The orbital period of MAXI J1305-704

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Abstract

MAXI J1305-704 is a candidate black hole X-ray binary discovered by MAXI in 2012. The system parameters are relatively unknown, with no dynamical determination of the mass of the compact object as of yet. There have also been several conflicting measurements of the source's orbital period, the most recent of which is $P_{\rm orb} = 9.74$h, based on the observation of deep X-ray dips in the X-ray light curve. We reanalyze a 40 ks *Suzaku* observation of MAXI J1305-704 in order to disentangle the multiple periodicities previously reported. Using timing analysis techniques, we suggest that the orbital period is instead $\sim$ 5h. We also present optical spectroscopy of the source in outburst that provides a mass function, but its value is too low to constrain the nature of the compact object.

Key words: black hole physics — X-rays: binaries — X-rays: individual: MAXI J1305-704

1. Introduction

Galactic black hole X-ray transients (BHXRTs) are low-mass X-ray binaries consisting of a black hole (BH) accreting from a low-mass ($\leq 1M_{\odot}$) companion. They are characterized by long periods of quiescence (years to decades) followed by X-ray outbursts that can increase the luminosity by several orders of magnitude. BHXRTs have proven to be important in studying X-ray binaries (XRBs) as in quiescence they provide the opportunity to detect the donor itself, which is mostly impossible in luminous, persistent XRBs (Charles & Coe 2006)

Determining the system parameters of BHXRTs is crucial for understanding their formation and evolution. However, it is challenging as most systems are too faint in quiescence for radial velocity studies using the current generation of large telescopes. A key parameter required for determining the mass function (and therefore the nature) of the compact object is the orbital period ($P_{\rm orb}$) of the system, which can often be measured in outburst (see e.g. Zurita et al. 2008).

Since its launch in 2009 *MAXI*/GSC (Matsuoka et al. 2009) aboard the ISS has discovered 6 new candidate BH systems. One such system, MAXI J1305-704 (hereafter J1305), was discovered in April 2012 (Sato et al. 2012). Optical follow up revealed a new source not present in archival *Digitized Sky Survey* (DSS) images (Greiner, Rau & Schady 2012) and a spectrum typical of an LMXB in outburst (Charles et al. 2012). Pointed observations of the source with *Swift* revealed a soft, disk-dominated spectrum (Kennea et al. 2012a).

The $P_{\rm orb}$ of J1305 is the subject of much debate, owing to the wide range of values that have been reported. *Swift* observations of the source during its initial outburst revealed dips in the X-ray light curves accompanied by spectral hardening. The dips occurred at irregular times and made determining the exact periodicity difficult but $P_{\rm orb}$ has been suggested to be 1.5h or 2.7h (Kennea et al. 2012b). Subsequently, Shidatsu et al. (2013) reported $P_{\rm orb} = 9.74 \pm 0.04$h based on the discovery of deep dips in *Suzaku* light curves. However, this value was determined by simply measuring the time between the dips, rather than a formal timing analysis. The discovery of dips in multiple X-ray observations indicates that J1305 has a high inclination angle, a hypothesis supported by the presence of strong Fe L absorption features around 1keV in the *Chandra*/HETGS spectrum of the source (Miller et al. 2012). However, detailed constraints on the inclination have not yet been obtained.

Here, we summarize our reanalysis of the *Suzaku* observations of J1305 presented by Shidatsu et al. (2013), focusing in particular on timing analysis of the light curves. We also present optical spectroscopy of the source at the peak of its 2012 outburst and study the emission features, attempting to place a limit on the mass of the compact object.

2. Observations and Data Reduction

2.1. X-ray observations

We used archival *Suzaku*/XIS (0.2 – 12keV) observations of J1305 from 2012 July 20 giving ∼40ks (OBSID: 907001010). The observation took place whilst the source was in a low/hard accretion state (Shidatsu et al. 2013), displaying an average count rate of ≈ 5 cts s^{-1} so pileup effects are negligible and can be ignored. We reduced the data with HEASOFT v6.19, emulating the analysis performed by Shidatsu et al. (2013) and using XSELECT to generate light-curves in the standard manner.

