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OPTICAL AND X-RAY OBSERVATIONS OF THE LOW-MASS X-RAY BINARY EXO 0748−676

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ABSTRACT

Optical and X-ray observations of EXO−676 in late March 1989 are presented. Our optical observations provide some support for the previously observed correlation between the mean optical brightness and light curve morphology. Unexpectedly, the mean X-ray and optical flux levels during this period do not reflect similar system states. The optical counterpart is found to be in an intermediate to low state ($V_{\Phi=0.5} = 17.18 \pm 0.02$) while X-ray data imply a bright (high) state. The changed relationship between optical and X-ray fluxes is evidence showing that EXO 0748−676 has possibly evolved. We fail to find correlated variability in simultaneous X-ray and optical observations. The lack of covariability is attributed to the limited simultaneous coverage of the source and/or significant geometric modulation in the optical light curve.

Subject headings: binaries: close — stars: individual (EXO 0748−676) — X-rays: stars

1. INTRODUCTION

In low-mass X-ray binaries (LMXB) the majority of the system luminosity is thought to be a consequence of mass transfer (via Roche lobe overflow) from a late-type secondary onto a compact object. The large ratio of X-ray to optical luminosity suggests that optical emission is due to the reprocessing of higher energy photons by material contained within the system. Reprocessing in LMXBs is thought to occur primarily in the accretion disk that surrounds the compact object, however, observations of double peaked optical bursts, burst rise times that are correlated with orbital phase (EXO 0748−676; Schoembs & Zoeschinger 1990, hereafter SZ90) and sinusoidal variation in the optical light curve indicate that substantial reprocessing could also occur in the atmosphere of the secondary star. *UBV* color-color plots of LMXB optical counterparts (Fig. 4 of Bradt & McClintock 1983) suggest that perhaps an emission mechanism similar to a blackbody process is responsible for the optical light. Assuming that the optical radiator thermally reprocesses some fraction of the X-ray flux as a blackbody (with characteristic temperature T) then the reprocessing relationship between the optical and X-ray fluxes is (Endal, Devinney, & Sofia 1976)

$$F_{\text{opt}} \propto F_x^{\alpha} \quad (1)$$

with the value of α given by

$$\alpha = h\nu/4kT[1 - \exp(-h\nu/kT)] , \quad (2)$$

where ν is the observational frequency. Temperatures derived for bursts show the blackbody temperatures are around 10^5 K (4U 1636−53, Pedersen et al. 1982), while time-averaged quiescent levels of radiation measured near bursts show a mean temperature $T \sim 10^4$ K.

It is theoretically possible to test reprocessing in LMXBs through observations of simultaneous quiescent (nonburst) X-ray/optical emission. The reprocessing relationship (eq. [1]) predicts these bands will show correlated variability, however, the majority of simultaneous observations to date have failed to show the expected X-ray/optical behavior. Prior observations have shown that the quiescent X-ray/optical behavior in various systems can be correlated (4U 1735−44; Corbet et al. 1989, hereafter C89), correlated only during the times of highest emission (4U 1556−605; Motch et al. 1989a), anticorrelated (4U 0614+09; Machin et al. 1990), or display bimodal behavior wherein both correlated and anticorrelated states have been observed (Sco X-1; Canizares et al. 1975; Ilovaisky et al. 1980; and Augusteijn et al. 1992). In 4U 1735−44, where covariability allows an estimate of the blackbody temperature of the reprocessing site, C89 have found the value to be low ($T \cong 7000$ K) which they explain to be due in part to possible geometrical effects. Other authors have also noted the possible effect of LMXB system geometry in explaining their uncorrelated and anticorrelated observations (Machin et al. 1990; Motch et al. 1989a). The exact role that system geometry plays in modifying the X-ray and reprocessed optical emission from LMXBs is unknown; clearly, a greater number of observations of both new and previously observed systems are needed.

This paper presents the first simultaneous results for the transient system EXO 0748−676. First discovered in 1985 February by the *EXOSAT* satellite, this system provides an excellent opportunity with which to study the nature of geometry and reprocessing in LMXB. Motch et al. (1989b, hereafter M89) have found evidence of reprocessing in this system from the tight correlation between the mean quiescent optical and X-ray emission measured over a period of months.

