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A 2 h periodic variation in the low-mass X-ray binary Ser X-1

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ABSTRACT

Spectroscopy of the low-mass X-ray binary Ser X-1 using the Gran Telescopio Canarias have revealed a ≃2 h periodic variability that is present in the three strongest emission lines. We tentatively interpret this variability as due to orbital motion, making it the first indication of the orbital period of Ser X-1. Together with the fact that the emission lines are remarkably narrow, but still resolved, we show that a main-sequence K dwarf together with a canonical 1.4 $M_{\odot}$ neutron star gives a good description of the system. In this scenario, the most likely place for the emission lines to arise is the accretion disc, instead of a localized region in the binary (such as the irradiated surface or the stream-impact point), and their narrowness is due instead to the low inclination ($\lesssim$10°) of Ser X-1.

Key words: accretion, accretion discs – stars: individual: Ser X-1 – X-rays: binaries.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are interacting binaries where a low-mass donor transfers matter on to the neutron star or black hole via Roche lobe overflow. This process forms an accretion disc and gives rise to the observed X-rays, making them among the brightest X-ray sources in the sky (see e.g. the collected reviews in Lewin & van der Klis 2006). Although optical counterparts for many of the bright LMXBs have been known for a long time, kinematic studies of these systems are often not straightforward. This is mainly due to reprocessing of the X-rays in the outer accretion disc that completely dominates the optical light. This situation has changed only with the advent of sensitive spectrographs on very large telescopes.

Using phase-resolved medium resolution spectroscopy of Sco X-1, Steeghs & Casares (2002) detected the presence of narrow high excitation lines that were strongest in the Bowen region (a blend of N III λ4634/4640 and C III λ4647/4650). These narrow lines originate from the irradiated surface of the donor star and allowed for the first time a radial velocity study of both binary components in Sco X-1 which led to constrain its mass function. Phase-resolved spectroscopic studies of about a dozen other bright LMXBs have revealed the presence of these narrow components in the Bowen region in most LMXBs and provided in many cases the first constraints on the mass of their compact objects (e.g. Cornelisse et al. 2008 for an overview).

One such bright LMXB is Serpens X-1 (Ser X-1). It was discovered in the 1960s (Friedman, Byrom & Chubb 1967), but its optical counterpart (MM Ser) was only identified about 10 years later (Davidsen 1975). Further observations taken in good seeing conditions showed that the optical counterpart consisted of a blend of two stars that are separated by ≃2.1 arcsec (Thorstensen, Charles & Bowyer 1980). Subsequently, one of these was itself revealed to be a blend of two stars that are only separated by 1 arcsec (Wachter 1997). Both spectroscopy (Hynes et al. 2004) and radio observations (Migliari et al. 2004) confirmed that the bluer of the stars is the true optical counterpart. Due to the well-established presence of thermonuclear X-ray bursts from Ser X-1, the compact object is known to be a neutron star (Li & Lewin 1976). Furthermore, Ser X-1 was one of the first neutron star LMXBs in which a broad relativistic iron line was detected, and modelling of this line inferred inclination an of <25° (Bhattacharyya & Strohmayer 2007; Ng et al. 2010). However, despite over 40 years of study little else is known about Ser X-1.

Here, we present the results of a spectroscopic study of Ser X-1 using the Gran Telescopio Canarias (GTC) at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma (Spain). We detect a ≃2 h periodic variation that we interpret as the orbital period. Although the emission lines are very narrow and sharp (as was already reported by Hynes et al. 2004), we present further evidence that this is due to the low inclination of the system instead of the lines being formed on the irradiated surface of the donor star or the stream-impact point.