2.2. Optical observations

J1305 was observed on the nights of 2012 April 15–16 with the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT; Buckley et al. 2006) at the SAAO. A total of 2.25h of continuous spectroscopy was obtained on each night using the G2300 VPH grating with individual integration times of 600s. We used a slit width of 0.6″, covering a wavelength range of 4040 – 5110 Å.

We used standard data reduction techniques for SALT as described by Crawford et al. (2010). Wavelength calibration was performed with IRAF (Tody 1986) to achieve the solution for the Xe and CuAr comparison arcs. We then transformed the 2D spectra on to the wavelength scale and extracted the 1D spectra with the IRAF task APALL.

3. Results

3.1. X-ray Light Curves

The 128s binned *Suzaku* light curves are presented in Fig. 1. Only the XIS-3 light curves are plotted for clarity, but the XIS-0/1 light curves are almost identical. They exhibit significant variability in both bands, with deep dips appearing at irregular intervals accompanied by notable increases in the hardness ratio.

It is difficult to estimate the periodicity of the dips by eye due to data gaps, mostly due to the low-Earth orbit of the spacecraft. We therefore undertook a Lomb-Scargle analysis on both the light curves and the HR to determine a central peak frequency followed by a Monte-Carlo simulation based on 'bootstrap-with-replacement.' The distribution of peak frequencies resulting from 10000 iterations of this process indicates the error on the peak frequency. The periodograms exhibit a number of periodicities (Fig. 2), making it difficult to determine the true $P_{\rm orb}$. The strongest peaks correspond to periods of 3.14±0.06h (3.23±0.05h) and 4.98±0.05h (4.99±0.04h) in the 0.7 – 2keV (2 – 10keV) energy band.

Fig. 3 shows the folded *Suzaku* light curves on the two most significant peaks from Fig. 2. The folded light curves show differing morphology and are explored further in Section 4.1.

3.2. Optical spectrum

The averaged optical spectrum of J1305 (Fig. 4) exhibits strong double-peaked Balmer emission (H_β, H_γ and H_δ) and He II λ4686, indicative of a high inclination binary. Also evident is strong emission in the Bowen region (λ4640 – 4660), a blend of narrow, high-excitation N III and C III emission lines arising from the irradiated surface of the donor star.

Closer inspection of the Bowen region reveals that the lines are extremely broad and blended together, making any estimation of emission line properties (e.g. FWHM) highly uncertain and is therefore not attempted. The lack of sharp features in the region makes the Bowen fluorescence technique for measuring the mass of the compact object (Steeghs & Casares 2002) extremely difficult, and is beyond the scope of this work.

4. Discussion and Conclusions

4.1. The Orbital Period

To investigate the multiple periodicities present in the periodograms in Fig. 2 we must study the light curve folded on these periods. The phase-folded X-ray light curves in Fig. 3 display differing morphology dependent on the period used in the folding. The dipping structure seen in Fig. 1 is recovered in both bands of the ∼ 5h folded light curves. Deep dips are seen in the 0.7 – 2keV band, whilst shallower dips appear in the 2 – 10keV folded light curve, echoing the apparent dichotomy in dipping structure in the two energy bands as seen in Fig. 1.

When folded on the other major peak in Fig. 2 (3.14/3.23h), the dipping structure is not at all clear in the 0.7 – 2keV band, though it is visible in the 2 – 10keV energy band, albeit with large uncertainties. There are also empty bins in the folded data on these periods. It is possible that the ∼ 3.2h period can be attributed to double the spacecraft's $P_{\rm orb}$ (1.6h; Mitsuda et al. 2007). There are no peaks in the periodogram at 1.6h, but this could be due to an irregular observing pattern of the source over the total ∼ 30.5h observation. The fact that the dipping structure is only revealed in both bands of the 4.98/4.99h folds of the *Suzaku* light curves implies that out of the proposed periods, this period appears to be the best candidate for the $P_{\rm orb}$ of J1305.

