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A study of the new X-ray transient RXTE J2123−058 during its post-outburst state

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ABSTRACT

We carried out *I*, *R*, *V* and *B* photometric observations of the neutron star X-ray binary RXTE J2123−058 shortly after the end of the X-ray outburst in mid-1998. We adopt the low-mass binary model to interpret our observations. After folding our data on the 0.24 821-d orbital period, and correcting for the steady brightness decline following the outburst, we observed sinusoidal oscillations with hints of ellipsoidal modulations which became progressively more evident. Our data also show that the decline in brightness was faster in the *V* band than in the *R* and *I* bands. This suggests both the cooling of an irradiation-heated secondary star and the fading of an accretion disc over the nights of our observations.

Key words: accretion, accretion discs – binaries: close – stars: individual: RXTE J2123−058 – stars: neutron – X-rays: stars.

1 OVERVIEW

RXTE J2123−058 was discovered as an X-ray transient by the *Rossi X-ray Timing Explorer* satellite (*RXTE*) in late June of 1998 (Levine, Swank & Smith 1998). Its X-ray flux in the 2–12 keV band was about 100 mCrab in the five measurements by the All Sky Monitor (ASM) on board *RXTE* on June 27–28, and was 65, 67 and 56 mCrab at 2–10 keV in the observations by the Proportional Counter Array (PCA) on June 27.09, 29.04 and 29.70 respectively (Takeshima & Strohmayer 1998). Two X-ray bursts were detected on June 27.98 and 29.70. A preliminary analysis suggested that they were Type I bursts (Takeshima & Strohmayer 1998).

The optical counterpart of RXTE J2123−058 was identified at the location RA = $21^{h}23^{m}14\overset{s}{.}54$, Dec. = $-5°47'52\overset{''}{.}9$ (equinox J2000: Tomsick et al. 1998a). Prior to the outburst it was barely visible as a faint star in a digitized UK Schmidt plate. During the outburst on June 30.44 UT the star brightened up to $U = 16.40$, $B = 17.28$, $V = 17.30$, $R = 17.24$ and $I = 17.22$ mag (with an uncertainty of 0.05 mag). The *R*-band light curve obtained between July 2 and 12 (Casares et al. 1998) showed triangular-shaped minima with a central depth of 0.65 mag. Based on this observation, a period of either 0.993 or 0.4965 d was proposed. The *V*-band observations on June 30–July 4 and July 15 and 16 (Tomsick et al. 1998b) showed quasi-sinusoidal oscillations, with an amplitude of 0.9 mag and a best-fitting period of 5.957 ± 0.003 h (0.248 21 ± 0.0001 d). The latter value is one-half of the 0.4965-d period that was previously proposed, but is consistent with the 5.9567 ± 0.0033 h period derived from the *V*-band data obtained by Ilovaisky & Chevalier (1998) from independent observations on July 3–18. The mean light curve had a flat top lasting a quarter of the orbital cycle and a broad triangular minimum which spanned the rest of the cycle. At maximum light, the *V*-band brightness was 16.8 mag. The ephemeris for the time of minimum brightness was HJD 245 1009.888(3) + 0.2482(1) × *N*. Optical bursts of amplitude ~0.3 mag were detected on June 30 and July 1 (Tomsick et al. 1998b).

The X-ray brightness of RXTE J2123−058 declined steadily after the outburst on June 29 (see Fig. 1: quick-look results provided by the *RXTE* team). By late August the 1-d average count rates had dropped to the pre-outburst level. The optical brightness also declined, at a rate of 0.1 mag d^{-1} (Zurita & Casares 1998). The average *R* brightness of the source had dropped to 19.1 mag on August 16, but the orbital modulation had increased from the previous value of 0.9 mag to 1.4 mag. Two narrow dips of 0.2 mag were observed at phases 0.0 and 0.5. From these data, Zurita, Casares & Hynes (1998) derived a revised ephemeris: HJD 245 1042.639(5) + 0.248 21(3) × *N*. On August 26 and 27, the *R* brightness was 21.50 ± 0.06 mag (Zurita & Casares 1998) and the light curve began to exhibit a secondary minimum, i.e. an ellipsoidal modulation owing to the tidal distortion and the uneven surface brightness distribution of the companion star. It is believed that the system had returned to its quiescent state by then.