2 OBSERVATIONS AND DATA REDUCTION

On 2011 July 6, we observed Ser X-1 for 4 h continuously (UT 21:45-02:23) using OSIRIS on GTC. For each exposure, we used

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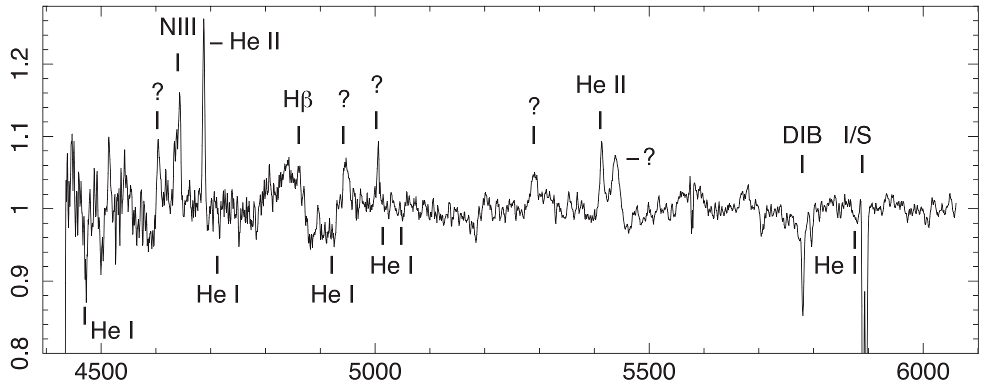

Figure 1. Average normalized OSIRIS/GTC spectrum of Ser X-1. Indicated are the most prominent identified emission lines, sky lines (I/S) and diffuse interstellar bands (DIB) while the unidentified features are labelled '?'. We note that several of these unidentified features were previously observed by Hynes et al. (2004).

the volume-phased holographic grism R1200V with a slit width of 1.0 arcsec, resulting in a total of 24 spectra with an exposure time of 600 s each. The seeing during the observations varied between 0.7 and 1.0 arcsec. Since Ser X-1 is ≃1 arcsec from a fainter field star, we aligned the slit in such a way that we minimized the contribution of this interloper. However, this does mean that no comparison star is included in the slit and we could therefore not correct for slit losses. Arc lamp exposures were taken for wavelength calibration during the daytime.

For the data reduction (i.e. debias, flatfielding, etc.), we used the PAMELA software that allows for optimal extraction of the spectra (Horne 1986). We determined the pixel-to-wavelength scale using a fourth-order polynomial fit to 20 lines resulting in a dispersion of 0.79 Å pixel^{-1}, an rms scatter of <0.05 Å and a wavelength coverage of λλ 4434–6060. 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 <6 km s^{-1}) by cross-correlating the sky spectra. For the corresponding analysis of the resulting data set, we used the MOLLY package.

3 DATA ANALYSIS

3.1 Spectrum

First, we created an average normalized spectrum of Ser X-1, and show the result in Fig. 1. The spectrum is very similar to that presented by Hynes et al. (2004), but there are also a few differences. To start with the similarities, the most prominent emission lines that are commonly detected in LMXBs are also present in our spectrum (and indicated in Fig. 1), and all of them are extremely narrow as shown in Table 1. In particular, a close-up of the Bowen region, presented in Fig. 2, suggests that the individual N III components (i.e. 4634 and 4640Å) are clearly separated, while there is also no hint of any C III lines. Furthermore, we detect He I λ4471 in absorption, and there are hints of features at the location of other He I transitions in our spectrum (which are indicated in Fig. 1). However, since He I λ4471 is on the edge of the wavelength coverage where the sensitivity starts to drop significantly, it is not possible to conclude anything else from this line. Finally, just like Hynes et al. (2004) we also detect the broad absorption trough just redwards of Hβ and the unidentified emission features at 4604 and 4945 Å. This confirms beyond doubt that they are not artefacts and must be true features of the system, and we have indicated them with a '?' in Fig. 1.

Table 1. Emission line properties in Ser X-1 for both lines that are typically observed in LMXBs (known lines) and emission lines that are unique to Ser X-1 (unknown lines). Included are the best-fitting period (P) and semi-amplitude (K) obtained via sine-wave fits for the lines where variability is observed. For the lines that are part of a blend, we have also indicated the properties of the full region. All FWHM measurements are the intrinsic broadening after deconvolving the instrumental resolution.