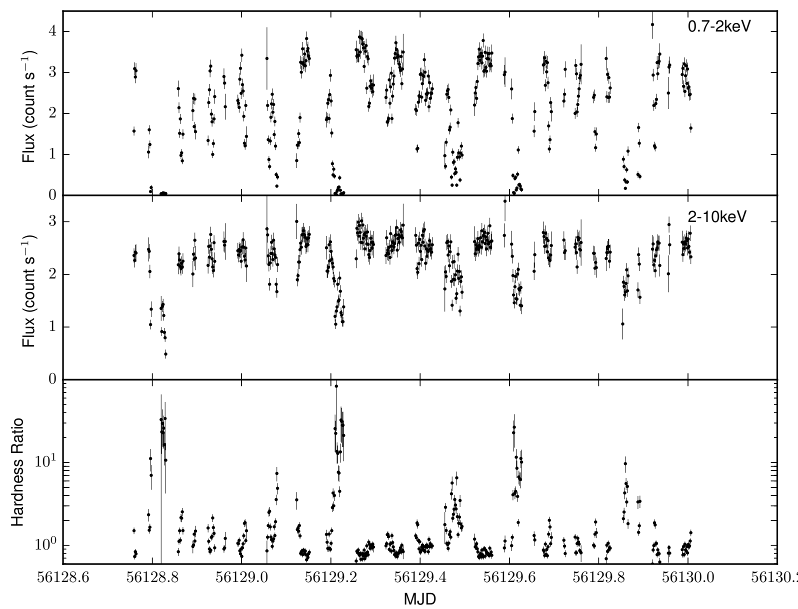

Fig. 1. *Suzaku* XIS-3 light curves in 128s time bins. Plotted are the 0.7 – 2keV (S; Top) and 2 – 10keV (H; Centre) energy bands and the hardness ratio, defined as H/S (Bottom).

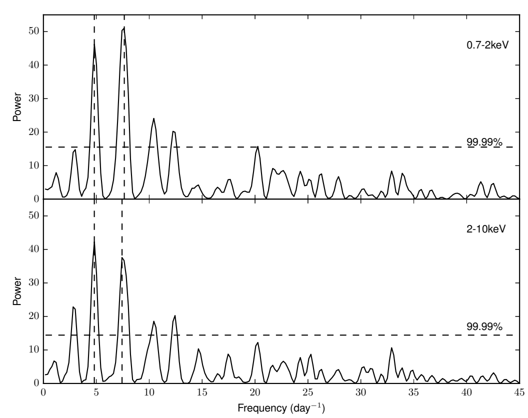

Fig. 2. Lomb-Scargle periodograms of the *Suzaku* light curves in the 0.7-2keV (Top) and 2-10keV (Bottom). The two most significant periodicities seen are marked in each panel with vertical dashed lines. The horizontal dashed lines in each panel represent the 99.99% significance level, determined by randomizing the flux positions in the light curves whilst maintaining the time stamps and performing 10000 iterations of the Lomb-Scargle algorithm.

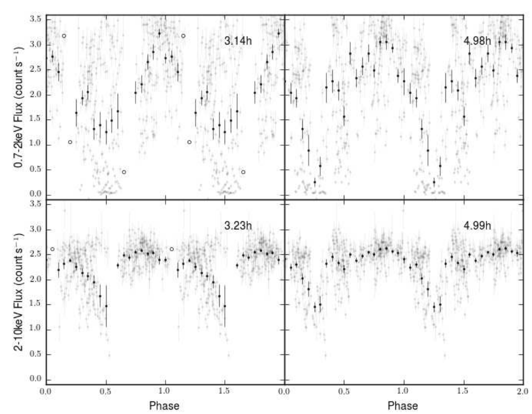

Fig. 3. *Suzaku* light curves of MAXI J1305-704, folded on the two most significant peaks (from Fig. 2). The top two panels are folds of the 0.7 – 2keV light curves and the bottom two panels are folds of the 2 – 10keV light curves. Open points represent data which have no estimated uncertainties due to only one unbinned point being available for binning. Also shown in light grey are the unbinned phase folded light curves in each energy band. The periods used for folding are designated in each panel.

