OPTICAL STUDIES OF THE TRANSIENT DIPPING X-RAY SOURCES X1755–338 AND X1658–298 IN QUIESCENCE

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ABSTRACT

We have studied the optical counterparts of X1755–338 and X1658–298 in their X-ray “off” states. The first observations of X1755–338 in quiescence show that the counterpart, V4134 Sgr, has faded by more than 3.5 mag in V. If the mass donor in the system is an M0 V star, as implied by the period, our upper limits on the brightness of the counterpart suggest that it is more distant than 4 kpc.

We observed V2134 Oph, the optical counterpart of X1658–298, on several occasions in 1997 April/May and found the source only ~1 mag fainter than when it is X-ray bright. Contemporaneous X-ray data confirm that the source remains in the quiescent state during our optical observations. Our optical light curve, folded on the 7.1 hr orbital period, does not show any modulation across the binary cycle. It is possible that the absence of detectable X-ray emission, despite the indication for an accretion disk and activity in the system, is related to a structure in the disk that permanently obscures the central X-ray source. The optical properties of V2134 Oph are unique among the known X-ray transients.

Subject headings: stars: individual (V4134 Sagittarii, V2134 Ophiuchi) — stars: variables: other — X-rays: stars

1. INTRODUCTION

About 10 systems among the low-mass X-ray binaries (LMXBs) exhibit irregularly shaped, recurrent dips in their X-ray light curves. These X-ray dippers are believed to be high-inclination systems in which azimuthal accretion disk structure extends above the plane of the binary and periodically blocks the line of sight to the central compact object. Modeling shows that for the majority of systems, this structure must be at the disk edge, at the impact point of the accretion stream (White, Nagase, & Parmar 1995 and references therein). The recurrence time of the dips is assumed to reflect the orbital period. The optical/IR emission from dippers also varies on the orbital period and originates largely from reprocessing of X-rays in the outer regions of the system.

Observations of LMXBs during X-ray quiescence offer the opportunity to study the optical counterpart “uncontaminated” by contributions to the optical/IR from reprocessed X-radiation in the disk and secondary. Light from the accretion disk usually dominates in the X-ray active state. During quiescence, the mass donor becomes visible, which allows the determination of its spectral type and radial velocity curve. Radial velocity measurements can provide the mass function and scale of the system and help to distinguish whether the compact object is a neutron star (NS) or a black hole (BH).

2. OBSERVATIONS

CCD B-, V-, Rc-, and Ic-band photometry of X1755–338 and X1658–298 was performed with the CTIO 1.5 m telescope in 1997 April/May under good seeing conditions (1”–1.2”). Exposure times ranged from 600 to 900 s at a pixel scale of 0.24 pixel^{-1}. Overscan and bias corrections were made for each CCD image with the task “QUADPROC” at CTIO to deal with the four amplifier readout. The data were flat-fielded in the standard manner using IRAF.

Our V-band images of the X1755–338 and X1658–298 fields are shown in Figures 1 and 2, respectively. All comparison stars used in the analysis are marked. Photometry was performed by point-spread-function fitting with DAOPHOT II (Stetson 1993). The instrumental magnitudes were transformed to the standard system through observations of several standard star fields (Landolt 1992). The resulting magnitudes of X1755–338, X1658–298, and several local comparison stars are listed in Table 1. The systematic error (from the transformation to the standard system) in these optical magnitudes is ±0.10 mag. For X1658–298, the intrinsic 1σ error of ±0.02 mag in the relative photometry was derived from the rms scatter in the light curve of comparison stars of similar brightness.

3. RESULTS AND DISCUSSION

3.1. X1755–338

X1755–338 was first noted for its very soft X-ray spectrum by Jones (1977). Observations with Einstein identified it as a BH candidate because of its location in the ultrasoft region of the X-ray color-color diagram (White & Marshall 1984). The Einstein spectra also indicated a lower than expected column density for a source close to the Galactic bulge. EXOSAT observations by White et al. (1984) revealed recurrent dips of 30 minute duration with a period of 4.4 hr. Unlike in other X-ray dippers, the hardness ratio did not change between dip and nondip periods. One explanation offered for this energy independence of the X-ray dips was a reduction in the metallicity of the absorbing medium by a factor of 600 from cosmic abundance values. Church & Balucinska-Church (1993) fitted the same observations with a two-component model and were able to reproduce the energy independence of the dips with absorption in material of cosmic abundances. They interpret the blackbody component of their model as emission from the
boundary layer between the accretion disk and the surface of an NS, calling into question the BH candidacy of X1755–338. Pan et al. (1995) reported the detection of a hard power-law tail in addition to an ultrasoft component in the X-ray spectrum of X1755–338 and strongly argued in favor of X1755–338 being a BH candidate. Simultaneous *Ginga* and *ROSAT* observations confirm the hard tail and also show the iron 6.7 keV line, indicating that the accreted material is not extremely metal deficient (Seon et al. 1995).