Line	EW (Å)	FWHM (km s^{-1})	P (h)	K (km s^{-1})
Known lines				
He II λ4686	1.20±0.07	180 ± 10	1.98 ± 0.13	38 ± 5
N III λ4640	0.81 ± 0.06	210 ± 12	2.19 ± 0.15	31 ± 5
He II λ5411[a]	1.01 ± 0.04	305 ± 44	1.98 ± 0.20	34 ± 8
Unidentified lines				
λ4604	0.68 ± 0.08	418 ± 62		
λ4945	0.57 ± 0.06	1061 ± 94		
λ5004	0.30 ± 0.04	246 ± 34	1.84 ± 0.34[b]	23 ± 12[b]
λ5290	0.42 ± 0.05	823 ± 85		
Blends				
Bowen	1.40 ± 0.09	717 ± 57		
He II λ5411[c]	3.62 ± 0.08	2220 ± 138		

[a]EW and FWHM are for the He II emission line only.
[b]Note that the sine-wave fit is formally not significant.
[c]EW and FWHM are for the full structure between 5400 and 5450 Å.

The two main differences between our spectrum and that of Hynes et al. (2004) are a much more complex structure around Hβ and several new features (which we have also indicated with a '?'). The detailed structure around Hβ (ranging from 4800 to 4950 Å) appears to form an inverted P Cygni profile, as if it were a single feature. However, within the current framework of LMXBs, it is difficult to understand how a significant infall component above the disc of Ser X-1 at velocities well over 4000 km s^{-1} (which are needed to produce such a profile) could occur. Furthermore, from the He I λ4471 absorption line, we already know that at least He I λ4922 will be present in absorption and contributing to this feature. We therefore think it more likely that the full complex around Hβ is made up of many blended emission and absorption lines.

Of the new features that are present in our spectrum, the broad emission components just redwards of He II λ5411 and the narrow one around 5004 Å are particularly interesting. They should have been clearly detected by Hynes et al. (2004) and to our knowledge have no counterpart in any other LMXB. To identify the narrow features at 4605 and 5004 Å, we used the atomic line list by van

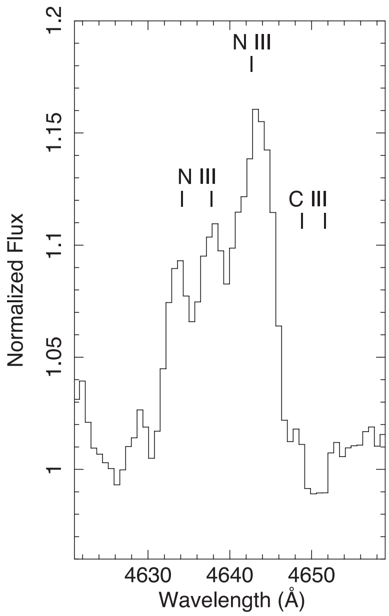

Figure 2. Close-up of the Bowen blend of Ser X-1 with the position of the expected N III and C III lines indicated. Note that the spectrum has not been corrected for the systemic velocity of $\simeq$92 km s^{-1}.

Hoof & Verner (1997) and the applied off-set of 92 km s^{-1} (see Section 3.2) from the He II λ4686 rest-frame wavelength as an estimate of the systemic velocity of Ser X-1. The 4605 Å feature corresponds to an N III transition (4603.8 Å), while that at 5004 Å is close to an N II one (5002.7 Å). We therefore tentatively conclude that these unknown transitions are due to ionized nitrogen.

We examined the broad feature at 5440 Å in the individual spectra by eye and note that it is extremely variable. Although present in all spectra, its strength and width show large changes from spectrum to spectrum. We illustrate this in Fig. 3 by showing the close-up of this region in two different spectra. Although we have no explanation for the strong variability displayed, the profile in the lower spectrum in Fig. 3 does suggest that it consists of several unresolved lines. Indeed, we note that a large number of N II/N III transitions occur in this region that are close to the individual peaks displayed, but the quality and resolution of the individual spectra does not allow us to unambiguously conclude this.

