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The black hole nature of the X-ray transient MAXI J1305−704

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ABSTRACT

Key words: accretion, accretion disks – stars:individual (MAXI J1305−704) – X-rays:binaries.

1 INTRODUCTION

X-ray transients (XRTs), a sub-class of the low mass X-ray binaries (LMXBs), are highly evolved, interacting binaries in which the compact object (black hole or neutron star) accretes via an accretion disk fed by a cool, low mass donor star. Only occasionally these systems show an X-ray outburst, where the luminosity goes up by several orders of magnitude for a period of weeks to months, but most of the time they stay a state of quiescence. Interestingly, of the $\simeq$20 confirmed stellar-mass black hole X-ray binaries (BHXRBs), the large majority has been detected during a transient outburst (e.g. McClintock & Remillard 2006). However, during the outburst reprocessing of the X-rays in the outer accretion disk completely dominates the optical flux, thereby hiding any spectral signature of the donor star. It is only when the transient returned to quiesence, and X-ray reprocessing has switched off, that the donor star features are detectable and that dynamical studies could confirm the black hole nature.

In the last years $\simeq$half a dozen, both candidate and confirmed, BHXRBs have been detected in the halo (see e.g. Shaw et al. 2013). Interestingly, most of these BHXRBs have short (i.e. 2-5 hrs) orbital period, suggesting a different evolutionary path than those located in the Galactic disk. Although determining their system parameters is therefore crucial to start understanding this population, it is also challenging since most of these systems are too faint in quiescence for radial velocity studies using the current generation of large telescopes, However, an alternative path to obtain dynamical constraints on the system parameters was opened when Steeghs & Casares (2002) used narrow emission components, arising from the irradiated surface of the donor star, to obtain the first radial velocity curve of the mass donor in Sco X-1. These narrow components were most visible in the Bowen region (a blend of N III λ4634/4640 and C III λ4647/4650) and have been used to constrain the mass function for $\simeq$dozen neutron star X-ray binaries (see Cornelisse et al. 2008 for an overview).

One candidate BHXRB that is located in the halo is MAXI J1305−704 (MAXI J1305 from now on). It was discovered during an outburst by MAXI/GSC on 9 April 2012 (Sato et al. 2012), and Swift follow-up observations localized it with arcsec precision (Kennea et al. 2012a). Optical and radio counterparts were discovered quickly after the original detection (Coriat et al. 2012; Greiner et al. 2012). Interestingly, dip-like behaviour in X-rays was reported with a candidate periods of 1.5 and 2.7 hrs (e.g. Kennea et al. 2012b). Although these periods could not be confirmed during follow-up observations (see Kuulkers et al. 2012), it still suggests that MAXI J1305 has a moderately high inclination.

We performed spectroscopic observations on MAXI J1305 using the SALT telescope in Sutherland, South Africa (see Charles et al. 2012 for a brief description), and combined this with photometric observations using the 1.0 m telescope also located at Sutherland. In this paper we present the results of these observations in detail. In Sect. 2 the observations are described, and in Sect. 3 we present the results. We discuss our findings in Sect. 4 and show that MAXI J1305 is most likely a BHXRB with a 3.86 hr orbital period that harbours a precessing accretion disk.

