Measuring the black hole masses in accreting X-ray binaries by detecting the Doppler orbital motion of their accretion disc wind absorption lines

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ABSTRACT
So far essentially all black hole masses in X-ray binaries have been obtained by observing the companion star’s velocity and light curves as functions of the orbital phase. However, a major uncertainty is the estimate of the orbital inclination angle of an X-ray binary. Here we suggest to measure the black hole mass in an X-ray binary by measuring directly the black hole’s orbital motion, thus obtaining the companion-to-black hole mass ratio. In this method we assume that accretion disc wind moves with the black hole and thus the black hole’s orbital motion can be obtained from the Doppler velocity of the absorption lines produced in the accretion disc wind. We validate this method by analysing the Chandra/High Energy Transmission Grating observations of GRO J1655−40, in which the black hole orbital motion ($K_{BH} = 90.8 \pm 11.3$ km s$^{-1}$) inferred from the Doppler velocity of disc wind absorption lines is consistent with the prediction from its previously measured system parameters. We thus estimate its black hole mass ($M_{BH} = 5.41^{+0.98}_{-0.57}$ M$_{\odot}$) and then its system inclination ($i = 72^{\circ} \pm 8^{\circ}$), where $M_{BH}$ does not depend on $i$. Additional observations of this source covering more orbital phases can improve estimates on its system parameters substantially. We then apply the method to the black hole X-ray binary LMC X-3 observed with Cosmic Origins Spectrograph (COS) on board the Hubble Space Telescope (HST) near orbital phase 0.75. We find that the disc wind absorption lines of C iv doublet were shifted to $\sim 50$ km s$^{-1}$, which yields a companion-to-black hole mass ratio of 0.6 for an assumed disc wind velocity of $\sim 400$ km s$^{-1}$. Additional observations covering other orbital phases (0.25 in particular) are crucial to ease this assumption and then to directly constrain the mass ratio. This method in principle can also be applied to any accreting compact objects with detectable accretion disc wind absorption line features.

Key words: accretion, accretion discs – black hole physics – stars: luminosity function, mass function – X-rays: binaries – X-rays: individual: GRO J1655-40 – X-rays: individual: LMC X-3.

1 INTRODUCTION
Black holes (BHs) are believed to exist in many X-ray binaries (XRBs) and active galactic nuclei (AGN). Measurement of the motion of a BH with respect to its surrounding in such a system can in principle set strong constraints on the mass of the BH. However, in an AGN this is normally not possible because the time-scale of BH’s significant motion is too long and/or the BH is barely moving at all. In an XRB, the BH should move with respect to the system’s centre-of-mass (CM), making it possible to detect directly the BH’s motion with respect to the CM. However in a low-mass XRB (LMXB) the companion is normally much less massive than the BH, so that the BH barely moves or moves very slowly with respect to the CM. In some LMXBs, the companion’s mass is comparable or only several times less massive than the BH, e.g. in GRO J1655−40 (Zhang, Cui & Chen 1994; Orosz & Bailyn 1997), the BHs’ motion may be significant enough for direct detection. The most favourable systems for detecting BH’s motion should be high-mass XRBs (HMXBs), in which the BHs move rapidly with respect to their CMs.

Orbital motion of double-peaked disc emission lines were observed for neutron star XRB Sco X-1 (Steehgs & Casares 2002), the BH XRB (BHXB) A0620−00 (Haswell & Shafter 1990; Orosz et al. 1994) and the BH GRS 1124−68 (Orosz et al. 1994). Unfortunately, a significant phase offset of velocity modulation was found from that expected based on the observed orbital motion of the companion, though the velocity semi-amplitude is consistent

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with the expected mass ratio (Orosz et al. 1994). Soria et al. (1998) observed the orbital motion of the double-peaked disc emission line He II λ4686 from GRO J1655−40 and found its velocity modulation phase and semi-amplitude in agreement with the kinematic and dynamical parameters of the system. Therefore, a more robust mass lower limit is placed based on the observed motion of the primary and thus ruling out any possibility for a neutron star to be the primary in the system (Soria et al. 1998). However, one major problem in accurately measuring the orbital motion of the primary from the observed double-peaked emission lines is how to determine reliably the line centre, because the lines are typically asymmetric and also variable.