The estimated high inclination of this system (75°–82°; Parmar et al. 1986) implies substantial geometric modification to the emission behavior of the X-ray source and reprocessing regions can occur. Observed geometrical behavior includes periodic eclipses that allow the unambiguous determination of the orbital period ($P_{\rm orb} = 3.824$ hr) and system phase Φ (where $\Phi \equiv 0.0$ for the middle of the X-ray eclipse) and irregular dipping behavior at certain phases ($\Phi \cong 0.65$, 0.8–1.2).

2. OBSERVATIONS

2.1. *X-Ray Data*

X-ray data were acquired by the *Ginga* satellite from March 24 17:30 UT to March 26 4:20 UT using the LAC (Large Area proportional Counter; Turner et al. 1989). For this observation the MPC1 and MPC2 modes were used with time resolutions of 0.0625–16.0 s. All X-ray data have been rebinned to 32 s as reduction software (LACQR) has limited the time resolution of our data to twice that of the observation integration time.

Coverage of the source is not continuous and gaps appear in the light curves due to the low Earth orbit of *Ginga* which caused Earth occultation and passages through the South Atlantic Anomaly (SAA). Details of the X-ray data and their reduction are given in Smale et al. (1989, hereafter S89). The X-ray bands utilized in this paper are given in Table 1.

2.2. *Optical Data*

The optical observations were made on 1989 March 21, 23, and 25. The reduced data appear in Figure 1 along with simultaneous X-ray data. Data appearing in Figure 1 are plotted versus the corresponding X-ray phase Φ using the ephemeris of S89. Only the March 25 optical data are actually simultaneous with *Ginga* X-ray observations with the total duration of these simultaneous data coming to 2300 s. The details of all our optical data are discussed below.

2.2.1. *Observation of March 21 and 23*

The observations of March 21 (UT 11:38–14:07) and March 23 (UT 9:57–12:10) were obtained in Australia (MSSSO, Siding Spring, New South Wales) using a standard V band filter and the MSSSO coated GEC CCD. Integration times of the CCD frames ranged between 300 and 900 s. These data were reduced to instrument magnitudes using the DAOPHOT package in IRAF, with values of the source V magnitude being derived through differential photometry using stars 6, 8, and 9 (Wade et al. 1985) as comparison stars.

Several potential problems exist which could affect the accuracy of this reduction: (1) observing conditions during the time that these frames were acquired were poor: full moon and cloudy conditions occurred during both nights; (2) in part due to weather conditions, no flat-field frames were available. No bias subtraction was performed and photometry was conducted using "raw" CCD frames; and (3) the comparison stars have $B-V$ colors that differ substantially from the source

TABLE 1

X-RAY BANDS USED IN ANALYSIS

X-Ray Band Number	Energy Bandwidth (keV)
1..............	0.55–2.24
2..............	2.24–5.69
3..............	5.69–10.32
4..............	10.32–20.9
5..............	0.55–20.9

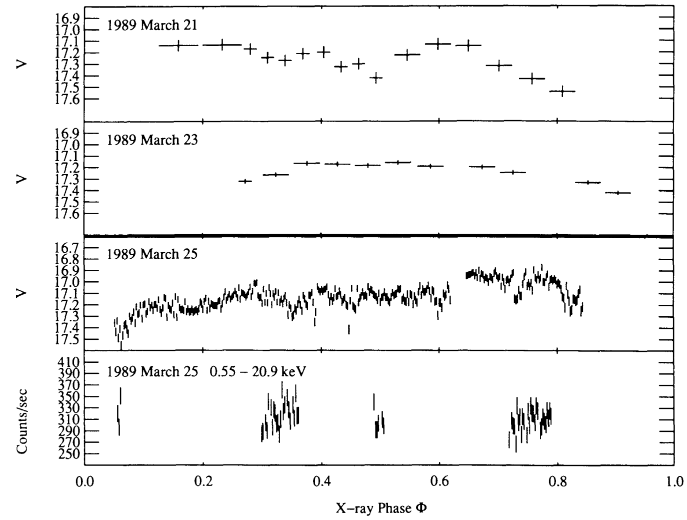

FIG. 1.—Optical light curves of EXO 0748−676 and simultaneous X-ray flux (0.5–20.9 keV). Only March 25 optical observations are simultaneous with X-ray data. A flarelike feature is seen in March 25 data set for phases $0.6 < \Phi < 0.8$.

