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# A search for the optical and near-infrared counterpart of the accreting millisecond X-ray pulsar XTE J1751–305

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## ABSTRACT

We have obtained optical and near-infrared images of the field of the accreting millisecond X-ray pulsar XTE J1751–305. There are no stars in the 0.7-arcsec error circle (0.7 arcsec is the overall uncertainty arising from tying the optical and X-ray images and from the intrinsic uncertainty in the *Chandra* X-ray astrometric solution). We derive limiting magnitudes for the counterpart of  $R > 23.1$ ,  $I > 21.6$ ,  $Z > 20.6$ ,  $J > 19.6$  and  $K > 19.2$ . We compare these upper limits with the magnitudes one would expect for simple models for the possible donor stars and the accretion disc subject to the reddening observed in X-rays for XTE J1751–305 and when put at the distance of the Galactic Centre (8.5 kpc). We conclude that our non-detection does not constrain any of the models for the accretion disc or possible donor stars. Deep, near-infrared images obtained during quiescence will, however, constrain possible models for the donor stars in this ultracompact system.

**Key words:** stars: individual: XTE J1751–305 – stars: neutron – X-rays: stars.

## 1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are typically old ( $> 10^8$  yr) binary systems in which a low-mass companion star ( $\gtrsim 1 M_{\odot}$ ) transfers matter to a neutron star or a black hole. The neutron-star LMXBs are thought to be among the predecessors of the millisecond radio pulsars. As a result of accretion of matter and decay of the magnetic field during the LMXB phase, the neutron star spins-up to millisecond periods (see Bhattacharya 1995, for a review). However, until 2002 March only six LMXBs were known to show pulsations (see Jonker & van der Klis 2001, for a short overview), and only one of them, a transient system, was shown to have a millisecond period (SAX J1808.4–3658; Wijnands & van der Klis 1998;

Chakrabarty & Morgan 1998). In 2002, Markwardt & Swank (2002) (see also Markwardt et al. 2002) and Galloway et al. (2002b) (see also Galloway et al. 2002a) discovered millisecond pulsations in two other transient sources, XTE J1751–305 and XTE J0929–314, in outburst.

There are two main reasons to search for the companion stars of accretion-powered millisecond X-ray pulsars. First, accretion-powered millisecond X-ray pulsars have most likely accreted a substantial amount of matter as they were spun-up by accretion to a period of milliseconds. A spectroscopic determination of the radial velocity curve of the companion star yields a lower limit to the mass of the neutron star; measuring a mass of considerably more than  $1.4 M_{\odot}$  for even one neutron star would imply the firm rejection of many proposed equations of state [see the discussion by van Paradijs & McClintock (1995); for an overview of the mass determinations of millisecond radio pulsars in neutron star–white dwarf

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**Table 1.** Log of the observations. MJD and start time refer to the time at the start of the first observation.

Telescope	Instrument	Observation date (2002) and start time (UT)	MJD (UTC)	Bessel filters	Exposure time (s)	Airmass	Seeing (arcsec)
Danish	DFOSC	Apr 08 08:51	52372.36870	<i>R</i>	900	1.01	~1.2
Magellan	Classic-CAM	Apr 09 08:02	52373.33472	<i>K(s)</i>	60	1.05	~0.65
Magellan	Classic-CAM	Apr 09 07:32	52373.31388	<i>J</i>	280 (11 × 20 + 60)	1.05	~0.65
Magellan	MagIC	Apr 13 07:43	52377.32153	<i>I</i>	240 (3×)	1.05	~0.6
Magellan	MagIC	Apr 14 08:30	52378.35416	<i>I</i>	30 (1×), 240 (18×)	1.00–1.03	~0.7
UKIRT	UFTI	Apr 14 14:41	52378.61201	<i>J</i>	600 (2 × 5 × 60)	1.6	~0.8
UKIRT	UFTI	Apr 14 14:55	52378.62161	<i>K</i>	600 (2 × 5 × 60)	1.6	~0.65
UKIRT	UFTI	Apr 18 14:47	52382.61623	<i>J</i>	600 (2 × 5 × 60)	1.6	~0.65
UKIRT	UFTI	Apr 18 15:06	52382.62925	<i>K</i>	600 (2 × 5 × 60)	1.6	~0.5
NTT	SUSI2	Apr 18 08:33	52382.35682	<i>R</i>	600	1.00	~0.8
NTT	SUSI2	Apr 18 08:23	52382.34950	<i>I</i>	600	1.00	~0.9
NTT	SUSI2	Apr 18 08:12	52382.34185	<i>Z</i>	600	1.01	~0.8
3.6 m (spec)	EFOSC	May 01 07:19	52395.30470	Gr12, 0.7'' slit	1500	1.01	~0.9