We have carried out *V*-, *B*-, *R*- and *I*-band photometric observations of the X-ray transient RXTE J2123−058 from 1998 August 14 to 26. During our observations, the X-ray flux was in the final stage of decline and had almost reached the pre-outburst

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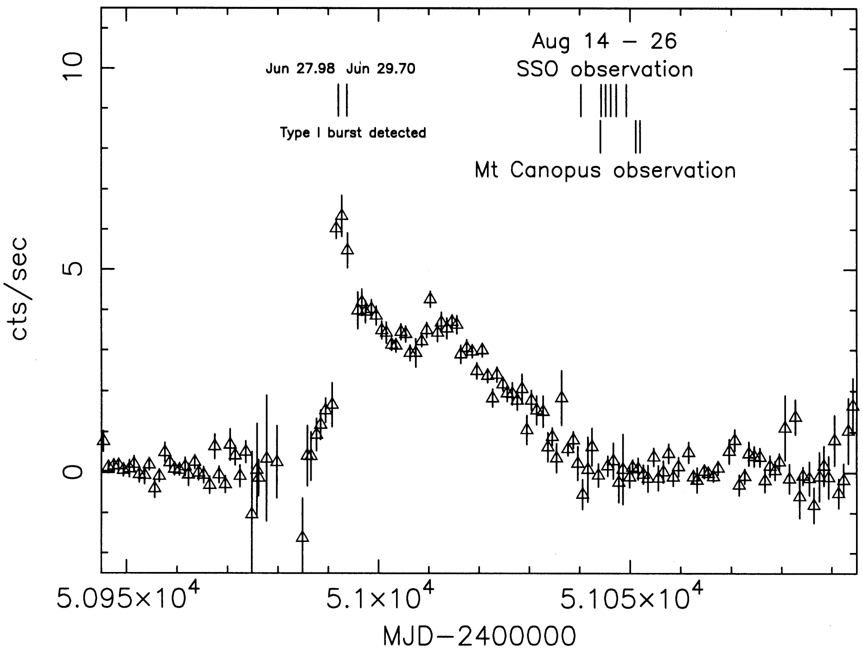

Figure 1. Dates of our photometric observations of RXTE J2123−058, with reference to its *RXTE*/ASM (2–10 keV) X-ray light curve during the outburst. The dates when the two Type I X-ray bursts were detected are also marked.

level. The system was in transition from an outburst to a quiescent state. Based on the currently available information, we propose a low-mass halo neutron star binary model for the system, and attempt to interpret our photometric data in the light of the proposed model.

2 OBSERVATIONS

The observations on 1998 August 14, 18, 19, 20, 21 and 23 were carried out with the Australian National University (ANU) 40-in telescope at the Siding Spring Observatory (SSO). We used a TEK 2048 × 2048 CCD mounted on the telescope. We took series of 300-, 400- and 600-s exposures in *V*, *R* and *I*, and a few exposures in *B* for colour calibration. The observing conditions were photometric during most of the runs. When the conditions were not photometric, the magnitude of RXTE J2123−058 was determined from a comparison with a calibration star in the same field. Standard fields from the Landolt (1992) catalogue were observed on each night.

The observations on August 18, 25 and 26 were carried out with the University of Tasmania (UTas) 1-m telescope at Mount Canopus. During the observations, the seeing was about 1.2 arcsec, and there were light clouds. We used an SBIG ST-6 375 × 242-pixel chip mounted at the Cassegrain focus. The exposure times were all 600 s.