In an XRB, both the accretion disc and its wind move with the BH, and thus provides us with another opportunity to measure the BH’s motion via Doppler shift of absorption features of the accretion disc wind. Accretion disc winds are ubiquitous in XRBs and are normally detected through ionized absorption lines, typically with around $10^3$ km s$^{-1}$ or less (e.g. Miller et al. 2004, 2006, 2008; Ueda et al. 2004), but can reach to about $10^4$ km s$^{-1}$ in some extreme cases, e.g. in the newly discovered BH transient IGR J17091−3624 (King et al. 2011). In particular, the high-quality Chandra/High Energy Transmission Grating (HETG) observations of the BHXB GRO J1655−40 have found many highly ionized narrow absorption lines, which are interpreted as evidence of magnetic-field-driven accretion disc wind (Miller et al. 2006; Kallman et al. 2009; Luketic et al. 2010); however, the absorption lines are also interpreted to be from the absorption by X-ray-heated thermal wind (Netzer 2006). Regardless of the origin of the accretion disc wind, the orbital motion of its many absorption lines may be measured reliably, because typically many narrow absorption lines are present with high signal-to-noise ratios and appear to be rather stable when observed.

In this work, we model the Doppler motion of wind absorption lines from the LMXB GRO J1655−40 and HMXB LMC X-3 to constrain directly the companion-to-primary mass ratio in order to measure their BH masses and orbital inclination angles. We first describe the methodology and test its feasibility by applying it to Chandra/HETG observations of GRO J1655−40, revealing for the first time the velocity modulation of wind absorption lines in an XRB and thus providing a new measurement of its BH motion and orbital inclination angle. We then apply this method to the Cosmic Origins Spectrograph (COS) on board the Hubble Space Telescope (HST) (hereafter HST/COS) observations of LMC X-3, attempting to constrain the companion-to-primary mass ratio. Finally, we discuss further observations needed to achieve the required accuracy of BH mass estimate for LMC X-3, as well as potential problems and uncertainties of applying this method.

2 METHODOLOGY

So far, all BH masses in XRBs have been estimated using Kepler’s third law of stellar motion, expressed in the so-called the mass function,

$$f(M) = \frac{P_{orb} K_C^2}{2 \pi G} = M_{BH} \sin^2 i / (1 + q)^2,$$

where $P_{orb}$ is the orbital period, $K_C$ is the semi-amplitude of the velocity curve of the companion star, $M_{BH}$ is BH mass, $i$ is the orbital inclination angle and $q \equiv M_C / M_{BH}$ is the mass ratio. Since the only direct observables are $P_{orb}$ and $K_C$, both $M_C$ and $i$ have to be determined indirectly in order to obtain the BH mass estimate reliably. The companion’s mass $M_C$ can be determined relatively reliably by the observed spectral type of the companion star. For LMXBs, $i$ can be estimated by modelling the optical or infrared light-curve modulation, though model dependence and other uncertainties (such as accretion disc contamination) cannot be circumvented completely. For HXMBs, $i$ is normally not determined very well; in many cases, observations or lack of eclipse of the accretion disc emission by the companion is used to put some constraints on the possible ranges of $i$. For details of BH mass estimates using this method, please refer to Remillard & McClintock (2006).