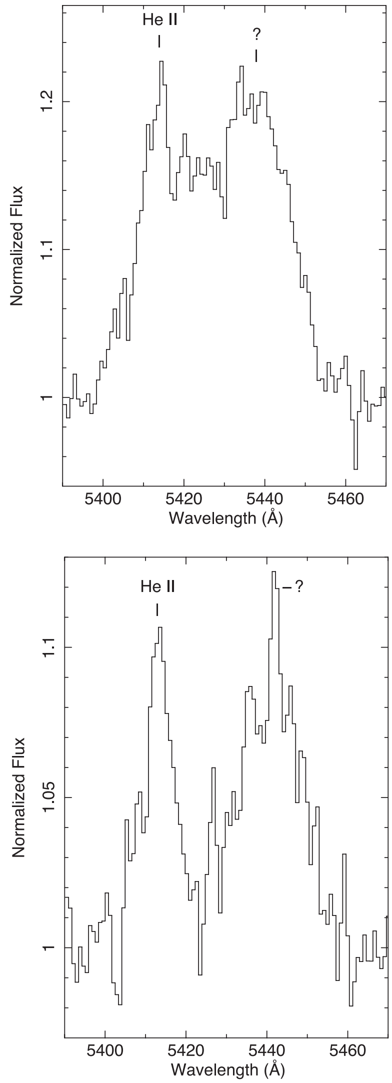

Figure 3. Close-up of the He II λ5411 emission line for two spectra of Ser X-1. Although He II is clearly detected in both spectra (and labelled as such), a broad and highly variable unidentified feature is also present (labelled '?').

3.2 Radial velocities

Following the report of Hynes et al. (2004) of a small drift of He II λ4686 over the period of $\simeq$an hour, we inspected the trail of this line by eye. We could clearly see some movement over time and therefore averaged two consecutive spectra together to improve the signal-to-noise, thereby creating 12 spectra in total. For each of these spectra we then determined the full width at half-maximum (FWHM), equivalent width (EW) and radial velocity. Our FWHM measurements show that the line is resolved and we therefore corrected our measurements for instrumental broadening using a nearby line in our arc spectrum. Since both the FWHM and EW do not change significantly during our observations, we present their average value in Table 1. Finally, we note that the average radial velocity is consistent with that observed by Hynes et al. (2004), and in Fig. 4 we show the resulting radial velocity curve.

Interestingly, the radial velocity curve does appear to show periodic motion. We therefore checked other strong emission lines (i.e. the Bowen region and He II λ5411) to see if similar variability is present. The Bowen region also shows that there are no strong changes between the spectra in both strength and width of the individual components that make up the blend. We also note that there are clear velocity shifts in N III λ4640, the strongest component of the Bowen region, and therefore measured the FWHM, EW and radial velocity for this line. We present the results in Fig. 4 and Table 1. Finally, we also measured the average EW and FWHM of the full Bowen blend, and list these results in Table 1.

As already pointed out in Section 3.1, the region around He II λ5411 is more complex due to the strongly variable component just redwards (see Fig. 3). However, He II is itself clearly visible in the individual spectra and again it is moving, and in Fig 4 we give its radial velocity curve. However, the FWHM and in particular EW measurements of the individual spectra gives such a large spread (see Fig. 3) that we have opted to only measure these values from the average of all spectra, giving the results in Table 1. Finally, we

