X-RAY NOVA XTE J1550−564: OPTICAL OBSERVATIONS

RAJ K. JAIN[1] AND CHARLES D. BAILYN
Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101; raj.jain@yale.edu, bailyn@astro.yale.edu
JEROME A. OROSZ
Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802-6305; orosz@astro.psu.edu
RONALD A. REMILLARD
Center for Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Building 37, Cambridge, MA 02139-4307; rr@space.mit.edu
AND
JEFFREY E. MCCLINTOCK
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138-1516; jem@cfa.harvard.edu

ABSTRACT

We report the identification of the optical counterpart of the X-ray transient XTE J1550−564 described in two companion papers by Sobczak et al. and Remillard et al. We find that the optical source brightened by ≈4 mag over the quiescent counterpart seen at $B \approx 22$ on a SERC survey plate and then decayed by ≈1.5 mag over the 7 week–long observation period. There was an optical response to the large X-ray flare described by Sobczak et al., but it was much smaller and delayed by ≈1 day.

Subject headings: black hole physics — stars: individual (XTE J1550−564) — X-rays: stars

1. INTRODUCTION

Soft X-ray transients, also called X-ray novae (XNs), are mass-transferring binaries in which long periods of quiescence (when the X-ray luminosity is $\leq 10^{33}$ ergs s^{-1}) are occasionally interrupted by luminous X-ray and optical outbursts (Tanaka & Shibazaki 1996). X-ray novae are unique objects since they provide the most compelling evidence for the existence of stellar mass black holes (Cowley 1992). Using optical photometry and spectroscopy, eight XNs have been shown to contain a black hole (van Paradijs & McClintock 1995; Bailyn et al. 1998; Orosz et al. 1998b), since the mass of the primary exceeds the maximum stable limit of a neutron star ($\approx 3\ M_\odot$; Chitre & Hartle 1976).

The soft X-ray transient XTE J1550−564 was discovered with the All-Sky Monitor (ASM; Levine et al. 1996) on the *Rossi X-Ray Timing Explorer* (*RXTE*) in 1998 September 6 (Smith et al. 1998). This object became the brightest X-ray nova yet observed by *RXTE* (Remillard et al. 1998). A high-frequency QPO at ≈185 Hz has been observed on two well-separated occasions (McClintock et al. 1998; Remillard et al. 1999, hereafter Paper II). Although the true nature of this object has yet to be confirmed, XTE J1550−564 is likely to be a black hole based on its characteristic soft X-ray spectrum, the hard power-law tail (Sobczak et al. 1999, hereafter Paper I), and high-frequency QPOs (Paper II).

Shortly after the X-ray discovery, the optical counterpart was identified within the *RXTE* error box (Orosz, Bailyn, & Jain 1998a). We present optical light curves obtained during the outburst of XTE J1550−564 as part of a multiwavelength campaign. The spectral analysis of the *RXTE* Proportional Counter Array data as well as the ASM light curve and a timing study based on the same *RXTE* observations are presented in companion papers (Paper I; Paper II).

Although much can be learned about XNs by studying the X-ray data alone, simultaneous optical observations can provide tighter constraints for various accretion disk models. For example, optical, UV, and X-ray data obtained during quiescence of several black hole XNs have been used to demonstrate the successful application of the advection-dominated accretion flow (ADAF) model, whereas thermal emission from a thin-disk model is inconsistent with these observations (Narayan, McClintock, & Yi 1996; Narayan, Barret, & McClintock 1997a; Narayan, Garcia, & McClintock 1997b). Furthermore, the 6 day time delay between the optical and X-ray outbursts of GRO J1655−40 observed in 1996 April (Orosz et al. 1997) has also been successfully modeled by an accretion flow consisting of a cold outer disk and a hot inner ADAF region (Hameury et al. 1997). The extensive X-ray and optical coverage of the outburst of XTE J1550−564 provides further opportunities to test accretion disk models and ADAF models in particular. We report our optical observations, data reductions, and results.