A faint, blue star with a featureless spectrum was suggested as the optical counterpart of X1755–338 by McClintock et al. (1978). Mason, Parmar, & White (1985, hereafter MPW) obtained simultaneous optical and *EXOSAT* observations of X1755–338. Their detection of sinusoidal modulation in the *V* band with an amplitude of 0.4 mag and a period of 4.46 hr confirmed the identification of the counterpart (V4134 Sgr). The optical minimum occurs 0.15 cycles later than the center of the X-ray dip, consistent with the idea that the X-rays are being absorbed in material located at the impact point of the accretion stream with the accretion disk.

In 1996 January, X1755–338 was observed by the *Rossi X-Ray Timing Explorer* (RXTE) in an X-ray off-state (a factor of 100 fainter than usual) for the first time (Roberts et al. 1996). We obtained optical observations in order to determine the nature of the mass-donating star. The *RXTE* All Sky Monitor (ASM) light curve (available on the Web) confirms that the source remained in the off state during our observations. Figure 1 displays our *V*-band observation of the X1755–338 field from 1997 April 28 UT. For comparison, a section of the finding chart that shows the source in its bright state is also reproduced (with the kind permission of K. Mason). The counterpart has faded from its on-state brightness of $V = 18.5$ (MPW) to undetectable magnitudes. We obtained upper limits on the counterpart brightness of $V > 22$, $R > 21.5$, and $I > 21$. Our *V* magnitudes for comparisons 1–4 (see Table 1) agree with the measurements of MPW within the uncertainties. The distance to X1755–338 is not well determined. Estimates in the literature range from 1 to 9 kpc, and values for the visual extinction lie between $1 < A_V < 2$ (MPW).

In order to derive a distance from our magnitude limits, we must consider the origin of the optical quiescent emission in X1755–338. In quiescence, the main light source in the system is most likely the mass-donating star. There is evidence for a disk even in quiescence in soft X-ray transients, but it generally does not contribute much of the light in the system (McClintock & Remillard 1990; Marsh, Robinson, & Wood 1994).

### Table 1: Photometry of X1755–338 and X1658–298

| Object   | $V$  | $(B-V)$ | $(V-R)$ | $(R-I)$ |
|----------|------|---------|---------|---------|
| V4134 Sgr…….. | $\geq 22$ | ... | ...$^b$ | ...$^b$ |
| 1         | 18.12 | 0.78    | 0.65    |         |
| 2         | 18.30 | 0.78    | 0.69    |         |
| 3         | 18.52 | 0.98    | 0.86    |         |
| 4         | 18.23 | 1.06    | 0.89    |         |
| X1658–298 |      |         |         |         |
| V2134 Oph…….. | 19.54 | 0.80    | 0.53    | 0.49    |
| 1         | 21.74: | ...$^a$ | 1.46    | 1.43    |
| 2         | 16.29 | 1.34    | 0.82    | 0.68    |
| 3         | 18.32 | 0.92    | 0.56    | 0.53    |
| 4         | 18.24 | 1.01    | 0.60    | 0.58    |

$^a$ $R > 21.5$.

$^b$ $I > 21.0$.

$^c$ Nomenclature of comparisons follows MPW.

$^d$ The star is not detected in $B$. 

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Fig. 1.—*Left*: *V*-band exposure of V4134 Sgr (X1755–338), marked X, during outburst in 1984 (MPW). North is up, and east is to the left. *Right*: Our 900 s *V*-band exposure taken on 1997 April 28 UT with the CTIO 1.5 m telescope of the same field. Notice that the counterpart of X1755–338 has vanished.

Fig. 2.—600 s *I*-band exposure of the X1658–298 field. The field size is $96' \times 96'$. North is up, and east is to the left. V2134 Oph, the counterpart of the X-ray source, is flagged.
X1755–338 has been X-ray bright for over 20 yr, which is very different from typical transient behavior (relatively short X-ray outbursts separated by long periods of quiescence). For the remainder of the discussion, we assume that all of the light originates from the mass donor. Using the period-mass relations of Frank, King, & Raine (1992, p. 51) and Warner (1995, p. 111), together with the 4.46 hr period of the system (MPW), results in mass estimates for the donor star of 0.49 $M_\odot$ and 0.42 $M_\odot$, respectively. If the stars are normal main-sequence stars, these masses imply a spectral type of K9–M1 (Allen 1973, p. 209). Our upper limits in $I$ require an M0 V star with $A_v = 1$ to be at a distance $d > 5$ kpc and at $d > 4$ kpc for $A_v = 2$ (using the extinction relationship of Cardelli, Clayton, & Mathis 1989). Alternatively, if we make no assumption about the spectral type of the donor star, at a distance of 9 kpc with $A_v = 2$ the spectral type of the donor would have to be later than K3 in order not to be detected in $I$.

