux. Binning up the folded B and V light curves in

Figure 3, we can place a 90% upper limit of 0.03 mag on the

amplitude of any orbital variation in B—V. No high-

frequency variations were detected in the persistent X-ray

emission, with typical upper limits of 1%—3% on the rms

amplitude of any quasi-periodic oscillations between 500

and 1200 Hz.

4. DISCUSSION

Variations in the depth and duration of dips in X-ray

binaries are well known. In the extreme case of the short-

period (50 minute) source X1916—053, dips can last for

10%—50% of the binary cycle and have depths of 10%—

100% (Smale et al. 1988). These dip depths and widths are

seen to vary on a timescale much greater than the orbital

period (4—6 days, Smale et al. 1989; Yoshida et al. 1995). In

this example, the variations in dip properties may be due to

the ñux-modulating e†ects of a third star in the system, a

scenario that is unlikely to be widespread among LMXBs.

X1254 — 690 itself shows variability in dip depth from 95%

to 20%, and has skipped a dip in the past; extracting the

complete light curves from the 1984 and 1985 EXOSAT

observations from the HEASARC archives, we ñnd that of

the 15 times of expected dipping covered by the data, 11

depth dips were observed, three shallow dips (∼20%), and

one case where the dip is undetectable.

However, the light curves observed in the current data set

display a lack of dip activity unprecedented among the dip

sources. In the EXOSAT observations of Courvoisier et al.

(1986), the dip duration was observed to be ∼0.8 hr, rep-

resenting 20% of the binary cycle. If dip activity from

X1254 — 690 had been nominal, we would have seen evi-

dence of six complete or partial dips during our RXTE

coverage. A priori, we cannot rule out the possibility that

dips occurred only during the intervals between obser-

vations during which RXTE was not obtaining data from

X1254 — 690, but this seems statistically unlikely. If a dip or

a nondip is equally likely to occur in a given cycle, the

probability of observing a dip on at least one of our six

opportunities is p dip > 98%. In other words, even if dips

occur as infrequently as half the time, the chances are slight

that we would fail to see evidence for one during our RXTE

coverage.

In reality, dips are observed from dipping sources greater

than 95% of the time. In addition, the appearance or non-

appearance of dips in adjacent cycles are not statistically

independent events. It therefore seems much more realistic

to postulate that dipping has ceased entirely during our

observations. We argue below that the optical behavior of the

source provides independent corroboration of this

assertion.

In LMXBs like X1254 — 690, it is generally believed that

the steady component of the optical ñux comes from the

disk (e.g., van Paradijs & McClintock 1995). Our measured

mean V magnitude of 19.0 is almost identical to the V

brightness observed by MEA when the source was dipping.

Also, our observed 2—10 keV X-ray ñux of 7.4 × 10−10 ergs

cm−2 s−1 is comparable to the nondip intensity observed

by Courvoisier et al. (1986). We therefore deduce that the

accretion disk radius and mean mass accretion rate are

unchanged; the disk just lacks the vertical structure usually

associated with the impact point of the accretion stream.

Detailed modeling of the disk during active dipping cycles

has shown that the typical aperture angle of the disk in

X1254 — 690 is 9°—13°, while the bulge itself extends to an

azimuthal height of 17°—25° (MEA). The inclination of the

system is restricted to 65°—73°. Thus, the absence of regular

dipping implies that this bulge height has shrunk in angular

size from 17°—25° to less than 10°.

We expect the varying component of the optical ñux to

have contributions from both the heated face of the second-

ary and the bulge. The full amplitude of the optical modula-

tion has been previously measured at ΔV = 0.40 ± 0.02

mag (MEA), and their subsequent modeling suggests that

ΔV = 0.25 mag of this originates in the heated face and

ΔV = 0.15 mag in the bulge. Our measured full amplitude

of ΔV = 0.28 ± 0.01 mag is therefore very close to the value

of
we would predict if the optical flux variations were now solely caused by the variable aspect of the heated face.

