The optical counterpart of XTE J0929-314: the third transient millisecond X-ray pulsar

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ABSTRACT
A blue and variable optical counterpart of the X-ray transient XTE J0929-314 was identified on 2002 May 1. We conducted frequent BVRI broad-band photometry on this object using the Mt Canopus 1-m telescope during May and June until it had faded to below 21st magnitude. Nearly continuous I-band CCD photometry on 2002 May 2–4 revealed a ~10 per cent sinusoidal modulation at the binary period lasting ~6 cycles during the latter half of May 2. The phase indicates that the modulation may be due to a combination of emission by a hotspot on the disc and X-ray heating of the secondary. The emission generally trended bluer with B – I decreasing by 0.6 mag during the observations, but there were anomalous changes in colour during the first few days after optical identification when the I-band flux decreased slightly while fluxes in other bands increased. Spectral analysis of the BVRI broad-band photometry shows evidence of a variable excess in the R and I bands. We suggest that this may be due to synchrotron emission in matter flowing out of the system, and note that similar processes may have been responsible for anomalous V- and I-band measurements in 1998 of the persistent millisecond X-ray pulsar SAX J1808.4-3658.

Key words: binaries close – pulsars general – pulsars individual XTE J0929-314 – stars low-mass – stars neutron – X-rays binaries.

1 INTRODUCTION
X-ray heating of three regions is generally believed to contribute to optical variability in low-mass X-ray binary (LMXB) systems. These are the accretion disc, a bright spot on the outer edge of the accretion disc due to inflowing material and the hemisphere of the companion facing the neutron star. In most LMXBs, the reprocessed X-ray optical flux dominates the optical light from the rest of the system (van Paradijs 1983; van Paradijs & McClintock 1995), particularly in the outburst phase. The companion itself may only be evident at a very faint level when the system is in quiescence. More recently, it has become apparent that synchrotron emission from matter flowing out of the system via bipolar jets makes a highly variable contribution to radio and infrared (IR) emission from many different classes of X-ray binaries (Fender 2003). In some cases, this emission may extend to the optical region (Hynes et al. 2000). At least one other persistent millisecond X-ray pulsar, SAX J1808.4-3658, is known to have a transient IR excess and radio emission probably due to synchrotron processes (Wang et al. 2001).

On 2002 April 30, an X-ray transient was discovered by Remillard (2002) using the All Sky Monitor (ASM) (Levine et al. 1996) on the Rossi X-ray Timing Explorer (RXTE) satellite. XTE J0929-314, the subject of this paper, was subsequently found to also be a millisecond X-ray pulsar by Remillard, Swank & Strohmayer (2002). Using additional RXTE proportional counter array (PCA) observations, Galloway et al. (2002a,b) reported a neutron star spin frequency of 185 Hz, a binary period of 2615 s and an implied companion mass of ~0.008 M⊙, about 8.5 Jupiter masses. A blue and variable optical counterpart was suggested by Greenhill, Giles & Hill (2002). This identification was supported by spectra obtained by Castro-Tirado et al. (2002) who found a number of emission lines superimposed on a blue continuum, which is typical of soft X-ray transients in outburst. A coincident radio source was also reported by Rupen, Dhawan & Mioduszewski (2002).

XTE J0929-314 was the third transient millisecond X-ray pulsar to be discovered. The first (SAX J1808.4-3658) has been studied extensively at all wavelengths (Chakrabarty & Morgan 1998; in’t Zand et al. 1998; Wijnands & van der Klis 1998; Giles, Hill & Greenhill 1999; Wachter et al. 2000; Wang et al. 2001; Wijnands et al. 2001; Homer et al. 2002; Markwardt, Miller & Wijnands 2002; Chakrabarty et al. 2003; Wijnands et al. 2003). The V-band flux from SAX J1808.4-3658 decayed from ~16.75 to 18.5 mag in 10 d suggesting an e-folding time of 5–6 d.

Of the other four known millisecond X-ray pulsars, only two have identified visible counterparts. XTE J1814-338 (Strohmayer...
et al. 2003) has been identified by Krauss et al. (2003) but no detailed optical or IR observations are available. The more recent IGR J00291+5934 (Galloway et al. 2005) has a detailed optical light curve (Bikmaev et al. 2005). The R-band flux from this object decayed from ~17.4 to 22.4 mag in 30 d giving an e-folding time of 5.66 ± 0.2 d. The study of all these systems is expected to provide important information on the evolutionary path by which a conventional LMXB system might turn into a millisecond radio pulsar.