2. OBSERVATIONS AND REDUCTIONS

We obtained photometry using the Yale 1 m telescope at the Cerro Tololo Inter-American Observatory, which is currently operated by the YALO (Yale, AURA, Lisbon, Ohio State) consortium. This telescope is ideally suited for observing X-ray transients and other objects that require continuous long-term monitoring. Data are taken every clear night by two permanent staff observers, and observations are requested by a queue that can be changed quickly in response to discoveries. The data reported here were acquired using the ANDICAM optical/IR camera that contains a TEK 2048 × 2048 CCD with 10.2 × 10.2 arcmin^2 field of view with a scale of 0″.3 pixel^{-1}. The IR array was not available at the time of our observations.

On September 8.99 (UT), we obtained images of two fields in response to the announcement of the initial detection of XTE J1550−564 by *RXTE* (Smith et al. 1998). For each field, a 60 s and a 300 s exposure was obtained in both *V* and *I*. The 300 s *V*-band images were compared with images of the same regions extracted from the Digitized Sky Survey (DSS) CD-ROM set (Sturch et al. 1993). We identified a $V \approx 16$ star as the optical counterpart, since it appeared in all of the CCD images we obtained, but not in the DSS image (Orosz et al.

[1] Also Department of Physics, Yale University, P.O. Box 208120, New Haven, CT 06520-8120.
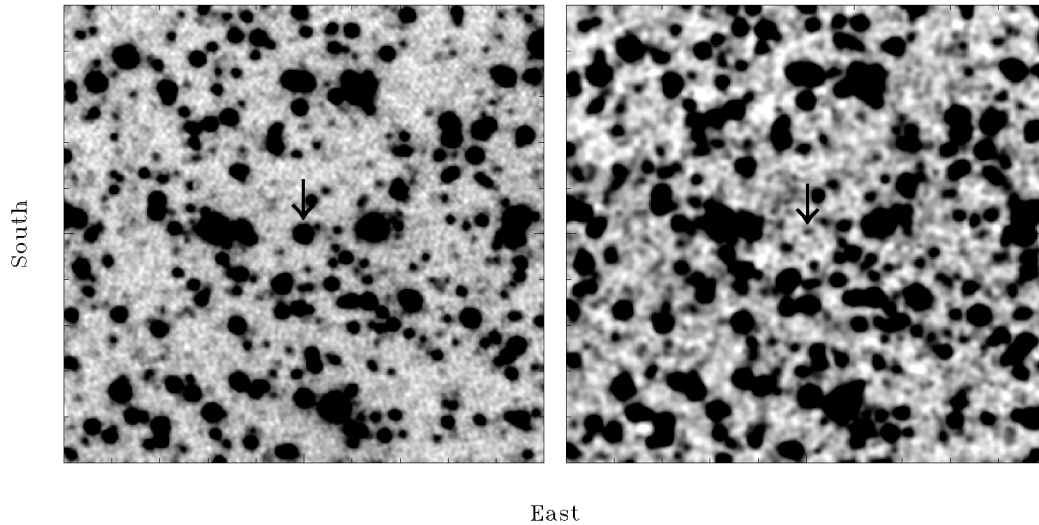
Fɪɢ. 1.—*Left*: The YALO 1 m telescope *V* image (2′ × 2′) of 1998 September 8. The optical counterpart is marked with the arrow. *Right*: A scanned image of the 1.22 m UK Schmidt SERC J Survey plate J2977 showing the same region of the sky. The arrow points to the optical counterpart in quiescence. Both images have been smoothed by convolution with a Gaussian (width = 1.5 pixels) and stretched by a similar amount to bring out faint objects. There is a slight mismatch between the effective bandpasses of the two images.
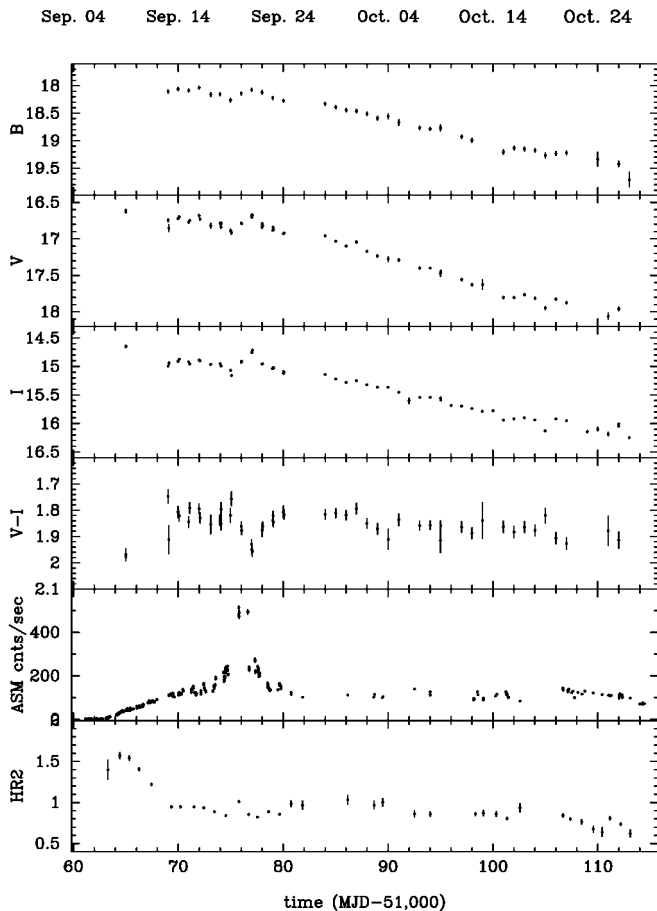

