Measuring masses in low mass X-ray binaries via X-ray spectroscopy: the case of MXB 1659-298

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ABSTRACT

The determination of fundamental parameters in low-mass X-ray binaries typically relies on measuring the radial velocity curve of the companion star through optical or near-infrared spectroscopy. It was recently suggested that high resolution X-ray spectroscopy might enable a measurement of the radial velocity curve of the compact object by monitoring the Doppler shifts induced by the orbital motion of the disc wind or the disc atmosphere. We analysed a Chandra–HETG+NuSTAR soft state observation of MXB 1659-298, an eclipsing neutron star low-mass X-ray binary (LMXB). We measured a radial velocity curve whose phase offset and semi-amplitude are consistent with the primary star. We derived the value for the semi-amplitude of the radial velocity for the compact object $K_1 = 89 \pm 19 \text{ km s}^{-1}$, constrained the mass of the secondary ($0.3 \leq M_2 \leq 0.8 \text{ M}_\odot$) and the orbital inclination of the binary system ($73 \leq i \leq 77^\circ$). These values are consistent with previous estimates from independent methods. Via the same technique, the next generation of X-ray observatories equipped with high spectral resolution instruments (e.g., Athena) will have the potential to measure the radial velocity curve of the primary in high inclination X-ray binaries to an accuracy of a few per cent.

Key words: Neutron star physics, X-rays: binaries, absorption lines, accretion, accretion discs, methods: observational, techniques: spectroscopic

1 INTRODUCTION

Dynamical masses of black holes and neutron stars (NS) in X-ray binaries (XRB) can be derived through phase-resolved photometric and spectroscopic campaigns in the optical or the near infrared (nIR; Cowley et al. 1992; Charles & Coe 2006, Casares & Jonker 2014). This is achieved by measuring the Doppler motion and rotational broadening of the absorption lines generated at the photosphere of the companion star. These quantities provide, under the assumption of co-rotation, a determination of the mass function, the mass ratio and the binary orbital inclination (e.g. Casares & Jonker 2014). Decades of optical-nIR spectroscopic studies have demonstrated the power of these techniques to determine the masses of compact objects, however they are limited to sources with relatively bright companion stars in quiescence or the presence of fluorescence lines from the donor in outburst (Steeghs & Casares 2002; Muñoz-Darias et al. 2005). However, often the semi-amplitude of the radial velocity of the compact object ($K_1$) remains elusive. Though, $K_1$ is fundamental to obtain a dynamical solution, whenever the mass ratio of the two stars cannot be determined, and it is of great value for searches of continuous gravitational waves (Watts et al. 2008).

It was recently proposed an alternative technique to determine the mass of compact objects, based on high spectral resolution X-ray spectroscopy (Zhang et al. 2012). This method relies on measuring orbital shifts in the observed energies of absorption lines from disc winds or disc atmospheres, since these are expected to trace the motion of the compact object around the centre of mass of the binary system (i.e. $K_1$). This technique has been already applied to a few black hole and NS systems (Zhang et al. 2012; Madej et al. 2014). However, it was concluded that the variability of either the source luminosity or random variations of the wind outflow speed can severely affect the accurate determination of the orbital motion of the compact object (Madej et al. 2014). In addition, for typical low-mass X-ray binaries (LMXB), the expected radial velocity of the primary is of the order of $K_1 \sim 10 – 150 \text{ km s}^{-1}$, therefore beyond the energy resolution of current X-ray instruments in the Fe K band, where the strongest absorption lines are present (Ponti et al. 2012; Diaz-Trigo et al. 2013).

Here, we report on the determination of the radial velocity curve of the primary in MXB 1659-298. This was achieved by applying the method proposed by Zhang et al. (2012) to several absorption lines in the soft X-ray band, where current X-ray instruments provide the highest energy resolution. MXB 1659-298 is a transient LMXB displaying type-I X-ray bursts, therefore indi-
cating a neutron star primary (Lewin et al. 1976; Galloway et al. 2008). It is a high inclination system, showing dipping and eclipsing events, with an orbital period of $P_{\text{orb}} = \approx 7.1$ hr and an eclipse duration of $\approx 900$ s (Cominsky 1984; Jain et al. 2017; Iaria et al. 2018).