4.2. System Parameters

The previous estimate of $P_{\rm orb} = 9.74$h would require an evolved donor star with M_2, R_2 and ρ_2 less than that of the Sun (Shidatsu et al. 2013). With our revised $P_{\rm orb} = 4.98$h we calculate the radius of the donor to be $R_2/R_\odot = 0.55 - 0.7$ using a sensible range of mass ratios ($M_2/M_1 = 0.1 - 0.2$; where M_2, M_1 are the mass of the donor and compact object, respectively) with the standard approximations for Roche lobe geometry (Eggleton 1983). We also calculate the density of the donor to be $\log(\rho_2/\rho_\odot) \approx 0.51$. These values are

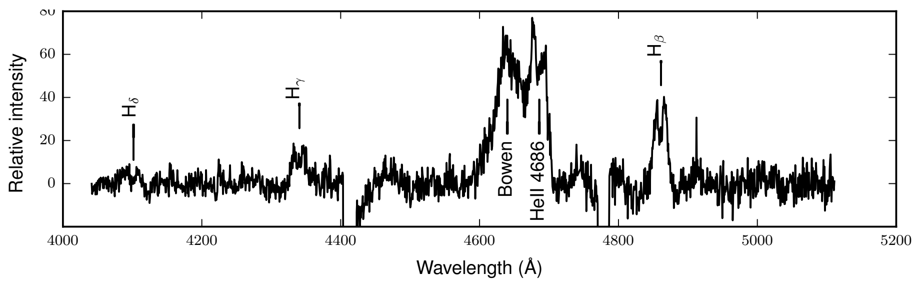

Fig. 4. Averaged, continuum-subtracted optical spectrum of J1305 obtained with SALT/RSS on the nights of 2012 April 15 - 16.

consistent with low-mass donors of spectral type K5 – M1 (Cox 2000).

As well as determining $P_{\rm orb}$ from the *Suzaku* light curves we can also attempt to place a limit on M_1 by estimating K_2, the radial velocity semi-amplitude of the donor, from the optical spectrum. Orosz et al. (1994) and Orosz & Bailyn (1995) showed that there is a relation between the projected velocity of the outer disc, v_D, and K_2 ($v_D/K_2 = 1.1 - 1.25$) where the peak-to-peak separation of the Balmer lines can be used as an indicator of v_D (Warner 1995). Utilizing a double-Gaussian fit to H_β, we measure the peak-to-peak separation to be 783 ± 37 km s^{-1} and derive a lower limit to $K_2 \geq 313$ km s^{-1}.

Combining the preferred $P_{\rm orb}$ with this conservative lower limit on K_2, we derive an absolute lower limit on the mass function for J1305 of $f(M_1) = M_1 \sin^3 i/(1+q)^2 = K_2^3 P_{\rm orb}/2\pi G \geq 0.66 M_\odot$ where i is the binary inclination and $q = M_2/M_1$. Since both $\sin i$ and q must be positive, $f(M_1)$ truly provides an absolute lower limit on M_1. However, this is well below $1.4 M_\odot$, the canonical value for the mass of a neutron star, and therefore does not allow a determination of the true nature of the compact object.

4.3. Conclusions and Future Work

Using archival *Suzaku* data we have determined $P_{\rm orb}$ of the candidate BHXRT MAXI J1305-704 to be 4.98 ± 0.05h based on the presence of deep dips in both the 128s binned and folded *Suzaku* light curves. Though this is the preferred period, we cannot completely rule out other periods suggested by the Lomb-Scargle periodogram analysis. We also placed a lower limit on the mass of the compact object $M_1 \geq 0.66 M_\odot$, however this does not yet constrain the nature of the compact object.

The work presented here is ongoing and requires further investigation of the optical spectrum. For example, He II λ4686 exhibits variability in the individual spectra, perhaps indicating that at least some of the He II emission originates on the X-ray heated face of the donor or the stream/disc impact region, i.e. the hotspot. In order to investigate this we plan to use Doppler tomography to map the emission features in velocity space, recovering the structure of the emission regions. Doppler tomography may also enable us to study the Bowen region in greater detail and perhaps provide a better constraint on K_2 and therefore M_1. The best constraints on K_2 will come from observations of the source in quiescence. However, J1305 was not detected in the DSS, and therefore spectroscopy of the donor may require the next generation of optical telescopes such as the European Extremely Large Telescope (E-ELT).

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