Another, more circumstantial piece of corroborating evidence for our theory is supplied by our measured mean $B - V$ of $0.15 \pm 0.02$ mag compared to the mean $B - V$ of $0.31 \pm 0.05$ mag observed when the source was dipping (MEA). Based on evidence from similar systems such as X1636−536 ($P_{\text{orb}} = 3.80$ hr), we would expect the photospheric temperature of the heated face to be $\sim 25,000$−$35,000$ K (e.g., Smale & Mukai 1988), a value that matches the estimates from hydrodynamic modeling of irradiated companion star envelopes (typically 20,000−40,000 K; Tavani & London 1993). The illuminated surfaces of X-ray−heated accretion disks should have a similar effective temperature. However, the outer edge of the accretion disk (including much of the outer bulge) will be screened from the direct illumination, and should therefore be much cooler; modeling of the UV, optical, and IR light curves of X1822−371 ($P_{\text{orb}} = 5.57$ hr) indicates an effective temperature of $14,500$ K for these outward-facing regions (Mason & Córdova 1982), incidentally comparable to the “bright spot” temperatures observed in cataclysmic variables of $15,000$ K (Wood et al. 1989).

So, for high-inclination sources with disk-edge structure, such as X1254−690 and X1822−371, cooler material will generally obscure at least part of the hotter, inner disk regions. A disappearance or reduction in the size of the azimuthal structure then leads to a more direct viewing of these hot regions and an increase in the apparent mean emission temperature. Although hard to model without a more detailed knowledge of the system, the reduction we see in $B - V$ is in the correct direction for such an increase in the mean temperature of the overall optical emission.

Thus, the X-ray and optical data sets each independently suggest a shrinkage in the size of the bulge at the point where the accretion stream hits the disk.

The existence of azimuthal structure at the edge of the accretion disks in LMXBs is empirically well established but theoretically difficult to explain. Phenomenological modeling of the dipping sources shows that this structure must have a scale height of $\sim 15\%$ of the disk radius or more, and sustain itself over time intervals of weeks to months. However, such a scale height is more than can be naturally produced by either irradiation or disk turbulence (King 1995 and references therein). On the other hand, material in ballistic orbits cannot produce the heavily structured appearance of the obscuring material. In the absence of a good physical model for the vertical disk structure, the reason for its reduction or disappearance can be only conjecture. However, the disappearance may perhaps be connected with a short-lived ( $\sim$ hours to days) reduction in the accretion flow from the secondary. Such a variation could be smoothed out by viscosity effects during the transfer of material through the accretion disk, leaving the time-averaged X-ray flux unchanged.

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.

REFERENCES

Alexander, T. 1997, in Astronomical Time Series, ed. D. Maoz, A. Sternberg, & E. Leibowitz (Dordrecht: Kluwer), 163
Cowboisier, T. J.-L., Parmar, A. N., Peacock, A., & Pakull, M. 1986, ApJ, 309, 265
King, A. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 419
Landolt, A. U. 1992, AJ, 104, 340
Mason, K. O., & Córdova, F. A. 1982, ApJ, 262, 253
Mochizuki, C., Pedersen, H., Beuermann, K., Pakull, M. W., & Courvoisier, T. J.-L. 1987, ApJ, 313, 792 (MEA)
Smale, A. P., Mason, K. O., White, N. E., & Gottwald, M. 1988, MNRAS, 232, 647
Smale, A. P., Mason, K. O., Williams, O. R., & Watson, M. G. 1989, PASJ, 41, 607
Smale, A. P., & Mukai, K. 1988, MNRAS, 231, 663
Stetson, P. B. 1993, DAOPHOT II User’s Manual (Victoria: Dominion Astrophysical Observatory)
Tavani, M., & London, R. 1993, ApJ, 410, 281
van Paradijs, J., & McClintock, J. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 58
Wood, J. H., Horne, K., Berriman, G., & Wade, R. A. 1989, ApJ, 341, 974
Yoshida, K., Inoue, H., Mitsuda, K., Dotani, T., & Makino, F. 1995, PASJ, 47, 141