[$\Delta(B-V) \approx 0.8$]. Despite these problems, the reduced data are seen to be well behaved within tests of consistency. Ratios of the derived magnitudes of the comparison stars show deviations of ≤ 0.01 from a constant value over the course of our observations. As comparison stars significantly drifted across the chip over our observations, the stable ratios show the change in response across the CCD is minimal and our data are not significantly degraded through the lack of flat fielding, bias subtraction or because of weather conditions. The derived V magnitudes of EXO 0748−676 and comparison stars appear accurate. Our comparison star magnitudes match well within the error of values determined by Schmidke (1991) and, mean emission level of EXO 0748−676 in CCD and March 25 data are within reasonable agreement to each other. An estimate of the systematic error on observations of EXO 0748−676 may be gauged from the stability of the V magnitude of a field star of similar brightness. Utilizing star 7 (Wade et al.; $V = 17.8$) this method obtains an error (from scatter about the mean, 1 σ) of 0.05 mag for the March 21 observations and 0.02 mag for those observations taken March 23. These are the errors which appear in Figure 1.

2.2.2. *Observations of March 25*

Optical data were obtained on March 25 (UT 2:49–6:23) at the European Southern Observatory La Silla, Chile, using the 1.54 m Danish telescope. A dual channel EMI9789QA photomultiplier tube was used to measure both the source and sky background simultaneously in white light with the more sensitive channel measuring the source. The difference in channel sensitivity, measured from near-simultaneous observations of spectro-photometric standard stars (Stone & Baldwin 1983, 1984), was accounted for in the background subtraction. From the instrument response curve and calculated white-light magnitudes for the standard stars it was possible to determine the extinction. The similar colors of EXO 0748−676 and the standard stars (Table 2) allowed the conversion of instrument magnitudes to a standard system V magnitude. The paucity of suitable standard observations for use in conversion to a standard system magnitude limited the overall accuracy in calibration of all reduced data points to the same error of ± 0.08

TABLE 2

COLORS OF EXO 0748−676 AND PMT STANDARDS

Source	$B-V$	$U-B$
EXO 0748−676	0.07	−0.86
EG 274	−0.14	−0.96
LTT 4364	0.20	−0.63
LTT 4816	0.18	−0.70
LTT 7987	0.07	−0.66

mag (1 σ). The smaller errors shown in Figure 1 are those of standard counting statistics, and are used in order to highlight the significant features of the light curve. The data appearing in Figure 1 have been rebinned to 32 s from the original 10 ms integration time.

Observation of the source for this night is not continuous as instrumental and observing difficulties caused gaps which appear in the data set. There is what seems to be a discontinuity in the average flux of the source; after the gap at $\Phi \sim 0.65$ the average flux of the source jumps by ~ 0.2 magnitude. The change in the flux late in the cycle ($0.65 < \Phi < 0.8$, hereafter the "flare"), although unusual and occurring during high airmass (all flare data collected while airmass ≥ 1.9) this feature is most likely intrinsic to the source. Examination of the sensitivity of both channels reveals stable behavior over the time of the observations. Similarly, the sky background data are smoothly varying, with no discontinuities or jumps at the corresponding time of the flare.

3. OBSERVATIONAL RESULTS

3.1. *Optical Light Curve*

The optical light curve of EXO 0748−676 is known to be variable with significant variation even appearing between consecutive cycles (e.g., SZ90). In order to compare our observations to earlier data we have folded the optical data on the orbital period (Fig. 2). The March 25 data were rebinned to the mean CCD integration time (600 s) before folding to give an approximately equal weighting for each data set in the mean curve. For those bins which contain one or two data points the errors are taken to be the observational error (marked with a box) while for those phase bins which have three or more observations errors are estimated from the scatter of the data points. The morphology of our folded curve matches that seen in previous photometric observations (Crampton et al. 1986; Schmidke & Cowley 1987; van Paradijs, van der Klis, & Pedersen 1988; M89; SZ90) with our mean curve displaying the expected flattened sinusoidal profile. Earlier observations of the optical light curve show gross modulation to be phase locked and the minimum light coincident with the X-ray eclipse ($\Phi = 0$). Although we have no optical observations for $0.9 < \Phi < 0.05$, our folded light curve shows clearly that the minimum optical brightness will be near the expected X-ray phase.

