

# (No) dynamical constraints on the mass of the black hole in two ULXs

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We present the preliminary results of two Gemini campaigns to constrain the mass of the black hole in an ultraluminous X-ray source (ULX) via optical spectroscopy. Pilot studies of the optical counterparts of a number of ULXs revealed two candidates for further detailed study, based on the presence of a broad He II 4686 Å emission line. A sequence of long-slit spectra were obtained for each object, and the velocity shift of the ULX counterpart measured. Although radial velocity variations are observed, they are not sinusoidal, and no mass function is obtained. However, the broad He II line is highly variable on timescales shorter than a day. If associated with the reprocessing of X-rays in the accretion disc, its breadth implies that the disc must be close to face-on.

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## 1 Introduction

The key uncertainty responsible for driving the study of ultraluminous X-ray sources (ULXs) over the past decade is the mass of the compact objects powering this extraordinary phenomenon. This unknown has been addressed by various ingenious methods, drawing evidence from across the electromagnetic spectrum, many of which are discussed elsewhere in these proceedings. (A separate discussion of many of these methods, and their results, is presented in Zampieri & Roberts 2009). A consensus has emerged that ULXs are powered by accretion onto a black hole; but the question of the mass of these black holes remains unanswered.

The reason that ULX masses remain mired in controversy is that none of the currently utilised methods provides a direct, unambiguous measurement of the black hole mass. This is perhaps best exemplified by X-ray spectral analyses. A great deal of progress has been made in recent years on the basis of *Chandra* and *XMM-Newton* spectra, firstly identifying soft excesses consistent with the cool accretion disc signature one would expect from a  $\sim 1000M_{\odot}$  intermediate-mass black hole (e.g. Miller et al. 2003; Miller, Fabian & Miller 2004). Latterly this interpretation has been strongly challenged by the detection of a spectral break at energies of a few keV, identified in the best quality *XMM-Newton* data for a wide range of ULXs. This implies that ULXs are operating in an unfamiliar spectral state, most likely associated with super-Eddington processes (Stobbart, Roberts & Wilms 2006; Roberts 2007; Gladstone, Roberts

& Done 2009; also Gladstone, these proceedings). This ‘ultraluminous state’ appears to display the characteristic imprint of a strong outflowing wind, as predicted for super-Eddington emission (e.g. Begelman, King & Pringle 2006; Poutanen et al. 2007), and so implies that ULXs harbour small,  $\lesssim 100M_{\odot}$  black holes.

However, neither of the above examples provides a direct mass estimate and, worse still, for most ULX X-ray spectral data degeneracy is a problem as the quality is sufficiently poor that neither model can be rejected<sup>1</sup>. Other indirect methods suffer similarly - the QPOs detected in the power density spectra of NGC 5408 X-1 can be used to infer the presence of an IMBH (e.g. Strohmayer & Mushotzky 2009; also Strohmayer these proceedings), but this assumes both a specific type of QPOs and a sub-Eddington accretion state. Neither may be true for this source (Middleton et al. 2010; also these proceedings). Similarly, different models for the optical colours and magnitudes of various ULX counterparts lead to a range of mass estimates (e.g. Copperwheat et al. 2006; Madhusudhan et al. 2009; Patruno & Zampieri 2010). It is clear therefore that we require a ‘clean’ test of ULX mass, untainted by model assumptions.

The obvious way forward is to perform similar experiments to those that have a near four-decade heritage for Galactic systems: dynamical studies based on the co-orbital motion of the accreting compact object and its companion, donor star (see e.g. Charles & Coe 2006; Casares 2007). In such experiments one commonly obtains optical (and/or

<sup>1</sup> Indeed, other spectral models may also be applied in some cases, for example slim disc spectra (e.g. Vierdayanti et al. 2006), or reflection-dominated spectra (Caballero-García & Fabian 2010), to name but two.