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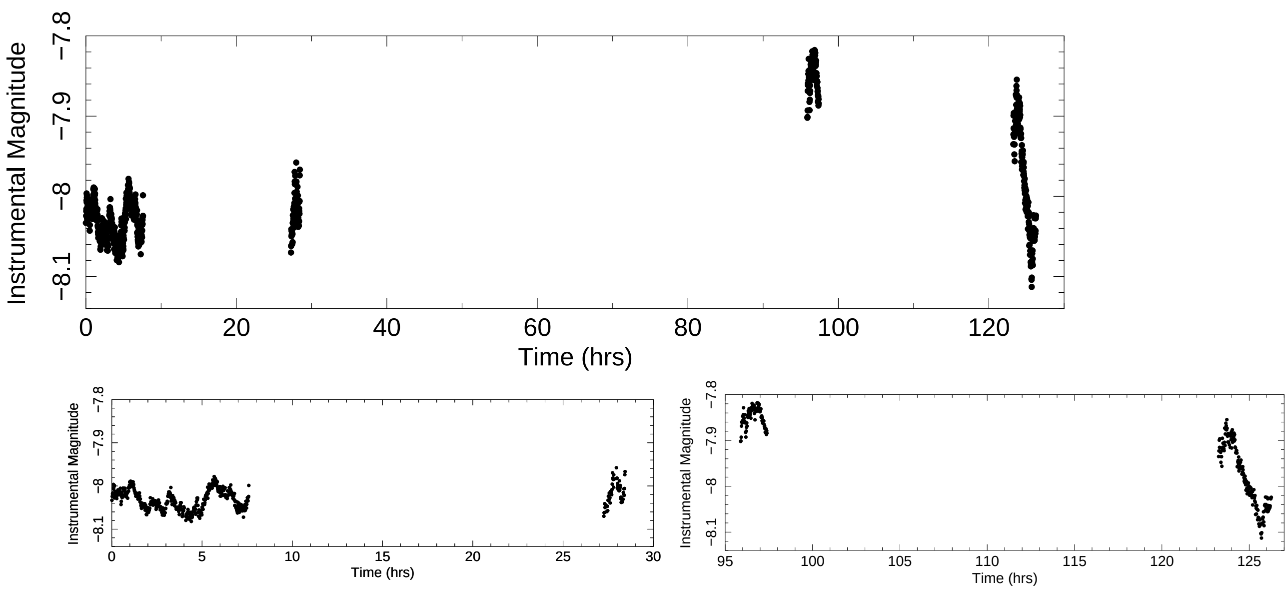

Figure 1.

Table 1. MAXI J1305 observing log.

Date/start time (dd-mm-yy/UT)	# obs.	exp. time (s)	seeing (arcsec)
Photometry			
12-04-12/19:00			
13-04-12/18:20			
16-04-12/closed			
17-04-12/18:20			
Spectroscopy			
17-04-12/03:58			
20-04-12/02:20			

2 OBSERVATIONS AND DATA REDUCTION

2.1 Photometric observations

On 12-13 April, and again on 16-17 April 2012 we obtained photometric observations of MAXI J1305 using the 1.0m telescope at SAAO. The new SHOC (Sutherland High-Speed Optical Camera) CCD was used, which is a Andor iXon 888 EM CCD camera with 1024×1024 pixels. During each night we obtained **Marissa, what band did you use?** band images with a time-resolution ranging between 1 to 5 sec, and in Table 1 we present an overview of the observations. In total we obtained close to 18,800 images spread out over the 4 nights.

For the reduction we used the ...**Marissa, I need your input here for the reduction.**

2.2 Spectroscopic observations

On both April 15 and 16 2012 we obtained approximately 2 hrs of phase-resolved spectroscopy of MAXI J1305 using the Robert Stobie Spectrograph (RSS) attached to the SALT telescope at Sutherland observatory (SAAO). During each night we used the G2300 volume-phase holographic grating with an integration time of 10 min each. We used a slit width of 0.6″, giving a wavelength coverage of λλ4050-5100 with a resolution of 105 km s^{-1} (FWHM). Arc lamp exposures for wavelength calibration were obtained regularly between science observations **How often?**. In Table 1 we give an overview of the observations.

For the reduction we used...**Deatrick, I need your input here.**

The PAMELA software was used for the data reduction (i.e. debias, flatfielding etc), which allows for optimal extraction of the spectra (Horne 1986). The pixel-to-wavelength scale was determined using a 4th order polynomial fit to 8 lines resulting in a dispersion of 0.73 Å pixel^{-1}, an rms scatter of <0.01 Å, and a wavelength coverage of λλ4434-6060. The final resolution around the He II λ4686 emission line is 107.6 km s^{-1} (FWHM). Finally we also corrected for any velocity shifts due to instrument flexure (always <10 km s^{-1}) by cross-correlating the sky spectra. For the corresponding analysis of the resulting dataset we used the MOLLY package.

3 PHOTOMETRY

In Fig. 1 we show the full (top panel), and close-ups of the 12/13 and the 15/16 April (bottom panels) lightcurves of MAXI J1305 binned to time-resolution of 1 minute. The first thing we note is the strong variability that occurs from night to night, while also the strength of the nightly variability changes dramatically. For example, during the first night the amplitude of the variability is ≃0.1 magnitude, while during the 4th night the amplitude has gone up to ⩾0.25 magnitude. This suggest that something is changing in MAXI 1305 on a timescale much longer than the orbital period.