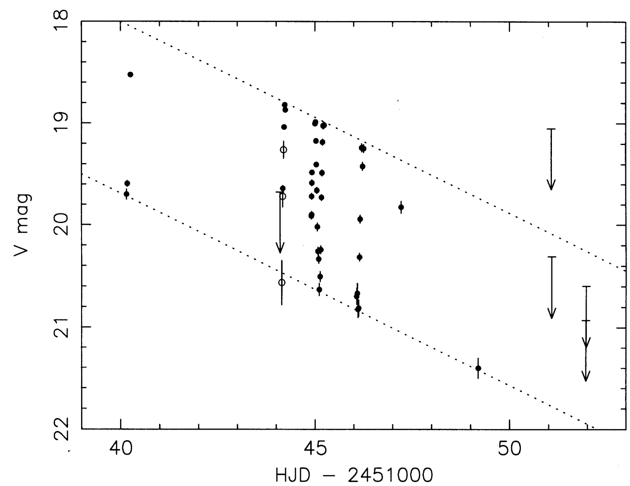

Figure 2. The decline in the *V*-band brightness during our observations. The data obtained by the ANU 40-in telescope at Siding Spring are represented by the filled circles, and the data obtained by the UTas 1-m telescope at Mount Canopus by open circles. When RXTE J2123−058 was not visible, an upper limit was set by the brightness of the faintest detectable star in the field. The two dotted lines are the estimated cycle-to-cycle upper and lower limits to the *V*-band magnitude for the data obtained by the ANU 40-in telescope. The decline in *V* is approximately linear between August 18 and 20. The slope of the lines is 0.20 mag d^{-1}. The available data are not sufficient to guarantee that the linear behaviour extends beyond that time-span.

3 PHOTOMETRIC LIGHT CURVES

The *V*-, *R*- and *I*-band data all show a large cycle-to-cycle modulation. The *V*-band light curve obtained at SSO between August 18 and 20 is shown in Fig. 2. The minimum values measured within each observed cycle are bounded by a straight line with a slope of 0.20 mag d^{-1}. The corresponding maxima are also bounded by a straight line with the same slope. This suggests a (quasi-)linear decline in the *V* brightness during these three nights. However, the available data are not sufficient to ascertain whether the linear behaviour extends to the whole time-span of our observations (August 14 to 23).

In order to deconvolve the effect of the brightness decline from the orbital modulation, we apply a fit with sinusoidal and linear components to the light curves. Each data point is then corrected to remove the effects of the linear decline. We consider only the observations on August 19–20 for which the sampling is sufficient and the decline is presumably closest to linear. The best-fitting linear corrections in each band are $0.200 \pm 0.001\,\mathrm{mag\,d^{-1}}$ for *V*, $0.085 \pm 0.002\,\mathrm{mag\,d^{-1}}$ for *R* and $0.020 \pm 0.010\,\mathrm{mag\,d^{-1}}$ for *I* (top and middle panels in Figs 3, 4 and 5). The corrected phase-dependent *V*-, *R*- and *I*-band light curves (folded with a period of 0.248 21 d) are shown in the bottom panels of Figs 3, 4 and 5.

We also observed the system in the *B* band briefly on August 14 and 18 (only six images taken). The *B* brightness (not shown) varied between 18.5 and 20.0 mag during our observations.

The photometric data in different bands were not taken simultaneously, therefore we cannot calculate the colour excess without interpolations; however, the rapid decline in brightness and the sparse sampling during our observations do not permit a reliable interpolation.

4 THE NATURE OF THE SYSTEM

The detection of Type I X-ray bursts implies that the compact star in RXTE J2123−058 is a neutron star. The distance determined by assuming an Eddington flux during the X-ray burst is about 14 kpc (Homan et al. 1999). However, the peak flux during the burst might not be at the Eddington limit. More often X-ray bursts are weaker, i.e. the peak luminosities are sub-Eddington (see e.g. Lewin, van Paradijs & Taam 1995). When the persistent flux is high (which indicates a high accretion rate), the hydrogen–helium rich matter on the surface of the neutron star might be heated to the ignition temperature for the thermonuclear reaction such that 'premature' bursts may occur. If we conservatively estimate that