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UV/IR) spectra at a series of different epochs, and measures the semi-velocity amplitude  $K$  and period  $P$  for the sinusoidal orbital motions, as traced out by shifts in the observed emission and/or absorption line wavelengths. Measurements are usually taken from periods when the donor star dominates the optical light, and used to infer a mass function  $f(M)$  that places a lower limit on the black hole mass,  $M_X$ . However, it is also possible to use emission features originating in the accretion disc to produce a mass function (e.g. Orosz et al. 1994; Soria et al. 1998) such that

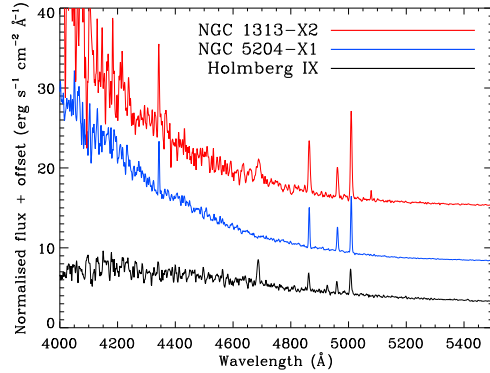
$$f(M) = \frac{M_C^3 \sin^3 i}{(M_C + M_X)^2} = \frac{PK_X^3}{2\pi G}, \quad (1)$$

where  $M_C$  is the mass of the companion star,  $K_X$  the semi-velocity amplitude of the black hole, and  $i$  the inclination of the orbital plane to our line-of-sight, thus placing limits on the mass of the black hole.

We can take encouragement from the recent reports of mass functions for two extragalactic BHBs, M33 X-8 and IC 10 X-1 (Orosz et al. 2007; Prestwich et al. 2007; Silverman & Filippenko 2008). However, most ULXs are at least three times more distant than these objects, with  $m_V \sim 20.5$  **at best** (Motch, these proceedings) and more typically  $m_V > 24$  (Roberts, Levan & Goad 2008). Furthermore, many are located in complex fields, where their spectroscopic signal could be confused with neighbouring nebulae and/or stars. Indeed, only a handful of ULXs might be accessible for mass function measurements with current facilities. Very few attempts have been made to date, and these have been unsuccessful. Kaaret & Corbel (2009) obtained 6 VLT/FORS observations of NGC 5408 X-1 over 3 days, but found no stellar absorption lines to base a mass function on. Pakull, Grisé & Motch (2006) obtained multi-epoch data for NGC 1313 X-2 and did find an interesting velocity shift ( $\Delta v \sim 380 \text{ km s}^{-1}$ ) in the centroid of a broad He II line, but were unable to constrain a mass function from subsequent follow-up data (Grisé et al. 2009). Hence the first mass function measurement for a ULX remains a tantalising goal. Here, we detail the preliminary results of a new attempt to obtain the mass functions of two ULXs, Ho IX X-1 and NGC 1313 X-2, using the Gemini observatory telescopes.

## 2 Steps towards determining the dynamical mass of a ULX

We have been developing a programme for the past few years, with the sole aim of obtaining a dynamical mass measurement for a ULX. The programme has three main steps: (i) identify the optical counterparts to ULXs on the basis of the most accurate available X-ray positions from *Chandra*, and *HST* imaging; (ii) obtain pilot optical spectroscopy to investigate the presence of useful spectral features; and (iii) undertake the radial velocity measurements campaign.



**Fig. 1** Pilot optical long-slit spectra of the ULX counterparts. Data were taken by the GMOS instruments on Gemini-N (NGC 5204 X-1 & Ho IX X-1) and Gemini-S (NGC 1313 X-2), using the B600 gratings. The optical magnitudes of the counterparts (extinction-corrected Vegamags, in *HST* filters) and exposure times were:  $m_{555} = 23.3$ , 3 hr (NGC 1313 X-2);  $m_{606} = 22.3$ , 0.8 hr (NGC 5204 X-1);  $m_{555} = 22.5$ , 1.5 hr (Ho IX X-1).