Fɪɢ. 2.—*From top to bottom*: The *B*, *V*, *I*, and *V*−*I* light curves. The *RXTE* ASM light curve (note the bright flare near day 51077), and the *RXTE* HR2, which is defined as the ratio of ASM count rates between 5–12 and 3–5 keV. MJD is defined as JD −2,400,000.5.

1998a; see Fig. 1). There were several *Hubble Space Telescope* (*HST*) guide stars in the CCD image, which allowed us to determine the J2000 coordinates of $\alpha = 15^{\mathrm{h}}50^{\mathrm{m}}58\fs78$, $\delta = -56°28'35\farcs0$, with errors of $\lesssim 2''$. The quoted error corresponds to the maximum systematic error present in the *HST* Guide Star Catalog (Russell et al. 1990). A variable radio source was detected on September 9 at a position consistent with that of the optical transient (Campbell-Wilson et al. 1998). Finally, spectroscopic confirmation came on September 16, when Castro-Tirado et al. (1998) showed that the optical variable had emission lines of H, He ɪɪ, and N ɪɪɪ, typical of X-ray transients in outburst.

We observed the source on all nights for which weather and instrumentation permitted between 1998 September 8.99 and October 26.9, when the object was no longer observable in the night sky (see Fig. 2). The exposure times were 120–300 s for *V* and *I* and 300–600 s for *B*. The seeing varied from night to night, ranging from 1″.3 to 3″, with a typical value of 1″.7. A time series of the optical data was obtained using the IRAF versions of DAOPHOT and ALLSTAR and the stand-alone code DAOMASTER (Stetson 1987, 1992a, 1992b; Stetson, Davis, & Crabtree 1990). The DAOPHOT instrumental magnitudes were calibrated to the standard scales using standard stars from the list of Landolt (1992).