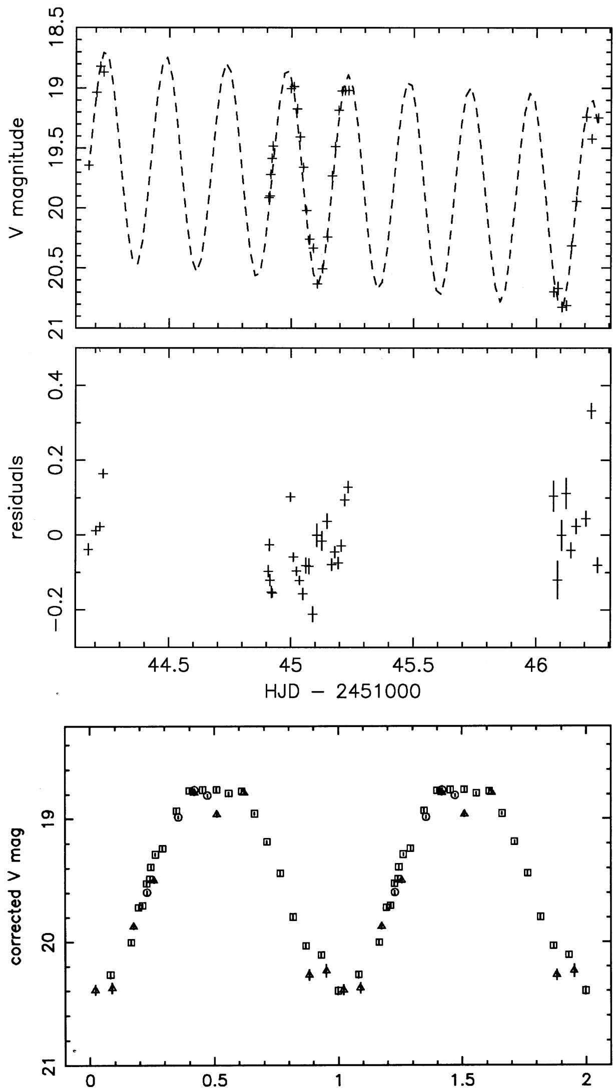

Figure 3. The best sinusoidal fit to the *V*-band light curve from the August 18–20 observations (top), the residuals of the fit (middle) and the folded *V*-band light curve (bottom). The rate of decline in the *V* brightness deduced from the fit is $0.200 \pm 0.001\,\mathrm{mag\,d^{-1}}$, and the amplitude of the brightness modulations is 0.884 mag. The period is kept fixed at 0.248 21 d in our fit. Dates for the observations are August 18 (circles), 19 (squares) and 20 (triangles).