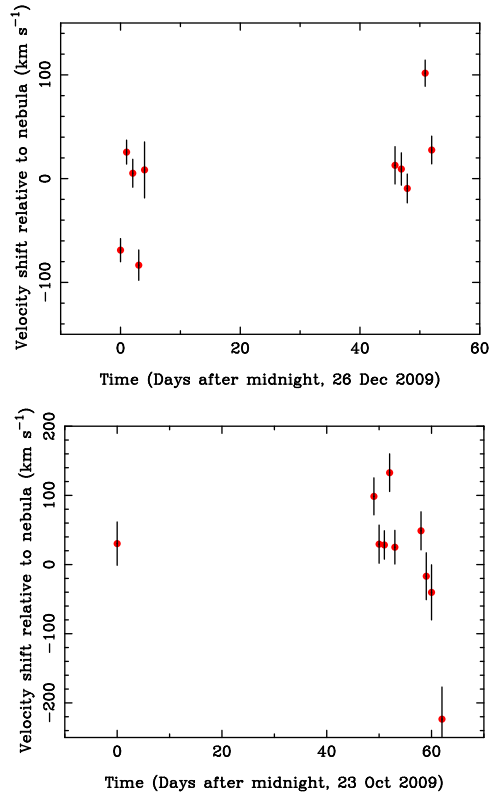
### 2.1 Pilot spectroscopy results

In the first step we surveyed nearby ( $d < 5$  Mpc) ULXs with available *Chandra* and *HST* data, and selected relatively bright ( $m_V \lesssim 23.5$ ) and isolated objects for further study. In Fig. 1 we show the pilot spectra, obtained using the GMOS instruments on the Gemini telescopes, for three X-ray luminous ( $L_X > 5 \times 10^{39} \text{ erg s}^{-1}$ ) ULX counterparts. Each has previously been identified in the literature, with positions shown by e.g. Liu, Bregman & Seitzer (2004, NGC 5204 X-1) and Ramsey et al. (2006, NGC 1313 X-2 & Ho IX X-1).

Fig. 1 shows the pilot spectra are dominated by a relatively featureless continuum, and emission lines from the bubble nebulae known to surround each of these three objects (Pakull & Mirioni 2002). However, one interesting feature is seen in two of the spectra: a broad He II 4686 Å line is evident in the spectra of NGC 1313 X-2 and Ho IX X-1. It is very plausible that this line could originate from the reprocessing of X-rays in the outer regions of the accretion disc, so could be used to trace radial velocity variations (as noted for NGC 1313 X-2 by Pakull et al. 2006) and therefore place limits on the black hole mass using Eq. 1.

### 2.2 New Gemini spectral monitoring campaigns

Ten follow-up Gemini observations were obtained for each of NGC 1313 X-2 (2.5 hr per observation on Gemini-S) and Ho IX X-1 (1.5 hr per observation on Gemini-N) in semester 2009B. Nine of the observations of NGC 1313 X-2 were performed over a 13-day period in December 2009, with a view to sampling over the known  $\sim 6$  day photometric period of this ULX (Liu, Bregman & McClintock 2009). The observations of Ho IX X-1 were split into two blocks of