### 3.2. X1658–298

X1658–298 is a transient X-ray burst source discovered in 1976 by Lewin, Hoffmann, & Doyt (1976). Observations during a temporary brightening of the source in 1978 showed dips in the X-ray light curve. Detailed analysis of the combined 1976–1978 data set by Cominsky & Wood (1984, 1989) revealed that some of the dips are in fact eclipses of the central X-ray source by the mass-donating star with a recurrence period of 7.1 hr. The dipping activity lasts for about 25% of the orbital cycle followed by an eclipse of ~15 minutes duration. X1658–298 entered an X-ray off state in 1979 and has not been detected in X-rays since.

The optical counterpart was identified during the 1978 X-ray outburst with a faint ($V = 18.3$), blue star (V2134 Oph) by Doxsey et al. (1979). Spectroscopic observations showed a blue continuum with emission lines of He II $\lambda$4686 and the C III/N III $\lambda\lambda$4640/4650 blend (Canizares, McClintock, & Grindlay 1979). In 1979 June, the counterpart was detected with $V = 21.5$; about a month later it was undetectable with a magnitude limit of $V > 23$ (Cominsky, Ossmann, & Lewin 1983). There is evidence that the source has been brightening gradually since then. Cowley, Hutchings, & Crampton (1988) mention obtaining a spectrum of the "very faint source" in 1986. Shahbaz et al. (1996) display a featureless spectrum of V2134 Oph taken in 1988 and estimate $V = 20.7$ for the brightness of the counterpart. Navarro (1996) reported that spectra taken in 1992/1993 showed He in emission, but that simultaneous VLA and Ginga observations failed to detect any radio or X-ray flux.

We observed V2134 Oph on several occasions in 1997 April/May and found the source at a mean brightness of $V = 19.54$, only ~1 mag fainter than when it is X-ray active. Since the only finding chart of X1658–298 was taken on photographic plates and is of limited quality, one of our I frames is displayed in Figure 2. We performed astrometry on our CCD frame to ensure that the observed star is indeed V2134 Oph and not a close companion unrelated to the X-ray source. Our position for V2134 Oph is $17^h02^m06^s.37, -29^d56^m44^s.33$ (J2000) with an internal uncertainty of 0.1 in each coordinate. Doxsey et al. (1979) list $17^h02^m06^s.37, -29^d56^m43^s.23$ for the counterpart (no error estimate is given), which differs by only 1" in declination. It therefore appears that the correct counterpart has been observed. A comparison between our $B - V$ color ($B - V = 0.80$) and that of Doxsey et al. (1979; $B - V = 0.37$) shows that the source is presently substantially redder than during outburst.

Cominsky & Wood (1984) discuss the properties of possible secondary stars consistent with producing a 15 minute eclipse in a 7.1 hr binary. The limiting cases are a 0.3 $M_\odot$ (M5) star that does not fill its Roche lobe viewed at an inclination of $i = 90^\circ$ and a 0.9 $M_\odot$ (G5) Roche lobe filling star viewed at an inclination of $i = 71^\circ$5. Using the period-mass relations of Warner (1995) and Frank, King, & Raine (1992) results in mass estimates of 0.75–0.78 $M_\odot$ for the donor star, which corresponds to a K0 main-sequence star. Cominsky (1981) derived a 15 kpc for X1658–298. At that distance, the small reddening ($E_{B-V} = 0.3$) and the limit of $V > 23$ imply that the secondary’s spectral type is later than K2. A K star companion is very typical for a large-amplitude X-ray transient. If we assume a K3 star mass donor at 15 kpc, it would contribute less than 5% to the current system brightness, so that most of the light is caused by an accretion disk. This is supported by our dereddened colors, which are marginally consistent (within the uncertainties) only with an F5 spectral type. Such a spectral type is too luminous for the previously observed faint source states.

Our optical light curve, folded on the 7.1 hr orbital period, does not show any modulation across the binary cycle (Fig. 3). This is somewhat surprising since many transients in quiescence display photometric variability because of ellipsoidal variations. However, these modulations could be masked by the presence of the apparently luminous accretion disk in X1658–298. An accretion disk with nonuniform illumination (e.g., with a hot spot) would also cause optical variability when viewed across the binary orbit. We place an upper limit of 0.02 mag (99% confidence) on the semiamplitude of any sinusoidal modulation in the folded light curve. Unfortunately, we cannot compare the outburst and quiescent variability characteristics, since there are no data available on the presence or absence of optical modulation during the 1978 outburst. We do not observe any eclipses, but owing to our limited phase coverage and the short duration of the eclipses, they could have been easily missed.

The optical behavior of X1658–298 is very different from other X-ray transients, which are characterized by a steep increase in optical brightness during an X-ray outburst and roughly constant magnitudes in quiescence. X1658–298, in contrast, seems to be brightening gradually in the optical with no accompanying evidence for an increase in the X-ray emis-
sion. The RXTE ASM confirms that the source remains at less than 1 mcrab during our observations. It is possible that the absence of X-ray emission, despite the indication for an accretion disk and activity in the system, is related to the apparent high inclination of X1658–298. Changes in the accretion rate could have altered the structure in the outer parts of the accretion disk in such a way that it now permanently obscures the X-rays emanating from the central source. This would also block our view of the inner, hotter regions of the disk, which is consistent with the redder colors of our observations.

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