The close-up of the second half of the observations in Fig. 1 (i.e. during 15/16 April) suggest a sinusoidal modulation in the lightcurve, which in other high inclination X-ray binaries (e.g. GR Mus) has been interpreted as primarily resulting from viewing different aspects of the irradi-

Table 2. Least square fit results and resulting chi square statistic to potential orbital periods for MAXI J1305.

Period (hrs)	χ^2 (265 d.o.f.)	Period (hrs)	χ^2 (265 d.o.f.)
2.50	4276	3.86	848
2.75	2726	4.46	1020
3.04	1554	5.58	1306
3.40	958	6.51	1608

ated surface of the donor star at different orbital phases (e.g. Motch et al. 1987). Interestingly, this sinusoidal modulation is completely absent during the first half of the observations, as if the irradiated donor star surface is not visible. Unfortunately, during the periods that the modulation is present, the data suggest that we did not observe a full orbital period during 16 April, and only observed the minimum during 15 April.

A period analysis of only the 15/16 April observations does therefore not allow us to distinguish between the many harmonic periods that fit the data, although it does rule out the potential 1.5 hr orbital period (Kennea et al. 2012b). On the other hand, the other potential candidate period of 2.7 hrs by Kennea et al. (2012b) is one of the potential periods that can fit the data. However, there are other periods that give a much better fit to the data. Using only the data from April 16 we obtain a best fit period of 3.80±0.04 hrs, which is further refined to 3.860±0.013 hr if 15 April data is included. Furthermore, using the 15/16 April data we also performed least-square fits to any of the potential harmonic periods to obtain a local best fit and list the best fit period and the goodness of fit (χ^2) in Table 2. We note that again the period around 3.8 hrs gives the best fit, and therefore propose the true orbital period to be 3.860±0.001 hrs, and use this period during the rest of the paper. Finally, under the assumption that the minimum in the lightcurve correspond to inferior conjunction of the secondary we estimate that orbital phase zero occured at HJD 2,456,034.320±0.037.

A close inspection of the 12/13 April observations does not show any evidence for a ≃3.9 hrs periodic variation. Furthermore, using the Lomb-Scargle technique (Scargle 1982), the resulting powerspectrum can be very well described by a power-law with an index of -1.07±0.06. This strongly suggest that the lightcurve is best described by flicker noise, which is most likely produced in the outer accretion disk.

4 SPECTROSCOPY

In Fig. 2 we present the average spectrum of MAXI J1305. As was already reported by Charles et al. (2012), the spectrum is dominated by emission lines that are typically observed in LMXBs, such as the Balmer series, He II and the Bowen blend. Furthermore we note an absorption feature just “redward” of Hβ, something that has also been observed in several other LMXBs such as GR Mus (Barnes et al. 2007) and X 1822−371 (Casares et al. 2003). Finally, we also note the presence of a narrow emission feature around 4743 Å that is not commonly observed in LMXBs. Given its narrowness compared to all other emission lines in the spectrum, we

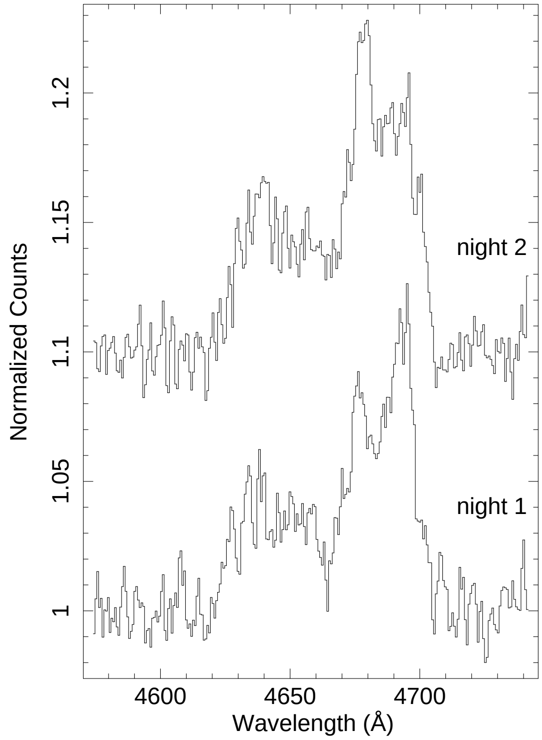

Figure 3.

think it most likely that this feature is an artefact of the data reduction.