binaries, see Thorsett & Chakrabarty (1999)]. In order to measure the radial velocity of the companion star spectroscopically, clearly a detection of the object is first required. Secondly, at present there are three known ways to produce compact X-ray binaries (Savonije, de Kool & van den Heuvel 1986; Tutukov et al. 1987; Tutukov & Fedorova 1989; Yungelson, Nelemans & van den Heuvel 2002; Podsiadlowski, Rappaport & Pfahl 2002; see Section 3 for a more elaborate account of these models). Detection of the companion star will allow us to differentiate between these different formation scenarios.

In this paper we present the results of our search for the optical and near-infrared counterpart of the ultracompact accreting millisecond X-ray pulsar XTE J1751–305 ( $P_{\text{orb}} = 42$  min; Markwardt et al. 2002). Early reports on the data presented in this paper were published by Jonker et al. (2002), Wang et al. (2002), Wang & Chakrabarty (2002) and Kong et al. (2002).

## 2 OBSERVATIONS AND ANALYSIS

We observed the region around the accurate *Chandra* X-ray position of the source using the 6.5-m Magellan, the 3.8-m UKIRT, the 3.58-m NTT and the 1.54-m Danish telescopes. A spectrum of the candidate optical counterpart presented by Kong et al. (2002) was obtained with ESO’s 3.6-m telescope at La Silla using grism number 12, which covers 601–1032 nm. A log of the observations can be found in Table 1. In the case of the near-infrared data, the total exposure time is given *and* the dither pattern. For example, in the case of the UKIRT *J*-band images, we took five exposures of 60 s each; in between each observation, the telescope was dithered; this pattern was repeated twice. In the case of the Magellan near-infrared observations, we obtained *J* and *K(s)* images of 60 s integration time each. We also obtained 11 *J*-band images of 20 s integration each.

The data reduction was performed in IRAF.<sup>1</sup> The near-infrared images (*J* and *K* bands) were sky-subtracted (using the sky determined from the dithered images), flat-fielded, aligned and combined to form one image per band per night. The Magellan near-infrared data have been linearized before the reduction. The optical images (*R*, *I* and *Z* bands) were reduced in the standard fashion. Aperture and point spread function fitting photometry were done using the packages APPHOT and DAOPHOT in IRAF. The spectrum obtained with