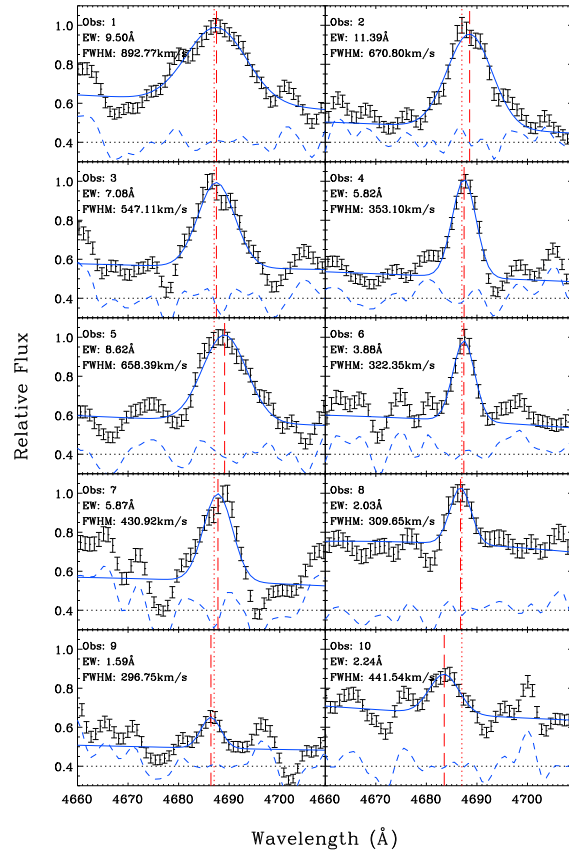
**Fig. 2** Observed radial velocity shifts of the ULX counterparts relative to the bubble nebulae, measured from the broad He II 4686 Å line, over the observation campaign. *Top panel:* Ho IX X-1. *Lower panel:* NGC 1313 X-2.

5 observations, in late December 2009 and February 2010. Details of the data analysis will be presented by Gladstone et al. (in prep.). In brief, spectra were extracted for both the counterpart, and for the surrounding nebula. The redshift of the region containing the ULX was constrained from the (off-ULX) nebular emission line spectrum for each observation, and this was then used as a fiducial marker to search for relative changes in the He II 4686 Å line centroid from the contemporaneous counterpart spectrum.

### 3 Provisional results

The results we present here are based on an initial analysis of the data, and focus primarily on NGC 1313 X-2. A further, more complete analysis is in preparation by Gladstone et al. and Roberts et al.

The preliminary results show that the campaign was successful on one count: we detected the anticipated shifts in the He II 4686 Å line with respect to its local vicinity (see Fig. 2), measuring velocity shifts of  $\pm 100$  km s<sup>-1</sup> for Ho IX X-1, and up to  $\sim 200$  km s<sup>-1</sup> for NGC 1313 X-2. However, the data was not consistent with sinusoidal variations in either case. Simple sinusoid fitting to both datasets resulted in poor fits, with  $P = 1.73$  days,  $K = 77$  km s<sup>-1</sup> and  $\chi^2_\nu \sim 5$  for Ho IX X-1; and  $P = 3.01$  days,  $K =$

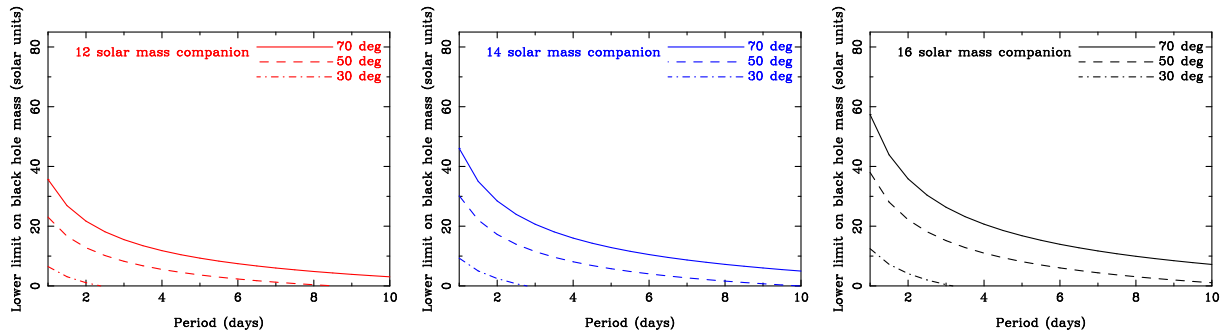


**Fig. 3** He II 4686 Å line profiles from the NGC 1313 X-2 data. The best fitting Gaussian profile is shown as a solid blue line, and the data residuals to this fit as a dashed blue line below the data. The vertical dashed and dotted lines show the rest wavelength and the line centroid, respectively. The relative flux is shown with the peak line flux normalised to unity for all good ( $\geq 9\sigma$ ) line detections. The last two detections have lower statistical significances, of 4 and  $6\sigma$  respectively.