Comparison between nights shows that the optical light-curve morphology can change significantly. The prominent broad minimum late in the cycle of March 21 is weakened in the March 23 cycle and not evident at all on March 25. Small amplitude fluctuations (amplitude ~ 0.1 mag and time scale ~ 0.1 phase) occur in our observations (March 21 and 25) and are reminiscent of the stochastic dipping of the X-ray light curve. During the observed times of X-ray dipping ($\Phi = 0.65$, 0.8–0.2) the X-ray spectrum is found to harden which Parmar et al. (1986) interpret as being due to photoelectric absorption, perhaps caused through occultation of the X-ray source by the disk rim. Earlier investigators (Schmidke & Cowley 1987) have noted that a possible relationship between the optical fluctuations and dipping might exist; however, our data do not show this. The observed fluctuations do not occur for the expected dipping times and, where simultaneous X-ray data exist, no corresponding X-ray hardening occurs during the optical fluctuation (partial coverage of $\Phi = 0.35$ fluctuation on March 25, shown in Fig. 3).

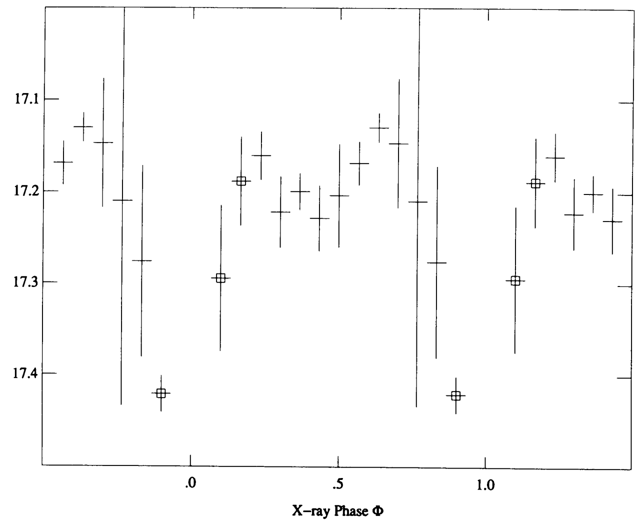

FIG. 2.—The folded light curve using all the 1989 March observations. All time bins have errors estimated from the scatter between data points that fall within them except for those bins identified by the box symbol. Errors for these bins have been estimated using the observational error of the data contained therein.

3.2. *Optical Light-Curve Morphology and X-Ray/Optical Mean Emission States*

The shape of the mean optical ight curve has been shown by M89 to be correlated with the mean optical emission level (which M89 suggest is best determined from the visual magni-

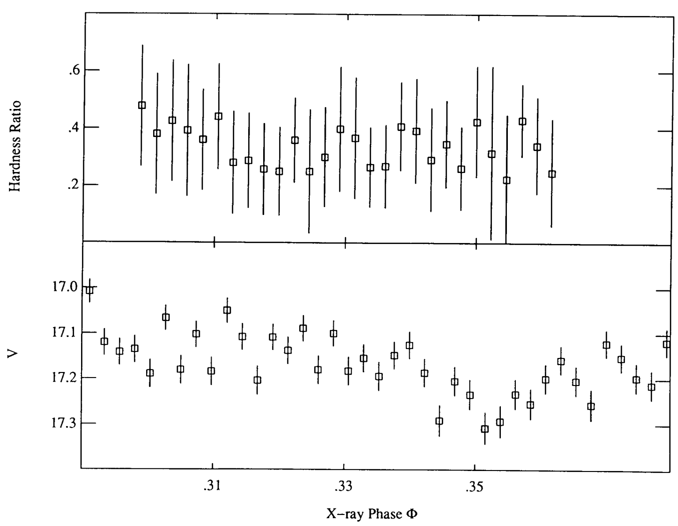

FIG. 3.—X-ray hardness ratio compared to a fluctuation feature of March 25 optical data. The hardness ratio is known to increase significantly during episodes of X-ray dipping, however no change in hardness is apparent for the simultaneous coverage of this optical fluctuation.

tude at $\Phi = 0.5$). The optical counterpart is thought to display two states, a high state ($V_{\phi=0.5} = 16.9$) in which a broad minimum from phase 0.6–1.2 is observed and a low state ($V_{\phi=0.5} = 17.3$) for which the optical light curve is seen to flatten and the broad minimum disappears.