In this paper, we describe the optical variability of XTE J0929-314. The measurements were made in the BVRI bands during a period of ~9 weeks following its discovery.

2 OBSERVATIONS

All the observations described in this paper were made using the 1-m telescope at the University of Tasmania Mt Canopus Observatory. The CCD camera, its operating software (CICADA), the image reduction and analysis tools (MIDAS and DOPHOT) were identical to that described in Giles et al. (1999). The CCD camera contains an STe chip, which is a thinned back illuminated device providing 512 × 512 pixel with an image scale of 0.434 arcsec pixel⁻¹. The Cousins standard BVRI filters (Bessell 1990) were used for the observations.

The data were calibrated using a sequence of observations of 11 standard stars within the RU149D and PG1047 fields of Landolt (1992) to derive the magnitudes of five local secondary standards close to XTE J0929-314 and within the CCD frame. These local standards are marked as stars 1–5 on the finder chart in Fig. 1, and we tabulate their derived magnitudes in Table 1. The magnitudes for XTE J0929-314 were then obtained using differential photometry relative to these local secondary standards. We did not use the same stars for all colours, but used a combination of three of the five as indicated in Table 1. This multi-star process revealed that differential colour corrections are negligible. A few observations were interrupted or terminated early by the arrival of clouds. The complete data set from 2002 May 1 to July 1 [HJD 2452(396) – 2452(457)] is detailed in Tables 2 and 3 and forms the subject of this paper.

3 RESULTS

3.1 Source position

To determine the source position, we selected the nearest nine stars to the candidate from the Hubble Guide Star Catalogue 2.2 downloaded from the NASA HEASARC web site. We used the CCD coordinates of these stars and the proposed candidate on the best-quality I-band image from May 2 (HJD 397) to derive an accurate source position for XTE J0929-314 of R.A. 9h29m20s.19 Dec. − 31°23′3″2 with

![Figure 1](image-url)
Table 3. A journal of the $B$, $V$- and $R$-band observations.

| HJD$^a$ (−2452000) | $B$ mag | Int. | HJD$^a$ (−2452000) | $V$ mag | Int. | HJD$^a$ (−2452000) | $R$ mag | Int. |
|---------------------|---------|------|---------------------|---------|------|---------------------|---------|------|
| 395.92676           | 19.18(4)| 300  | 396.03104           | 19.32(3)| 600  | 398.98608           | 19.07(4)| 600  |
| 395.92676           | 19.18(4)| 300  | 399.00464           | 19.04(3)| 600  | 405.02222           | 18.94(4)| 1200 |
| 395.94162           | 19.17(4)| 120  | 404.96179           | 18.71(2)| 1200 | 405.88013           | 18.83(2)| 1200 |
| 395.99146           | 19.07(9)| 120  | 405.86371           | 18.68(1)| 900  | 405.98022           | 18.87(2)| 1200 |
| 395.99707           | 19.05(8)| 120  | 405.89260           | 18.70(2)| 900  | 407.94819           | 18.93(3)| 600  |
| 395.92676           | 19.18(4)| 300  | 399.00464           | 19.04(3)| 600  | 405.02222           | 18.94(4)| 1200 |
| 395.94162           | 19.17(4)| 120  | 404.96179           | 18.71(2)| 1200 | 405.88013           | 18.83(2)| 1200 |
| 395.99146           | 19.07(9)| 120  | 405.86371           | 18.68(1)| 900  | 405.98022           | 18.87(2)| 1200 |
| 395.99707           | 19.05(8)| 120  | 405.89260           | 18.70(2)| 900  | 407.94819           | 18.93(3)| 600  |

$^a$Times of mid-integration. Some integrations terminated early.

a relative error of ±0.1′ (equinox J2000.0). This is 0.7 from our initial position estimate in Greenhill et al. (2002) and only ~0′.2 away from the radio position given by Rupen et al. (2002). Chandra observations confirmed that the X-ray source was ~1.25 from our optical position (Juett, Galloway & Chakrabarty 2003). We note that this difference is twice their quoted error.

In Fig. 1, we provide a finder chart for XTE J0929-314 constructed from an $I$-band CCD image from May 2. The object is the central star in a line of three, and for the first few weeks was seen to be of similar brightness to its two neighbours.