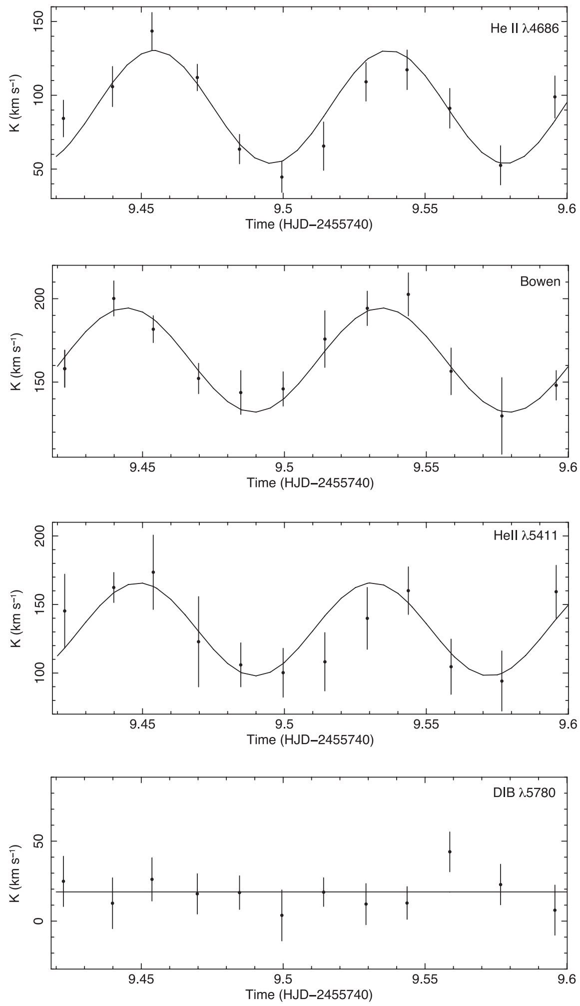

Figure 4. Radial velocity curves for the three strongest emission lines and a DIB (around 5780 Å) present in the spectrum of Ser X-1. The emission lines are from top to bottom: He II λ4686, N III λ4640 and He II λ5411. Overplotted is the best-fitting sine curve for each line. The radial velocity curve of the DIB on the other hand shows no obvious velocity movement.

also measured the FWHM and EW of the full complex between 5400 and 5450 Å, and these are also included in Table 1.

We also searched for variability in the unidentified emission lines in Fig. 1 (those indicated with '?'). Most lines are either too weak or show no variability, and we therefore only present their FWHM and EW in Table 1. The emission line at 5004 Å is the only one that shows some evidence of variability although at a low significance of $\simeq 2\sigma$. Interestingly, a sine-wave fit to its radial velocity curve gives a period and amplitude that are consistent with the lines discussed above. For completeness, we list the fit results in Table 1, but will not include them in any further analysis.

Fig. 4 shows that the three emission lines all have a variability with a period, semi-amplitude and phasing that are similar within the errors. To verify that the variability does not have an instrumental origin, we also measured the radial velocities of a diffuse interstellar band (DIB) around 5780 Å. This is included as the bottom panel of Fig 4, and shows clearly no velocity shifts in the DIB feature to a limit of <9.4 km s^{-1} (99 per cent confidence). Finally, for the He II λ4686 radial velocity curve, a χ^2-test indicates that the variability is highly significant, since fitting it to a constant velocity gives $\chi^2_\nu = 5.7$ (for 11 degrees of freedom).

We therefore conclude that the variability in the three emission lines is real, and fitted the radial velocity curve for each emission line with a sine wave (resulting in $\chi^2_\nu = 0.85$ for He II λ4686). We list the resulting periods and semi-amplitudes in Table 1, and note that apart from the systemic velocity, γ, all parameters are similar within the errors. The differences in γ are most likely due to the fact that both N III λ4640 and He II λ5411 are blended with nearby lines, thereby producing an off-set. This is further strengthened by the fact that their FWHM is much broader than He II λ4686. Since we do not expect He II λ4686 to be blended, we think that this line provides the best estimate of the systemic velocity, which we measure as $\gamma = 92 \pm 4$ km s^{-1}.