Our optical light curves were examined to determine if their morphology was indicative of one of the emission states identified by M89. Our data were cross-correlated with data points linearly interpolated from M89 curves (Fig. 3 in M89) and cross-correlation was performed in magnitude space. Table 3 lists the resultant unweighted correlation coefficients (r) and the corresponding probabilities of significance (P). The results show high overall probabilities of correlation exist between our data and either of the M89 curves. March 21 data are correlated best with the M89 high state curve and the March 23, 25, and folded light curves most significantly correlated with the M89 low-state curve. These correlations as a whole imply a low to intermediate state light-curve morphology for the source during the period of our observations and is a result which is consistent with the measured optical state of the source ($V_{\Phi=0.5} = 17.18 \pm 0.02$, determined from the mean optical flux of the folded light curve between $0.4 < \Phi < 0.6$). While we cannot exclude the effect of stochastic variability in significantly driving values of the correlations toward signifying one M89 morphological state over the other, the overall high correlations suggest the majority of the light-curve modulation is stable, and thus we tentatively confirm the existence of a correlation between the optical light-curve shape and mean emission state.

M89 have observed the out of eclipse mean X-ray (1–20 keV) and optical (V band) emission to be tightly correlated in EXO 0748−676. Using the M89 results as a predictor, we find our X-ray observations reflect a system state different from the optically determined one. S89 find the 1–20 keV flux of EXO 0748−676 is 8.8×10^{-10} ergs cm^{-2} s^{-1} on March 24–26 a value indicative of the bright state, clearly different from the observed intermediate to low optical emission state. The apparent discrepancy in the relationship of the X-ray/optical emission observed in our data with that observed by M89 is possibly linked to the transient nature of this system. We note our observations of this source occur further in time from the initial X-ray outburst of this system than do those of M89. It may be that in the time since the M89 observations a new relationship between the X-ray and optical emission has developed due to some intrinsic change in the source. For example, a shift in the size of the X-ray reprocessing site is a possible explanation.

3.3. *X-Ray Reprocessing and Geometric Modulation*

Simultaneous X-ray/optical data may be used to test reprocessing theory. The reprocessing relationship (eq. [1]) predicts that X-ray and optical light will covary with a certain slope α in a flux-flux plot. Each X-ray band (1–5) was cross-correlated with simultaneous March 25 data. In these calculations no adjustment was made for an optical time lag as this has been estimated to be only a few seconds (from optical burst data, SZ90) which is a negligible effect given the 32 s binning of our data. We find no significant correlation exists between any X-ray band and our optical observations.

The lack of significant covariablity in EXO 0748−676 is puzzling. We note two factors that may be present in masking reprocessing information.

1. Correlated variability may be hidden by nonreprocessing modulation. In prior studies of this kind, authors have noted the role accretion geometry may play in obscuring a reprocessing signal (Motch et al. 1989a; Machin et al. 1990; C89). We attempted to remove the "geometric modulation" from our data to recover any "reprocessing modulation." As the X-ray data did not show strong geometric modulation (no X-ray data were obtained during the eclipse nor does X-ray dipping occur—evident through the lack of change in the X-ray hardness ratio) we attempted to remove geometric behavior only from the optical light curve. There were too few data to minimize geometric modulation by inspecting short intervals of data, therefore the folded light curve was adopted as the mean geometric behavior and subtracted from the data set in magnitude space. Figure 4 shows the 0.55–20.9 keV versus optical flux for both folded curve subtracted and unsubtracted optical data. As some systems have shown covariability only during times of maximum optical emission (Sco X-1, Canizares et al. 1975; 4U 1556−605, Machin et al. 1990), we have distinguished between flare and nonflare data (identified with crosses and filled circles, respectively, in the diagram). The expected