We also created for each night an average spectrum and present a close-up of He II λ4686 and the Bowen region in Fig 3. The first thing to note is the fact that due to the their broadness He II and Bowen are blended together. This makes any estimate of the emission line properties (such as the equivalent width and full width at half maximum) uncertain, and we therefore do not attempt this. Furthermore we also want to point out that, in particular He II, there is large variability in the emission line profiles from night to night. In particular during the first night the blue wing of He II is strongest, while during the second night the red wing is dominating. We think this is most likely due to the fact that we only observed 60% of an orbital period per night. Finally, we note that there is no obvious presence of narrow emission components in the Bowen region during the first night, although during the second night there might be something present around 4640 Å.

In order to obtain any radial velocity measurements from He II λ4686 we first created an average spectrum. From this spectrum we estimated the central wavelength, width and strength for both the He II and Bowen component by fitting two gaussians simultaneously. Under the assumption that the Bowen blend does not significantly change we kept its values fixed while fitting a gaussian to He II in the individual spectra. The resulting radial velocity curve is presented in Fig. 4, and we again note that it is not possible to unambiguously determine the orbital period of MAXI J1305. However, we do note that a period of 3.86 hrs does provide fit that is comparable to that of other periods (i.e. its reduced chi-square is ${\chi^2}_\nu \leqslant 1$). However, the only thing that we

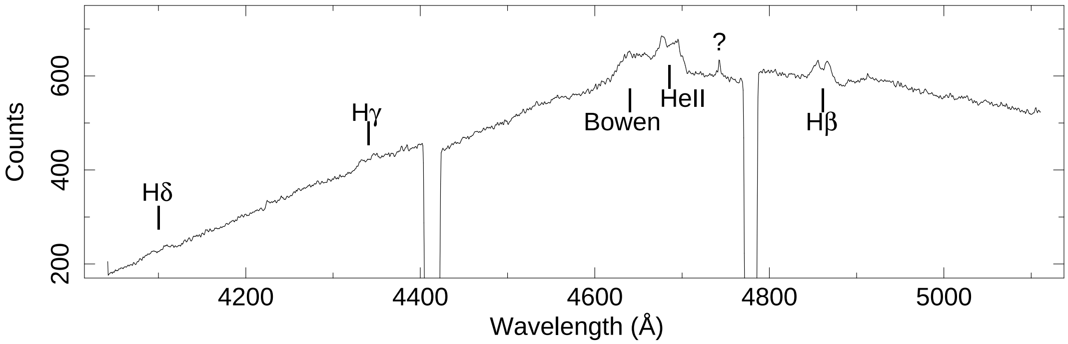

Figure 2.

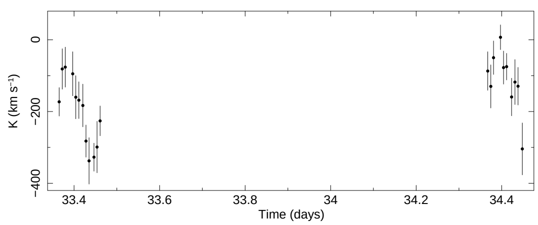

Figure 4.

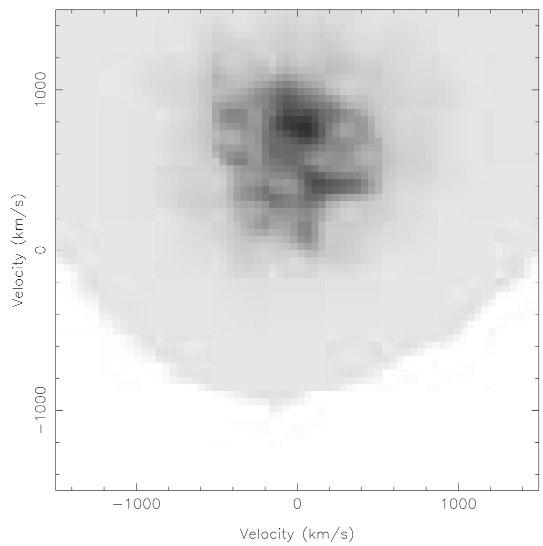

Figure 5.

can claim is that for all potential periods the corresponding systemic velocity is -175±13 km s^{-1}.