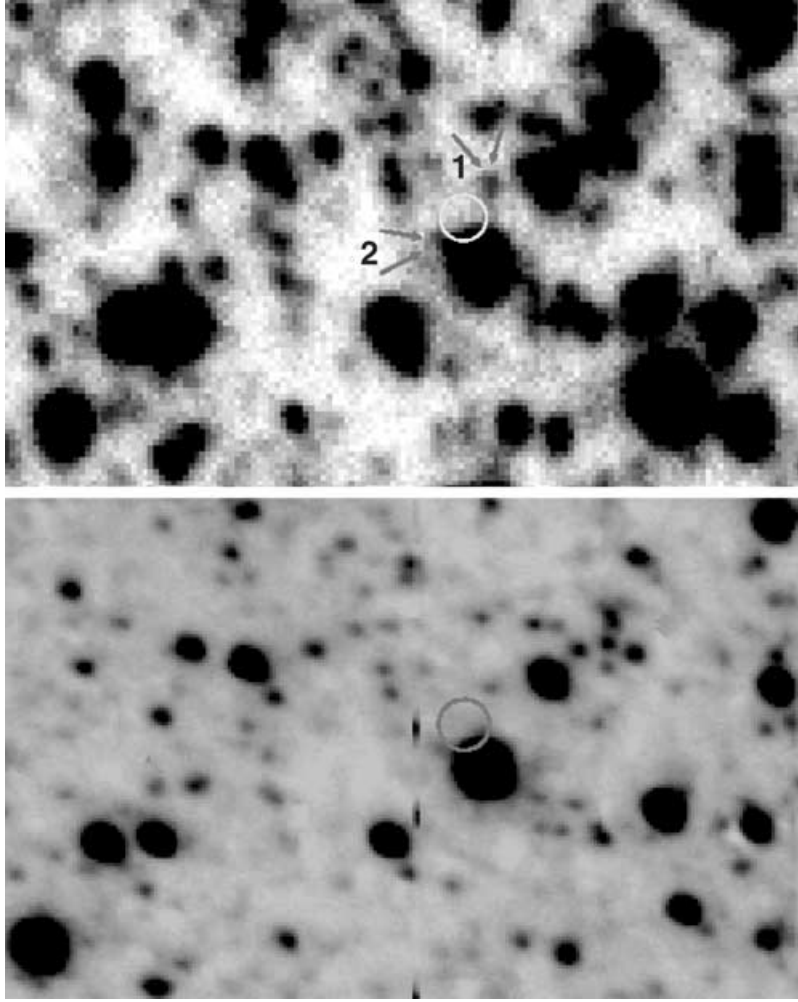
ESO’s 3.6-m telescope was extracted using the task APALL in the package SPECRED in IRAF. All nights were photometric, except for the nights of 2002 April 13 and 14, when the humidity was very high at Magellan, and 2002 April 14, at UKIRT, when thin cirrus was present. The *J*-band observations during that night also suffered from a bright sky as they were obtained partially during twilight. Charge overflow from a neighbouring bright star covered the location of XTE J1751–305 on the charge-coupled device (CCD) in our image obtained with the Danish telescope, rendering it impossible to determine whether a source is present or not at the *Chandra* X-ray location. Hence, we will not consider this observation any further.

We derived an astrometric solution for the optical *I*-band image obtained with the NTT of the field of XTE J1751–305 using the positions of four nearby unsaturated stars that appear in the USNO-A1.0 catalogue. The rms of the fit was 0.015 arcsec. The typical astrometric error of stars in the USNO-A1.0 catalogue is 0.25 arcsec (68 per cent confidence); the uncertainty in the X-ray position is dominated by the *Chandra* aspect solution (0.6 arcsec; 90 per cent confidence; Markwardt et al. 2002). Hence, the overall astrometric uncertainty in the position of the error circle is 0.7 arcsec (90 per cent confidence). Next, we tied the astrometric solution of the *I*-band image to the optical *R* and *Z* bands and to the near-infrared *J*- and *K(s)*-band images by assigning the known position of several stars (from the *I* band) to the *R*-, *Z*-, *J(s)*- or *K*-band image; this did not increase the error in the astrometry significantly.

In Fig. 1 (top panel) we show the *R*-band image from our NTT observations. Separately, in Fig. 1 (bottom panel) we show the near-infrared UKIRT (*K*-band) image. From the astrometry it is clear that each of the two candidate counterparts (both indicated with two arrows in the top panel) is just outside the 90 per cent confidence error circle [Wang et al. (2002) initially proposed star 1 as the counterpart, but see also Wang & Chakrabarty (2002); Kong et al. (2002) proposed star 2 as the counterpart, see Fig. 1]. Hence, it is unlikely but not ruled out that the counterpart was detected.

We determined  $3\sigma$  upper limits on the presence of a star in the error circle of each of the images obtained under photometric conditions. To do this we added a simulated artificial star (created using the point spread function of the stars in the image) at the position of the error circle. The magnitude of this extra star was varied and measured using the standard photometric tasks. We define the  $3\sigma$  limiting magnitude as the magnitude at which the error in the magnitude of such an artificial star is  $\sim 0.3$  mag [an 0.3 mag error is equivalent to a  $\sim 30$  per cent error on the flux measurement, i.e. a

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatories.