On the other hand, the mass ratio $q$ can be determined directly according to the law of momentum conservation, i.e.

$$M_C / M_{BH} = K_{BH} / K_C,$$

if the semi-amplitude of the velocity curve of the BH $K_{BH}$ can be observed directly. Since a BH is not directly observable, we can only hope to observe any emission or absorption line feature comoving with it. The accretion disc certainly moves with the accreting BH. However, any line feature of the inner accretion disc suffers from the broadening of disc’s orbital motion and distortions by relativistic effects around the BH, thus making it practically impossible, or difficult to the least, for detecting the binary orbital motion of the BH. Emission-line features from the outer disc region are normally detected with double peaks, which can be modelled to obtain the semi-amplitude of the velocity of the compact object, as discussed above. However, a major uncertainty is to determine the mean separation between the emission regions of the blueshifted and redshifted components.

Fortunately, as we have discussed above, absorption line features of accretion disc winds in BHXBs have been routinely detected with high significance. This suggests that the accretion disc wind in an XRB moves with the disc that produces the wind, since otherwise the wind from the disc would not intercept the continuum emissions produced from the same disc. In this case, the Doppler motion of wind absorption line features can be considered as that of the BH, unless the wind interacts strongly with the surrounding interstellar medium (ISM) or the wind intrinsic velocity has systematic orbital dependence. It has been found recently that large-scale (pc) cavities exist around microquasars (XRBs producing relativistic jets) and perhaps are ubiquitous in all BHXBs producing strong winds (Hao & Zhang 2009). This suggests that at least in the vicinity of the BH, the wind cannot interact directly with ISM. The interactions of disc winds with ISM at pc-scale would not complicate the observations, because it takes much longer than an orbital period before the winds could arrive at the boundaries of these cavities, and thus the wind should have lost any possible memories of the orbital motion of the compact object. For disc-fed accretion, the wind velocity is not expected to have any orbital phase modulation; for stellar-wind accretion, the focused wind may complicate the situation considerably through. We therefore suggest to apply this method to only those systems in which the accretion is disc fed, i.e. no significant wind interaction happens between the stellar and accretion disc winds. Nevertheless, only observations can tell us in which kinds of systems this method can be used reliably.

3 APPLICATION TO THE LMXB GRO J1655–40: A TEST STUDY

GRO J1655−40, discovered as an X-ray transient by Zhang et al. (1994), is a well-known and best studied BHXB and the second source with superluminal relativistic jets detected (Harmon et al. 1995; Hjellming & Rupen 1995; Tingay et al. 1995). Its system parameters remain so far the best measured among all known BHXBs,
with \( P_{\text{orb}} = 2.621 \pm 0.000\,20 \text{d}, \nu q = M_{\text{BH}}/M_{\odot} = 2.6 \pm 0.3, \) \( i = 70.2 \pm 1.9 \) and \( M_{\text{BH}} = 6.3 \pm 0.5 M_{\odot} \) (all 95 per cent confidence) (Orosz & Bailyn 1997; Greene, Bailyn & Orosz 2001). Its precise BH mass and inclination measurements allow its BH spin parameter to be determined from its X-ray continuum fitting, first proposed by Zhang, Cui & Chen (1997) and then refined by incorporating detailed modelling of various effects (e.g. Davis et al. 2005; Li et al. 2005; Yao et al. 2005; Shafee et al. 2006; Steiner et al. 2009; McClintock et al. 2011). However, possible sources of systematic errors are in the modelling of the ellipsoidal light modulation of the companion star and contamination of the disc’s continuum emission in the optical to infrared bands. Soria et al. (1998) observed the velocity curve of the double-peaked disc emission line He II \( \lambda 4686 \) from GRO J1655—40 and derived its projected radial velocity semi-amplitude determined for the primary as \( K_{\text{BH}} = 76.2 \pm 7.5 \text{ km s}^{-1} \), yielding \( M_{\text{BH}} = 6.62 \pm 0.74 M_{\odot} \) and \( i = 66.6 \pm 7.7 \) (all 68.3 per cent confidence), fully consistent with that determined from the companion’s velocity curve and ellipsoidal light variation.