Finally, we phase-folded both the Bowen blend and He II λ4686 in eight bins to check for other emission features moving around on a similar period (but at a different phase and semi-amplitude). A visual inspection does not show any other moving component. Furthermore, we created averages by co-adding spectra spanning 0.25 orbital cycles around the expected minimum and maximum of both N III λ4640 and He II λ4686. At both extrema, the lines can be very well described by a single Gaussian and the addition of a second Gaussian (either as a broader underlying feature or a second narrow peak) does not significantly improve the fit (according to an *F*-test). We therefore conclude that the emission lines can be represented by a single component.

4 DISCUSSION

We have presented evidence for a $\simeq$2 h periodic radial velocity variation in the emission lines from Ser X-1 from our GTC observations. Although this variation is based only on approximately two cycles worth of data, and therefore still needs confirmation, we tentatively conclude that we have detected the orbital period of Ser X-1. For the rest of the discussion, we will assume that the variability is truly due to orbital motion and consider what the implications are for the properties of this system.

Another important observation is the fact that most emission lines are narrow and are best described by a single component. This strongly suggests that they are located in a single region somewhere in the binary. Hynes et al. (2004) have already listed several potential locations: the outer accretion disc, the irradiated surface of the donor star or the stream-impact point. Based on our proposed orbital period, we can now explore these different suggestions to find out what the consequences for the system parameters of Ser X-1 will be.

Could the emission lines arise from the irradiated surface of the donor star? Narrow components arising from the irradiated donor star surface have been observed in many persistent LMXBs (see e.g. Cornelisse et al. 2008 for an overview). These narrow components are in general strongest in the Bowen region, but there are also examples (e.g. EXO 0748−676) where the He II lines show a large component arising from the irradiated surface (Muñoz-Darias et al. 2009). Although the narrow components in many LMXBs have an FWHM comparable to that observed for Ser X-1, their radial velocity semi-amplitudes are typically an order of magnitude larger (e.g. Casares et al. 2006; Barnes et al. 2007; Cornelisse et al. 2007). If the lines arise from the irradiated surface of the donor star, then the observed FWHM of the emission lines of $\simeq$180 km s^{-1} must be due to rotational broadening only (since there is no evidence that the lines consist of multiple components). In this case, we can easily show that for any reasonable mass ratio of Ser X-1, the FWHM is incompatible with the observed radial velocity semi-amplitude of $K_{em} = 38$ km s^{-1}.

As a first-order estimate to interpret our measurements, we must assume a large mass ratio and that the accretion disc in Ser X-1 is not shadowing the donor star, i.e. K_{em} is tracing emission coming from L1. This will lead to the largest so-called K-correction in order to derive the true radial velocity semi-amplitude of the donor star. Using the K-correction polynomials by Muñoz-Darias, Casares, Martinez-Pais (2005) for $q = 0.8$ (the largest mass ratio for which their K-correction is still valid to 1 per cent) gives a radial velocity semi-amplitude of the donor star of $K_2 = 111$ km s^{-1}. From this value of K_2, together with $q = 0.8$ we can estimate a rotational broadening of the emission lines of $V\sin i = 0.462 K_2 q^{1/3}(1+q)^{2/3} =$ 70 km s^{-1} (Wade & Horne 1988). This is much smaller than the 180 km s^{-1} we observe, and suggests that $q \gg 0.8$. Even for the highly unlikely assumption of $q \simeq 1.0$ these numbers will still not work, and we cannot obtain a sensible solution, and we therefore reject the suggestion that the lines arise from the donor star.

If we instead assume that the emission lines are produced in the accretion disc (or the stream-impact region), we find that it is possible to create a consistent set of system parameters. As an X-ray burster, the compact object is a neutron star, whose mass we will assume is close to the canonical value of 1.4 M$_\odot$. Furthermore, from our proposed short orbital period we can also infer that the donor star, if it is a main-sequence star, must be of a late spectral type such as a M5V dwarf (which has a mass of 0.14 M$_\odot$). Under these assumptions, we can use Kepler's law to calculate that the binary radius is $a = 0.9\,R_\odot$. Furthermore, the donor's Roche lobe would then be 0.2 R$_\odot$ (Paczynski 1971), i.e. comparable to the radius of such a late-type star.