3.2 The X-ray light curve

XTE J0929-314 is one of the faintest transients to be found by the ASM experiment on RXTE, and this detection is only possible due to its angular distance from the Galactic Centre region, which minimizes bright source confusion and consequent positional uncertainties. Our optical candidate was only 0.5 from the X-ray position of Remillard (2002). The transient was discovered near the time of peak X-ray flux, towards the end of April. It was then observed periodically with the PCA experiment on RXTE [obs id 70096-03-(*-**)] as part of a proprietary Target of Opportunity campaign (Galloway et al. 2002b; Juett et al. 2003). In the top panel of Fig. 2, we show the ASM intensity history for this transient up to just past the time when regular PCA observations commenced. Note that there is a single early PCA observation at HJD 397.0. The ASM points are plotted as daily averages since the data for individual dwell cycles are too noisy for such a relatively faint source. The 38 PCA values are averages over individual PCA observation ids that typically last 1000–4000 s. The two X-ray light curves in Fig. 2 are similar to fig. 1 in Galloway et al. (2002b) except that both vertical axes are now drawn with ‘X-ray magnitude’ scales. The final three PCA

![Figure 2. The RXTE ASM (+) and PCA (•) light curves for XTE J0929-314 are shown in the upper panel from April 5 to June 19 (HJD 370-445). The right-hand PCA axis is in units of $10^{-10}$ erg cm$^{-2}$ s$^{-1}$ for the 2–10 keV band. The centre panel light curve shows all the $I$ data with a linear fit to the decay interval. The lower panel shows the BVRI-band light curves for the average flux on each night.](https://academic.oup.com/mnras/article-abstract/361/4/1180/1114988)
3.3 The optical light curves

In Fig. 2, we plot our sets of BVRI-band data from Tables 2 and 3. The tight clusters of I data on May 2–4 (HJD 397, 398 and 399) are shown in greater detail in Fig. 4. There is an evidence of variability in the range 0.05–0.1 mag on a time-scale of hours during several nights when long runs of I-band measurements were made. Greenhill et al. (2002) reported variability of up to ~0.5 mag on the first night (HJD 396) of our observation. Preliminary analysis suggested that a short duration (time-scale ~30 min) ~0.5-mag flare occurred in V on this night. Subsequently, we became aware of water vapour condensation on the filter during this ‘event’ and we became doubtful of the reality of the flaring. In the following section, we describe evidence for a low-amplitude orbital-period modulation seen in the I-band flux at about HJD 397. It is of interest to note that no significant variations were seen in X-rays during the RXTE PCA observations (Galloway et al. 2002b). The upper limit to the orbital period modulation of the 2–10 keV X-ray flux was < 1.1 per cent (3σ) (Juett et al. 2003).

In Fig. 3, we plot the mean $B - V$ and $V - I$ colour indices for the nights when these three colours were measured. In order to minimize the effects of source variability, the colour indices for each night are derived from one or more measurements in the different colours taken within a time interval of ~1 h. The overall trend was for the spectrum to become hotter (more blue) over the principal five weeks of observation. This suggests, assuming that most of the light comes from an accretion disc, a trend towards increasing disc temperature as the accreting matter diffuses inwards. There was also a brief decrease in $B - V$ and $V - I$ (increase in colour temperature) between 2002 May 1 and 4 (HJD 396-399), followed by a recovery to the overall trend line. This can be seen in Fig. 2 where, for the first few days following optical identification, the I-band flux decreased slightly while fluxes in the other bands increased.

The light curves in BVRI are approximately triangular in profile, on a linear scale, and similar to, but delayed by, ~13 d relative to the X-ray light curve. During the time interval of May 1–11 (HJD 396–406), the BVRI fluxes increased by ~75 per cent while the X-ray flux decreased by ~50 per cent. We can think of no physical process whereby X-ray emission can lead optical emission by 13 d. In SAX J1808.4-3658, the optical decline preceded the X-ray by 3 ± 1 d (Giles et al. 1999). Since we have no information on the optical flux during April, we conclude that the apparent similarity between the optical and the X-ray light curves is coincidental. The optical decay evident in the centre panel of Fig. 2 has an e-folding time of 22.2 ± 1.1 d. This appears to be qualitatively different to that for SAX J1808.4-3658 and IGR J00291+5934.

3.4 Search for binary modulation

On the nights of May 2–4 (HJD 397, 398 and 399), we monitored the object at I continuously in an attempt to observe an orbital period modulation. These data are plotted in Fig. 4. In mid-May, Galloway et al. (2002a) detected a 2614.75(15)-s orbital period modulation of the X-ray pulsation frequency. No amplitude modulation of the X-ray flux was detected. Their orbit ephemeris placed the neutron star on the far side of the companion at 2002 May 11.4941(2) UT (HJD 405.9941). The solid sine curves in the lower part of each panel in Fig. 4 represent the modulation (arbitrary amplitude) expected from X-ray heating of the companion star as in SAX J1808.4-3658 (see fig. 1 in Giles et al. 1999 and fig. 2 in Homer et al. 2002).
The first PCA X-ray observation (obs. 01-00) occurred during the time we detected an orbital period modulation on the night of 2002 May 2 (HJD 397), and its duration is shown in the top panel of Fig. 4. However, this observation consists of crossed slews to determine the X-ray source position and is thus not suitable for modulation analysis. As noted earlier, no X-ray amplitude modulation was reported in any of the many following RXTE PCA observations (Juett et al. 2003).