**Figure 1.** *Top:* The *R*-band image ( $\sim 27 \times 14$  arcsec<sup>2</sup>; 10 min integration; north is up, east to the left) of the region of XTE J1751–305 obtained with the 3.58-m NTT. The X-ray error circle for the location of the source is overplotted (0.7 arcsec; 90 per cent confidence). The double set of arrows indicate the locations of the possible counterparts proposed by Wang & Chakrabarty (2002, star 1) and Kong et al. (2002, star 2). *Bottom:* The UKIRT *K*-band image obtained on 2002 April 18 ( $\sim 27 \times 14$  arcsec<sup>2</sup>; 10 min integration; north is up, east is to the left) of the region of XTE J1751–305. The *Chandra* error circle is overplotted. The vertical black strips in the centre of the image are artefacts introduced when combining the dithered images.

three-sigma detection; see also Hulleman et al. (2000)]. For all the images we need  $\sim 3$ – $5$  trials to cover the error circle (the number of trials is different for the different images; it varies as a function of the seeing). We did not take the number of trials into account when calculating the upper limits (the error introduced by this is  $\sim 0.1$  mag). The error on the determined limiting magnitude is also  $\sim 0.1$  mag. Together with the uncertainty in the photometric zero-point (at most 0.1 mag), this yields an uncertainty of  $\sim 0.2$  mag in the limiting magnitudes.

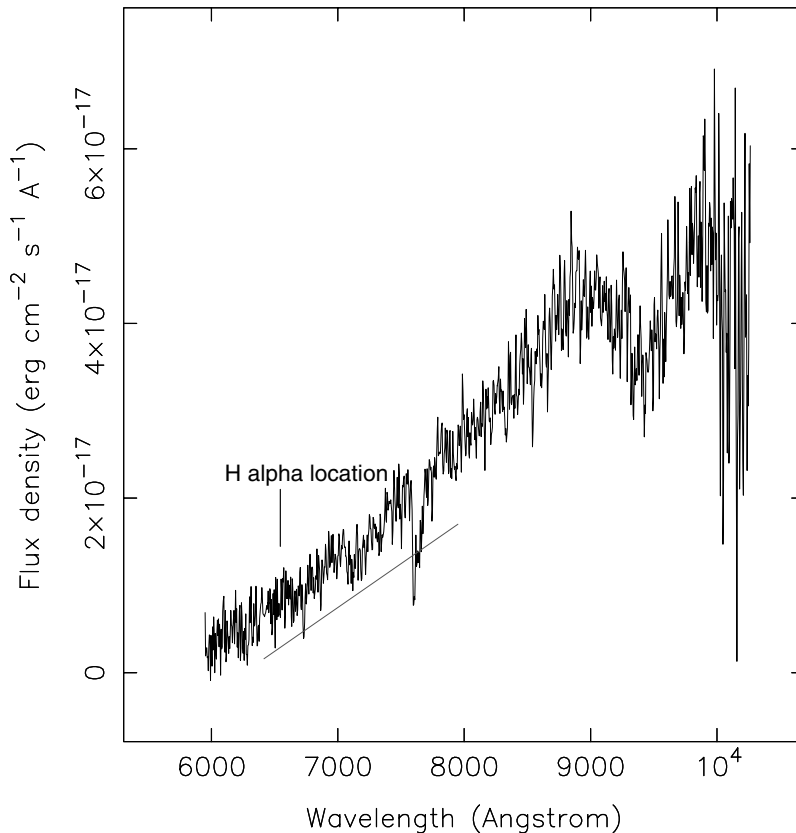
For the NTT *Z*-band image we converted the (Sloan)  $z'$  magnitude of the observed standard star (PG0918+029D) to the UKIRT UFTI *Z* band using the transformation given on the UKIRT website. However, since the NTT and the UKIRT *Z* bands differ, and there is no cross-calibration of these two *Z* bands, in doing so we introduced an uncertainty in the *Z*-band magnitudes that can be more than 0.2 mag. Therefore, the *Z*-band upper limit is given as reference only; it should be considered approximate. The upper limits are given in Table 2.