The optical counterpart of MXB 1659-298 was found to have $V \sim 18$ during outburst (Doxsey et al. 1979) and to display orbital brightness variations as well as narrow eclipses (Wachter et al. 2000). The optical spectrum during outbursts is rather typical for a LMXB, with a blue continuum, He II and Bowen blend emission but no spectral features from the donor (Canizares et al. 1980; Shahbaz et al. 1996). During quiescence, MXB 1659-298 is very faint with $V > 23$ (Cominsky et al. 1983), $R = 23.6 \pm 0.4$ and $I = 22.1 \pm 0.3$ (Filippenko et al. 1999; Wachter et al. 2000). Assuming a reddening of $E_{B-V} = 0.3$ (van Paradijs & McClintock 1995) and based on the observed $(R - I)_0 = 1.2$ and the empirical period-mass relation, Wachter et al. (2000) suggested that the companion star is an early K to early M main sequence star.

MXB 1659-298 started a new outburst on August 2015 (Negoro et al. 2015). LMXB observed at high inclination, such as MXB 1659-298, are known to display strong ionised absorption during the soft state, associated with an equatorial wind or the disc atmosphere (Diaz-Trigo et al. 2006; Ponti et al. 2012). Therefore, in order to perform the first high energy resolution study of the ionised absorber in MXB 1659-298, we triggered Chandra and simultaneous NuSTAR observations.

2 ANALYSIS

The NuSTAR (Harrison et al. 2013) observation (obsid 900201017002) started on 2016-04-21 at 14:41:08 UT. The data were reduced with the standard nupipeline scripts v. 0.4.5 and the high level products produced with the nuproducts tool. The Chandra spectra (obsid 17858 on 2016-04-21 13:44:43 UT) and response matrices have been produced with the CHANDRA_REPRO task, combining the positive and negative first orders. The light curve was extracted with the DMEXTRACT task. Bursts were singled out by visually inspecting the Chandra and NuSTAR light curves and selecting intervals of enhanced emission (typically lasting $\approx 100 - 200$ s; Fig. 2).

Figure 1 shows the mean Chandra and NuSTAR spectra. As hoped, we caught the source during the soft state. The simultaneous spectra show, in addition to the typical soft state continuum, an array of more than 60 absorption lines. The absorption lines are due to highly ionised plasma (Ponti et al. in prep). The strongest lines are labeled in Fig. 1 and they correspond to the Lyo transitions (as well as the Fe XXV line) of the most abundant elements. The broad band continuum can be fit by the sum of a disk black-body ($kT_{\text{BB}} \approx 1.1 - 1.5$ keV), black-body ($kT_{\text{BB}} \approx 2.5 - 3.0$ keV) and a Comptonisation component, all absorbed by neutral material ($N_H \approx 1.5 - 2.1 \times 10^{23}$ cm$^{-2}$; for more details Ponti et al. in prep).

Figure 2 shows the first order Chandra light curve. Two eclipses are detected, preceded by intense dipping activity. By fitting the eclipse transitions, we determined the eclipse center with an accuracy of seconds ($P_{\text{orb}} = 25.618$ ks, consistent with previous results; Jain et al. 2017; Iaria et al. 2018). We first divided the dataset into intervals of $3659.7$ s, so that 7 intervals cover an entire orbital period. The start of the first interval is chosen so that it begins just after the end of the eclipse (see grey dotted lines in Fig. 2 we define as phase 0 the eclipse center). We then removed the periods affected by bursts and eclipses. This resulted in a shorter cleaned exposure for the $\sigma$th interval, because of the presence of the eclipses. We then extracted the HEG and MEG first order spectra corresponding to the first intervals after the eclipses (accumulating the spectra over both orbital periods), and so forth.

3 PHASE DEPENDENT ABSORPTION VARIATIONS

We started by simultaneously fitting the HEG and MEG spectra within a narrow energy band ($\Delta \lambda / \lambda \approx 0.06$) centred on the absorption feature under consideration. We applied this process for the four strongest soft absorption lines: Mg XII Lyα ($\lambda_0 = 8.4210$ Å); Si XIV Lyα (6.1822); S XVI Lyα (4.7292) and Ar XVIII

**Figure 1.** Chandra-NuSTAR spectra of MXB 1659-298, accumulated on 2016-04-21. The black, red, green and blue points show the MEG, HEG, FPMA and FPMB mean spectra, respectively. As is typical for the soft state, the spectra are best fitted with an absorbed disk black-body, a black-body and a Comptonisation component (Ponti et al. in prep). Additionally, more than 60 absorption lines are detected, signatures of an additional ionised absorption component (the strongest Lyα lines detected are indicated, as well as the Fe XXV line). The inset shows a zoom into the Si XIV Lyα line.