### 3.5 Spectral changes

There are many occasions mentioned in Tables 2 and 3 where we have $BVRI$ values on the same night, but some caution is required in combining these into broad-band spectra due to the variability detected on several nights. In most instances, the different colour averages for each night are derived from one or more measurements taken in a time interval of $\sim$1 h. It should be clearly noted that the central wavelength and bandwidth for the $R$ and $I$ filters differ between the Cousins and older Johnston systems, and this can affect the apparent spectral shape. Here we use the Cousins $R$ and $I$ parameters. In Fig. 6, we plot the broad-band $BVRI$ spectra from eight nights, 2002 May 1, 4, 11, 13, 14 and June 1, 7 (HJD 396, 399, 406, 408, 409, 414, 427 and 432).

Also shown is a curve representing a power-law approximation to the emission from an optically thick, X-ray heated disc. The distribution is given by the equation $F_\lambda \propto \lambda^{-0.42} e^{-A_V/1.086}$, where $F_\lambda$ is the reddened flux at wavelength $\lambda$ and $A_V$ is the wavelength-dependent reddening correction towards the source. The amplitude is arbitrary and the spectrum is reddened assuming interstellar extinction.

The data commencing from HJD 396.92 ($\sim 22$ h UT) for these slow and many error limits are smaller than the points representing the measurements. The full width diagonal solid line represents a simple power-law disc emission model with exponent $-3$, arbitrary amplitude and interstellar reddening corresponding to $A_V = 0.42$.

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**Figure 5.** The $I$-band light curve for part of the night of 2002 May 2 (HJD 397) folded at the orbital period. The solid curve is a best-fitted sinusoid at the X-ray period. The lower set of points shows the scatter for the constant nearby star. The horizontal bar represents the 600-s duration of the individual integrations.

**Figure 6.** The $BVRI$ broad-band spectra for XTE J0929-314. Each day’s spectrum is identified by the start of the HJD falling within the daily $\pm 4$ h observing window. The lines connect to the mean flux values on each night, and many error limits are smaller than the points representing the measurements. The full width diagonal solid line represents a simple power-law disc emission model with exponent $-3$, arbitrary amplitude and interstellar reddening corresponding to $A_V = 0.42$. 

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AV = 0.42. This value is scaled from the estimated value AV = 0.68 for SAX J1808.4-3658 (Wang et al. 2001) using the integrated column densities, N_H ≈ 1.3 × 10^{20} cm^{-2} for SAX J1808.4-3658 (Gilfanov et al. 1998) and N_H ≈ 7.6 × 10^{20} cm^{-2} for XTE J0929-314 (Jueett et al. 2003). A similar value for AV is obtained by using the relationship between AV and N_H given by Predelli & Schmitt (1995).

We have no information on the flux in B for the first night (HJD 396), but it is clear that the spectrum was heavily reddened on that occasion. On subsequent nights, the spectra were generally steeper for that date. Otherwise, the spectra were generally steeper for that date. On HJD 409 (and possibly HJD 432 although with less statistical significance) the flux band was strongly enhanced with strong Balmer line (Ha) emission. Balmer emission cannot, however, account for the variable excesses in I. Measurement errors were relatively large for the last two nights as shown in Fig. 6 (HJD 427 and 432), but it is clear that the red excess had disappeared and that the spectra were steeper (bluer) than during earlier observations.