We searched for variability in the *I*-band magnitude for the candidate counterpart proposed by Wang & Chakrabarty (2002) (star 1) by comparing the magnitudes in the Magellan and the NTT obser-

**Table 2.** Upper limits ( $3\sigma$ ) on the presence of a star at the position of the *Chandra* error circle.

Telescope	Observation date (2002 April)	Limiting magnitude
Magellan	09	$J > 19.6$
Magellan	09	$K > 18.2$
UKIRT	18	$J > 19.5$
UKIRT	18	$K > 19.2$
NTT	18	$R > 23.1$
NTT	18	$I > 21.6$
NTT	18	$Z > 20.6$

variations. The *I*-band magnitude of star 1 is consistent with being the same during the observations. Unfortunately, the *I*-band magnitudes of the candidate counterpart proposed by Kong et al. (2002) (star 2) could not be determined for the NTT image due to the presence of the nearby star. However, differential photometry showed that star 2 was not variable in the Magellan Sloan *i'*-band images taken a day apart (Kong et al. 2002).



**Figure 2.** Spectrum of the southernmost source identified with the marks in Fig. 1 (star 2; to the east of the bright neighbour), obtained with ESO’s 3.6-m telescope at La Silla on 2002 May 1. The line connects the magnitudes of this star in the *R* and *I* bands converted to flux densities at the central wavelengths of the *R*- and *I*-band filters.

The slit we used to obtain a spectrum using ESO’s 3.6-m telescope at La Silla had a width of 0.7 arcsec. The slit orientation was such that both stars 1 and 2 were in the slit as well as most of the position marked by the error circle. However, owing to the seeing of  $\sim 0.9$  arcsec during these observations, the spectrum of star 2 may have been contaminated by light of the bright nearby star. In order to investigate this, we converted the magnitudes of this bright nearby star ( $R = 18.3$ ,  $I = 16.2$ ) and those of star 2 ( $R = 22.6$ ,  $I = 19.2$ )<sup>2</sup> to flux densities, and we compared the amplitude of the spectral energy distribution according to these *R*- and *I*-band flux densities with the amplitude of the flux-calibrated spectrum. The fact that the flux density of the spectrum is higher than that of star 2 shows that the spectrum will have been contaminated with light from the bright nearby star. We note that in converting the magnitudes to fluxes we assumed that star 2 was not variable. We show the spectrum in Fig. 2. We also label the position of  $H\alpha$ , although it is unclear whether the donor star of XTE J1751–305 contains hydrogen or not. The spectrum is featureless except for the atmospheric absorption feature near 7613 Å and the band at  $\sim 9300$  Å. The spectrum of star 1 was not detected, rendering further support to the conclusion that the detected light from the position of star 2 was dominated by the bright nearby star.

<sup>2</sup>We note that the uncertainty on these magnitudes is large due to the non-photometric conditions at the time of the Magellan *I*-band observations; for comparison the best estimate of the magnitude of star 1 was 20.2.

### 3 DISCUSSION

We have obtained optical and near-infrared images of the field of the accreting millisecond X-ray pulsar XTE J1751–305. Two possible counterparts have been investigated, but since they both fall outside the 90 per cent confidence *Chandra* error circle we conclude that neither the optical nor the near-infrared counterpart was detected. The star closest to the error circle was suggested to be the counterpart by Kong et al. (2002) (star 2 in Fig. 1). We placed upper limits on the presence of a star in the error circle in the *R*, *I*, *Z*, *J* and *K* bands.

To evaluate the constraints that these upper limits can place on the properties of the system, we consider the possible evolutionary states for XTE J1751–305. To arrive at an approximately 40-min orbital period X-ray binary, there are essentially three evolutionary paths.

The first starts from a detached white dwarf–neutron star binary, which is brought into contact by angular momentum loss due to gravitational wave radiation. For a discussion of this scenario for ultracompact X-ray binaries, see Yungelson et al. (2002). The mass of the donor in this case would be  $\sim 0.02 M_{\odot}$  and the mass transfer rate  $\sim 10^{-11} M_{\odot} \text{ yr}^{-1}$ . Recently, Bildsten (2002) discussed XTE J1751–305 and the similar accreting millisecond X-ray pulsar XTE J0929–314 and calculated models for hot white dwarf donors, rather than the previously used zero-temperature models. He finds a luminosity of the order of  $10^{-3} L_{\odot}$  and an effective temperature of  $\sim 6000$  K for the donors.