Miller et al. (2006) detected many narrow and ionized absorption lines with Chandra/HETG observations of GRO J1655—40. The exact position of the point source cannot be determined accurately in the zeroth-order image, which is severely piled up due to its high flux. An offset in the source position will cause a systematic shift of all lines in the wavelength space. However, this shift is mostly cancelled out in the combined total spectrum if each line is detected in the spectra of both the +1 and −1 orders with similar count spectra. However, the combined lines will be broadened by the unknown systematic offset, which in turn will cause larger uncertainties in determining the centre of each line. There may also exist other sources of systematic errors which can cause offset between the centres of the same line in the spectra of the +1 and −1 orders.

Here we determine the position of the zeroth-order image by minimizing the relative offsets between the absorption lines in the +1 and −1 orders, and estimate the systematic error in determining the centre wavelength of each absorption line. We first fit each absorption line feature with a Gaussian profile in the +1 and −1 orders of the high-energy grating (HEG) and medium-energy grating (MEG) separately, i.e. we get a pair of profiles for each absorption line, integrated over the whole observation in order to get the highest signal-to-noise ratio. The local continuum around each line is assumed to have a power-law shape, but our results are insensitive to the continuum shape. For HEG and MEG, we obtain 43 and nine differences of the central wavelengths of these lines, respectively. We then use the Bayesian method to find the systematic offset, which in turn will cause larger uncertainties in determining the centre of each line. There may also exist other sources of systematic errors which can cause offset between the centres of the same line in the spectra of the +1 and −1 orders.

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We thus take the error for \( \sigma_{\text{d}} = 3.2 \times 10^{-4} \text{ Å} \) for HEG. Similarly, for MEG, we get \( \sigma_{\text{d}} = (9.7 \pm 0.8) \times 10^{-3} \text{ Å} \) for MEG, where \( \sigma_{\text{d}} = 9 \times 10^{-4} \text{ Å} \) is dominated by the systematic error. Taking these additional errors for MEG and HEG line wavelengths and requiring all pairs in HEG with \( d = 4.8 \times 10^{-3} \text{ Å} \) and in MEG with \( d = 9.7 \times 10^{-3} \text{ Å} \), we have a total of \( \chi^2 = 55 \) for 50 degrees of freedom, thus validating our method of determining the systematic errors. Since the wavelength bin (an image pixel) is \( 2.5 \times 10^{-3} \text{ Å} \) and \( 5.0 \times 10^{-3} \text{ Å} \) for HEG or MEG, we thus shift the spectra of the −1 and the +1 orders by one bin, towards the decreasing (−1 order) and increasing (+1 order) wavelength directions, respectively. This is identical to shifting the location of the point source by 1 pixel in the zeroth-order image. Finally, we combine the two shifted spectra as one single spectrum.

Because the observations lasted for about a quarter of the orbital phase of GRO J1655—40 and many absorption lines have high signal-to-noise ratios, here we divide the observations into four equal orbital intervals in order to detect the orbital motion of the absorption lines. For each combined spectrum, we again fit each absorption feature with a Gaussian profile to determine its central wavelength, line width and intensity. Table 1 lists the 45 lines in all four intervals with at least \( 3 \sigma \) detection that are included for further analysis; here only statistical errors are shown.

Fig. 1 shows the velocity distributions of the four groups of 45 lines and their average velocities; note that here the system velocity of the BHXB has already been subtracted. Adopting the orbital period and phase ephemeris from Greene et al. (2001) and assuming that the BH’s motion is exactly antiphased with the companion’s motion (Soria et al. 1998), we fit velocities of these lines simultaneously to a sinusoidal function. In the fit, the intrinsic velocity of each line is a free parameter, but all lines in the same orbital phase follow the same orbital modulation. This way, we have 46 free parameters (45 intrinsic velocities for all these lines plus the line-of-sight (LOS) velocity amplitude of the BH) with 180 data points. The fit results in \( K_{\text{BH}} = 93.8 \pm 11.1 \text{ km s}^{-1} \) with \( \chi^2 = 179 \) for 134 degrees of freedom; the systematic errors determined above are included for all lines.