**Figure 2.** First order Chandra HETG light curves of MXB 1659-298 (14.9 s time bins). Intense dipping activity (light grey) is observed, primarily before the two eclipses (dark grey). Thirteen bursts are also observed (affected by pile up at the burst peaks). The grey dotted vertical lines indicate the intervals used for the phase resolved study, while the solid lines at the bottom indicate the occurrence time of the bursts.
respectively. The vertical lines carry the same meaning as the top panel. The Mg XII expected line transition. (Bottom panel) Spectra and best fit models around the Mg XII transition, accumulated during phase 0.16-0.31 and 0.31-0.45, respectively. The dotted lines indicate the best fit Gaussian line energies, while the dashed line shows the expected line transition. (Top panel) Black squares, red circles and solid lines show the MEG spectra and best fit models at the energy of the Si XIV line, accumulated during phase 0.02-0.16 and 0.59-0.73, respectively. The dotted lines indicate the best fit Gaussian line energies, while the dashed line shows the expected line transition. (Bottom panel) Spectra and best fit models around the Mg XII transition, accumulated during phase 0.16-0.31 and 0.31-0.45, respectively. The dotted lines indicate the best fit Gaussian line energies, while the dashed line shows the expected line transition.

The Mg XII Lyα (3.7329 Å) line is fitted with the continuum using the best fit model of the mean Chandra+NuSTAR spectra, leaving only the normalisation of the disk black-body component and the column density of the neutral absorber free to vary as a function of phase.

Figure 2 shows that the spectra during interval 6 and 7 are affected by intense dipping activity. Dipping is typically caused by an increased column density of low ionisation absorption, causing a drop of the soft X-ray continuum flux (Sidoli et al. 2001; Boirin et al. 2004; Diaz-Trigo et al. 2006). This effect is captured in our narrow band fits by either an increase in the column density of the neutral absorber or a drop of the normalisation of the continuum (e.g., during interval 6). Because of the presence of the dips and the shorter cleaned exposure, we do not consider interval 7 here.

We independently fitted each strong absorption line as a function of phase (e.g., from interval 1 to 6; phases 0.02 to 0.88). We performed this by adding to the continuum a Gaussian absorption profile, with energy and intensity of the line free to vary as a function of phase (after verifying that the line width was consistent with being constant). For all lines, we observed that the line centroid energies showed a large blue shift in the first part of the orbit, compared with later on (e.g., see Fig. 3). To measure the amplitude and significance of this effect, we recorded for each of the strongest soft X-ray lines the velocity shift and its error, as a function of phase. The blue stars in Fig. 4 show, as a function of phase, the weighted average of the observed shifts for the four strongest soft lines (Mg XII; Si XIV; S XVI and Ar XVIII). A fit with a constant velocity provides a best fit value of $\gamma = -48 \pm 22 \text{ km s}^{-1}$ and a $\chi^2 = 14.2$ for 5 dof. We then added to the model a sinusoid with free amplitude and zero-phase ($\phi_0$; the period was assumed to be unity). The best fit yielded $\phi_0 = 0.54 \pm 0.05$, consistent with an orbital modulation induced by the motion of the primary ($\phi_0 = 0.5$). Therefore, we re-fitted the data leaving only the semi-amplitude ($i.e. K_1$) as free parameter ($i.e. \phi_0 = 0.5$). This significantly improved the fit ($\Delta \chi^2 = 12.7$ for the addition of one parameter, corresponding to a $\approx 3 \sigma$ improvement). The observed best fit values are: $\gamma = -49 \pm 16 \text{ km s}^{-1}$ and $K_1 = 80 \pm 22 \text{ km s}^{-1}$ (Fig. 4). The observed $\gamma$ might, in theory, trace a bulk outflow velocity of the ionised plasma, such as a wind, or be related with the systemic velocity of MXB 1659-298. However, the absolute wavelength accuracy of the HEG is $\pm 0.006 \AA$, corresponding to $\approx 140 \text{ km s}^{-1}$ at 1 keV ($\sim 3$ times larger than $\gamma$), therefore, we do not discuss $\gamma$ any further.