3. THE QUIESCENT OPTICAL COUNTERPART

The Royal Observatory Edinburgh (ROE) maintains a large archive of photographic plates of southern sky fields taken with the UK Schmidt telescope located at the Anglo-Australian Observatory. There are 10 plates on which the XTE J1550−564 field was well centered, and the exposure times were fairly long. S. Tritton of ROE kindly examined these 10 plates and photographed the ≈4′ × 4′ regions surrounding the positions of XTE J1550−564. The best quality plate is No. J2977 from 1977 March 20, which is the atlas plate for the SERC J survey.

A print of this plate was scanned using the Yale PDS micro-densitometer at a resolution of $0''.3$ pixel^{-1}. There is a faint star close to the position of XTE J1550−564 (see Fig. 1). We used the pixel coordinates of several bright comparison stars to determine the coordinate transformation between the CCD image and the scanned image. Based on this transformation, we find that the faint star in the scanned image is within $0''.5$ of the position of XTE J1550−564. Hence, this star is most likely the quiescent optical counterpart, although we cannot completely rule out the possibility that it is an unrelated field star. We performed aperture photometry of this faint star and several comparison stars in the scanned image and determined a B magnitude of $B = 22.0 \pm 0.5$ for the faint counterpart. This error represents the scatter in the differences between the calibrated magnitudes of the comparison stars and the magnitudes obtained from the scanned photographic image. The quiescent counterpart is not visible on any of the remaining nine plates, all of which have limiting magnitudes of $\lesssim 21$.

The amplitude of the outburst thus appears to be ≈ 4 mag, although this could be larger if the star appearing on the SERC J plate is not the actual quiescent counterpart. The outburst amplitude is intermediate between the relatively small optical outbursts seen in X-ray novae with early-type (F and A) companions like GRO J1655−40 and 4U 1543−47 (Bailyn et al. 1995; Orosz et al. 1998b) and the much larger outbursts seen in systems with later spectral types (van Paradijs & McClintock 1995). If this pattern holds, one may expect the secondary of XTE J1550−56 to be a main-sequence G star or perhaps an evolved giant. For main-sequence companions, Shahbaz & Kuulkers (1998) propose an empirical formula relating the orbital period to the outburst magnitude, which yields $P \approx 23$ hr for this case.

4. THE OUTBURST LIGHT CURVE

The optical magnitude of XTE J1550−564 varied much less during our observing period than the X-ray flux (see Fig. 2). During the span of 49 days that we have data for XTE J1550−564, the optical brightness in B, V, and I dropped by ≈ 1.5 mag, and the daily fluctuations were less than ≈ 0.15 mag between any two adjacent nights. In general, the B, V, and I magnitudes decayed steadily with the exception of an optical flare near September 21, which occurred approximately 1 day after the X-ray flare. There is also a 7 day plateau lasting from approximately October 15 to 21, during which the I magnitude fluctuated by less than 0.03 mag (the B and V magnitudes also fluctuated much less during this period compared with the previous 7 days).

The general features of the optical and X-ray light curves can be compared with other low-mass X-ray binaries (LMXBs) using the classifications by Chen, Shrader, & Livio (1997). Based on their classification, the exponentially decaying optical light curve of XTE J1550−564 with an e-folding time of ≈ 30 days can be described as a possible FRED (light curves that have either a Fast Rise or an Exponential Decay). In fact, most optical light curves of LMXBs are best described as possible FREDs, although the average e-folding time of 67.6 days (Chen et al. 1997) is longer than what we find for XTE J1550−564. Curiously, the optical decay is not correlated with the ASM X-ray light curve, which remains fairly constant after the flare.

Before we can compare properties such as the average intrinsic color and ratio of the X-ray–to–optical flux of XTE J1550−564 with those of other LMXBs, we must correct

for interstellar reddening. The reddening can be estimated from the average expected values of N_H that can be derived from the H I map by Dicky & Lockman (1990), in this case by using the FTOOLS routine NH. We obtained $N_H \approx 9 \times 10^{21}$ cm^{-2}, which yields an estimate of $A_V = 5.0$, assuming the relation between N_H and A_V of Predehl & Schmitt (1995). The Dicky & Lockman (1990) map represents the column density to infinity and thus might be an overestimate for a Galactic source embedded in the plane. However, the tentative distance of 6 kpc suggested in Paper I places the source 200 pc below the plane, well out of the Galactic dust layer. We note that the X-ray spectral analysis yields values of N_H about twice as large as is suggested by the H I maps—this may indicate self-absorption in the source.