Considering that some lines may be outliers, we reject the four groups of six lines with central velocities more than \( 300 \text{ km s}^{-1} \) from the median values of each distribution, as listed in Table 1. The remaining four groups of 39 lines have velocity dispersion (1σ) of about 60 km s\(^{-1}\), i.e. the rejected lines are more than 5σ away from the median values. The fit to the remaining four groups of 39 lines yields \( K_{\text{BH}} = 90.8 \pm 11.3 \text{ km s}^{-1} \) with \( \chi^2 = 131 \) for 116 degrees of freedom, a marginal improvement over the full data set fit. This means that the deviations of these possible outliers are not significant statistically and thus do not deserve further studies at this stage. Fig. 2 shows the fitting results; please note that the velocities are obtained by subtracting the fitted LOS intrinsic velocity of each line from the obtained central velocity of each line at this orbital phase. It is worth noting that the phase zero in this system was defined as that when the companion is receding from the observer at the maximum velocity (Orosz & Bailyn 1997). Nevertheless, both the results are statistically consistent with \( K_{\text{BH}} = 76.2 \pm 7.5 \text{ km s}^{-1} \) obtained by Soria et al. (1998). If we fit the four groups of 39 lines to a straight line, we get \( \chi^2 = 813 \) for 154 degrees of freedom. The linear model is thus rejected with high significance, compared to the sinusoidal model.

With the fitted \( K_{\text{BH}} = 90.8 \pm 11.3 \text{ km s}^{-1} \) and taking the other system parameters (except the inclination) of GRO J1655—40 from Greene et al. (2001), we first obtain its BH mass \( M_{\text{BH}} = 5.4^{+1.098}_{-0.57} M_{\odot} \) from equation (2) and then its system inclination \( i = 72.0^{+7.5}_{-7.5} \) from equation (1). All these (1σ) errors are obtained by Monte Carlo samplings, because of the asymmetry and coupling of some errors. These parameters, although with large uncertainties due to the very incomplete orbital coverage of observations, are consistent with all previous measurements. Therefore, the existing data of GRO J1655—40 validate our proposal that absorption lines produced in the accretion disc wind can be used to measure directly the orbital motion of the BHs in BHXBs.

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4 APPLICATION TO THE HMXB LMC X-3

LMC X-3 is another excellent object for applying this method. It is a bright XRB system in the Large Magellanic Cloud composed of a B3 V star and a central BH, and receding away from us at a systemic velocity \( v_s = +310\, \text{km}\,\text{s}^{-1} \) (Cowley et al. 1983, hereafter C83). It is one of the few BH systems that are persistently luminous in both X-ray and far-ultraviolet (FUV) wavelength bands. The BH is believed to be undergoing accretion from its B star companion via Roche lobe overflow with an orbital period of 1.7 d (C83); we therefore do not expect any significant contamination of the stellar wind to any absorption features of its accretion disc wind.

Spectroscopic observations of the B star indicate a large radial velocity semi-amplitude, \( K_C = 235 \pm 11\, \text{km}\,\text{s}^{-1} \) (C83). Taken the mass of the B3 V star as about 6\( M_\odot \), the BH mass in LMC X-3 is thus estimated to be \( 5-10\, M_\odot \), assuming an inclination angle of 50°–70° (C83; Kuiper, van Paradijs & van der Klis 1988; Soria et al. 2001). Because of the considerable uncertainty in its inclination (and thus BH mass), its BH spin has not been reliably determined yet with the X-ray continuum modelling method (e.g. Zhang et al. 1997; Steiner et al. 2010). Since the BH should be moving at a comparable velocity to its companion, it is possible to directly measure its orbital motion if the absorption lines produced in its accretion disc wind are detected.