It is also possible to form a 40-min binary from a helium star that transfers matter to a neutron star (e.g. Savonije et al. 1986; Tutukov & Fedorova 1989). Such a scenario goes through the 40-min period

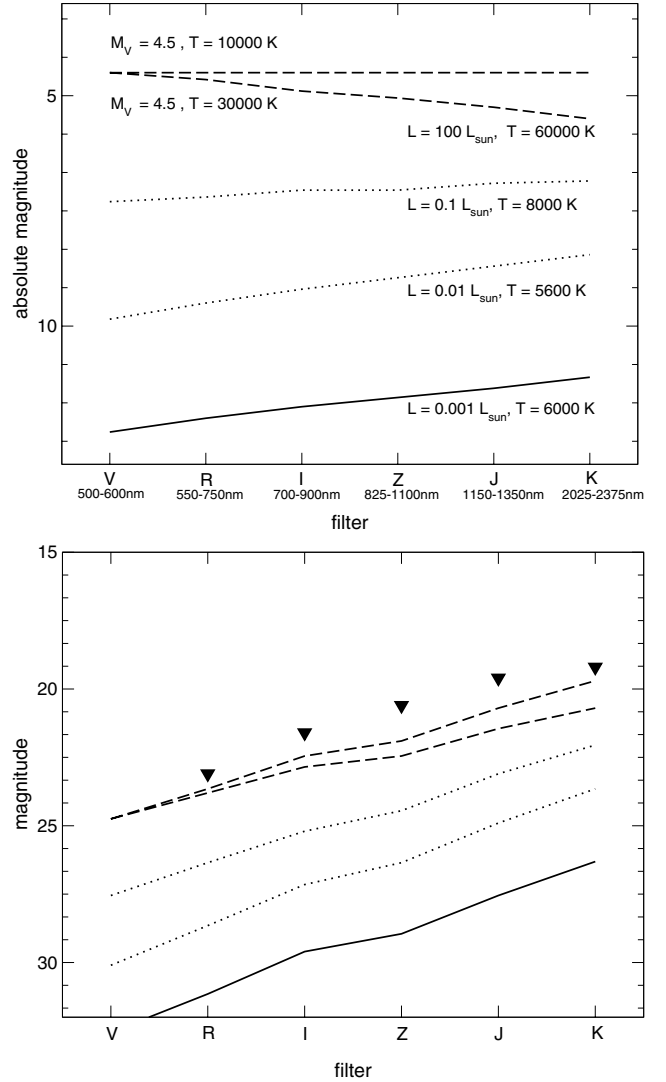
range twice. The first time, the system goes through the orbital period of 40 min while the orbital period decreases; then the donor is a luminous, hot helium star of about  $0.6 M_{\odot}$ . The mass transfer rate at that stage is of the order of  $10^{-8} M_{\odot} \text{ yr}^{-1}$ . After having reached a period minimum of about 10 min, the system returns to longer periods with a dim, semi-degenerate helium star donor, not unlike the low-mass white dwarfs in the first scenario.

The third evolutionary scenario producing ultracompact binaries involves a main-sequence star close to core hydrogen exhaustion that starts mass transfer to a neutron star (Tutukov et al. 1987; Podsiadlowski et al. 2002). Such a system evolves to shorter orbital periods than the standard period minimum for hydrogen-rich stars, since more and more helium-enriched layers are reached when peeling off the star. These systems go through a period minimum, again of the order of 10 min, and form white dwarf-like, low-mass, low-luminosity donor stars. Podsiadlowski et al. (2002) discuss possible models for XB 1832–330, which has an orbital period close to 40 min as well, so these models should also be applicable to XTE J1751–305. The donors in these models have masses between  $0.026$  and  $0.14 M_{\odot}$  and mass transfer rates between  $4.5$  and  $22 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ .

The X-ray observations already place some constraints on the system. The mass function for the companion ( $1.3 \times 10^{-6} M_{\odot}$ ; Markwardt et al. 2002) suggests that the companion is a low-mass star. If the companion were to be a  $0.6 M_{\odot}$  helium star, the inclination should be less than  $1.6^{\circ}$ . The two pre-period-minimum models of Podsiadlowski et al. (2002) with donor masses of  $0.14$  and  $0.094 M_{\odot}$  would imply inclinations less than  $6^{\circ}$  and  $9^{\circ}$ , respectively. Markwardt et al. (2002) infer a mass transfer rate of  $2.1 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ , assuming a neutron star radius of 10 km, a distance of 10 kpc and a recurrence time of 3.8 yr. Even though there is quite some uncertainty in the distance and recurrence time, the high mass transfer rate as expected from a helium star donor seems to be unlikely, even more so, because at such high rates the system would be expected to be a persistent X-ray source (Tsugawa & Osaki 1997).