4 DISCUSSION

Several features distinguish XTE J0929-314 from SAX J1808.4-3658. First, the maximum of the orbital period modulation occurs at phase 0.19 ± 0.05 rather than at phase zero. This points to an origin of X-ray heating in SAX J1808.4-3658, but the situation is more complex in XTE J0929-314. Galloway et al. (2002b) have shown that the companion in XTE J0929-314 is probably a very low-mass (~0.008 M\odot) helium white dwarf. The companion in SAX J1808.4-3658 is believed to be a ~0.05 M\odot brown dwarf (Bildsten & Chakrabarty 2001). The Roche lobe radii of the companion stars will therefore differ by almost an order of magnitude substantially reducing the X-ray radiation reprocessed by the companion in XTE J0929-314. We have estimated the amplitude L_{OB} of optical modulation due to heating of the companion star in XTE J0929-314 using the relation L_{OB} = L_{X0}/L_{XB} d_{B}/d_{A}^2 (R_{A}/R_{B})^2 L_{OB}, where L_{OB} is the optical modulation observed for SAX J1808.4-3658 (Giles et al. 1999), L_{X0}/L_{XB} is the ratio of the X-ray fluxes (Gilfanov et al. 1998; Jueett et al. 2003), d_{B}/d_{A} is the ratio of distances between the neutron stars and their companions and R_{A}/R_{B} is the ratio of the Roche lobe radii for the two systems. The estimated orbital modulation is ~25 per cent of that observed suggesting that, if it is generated thermally, much of the emission comes from a hotspot on the disc. This provides an explanation for the observed maximum phase, which lies mid-way between that expected from heating of the companion and from hotspot emission.

Turning to the spectral characteristics, the broad-band spectra from SAX J1808.4-3658 are well fitted by smoothly varying functions derived from a thermal disc model (Wang et al. 2001). However, there are significant, time-dependent, R- and I-band excesses in our XTE J0929-314 spectra. Nothing like this has been reported for SAX J1808.4-3658, although Wang et al. (2001) reported a strong, near-IR JH/K excess on one occasion, and this may well have extended to optical wavelengths. We have insufficient information to explain our observed spectral variability. As noted in Section 3.5, variable Balmer emission may be responsible for the R-band excesses but cannot contribute to the excesses in I. The remarkable changes in the red excesses between HJD 396 and 399 and between HJD 409 and 414 might perhaps be due to diffusion inwards of cool matter from a brief enhancement of mass transfer on to the disc from the companion star. Alternatively, the red excesses may be due to transient synchrotron emission from matter flowing out of the system via bipolar jets. The synchrotron spectrum is cut-off at wavelengths shorter than R.

As noted in Section 1, many different classes of X-ray binaries emit synchrotron radiation (Fender 2003). Rupen et al. (2002) identified a weak (~0.35 ± 0.07 mJy) 4.86 GHz radio source at the SAX J0929-314 position on 2002 May 3 and 7. Unfortunately, there do not appear to have been any IR observations during this outburst. We hypothesize that a rather similar phenomenon may have occurred during the 1998 outburst of the accreting millisecond pulsar SAX J1808.4-3658. Wang et al. (2001) noted that the V- and I-band fluxes measured by the JKT 1-m telescope on 1998 April 18.2 were about 0.2 mag brighter than measured ~0.5 d later when measured by the Mt Canopus 1-m telescope. They assumed that the discrepancy was due to calibration uncertainties in the JKT data. There was a clear IR (JHK) excess measured by the UKIRT telescope at 1998 April 18.6, just 0.4 d after the JKT measurements. Wang et al. (2001) proposed a synchrotron origin for this IR excess. We suggest that the synchrotron excess was also present at the time of the JKT measurements, and that it extended into the optical bands. It had disappeared at the time of the Mt Canopus measurements a few hours later.

5 CONCLUSIONS

The optical counterpart of XTE J0929-314 was variable on all time-scales down to a few hours during the 2002 May observations. On one occasion lasting ~4 h, the I-band flux was modulated at the orbital period with amplitude 0.09 ± 0.01 mag. No variability was apparent in the X-ray measurements (Galloway et al. 2002b). The peak of the orbital modulation occurs at a phase of 0.19 ± 0.05 relative to the X-ray ephemeris and appears to rule out X-ray heating of the companion as the source of the modulation unless it is combined with emission from a hotspot on the disc.

Broad-band BVRI spectra taken on eight nights have an approximately power-law distribution as expected for an optically thick accretion disc but with variable excesses in R and I. Overall, these excesses declined and the spectra steepened (became bluer) during the period of the observations. While variable Ha emission may be responsible for some of the excess in R, another explanation is required for the I-band enhancements. We suggest they may be due to emission from cool matter in the outer part of the disc following a transient episode of mass transfer from the companion. Alternatively, variable synchrotron emission, cut-off at R-band wavelengths, contributes to the emission spectrum.

There is a clear need for fast follow-up optical, IR and radio observations of millisecond X-ray pulsars. These should include polarimetry and high time resolution optical and near-IR photometry to test the synchrotron emission hypothesis. The feasibility of high-speed photometry at the pulsar spin frequency might also be investigated. Facilities for immediate data reduction and generation of light curves are essential in order to optimize observing strategies for these highly variable objects.

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