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Table 1. Velocity and width of each absorption line at each orbital phase, detected with more than 3\( \sigma \) significance. For each orbital phase, the numbers in the left and right are the velocity shift and width (broadening) of the absorption line; the 1\( \sigma \) errors are included in the parenthesis. The last column indicates if the line is within 300 km s\(^{-1}\) to the median velocity at each phase.
two \textit{FUSE} observations and four observations with the \textit{HST/COS} to LMC X-3 have been made (Hutchings et al. 2003; Wang et al. 2005; Song et al. 2010, hereafter S10). Again \textit{FUSE} does not have the combination of the required sensitivity, and the observations did not produce spectra with high enough signal-to-noise ratio for the purpose of this investigation. The \textit{HST/COS} does have the required performance to do so, although the available observations only covered a small portion of the orbital period of LMC X-3. In this work, we analyse the available \textit{HST/COS} UV spectroscopic observations of LMC X-3, aiming at constraining the systemic parameters and further demonstrating the feasibility of our proposed new method of measuring the BH's mass in an XRB.

From the \textit{FUSE} and \textit{HST/COS} observations, S10 detected variable \textit{OVI} and \textit{NV} emission lines and found that variability of their intensities are inconsistent with expectation of a stellar wind origin. Therefore, they attributed them to the heated stellar surface of the companion star. In fact, both absorption and emission features are detected in \textit{NV} (with G130M) and \textit{CIV} (with G160M) doublets (fig. 2 in S10) in the \textit{HST/COS} observations (programme 11642; please refer to S10 for detailed description of the \textit{HST/COS} observations and data analysis). However, since S10 focused on the origin of the emission variability and the connection between the emission features and the systemic parameters, these absorption features have not been explored in detail.

Here we analyse the \textit{CIV} doublet complexes (we do not conduct the same analysis to the \textit{NV} features because the absorptions are much less significant than those of \textit{CIV}). In Fig. 3, we decompose the observed \textit{CIV} doublet into three components for each line: one emission component and two absorption components. The emission component is assumed to come from the heated surface of the companion, the same as the \textit{OVI} and \textit{NV} emission lines (S10); its width and Doppler shift are fixed to those inferred from the \textit{OVI} and \textit{NV} emission lines in the decomposition. One absorption component (at zero velocity) is assumed to come from the Galactic ISM absorption. The other significant absorption component has a redshift of about 50 km s$^{-1}$ and may have two possible origins. One is the absorption produced in the stellar wind of the B3 V companion star. However, the orbital phase of the binary system was about 0.75 during the \textit{HST/COS} observations, i.e. the straight line connecting the companion star and the BH is perpendicular to our LOS (please be noted that, in contrast to GRO J1655$-$40, the orbital phase zero in LMC X-3 was defined as that when the BH is at its superior conjunction, i.e. the companion is just between the observer and the BH; C83; S10). In order for any stellar wind

![Figure 1](https://example.com/fig1.png)

**Figure 1.** Distributions of the line velocities in four equally spaced intervals and their average values, during the \textit{Chandra/HETG} observations lasting for more than 60 ks; note that here the system velocity of the BH XRB has already been subtracted. Panels from (a) to (d) corresponding to the phases shown in Fig. 2 from left to right.

![Figure 2](https://example.com/fig2.png)

**Figure 2.** Velocity curve of the 39 observed absorption lines, after rejecting six lines as suspected outliers and subtracting the LOS intrinsic velocity of each line at each orbital phase. The upper panel marks the velocity of each line, with its 1σ error bar slightly shifted horizontally for visual clarity; the inset shows all velocities, including the three data points out of the range in the main panel. The bottom panel shows the weighted average velocity of all lines in the upper panel at each phase; the solid curve is the fitted velocity curve with its orbital period and phase fixed at the values observed previously.