To search for the presence of narrow components in the Bowen region we used the technique of Doppler tomography (Marsh & Horne 1988). This technique allows us to search for structures in emission lines that are too faint in the individual spectra. In order to create the Doppler maps we used the ephemeris obtained from our photometric observations, plus the systemic velocity obtained from the He II λ4686 radial velocity curve. We simultaneously created maps for He II λ4686 and the Bowen region (where we only included N III λ4640) for both nights of observations individually. During the first night no obvious feature is present in the Doppler map of the Bowen region, but during the second night it is dominated by a compact spot at the position where a signature of the irradiated donor star surface is expected (i.e. the positive V_y-axis). In Fig. 5 we show the resulting map. Even after the addition of other narrow components that are typically observed in other LMXBs (such as N III λ4634.12 and C III λ4647.42/4650.25) there is always compact spot on the positive V_y-axis present, although its exact velocity ranges between 700-1000 km s^{-1}.

5 DISCUSSION

5.1 Precessing accretion disk

Our photometric and spectroscopic observations provide a first insight that MAXI J1305 most likely harbours an evolving accretion disk around a stellar-mass black hole. The X-ray observations already hinted at the presence of an evolving accretion disk. For example, Kennea et al. (2012; see also Kuulkers et al. 2012) pointed out that the strength and length of the X-ray dips changes from observation to observation. Furthermore, a long (30 ks) contineous observation suggested that there are also periods where dipping behaviour is not observed (Miller et al. 2012).

Similar behaviour as observed in MAXI J1305 is also present in most other known dipping sources such as the neutron star LMXB GR Mus (e.g. Diaz-Trigo et al. 2009) or XB 1916−053 (e.g. Smale et al. 1992). In these systems a large variation in dip depth and duration is observed, including periods where no dips are observed (e.g. Smale & Wachter 1999). Furthermore, also the optical lightcurves of these dipping sources show strong morphological changes over periods much longer than the orbital (e.g. Callahan et al. 1995; Smale & Wachter 1999). In these systems the X-ray dips are thought to be due to periodic obscuration of the inner accretion disk by a vertical structure in the outer accretion disk, such as an extended disk rim (White & Swank 1992; although see Cornelisse et al. 2013 for an alternative). Something similar could also explain the behaviour in MAXI J1305.

A vertical structure in the outer accretion disk that causes the dips in MAXI J1305 to change over a timescale that is longer than the orbital period could explain why no sinusoidal variation was observed during the first half of our photometric observations. If the vertical structure was extended enough that the donor star would be continuously within the shadow cast by the outer accretion disk, no X-ray irradiation of the donor star surface would occur. In this case the optical light would be dominated by the outer accretion disk, which is very well described by flicker noise only. During the second half of our observations on the other hand, the extended structure has decreased enough that irradiation of a part of the donor star surface occurs, which gives rise to the observed sinusoidal variation and is due to orbital modulation.

This scenario is further supported by the absence of any narrow components in the Bowen region during our first night of spectroscopic observations. These components are thought to arise on the irradiated surface of the donor star and their absence strongly suggest that the donor star was (almost) completely in the shadow of the accretion disk rim. During the second night of spectroscopy the vertical structure must have deminished since there is a hint of the presence of narrow components, and interestingly enough this does correspond with the $\simeq$2 hrs of photometry where we think there is a sinusoidal variation.

Finally, from other dipping LMXBs we know that the period of X-ray dipping activity can range from 0% all the way upto $\simeq$30% of the orbital period. This will make any period analysis on a limited and fractured data-set such as the X-ray observations of MAXI J1305 by the Swift satellite challenging, but it should still be able to confirm if our preferred orbital period of 3.86 hr provides a consistent result.

5.2 System parameters

6 CONCLUSIONS

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