To improve the determination of the velocity shift, we built a self-consistent photo-ionisation model ($\Lambda_{\text{soft}}$). The model table was computed with CLOUDY 17.00 (Ferland et al. 2013), providing as input the observed soft state spectral energy distribution, constant electron density $n_e = 10^{14} \text{ cm}^{-3}$, turbulent ve-

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1 The reported wavelengths correspond to the average of the wavelengths of the respective doublets (Mg XII: 8.4192, 8.4246; Si XIV: 6.1804, 6.1858; S XVI: 4.7274, 4.7328; Ar XVIII: 3.7311, 3.7365 Å), weighted over the oscillator strength. We repeated the analysis and we considered two Gaussian lines for the doublets, obtaining the same results.

2 We note that, due to the small energy band considered, a similar result is obtained by fitting the phase resolved spectra with a simple power law, with free normalisation only.

3 To estimate the uncertainties on the best fit parameters, we simulated $10^5$ radial velocity curves where each value of the velocity is due to a randomisation of the observed velocity assuming a normal distribution with a width as large as its observed uncertainty. Then, for each randomisation, we computed the best fit sinusoidal function. Finally, from the envelope of $10^5$ best fit functions, we determined the uncertainties on the best fit parameters from the lower 15.9 and upper 84.1 percentiles on the envelope of the functions.
velocity \( v_{\text{orb}} = 500 \text{ km s}^{-1} \) and Solar abundances (for more details see Ponti et al. in prep). We then fitted the phase resolved spectra, over the entire usable energy range (0.8-6 keV for MEG and 1.2 -7.3 keV for HEG). The advantage of this global fit, compared with the independent fit of each single line, is that the energy separation between the different absorption lines is set by the atomic physics in the model. We fitted the spectra with a disk black-body (DISKBB) plus black-body (BBODY) model absorbed by neutral (TBABS) plus ionised material (in XSPEC jargon: TBABS*(IA.absorb*DISKBB+BBODY); Arnaud 1996), with all parameters free to vary. The red points in Fig. 4 show the best fit velocity shift, as a function of phase. We note that the consideration of the full array of absorption lines led to results fully consistent with those obtained by analysing only the four strongest lines and to slightly reduce the error bars on the radial velocity measurement.

The fit with a constant could be rejected (\( \chi^2 = 21.3 \) for 6 dof). The fit significantly improved by adding a sinusoidal component (\( \Delta \chi^2 = 19.3 \) for the addition of one parameter, corresponding to \( \sim 3.5\sigma \) improvement), producing an acceptable fit (\( \chi^2 = 2.0 \) for 5 dof). The best fit yielded \( K_1 = 89 \pm 19 \text{ km s}^{-1} \) (see red solid and dashed lines in Fig. 4). The HEG relative wavelength accuracy is \( \pm 0.001 \) Å, corresponding to \( \sim 25 \text{ km s}^{-1} \) at 1 keV, comparable to the statistical uncertainties on the velocity shift at each orbital phase. Therefore, our measurement of \( K_1 \) is solid.

4 DISCUSSION

Direct measurements of \( K_1 \) have been possible for the case of X-ray binary pulsars, where the delay in the arrival time of the pulses accurately trace the orbit of the primary and therefore \( K_1 \). As an alternative, we used the absorption lines from ionised material likely absorbed by neutral (DISKBB) plus black-body (BBODY) model absorbed by neutral (TBABS) plus ionised material (in XSPEC jargon: TBABS*(IA.absorb*DISKBB+BBODY); Arnaud 1996), with all parameters free to vary. The red points in Fig. 4 show the best fit velocity shift, as a function of phase. We note that the consideration of the full array of absorption lines led to results fully consistent with those obtained by analysing only the four strongest lines and to slightly reduce the error bars on the radial velocity measurement.

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The measured radial velocity curve of the NS allowed us to derive the mass function of the system:

\[
\frac{K_1^3 P_{\text{orb}}}{2\pi G} = \frac{M_2^3 \sin^3 \iota}{(M_{\text{NS}} + M_2)^2},
\]

where \( M_{\text{NS}} \) and \( M_2 \) are the NS and the companion star masses, \( G \) the gravitational constant and \( \iota \) the orbital inclination. This equation sets the first constraint on the unknowns: \( M_{\text{NS}}, M_2 \) and \( \iota \).