Using the conventional relationship $A_V = 3.1 \times E(B-V)$ (Savage & Mathis 1979), we find $E(B-V) = 1.6$. This implies an intrinsic color of $(B-V)_0 = -0.25 \pm 0.04$ right after the flare, which is consistent with the average value of -0.09 ± 0.14 for a sample of LMXBs obtained by van Paradijs & McClintock (1995). Note that the much larger reddening implied by the X-ray column density in the absence of self-absorption results in an implausibly blue intrinsic color for XTE J1550−564. Using $A_V = 5.0$, we find an optical–to–X-ray flux ratio of ≈ 450 during the flare, comparable to the average value of 500 found by van Paradijs & McClintock (1995). This estimate assumes a flat optical spectrum between 3000 and 7000 Å, and a 2–20 keV X-ray flux derived from the spectral decomposition described in Paper I.

The optical response to the large X-ray flare that occurred near September 21 (see Paper I) was quite muted, with an amplitude of ≤ 0.2 mag. The $(V-I)$ color increased during the flare, which means that the optical outburst was redder than during the decay (see Fig. 2). On the other hand, the ASM hardness ratio (HR2, defined as the ratio of ASM count rates between 5–12 keV bands and 3–5 keV bands) increased, which means that the X-ray light curve was "bluer" during the flare (see Paper I for details). Although detailed spectral information about the optical flare is unavailable, the color and hardness ratios indicate a change in the spectrum across a wide range of wavelengths during the flare.

The optical response to the flare is delayed by about a day relative to the X-rays. To quantify this delay, we parameterized the light curves as described below. The fits are not perfect, and somewhat different results can be obtained with different fitting schemes. However, the qualitative relations between the different light curves persist no matter how the data are described. We fitted the ASM flare with a Lorentzian with a centroid of $51,076.2 \pm 0.1$ and an FWHM of ≈ 1.5 days (for convenience, we express time in days in the units of MJD = JD 2,400,000.5, where MJD 51,075 is 1998 September 19). We estimated the centroid and FWHM of the optical flare using a Gaussian to fit the flare and a linear component to fit the decay. We determined the centroids for the B, V, and I bands to be $51,077.3 \pm 0.2$, $51,077.05 \pm 0.02$, $51,077.05 \pm 0.03$, respectively, all of which occur approximately 1 day later than the X-ray peak as noted above. There is no significant offset between the times of the peaks of the optical flare in the B, V, and I light curves. In contrast, the duration of the optical event varied strongly with filter. One self-consistent solution yields the following values of FWHM for B, V, and I, respectively: 2.1 ± 0.5, 1.6 ± 0.1, and 1.6 ± 0.05 days. The relationship between the X-ray and optical flares is in dramatic contrast to the onset of the 1996 April outburst of GRO J1655−40, described by Orosz et al. (1997), in which the optical event pre-

ceded the X-rays by 6 days. That event was interpreted (Hameury et al. 1997) as an "outside-in" instability in the accretion disk. The flare in XTE J1550−564, on the other hand, appears to have begun deep in the accretion flow and subsequently propagated outward.

5. SUMMARY

We have identified the optical counterpart of XTE J1550−564 and analyzed the *B*, *V*, and *I* light curves from 1998 September 8.99 to October 26.9. We find that the X-ray and optical light curves are poorly correlated. The large X-ray flare was followed a day later by a small (0.2 mag) increase in the optical brightness. The tentative identification of a qui-

escent counterpart in sky survey images suggests that it will be possible to measure the mass function of the object after it has returned to quiescence.

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