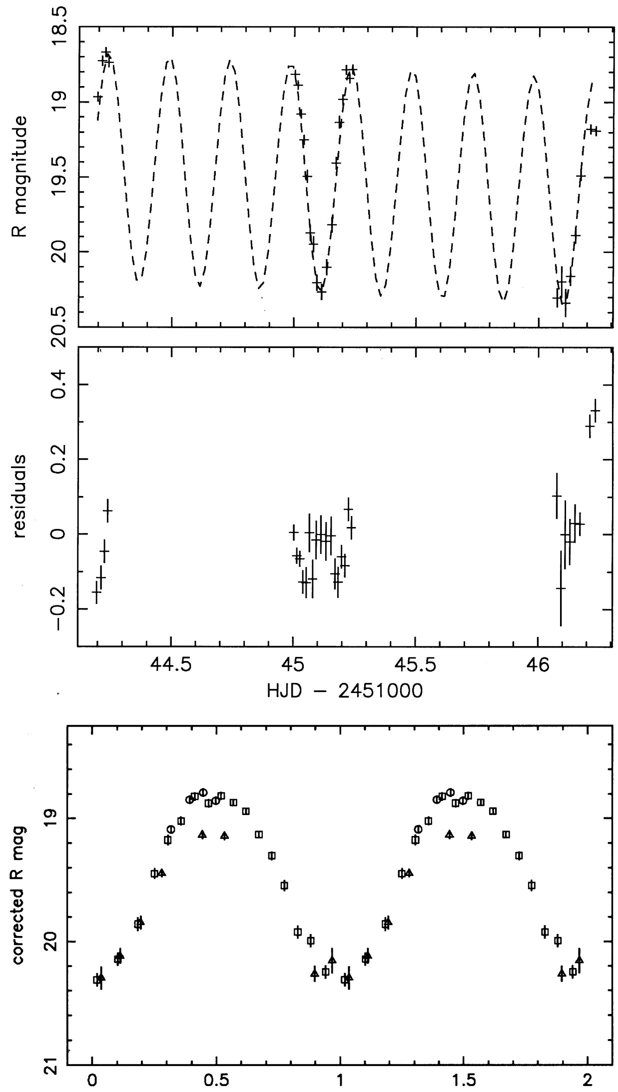

Figure 4. The best sinusoidal fit to the *R*-band light curve from the August 18–20 observations (top), the residuals of the fit (middle) and the folded *R*-band light curve (bottom). The rate of decline in the *R* brightness deduced from the fit is $0.085 \pm 0.002\,\mathrm{mag\,d^{-1}}$, and the amplitude of the brightness modulation is 0.761 mag. The period is kept fixed at 0.248 21 d in our fit. Dates for the observations are August 18 (circles), 19 (squares) and 20 (triangles).

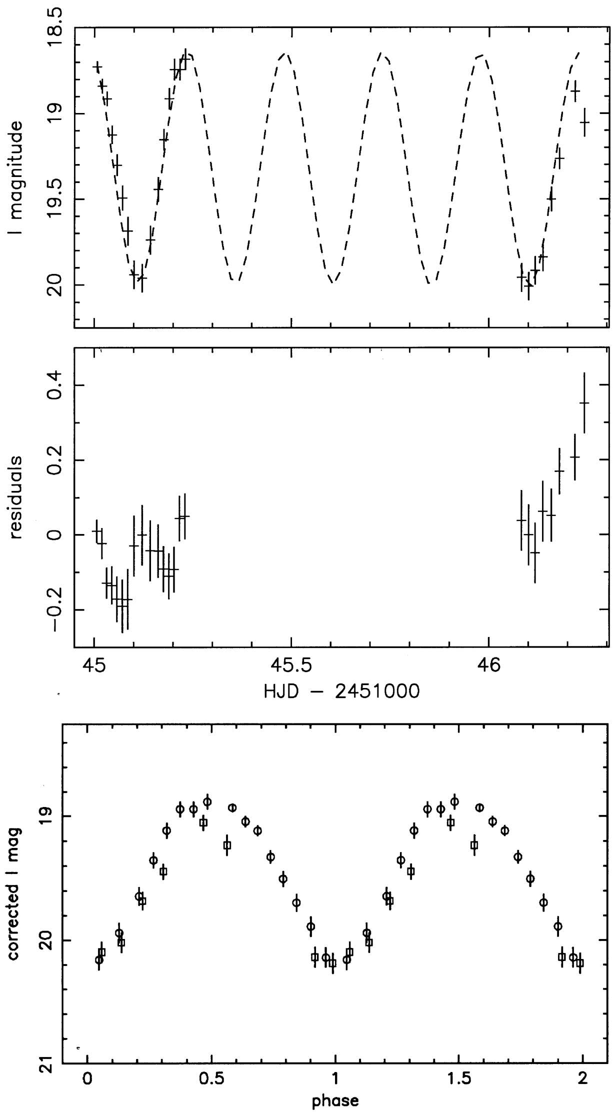

Figure 5. The best sinusoidal fit to the I-band light curve from the August 19–20 observations (top), the residuals of the fit (middle) and the folded R-band light curve (bottom). The rate of decline in the I brightness deduced from the fit is $0.020 \pm 0.010\,\mathrm{mag\,d^{-1}}$, and the amplitude of the brightness modulations is 0.681 mag. The period is fixed to be 0.248 21 d in the fit. Dates for the observations are August 19 (circles) and 20 (squares).

the peak luminosity during the peak of the X-ray burst is only 1/10 of the Eddington luminosity (there is, for example, a factor of about 6 to 7 between the maximum and minimum peak burst luminosities in 4U/MXB 1636–53: see Fujimoto et al. 1988), then the corresponding distance will be reduced by a factor of 3. This will lower the estimated distance of the source to about 5 kpc.