The knowledge that the eclipse duration lasts \( \Delta T_{\text{ecl}} = 899.1 \pm 0.6 \) (Iaria et al. 2017) adds an additional constraint. Indeed, following Iaria et al. (2017), we have computed the size of the occulted region \( x \) (see fig. 5 in Iaria et al. 2017) as:

\[
x = \frac{\pi a \Delta T_{\text{ecl}}}{P_{\text{orb}}},
\]

where \( a \) is the orbital separation (\( a^3 = \frac{G(M_{\text{NS}}+M_2)}{4\pi^2} \)). This allowed us to constrain \( \iota \) as a function of \( M_{\text{NS}} \) and \( M_2 \):

\[
tan^2 (\iota) = \frac{R_2^2 - x^2}{a^2 - (R_2^2 - x^2)},
\]

where \( R_2 \) is the companion star radius, by assuming that the secondary star is filling its Roche lobe (\( R_2 = R_L \); Paczyński 1971):

\[
R_2 = R_{L2} = 0.462 a \left( \frac{M_2}{M_{\text{NS}} + M_2} \right)^{1/3}.
\]

By applying these two constraints to the three unknowns, we estimated that, for any reasonable NS mass (\( 1.2 \leq M_{\text{NS}} \leq 3 \text{ M}_\odot \)), the companion star mass should lie within the range \( 0.3 \leq M_2 \leq \)
0.8 M_Ө and the orbital inclination 73° ≤ i ≤ 77° (Fig. 5). The measured ranges of the most likely companion star masses and orbital inclinations are consistent with previous methods (Wachter et al. 2000). This demonstrates that it is possible to constrain the fundamental parameters of MXB 1659-298 with current X-ray data and that this method can be applied to other systems.

4.2 Limitations and relevance of the method

The technique employed here presents also limitations. For example, it requires the presence of a further constraint (e.g., via optical/nIR observations; Casares & Jonker 2014), in order to eliminate the degeneracy between the orbital inclination and the masses of the two stars. Additionally, it assumes that the bulk motion of either the accretion disc wind or of the ionised disc atmosphere is azimuthally symmetric and constant during the orbit. Despite this assumption appears reasonable at first approximation, second order effects might be present. For example, the wind outflow velocity might vary, implying that the radial velocity curve should be averaged over several orbital periods. Besides, the wind/atmosphere is likely structured into a multi-phase plasma, characterised by different physical parameters, possibly complicating the analysis. Additionally, the wind/atmosphere kinematic might be perturbed by the material transferred from the companion star or by the presence of disc structures (e.g., eccentric discs; strong warps).

Currently the main limitation is due to the large statistical uncertainties on the determination of the radial velocity curve. However, the next generation of X-ray spectrographs/calorimeters will mend this state of affairs. Indeed, compared with HETG, XARM and Athena will improve the resolving power and the figure of merit for weak line detections at 6 keV, by a factor of ≈ 6, 12 and ≈ 8, 40, respectively, while Arcus at 1.5 keV will improve it by ≈ 3 and ≈ 7, respectively (Nandra et al. 2013; Kaastra et al. 2016; Gandhi 2018). We also note that this method can be applied to any LMXB displaying ionised absorption lines produced by the disc atmosphere/wind. This category comprises the majority of the high inclination LMXB (about half of the sample) during their softer states (Diaz-Trigo et al. 2006; Ponti et al. 2012).

4.3 The power of Athena-XIFU to constrain masses

To measure the power of future X-ray spectroscopy to constrain the mass function of MXB 1659-298, we simulated an Athena-XIFU 100 ks observation (assuming the “as proposed” version of the response matrix with reduced effective area, to preserve excellent spectroscopy at high throughput; Barret et al. 2016). We assumed the same observed flux (F_{0.5-10 keV} = 9.5 × 10^{-10} erg cm^{-2} s^{-1}), spectral continuum and ionised plasma parameters as measured during the Chandra observation (Ponti et al. in prep). We further assumed that the ionised plasma is affected by the radial velocity curve of the primary, as observed. Figure 5 demonstrates that Athena observations will allow us to determine the amplitude of the radial velocity curve with an uncertainty of ≈1 %. The blue curves in Fig. 5 show the constraints that such an observation will allow us to deliver, translating into an uncertainty of ≈5 % on the mass of the primary, would the radial velocity of the companion star be known (e.g., via optical spectroscopy). Therefore, future X-ray missions will be able to deliver measurements of the radial velocity of LMXB to an accuracy of a few per cent.

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