Next, we estimate the expected absolute magnitudes of the different donor star and accretion disc models in the optical and near-infrared. Since the source was still in outburst when we obtained our observations, it is likely that the accretion disc dominates in the optical and near-infrared. We assumed an absolute visual magnitude of the disc of 4.5 based on the observed absolute magnitude of 4U 1916–053 of 5.3, which has a similar orbital period, but allowing for the higher X-ray luminosity of XTE J1751–305 (assuming that the disc luminosity scales with the square root of the X-ray luminosity, see van Paradijs & McClintock 1995), and the fact that 4U 1916–053 has a high inclination, reducing its absolute visual magnitude. Since these ultracompact systems have to have small accretion discs, they are expected to be hot (see van Paradijs & McClintock 1995). We estimated the absolute magnitudes for discs, modelling them as simple blackbodies of 10 000 and 30 000 K. The results are shown in Fig. 3 (dashed lines in the top panel).

The absolute magnitudes of the possible donor stars in a 40-min binary, again assuming simple blackbody spectral energy distributions, are calculated for the hot white dwarf scenario proposed by Bildsten (2002) and for the two pre-period-minimum models of Podsiadlowski et al. (2002). We did not consider their post-period-minimum model because according to Bildsten (2002) the companions in X-ray binaries will never cool down so much. Also, such a donor star would be very similar to the hot white dwarf donor model. For the hot helium star donor, we used a model having a luminosity of  $100 L_{\odot}$  and  $T = 60\,000$  K (see Tutukov & Fedorova 1989). Interestingly, the absolute magnitudes of this model fall on



**Figure 3.** *Top:* Absolute magnitudes for the theoretical models for the donor stars in 40-min period ultracompact X-ray binaries. Solid line: the hot white dwarf model from Bildsten (2002). Dotted lines: the pre-period-minimum models for XB 1832–330 of left two triangles in the top panel of fig. 16 of Podsiadlowski et al. (2002). Dashed lines: estimates for the outburst disc spectrum, based on an absolute visual magnitude of 4.5 and temperatures of 10 000 and 30 000 K. The top dashed line also gives the absolute magnitudes of the donor in the case of it being a luminous, hot helium star (from Tutukov & Fedorova 1989). The passbands we used for the filters are indicated (we assumed perfect step function filters). *Bottom:* The estimated magnitudes for the same models as in Fig. 3, assuming that the system is close to the Galactic Centre and taking the reddening into account ( $A_V = 5.6$ , based on the estimated  $N_H \sim 1 \times 10^{22} \text{ cm}^{-2}$ ). The filled triangles represent the upper limits on the counterpart of XTE J1751–305.

top of the 30 000 K disc model. The absolute magnitudes of all four models are shown in Fig. 3 (top panel).

To compare the theoretical models with our upper limits, we assumed XTE J1751–305 is near the Galactic Centre, with a distance modulus of 14.65 mag. Furthermore, we inferred an absorption ( $A_V = 5.6$ ), based on the measured  $N_H = 10^{22} \text{ cm}^{-2}$  (Miller et al. 2002) and calculated the absorption in the other bands according to the relations found by Rieke & Lebofsky (1985). The results are shown in Fig. 3 (bottom panel), where the single symbols denote the

upper limits. Unfortunately, our upper limits do not constrain any of the models. Further deep near-infrared imaging could, however, start to rule out several possible models for the counterpart of the accreting millisecond X-ray pulsar XTE J1751–305. According to the models presented above, XTE J0929–314, having an orbital period of  $\sim 40$  min and a reddening in the *V* band of  $\sim 0.65$  mag (Dickey & Lockman 1990), cannot have a distance much larger than the lower limit of 6.5 kpc derived by Galloway et al. (2002a). Otherwise it would not have been detected in outburst at  $V = 18.8$  (Greenhill, Giles & Hill 2002).

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