Although LMC X-3 has been intensively studied in the X-ray band, the previously operated and currently operating X-ray spectroscopic instruments lack the combination of the required sensitivity and resolution to measure the expected Doppler motion of any accretion wind absorption features. High-resolution UV spectroscopic observations of this source are rather sparse; so far, only

![Figure 3](https://example.com/fig3.png)

**Figure 3.** Spectrum of the available \textit{HST/COS} observations around \textit{CIV} doublet. Red curves indicate the fit to the emission from the heated surface of the companion star, green curves are the fit to the Galactic ISM absorptions at 0 km s$^{-1}$ and blue curves indicate the fit to the accretion disc wind absorptions at $\approx 50$ km s$^{-1}$ (local velocity $\approx \pm 400$ km s$^{-1}$). The vertical bars mark the central positions of these components.
to intercept significantly the emission from the inner disc region, a significant amount of stellar wind has to stream to the inner disc region, i.e. the system must be wind fed, against the common belief that LMC X-3 is actually disc fed. We thus rule out this possibility. The other and the only viable scenario is the absorption by the accretion disc wind, making it possible to directly measure the orbital motion of the BH. It is worth noting that the measured C iv absorption features in the spectrum of the previous absorption feature is consistent and the BH semi-amplitude of the companion star $K_C = 235 \text{ km s}^{-1}$, we can constrain the companion-to-BH mass ratio. At phase 0.75, the BH is receding from us at the maximum speed, and thus the relation of $V_{0.75}$ and $K_{BH}$ can be expressed as

$$V_{0.75} = V_{\text{wind}} + V_S + K_{BH},$$

where $V_{\text{wind}}$ is the intrinsic velocity of the accretion disc wind in our LOS. Assuming $V_{\text{wind}} = -400 \text{ km s}^{-1}$, a similar wind velocity found in GRO J1655−40 (Miller et al. 2006), from equation (4) we obtain $K_{BH} \sim 140 \text{ km s}^{-1}$. Plugging these numbers in equation (2), we further obtain $q = M_C/M_{BH} \sim 0.6$, which is consistent with the ratio usually adopted for the LMC X-3 system (e.g. C83). We therefore suggest that the observed C iv absorption feature is consistent to our model that the accretion disc wind moves with the BH and the observed Doppler shift is a combination of the wind velocity and the BH’s orbital velocity in our LOS.

In the above exercise, we assumed a $V_{\text{wind}}$ in order to obtain $K_{BH}$, since there is a degeneracy of $V_{\text{wind}}$ and $K_{BH}$ in equation (4). Unfortunately, the HST/COS G160M observation analysed only lasted for one HST orbit, and thus cannot break the degeneracy, i.e. we cannot put an independent measure of the BH’s velocity, without observing the orbital modulation of the Doppler motion of the wind. The HST/COS G130M observations in a shorter wavelength band covered a much larger part of the orbital period. As shown in Fig. 4, the combined spectrum revealed several complicated absorption features. Nevertheless, Si ii and Si iv absorption lines at $V_{0.75} \approx 50 \text{ km s}^{-1}$ are also detected; the apparent higher velocity components may arise from the outer part of the accretion disc with lower local velocities, mimicking the different velocities and ionization zones of AGN warm absorbers/outflows (e.g. Arav et al. 2005). However, the combination of the complexity of the observed absorption features and the rather incomplete orbital phase coverage of these previous HST/COS observations does not warrant further more quantitative analysis for breaking the above-mentioned degeneracy and probing the nature of those higher velocity components.

Clearly, observations covering more orbital phases are badly needed to break the degeneracy. Observations around phase 0.25 are the most favourable ones for this purpose. In contrast to the existing observations taken around 0.75 in which the BH is receding at the maximum velocity from us, at phase 0.25, the BH is expected to be moving towards us at the maximum velocity, so is the disc wind. Therefore, the relation between $V_{0.25}$ and $K_{BH}$ can be expressed as

$$V_{0.25} = V_{\text{wind}} + V_S - K_{BH}. \quad (5)$$

If $V_S = -400 \text{ km s}^{-1}$, as assumed, the $V_{0.25}$ is expected to be at $-230 \text{ km s}^{-1}$. The real measurement of $V_{0.25}$ from the future observations, together with $V_{0.75}$ measured from the existing observations, would allow us to solve $V_{\text{wind}}$ and $K_{BH}$ from equations (4) and (5) and then to reliably constrain $M_C/M_{BH}$ and system inclination angle $i$ (equations 2 and 1).