Interestingly, de Jong, van Paradijs & Augusteijn (1996) derived a mean disc opening angle for LMXBs of $\simeq 12^\circ$, making it possible that the disc in Ser X-1 is indeed flared sufficiently to shield the donor star completely from irradiation. This could explain the absence of any indication of emission from the irradiated donor star in Ser X-1. On the other hand, the presence of ionized nitrogen, combined with the absence of carbon suggest a more massive donor star. Ser X-1 does not show any hint of the typically observed C III λ4647/4650 in its spectrum (see e.g. Steeghs & Casares 2002), while the curious emission features in Fig. 1 (those labelled '?') could all be nitrogen transitions. This strange abundance could be due to the CNO fusion reaction cycle (e.g. Shen & Bildsten 2007), where proton capture on ^{14}N is the slowest step. Since the CNO cycle is only dominant in stars more massive than our sun, this would imply that the donor in Ser X-1 was originally much more massive and that the processed material was mixed to the surface by convection. However, we know from Hynes et al. (2004) that Hα has a similar strength as is typically observed in LMXBs (note that from our Fig. 1 it is not even clear if Hβ is detected), suggesting that the outer layers of the donor in Ser X-1 have not been stripped. It is therefore unclear if the spectrum of Ser X-1 can account for an evolved low-mass donor.

Despite the caveat mentioned above, we can still consider whether the emission is coming from the full outer accretion disc or a localized spot in the disc such as the stream-impact region using a low-mass donor. In the first case, the observed radial velocity curve should trace the motion of the compact object, while in the second case it would be that of the Keplerian orbit of the impact region. In both scenarios, we need an estimate of the size of the accretion disc, and we assume that it reaches at least the truncation radius (R_{trunc}). Using the system parameters described above, we estimate that $R_{trunc} = 0.60a/(1+q) = 0.45\,R_\odot$ (Frank, King & Raine 2002). Assuming a Keplerian accretion disc, the velocity at the edge of the disc would then be $\simeq$770 km s^{-1}. If the line emission arises in the stream-impact region, which we expect to be close to the edge of the disc, an inclination of $i \simeq 3^\circ$ is needed to explain the observed 38 km s^{-1} semi-amplitude. Furthermore, this inclination would also imply a non-projected FWHM of $\simeq$3650 km s^{-1}. Since these numbers, in particular the true FWHM, are rather extreme we think this unlikely.

For the case of disc emission on the other hand, we can estimate an inclination of the system of $i \simeq 9^\circ$ using the mass function ($f(M_2) = M_2 \sin^3 i/(1+q)^2 = K_1^3 P/2\pi G$). This suggests that the emission lines would have a non-projected FWHM of $\simeq$1150 km s^{-1}, which is compatible to the FWHMs observed in high-inclination LMXBs such as X1822−371 or GR Mus (Casares et al. 2003; Barnes et al. 2007). Furthermore, if Ser X-1 is observed at such low inclination, the spectral resolution of our data set would not allow us to resolve the double-peaked structure that is typical for emission lines that are formed in the accretion disc (and have typical peak separations of $\simeq$600 km s^{-1}), and the emission lines become indistinguishable from a single Gaussian.

Obviously, more complicated system geometries can be envisaged. One such complication, which is most likely important in Ser X-1, is the presence of strong tidal forces. For example, Whitehurst (1988) showed that the accretion disc becomes tidally unstable and asymmetric for systems with an extreme mass-ratio (i.e. $q \leq 0.3$). Since this is most likely the case in Ser X-1, the accretion disc will not be a simple Keplerian one as we have assumed here. However, we do not think that this will affect our main conclusion, namely that we have discovered a $\simeq$2 h periodic variability that we tentatively identify as the orbital period. If true, Ser X-1 is a low inclination system with the spectral lines dominated by emission from the accretion disc.

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