The 0.248 21-d period suggests that the system is a low-mass X-ray binary (see the catalogue of X-ray binaries compiled by van Paradijs 1995). In a low-mass system, the companion star must fill its Roche lobe to allow mass transfer to occur. We show in Fig. 6 the radius R_h of the companion star's Roche lobe (Eggleton 1983) as a function of its mass M_2 for a circular binary orbit and a 1.4-$\mathrm{M_\odot}$ primary. In the same diagram we also show the radii of stars in the mass range from 0.1 to $1.0\,\mathrm{M_\odot}$ derived from the evolutionary models given by Baraffe et al. (1998), at ages 0, 0.1 and 10 Gyr. The requirement that the radius R_2 of the companion star be approximately equal to its Roche lobe radius R_h

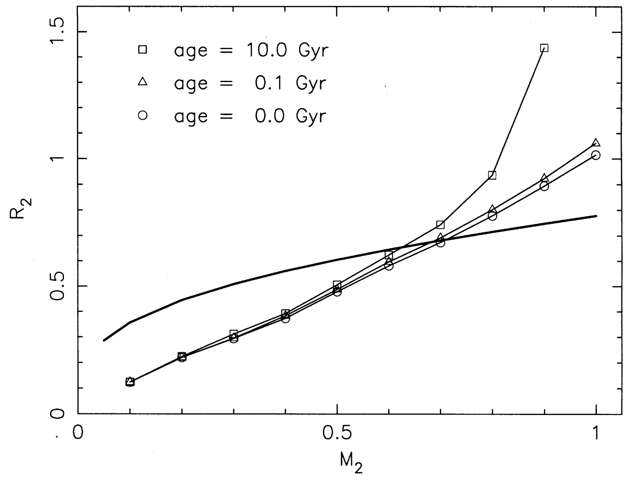

Figure 6. The Roche lobe radius (thick line) of the companion star in a neutron star binary with a circular orbit and an orbital period of 0.248 21 d, and the radius of the companion star for various ages. The Roche lobe radius is calculated using the Eggleton (1983) formula with the assumption that the mass of the neutron star is $1.4\,\mathrm{M_\odot}$. The radius of the star is derived from the luminosity–temperature relation in the evolutionary models given by Baraffe et al. (1998). Units are solar masses and solar radii on the x- and y-axes respectively.

implies $R_2 \lesssim 0.7\,\mathrm{R_\odot}$, and consequently restricts the mass of the companion star to be below $0.7\,\mathrm{M_\odot}$ if it is a hydrogen main-sequence star. Although a different mass limit can be obtained for helium stars, the detection of hydrogen absorption lines (Tomsick et al. 1998a) makes it unlikely that the companion star in RXTE J2123−058 is a helium star. The actual mass is probably slightly lower than $0.7\,\mathrm{M_\odot}$, as the star might have evolved off the main sequence. Moreover, the pre-outburst X-ray luminosity was weak, indicating that the star underfilled its Roche lobe. A low-mass companion star, a distance of ~10 kpc and Galactic coordinates of $l = 46°28'58''.4$ and $b = -36°11'57''.3$ imply that RXTE J2123−058 is an old low-mass X-ray binary in the Galactic halo.

5 COMPANION STAR

For a 0.7-$\mathrm{M_\odot}$ star with an age of about 10^8–10^9 yr, the absolute magnitudes in the V, R and I bands are $M_V \approx 6.8$, $M_R \approx 6.2$ and $M_I \approx 5.7$ (assuming a metal abundance $[M/\mathrm{H}] = -0.5$ and $Y = 0.25$) (Baraffe et al. 1998). At a distance of 15 kpc, the corresponding apparent magnitudes (neglecting extinction) are $m_V \approx 22.7$, $m_R \approx 22.1$ and $m_I \approx 21.6$. If we take a distance of 5 kpc, then the apparent magnitudes are $m_V \approx 20.3$, $m_R \approx 19.7$ and $m_I \approx 19.2$. As RXTE J2123−058 is probably a halo source, the extinction of its counterpart can be estimated from the reddening derived from H I measurement and galaxy counts. From the reddening map in Burstein & Heiles (1982) we obtain a colour excess $E(B-V) \approx 0.054$ for a halo source at $l = 46°28'58''.4$ and $b = -36°11'57''.3$. The corresponding extinctions are $A_V \approx 0.17$, $A_R \approx 0.11$ and $A_I \approx 0.09$. Hence the extinction-corrected magnitudes of a 0.7-$\mathrm{M_\odot}$ star at a distance of 15 kpc are $m_V \approx 22.9$, $m_R \approx 22.2$ and $m_I \approx 21.7$.