5 SUMMARY AND DISCUSSION

As shown in equation (2), $M_{BH}$ can be directly obtained if $K_{BH}$ can be measured, in addition to $M_C$ and $K_C$ measured by observing the companion star. In this work we suggest to measure $K_{BH}$ by detecting the Doppler orbital motion of the accretion disc wind absorption lines, assuming that the accretion disc wind moves with the BH and does not have systematic orbital phase dependence. This method has the potential of circumventing the model dependence and other uncertainties in estimating the orbital inclination angle, which is required in the method commonly used to measure the BH masses in XRBs by detecting the companion star’s velocity and light curves, as shown in equation (1). Actually, knowing the mass ratio with equation (2), one can in turn use equation (1) to derive the inclination angle, which can be used to calibrate the light-curve model used previously to derive the inclination angle.

Our analysis of the previous Chandra/HETG observations of GRO J1655−40 have revealed wind velocity modulation consistent with the orbital motion of the BH predicted from its previously measured system parameters. An independent projected radial velocity semi-amplitude measured here allows its inclination angle to be determined without using the modelling of its ellipsoidal light modulation of its companion. We find its BH radial velocity semi-amplitude $K_{BH} = 90.8 \pm 11.3 \text{ km s}^{-1}$. BH mass $M_{BH} = 5.41^{+0.38}_{-0.57} \text{ M}_\odot$ and system inclination $i = 72.0^{+7.5}_{-7.5}$°, where $M_{BH}$ does not depend on $i$ at all. However, the very limited orbital coverage of the observations does not allow more accurate system parameter measurements of this binary system. Nevertheless, with the velocity component of its orbital motion removed, we can obtain more accurate measurements of the intrinsic velocities of each line along our LOS, and thus may be able to constrain further the physical properties of the wind, by combining with the velocity broadenings of these lines; this is the subject our future work.

Our analysis of the previous HST/COS observations of the HMXB LMC X-3 has found absorption line features consistent with that predicted by assuming the previously measured dynamical parameters of LMC X-3 and the wind properties in LMC X-3.
being similar to that observed in another BHXB GRO J1655−40. Given the limitations of the previous HST/COS observations of LMC X-3 that do not allow us to break the degeneracy of the wind velocity and the BH orbital velocity, new HST/COS observations are required to cover significantly different orbital phases.

As mentioned in S10, the C IV features shown in Fig. 3 might be P Cygni profiles. However, the emission features agree well with all other emission lines detected, which are attributed to the heated stellar surface. Therefore, it is more reasonable to attribute the emission features in Fig. 3 to the heated stellar surface (as done in S10), thus invalidating the P Cygni profile interpretation. UV emission lines produced from the heated stellar surface are not unique in the system of LMC X-3, but are rather a common feature observed in XRBs (e.g. Vrtilek et al. 2003). Of course, new observations suggested above would definitely reveal the nature of the C IV features shown in Fig. 3.

In this work, we have also assumed that the accretion disc wind velocity is constant, at least during one full orbital phase, in order to apply this method reliably. In reality, the intrinsic wind velocity may have random fluctuations, though the fluctuations do not seem to be significant in GRO J1655−40 (Miller et al. 2006). However, it has been known that wind absorption features are not always detected, and it is also not fully understood when and why wind absorptions are present or absent. Future high signal-to-noise observations covering more orbital phases may shed some lights on this problem and test ultimately if our suggested method can be applied reliably and produce accurate BH mass measurements in BHXBs. The joint JAXA/NASA ASTRO-H mission is particularly suitable for making such observations, with its high-throughput spectroscopy provided by the microcalorimeter with high spectral resolution of $\Delta E \sim 7$ eV (Takahashi et al. 2010). Finally, we should point out that this method in principle can also be applied to other accreting compact objects, such as accreting neutron star and white dwarf binaries, with detectable accretion disc wind absorption line features.

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