TABLE 3

Cross Correlation between M89 Light Curves and March Optical Data

Date	High State Curve r	High State Curve P (%)	Low State Curve r	Low State Curve P (%)
March 21	0.5047	95.39	0.2222	59.18
March 23	0.7997	99.69	0.9535	>99.99
March 25	0.1240	97.60	0.4195	>99.99
Folded	0.6908	99.11	0.7671	99.78

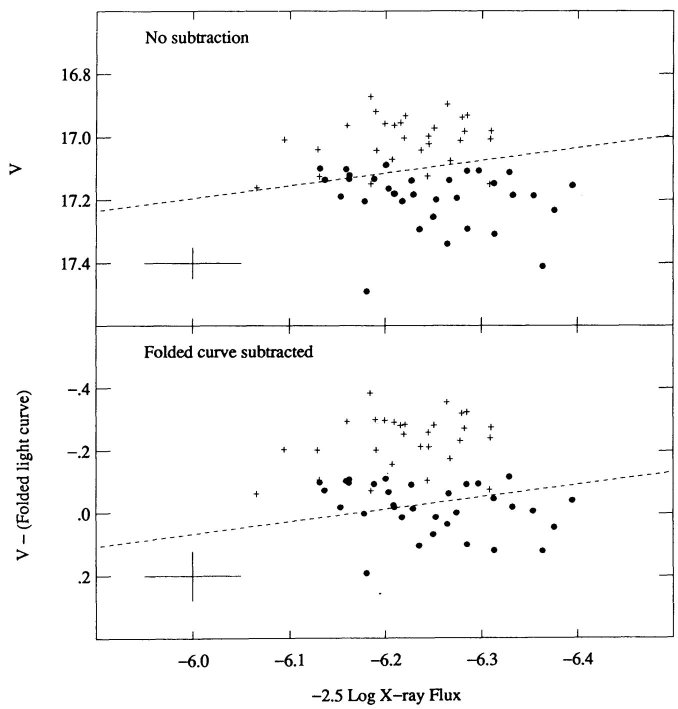

FIG. 4.—Simultaneous optical versus X-ray data (0.5–20.9 keV) for both subtracted (*top*) and unsubtracted (*bottom*) data sets. Flare and nonflare data are represented by crosses and filled circles, respectively, with typical errors shown in the left-hand corner. The dashed line in each diagram represents the expected slope from a blackbody of temperature $T = 3 \times 10^4$ K.

reprocessing relationship ($\alpha = 0.4$) is shown in Figure 4 for comparison. No significant reprocessing modulation was recovered in either the entire or flare exclusive portions of the subtracted data set. If either of the M89 folded light curves are substituted for the folded light curve in subtraction similar results are obtained. Strong geometric behavior in this system is possibly obscuring the reprocessing signal. We note that such a result is consistent with the suspected high inclination angle of this system. It is reasonable to expect that greater modulation from geometric effects would result as the viewing angle approaches that of the plane of the binary.

2. Our coverage of the system behavior is limited. The dynamical range and total time of other LMXB observations have often been longer than the known or estimated orbital period of the studied system. Relative to these previous studies our investigation is clearly limited. Our simultaneous observations range over less than one cycle with a total observational duration equal to $\sim 17\%$ of the orbital period.

4. CONCLUSIONS

Our data show that the relationship between the X-ray and optical emission has changed from that observed by M89. EXO 0748−676 may be in a previously unobserved reprocessing "mode" for which a changed system geometry has caused a new relationship between the mean X-ray and optical brightnesses. A smaller X-ray reprocessing area is one plausible explanation.

No evidence for X-ray reprocessing is found in our measurements of simultaneous quiescent emission. It is probable that the expected reprocessing correlation is masked by stronger uncorrelated geometric modulations and/or by the small dynamic range and limited total time of our data set. The changing morphology of the optical light curves and evidence of substantial geometric modulation point to the existence of a complex accretion geometry in this system. In order to determine the role of geometric modulation in masking reprocessing behavior longer simultaneous observations of EXO 0748−676 are required.

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