From the PCA count rates and the distance estimate (5–15 kpc), we obtain an estimate of $\sim 1 \times 10^{37}\,\mathrm{erg\,s^{-1}}$ for the X-ray luminosity during MJD ≈ 245 0995–245 1105. A fraction $(\pi R_2^2)/(4\pi a^2)$ of the X-rays would intercept the companion star, where R_2 is the radius of the companion star and a the orbital separation. If we substitute the values of R_2 and M_2 calculated in Section 4, this corresponds to a fraction of $\sim$3 per cent. Therefore energy will be deposited into the atmosphere of the companion star at a rate of $\sim 5 \times 10^{35}$ erg s^{-1}. An unheated 0.7-M$_\odot$ main-sequence star has a bolometric luminosity of about 1×10^{33} erg s^{-1} and an effective surface temperature of about 4800 K. The intrinsic luminosity of the companion star is therefore much lower than the power of the intercepted X-rays. We suppose that a quasi-equilibrium state is set up at the heated surface of the companion star, such that the rate of energy radiated away is the same as the rate of energy deposited. The effective surface temperature of the irradiatively heated atmosphere of the companion star could then reach 20 000 K.

During our observations, the system was in the process of returning to its quiescent state. On August 23 the ASM count rate had already dropped to the pre-outburst level (Fig. 1), which may be considered consistent with zero. Although the X-ray activity seemed to have ceased, the accretion disc had not completely dissipated, and the atmosphere of the companion star had not completely cooled down. Our photometric data obtained on August 19 and 20 show that the minimum brightnesses in the *V*-, *R*- and *I*-band light curves were $V \approx 20.8$, $R \approx 20.5$ and $I \approx 20.5$. The *V*-band brightness continued to drop and reached 21.4 mag on August 23. The star was finally not visible in the *B*-, *R*- and *V*-band data that we obtained on August 25 and 26 [cf. the *R*-band brightness of 21.5 mag on August 26 and 27 (Zurita & Casares 1998), which would imply a distance of $\sim$11 kpc if it were taken as the quiescent brightness of the companion star].

The optical brightness of RXTE J2123$-$058 was observed to decline at a rate of 0.1 mag d^{-1} in early August (Zurita et al. 1998). We observed a decline rate of 0.200 ± 0.001 mag d^{-1} in the *V*-band brightness between August 18 and 20. A decline is also seen in our *R*- and *I*-band data, but at lower rates of 0.085 ± 0.002 and 0.020 ± 0.010 mag d^{-1} respectively. A linear decline in brightness is equivalent to an exponential decline in luminosity. The faster decline in the *V* magnitude may indicate the fading or dissipation of the accretion disc (which was bluer than the companion star) after mass transfer ceased, in addition to the cooling of the atmosphere of the companion star. The photometric data also show hints of an ellipsoidal modulation around phase 0.5, which became more evident in our later observations. As we show in Fig. 3, the *V*-band light curve deviates from a sinusoidal-like curve by developing first a flat top around phase 0.5 on August 18, and then a local minimum on August 20. We attribute the gradual development of the secondary minimum at phase 0.5 to the fading of the accretion disc, which reveals the ellipsoidal modulation of the companion star.

6 SUMMARY

We have carried out a synergetic study of the X-ray transient RXTE J2123$-$058. The photometric observations were carried out from 1998 August 14 to 26, when the system was in transition from the outburst to the quiescent state. High-quality data were obtained in the *V*, *R* and *I* bands, which show approximately sinusoidal oscillations with a linear brightness decline when folded on a period of 0.248 21 d. The rate of decline measured from the *V* brightness during our observations was 0.200 ± 0.001 mag d^{-1}, more rapid than that the rate of 0.085 ± 0.002 mag d^{-1} for the *R* brightness and of 0.020 ± 0.010 mag d^{-1} for the *I* brightness. The folded light curves deviate significantly from a sinusoidal curve around phase 0.5, showing hints of ellipsoidal modulations, which tend to become progressively more evident. This suggests the presence of a fading accretion disc as well as an irradiatively heated companion star.

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