61 km s<sup>-1</sup> and  $\chi^2_\nu \sim 4$  for NGC 1313 X-2. Given the lack of evidence for sinusoidal (i.e. orbital) variations in the data, we must therefore conclude that the data does not provide a new, solid constraint on the mass function for either object.

Despite the lack of mass function measurements, the data does reveal interesting behaviour from the ULX counterpart. One notable feature is the highly variable nature of the broad He II 4686 Å line. In Fig. 3 we show the profile of this line in the 10 separate observations of NGC 1313 X-2. Over these observations, its FWHM varies from a peak of  $\sim 900$  km s<sup>-1</sup> down to the instrumental resolution ( $< 290$  km s<sup>-1</sup>), with variations of factor 2 seen in 24 hours. This dramatic variability implies at the minimum that the broad He II emission must be originating within 24 light-hours of the ULX.

Such variations might come from X-ray reprocessing in the outer regions of the accretion disc. If so, the broad lines



**Fig. 4** Mass limits on the black hole in NGC 1313 X-2, assuming the He II 4686 Å line originates in the accretion disc. We use the  $2\sigma$  upper limit of  $182 \text{ km s}^{-1}$  derived from the rms scatter of the velocity shift, companion stellar mass estimates based on Patruno & Zampieri (2010), and calculate lower limits on the mass (for a range of inclinations, as per the legend) based on Eq. 1.

tell us that the disc cannot be perfectly face-on (or else we would see no line-of-sight velocity variations). This means that there should be some information on the black hole orbit hidden within the radial velocity data: we therefore use the  $2\sigma$  upper limit derived from the scatter in radial velocity measurements for NGC 1313 X-2 to derive lower limits on its black hole mass for a range of orbital periods in Fig 4. However, as Kaaret & Corbel pointed out for NGC 5408 X-1, such small measured velocities are inconsistent with the expected velocities of material in the accretion disc ( $\gg 1000 \text{ km s}^{-1}$ ). A possible solution is that only a small component of the accretion disc rotational velocity is in the line-of-sight, i.e. the disc is very close to face-on ( $i \sim 0^\circ$ ). We see in Fig 4 that even at  $i = 30^\circ$  there is little or no lower limit on the black hole mass, other than at very short periods<sup>2</sup>. Hence if the disc is close to face-on, little can be said about the black hole mass.

## 4 Conclusion

The initial analyses of our campaigns to determine mass functions for two ULXs betray no strong evidence for periodic velocity variations from either object; and so no mass function is forthcoming. We do see some interesting phenomenology in the ULX counterparts, including strong variability in the He II 4686 Å line indicating it originates very close to the ULX. The FWHM of the broad line indicates that the ULX may be close to face-on; interestingly, both objects are X-ray luminous ( $L_X > 5 \times 10^{39} \text{ erg s}^{-1}$ ), and models of super-Eddington discs predict that their observed flux will be highest close to this line-of-sight (Mineshige, these proceedings). This is perhaps more circumstantial evidence for models of ULXs as super-Eddington stellar-mass systems rather than IMBHs. In the meantime, we still await the first determination of the mass function for a ULX.

<sup>2</sup> Although removing the last two, low significance radial velocity points, significantly reduces the rms scatter to  $44 \text{ km s}^{-1}$ , and this can lead to some interesting constraints, e.g. for a  $16 M_\odot$  companion and  $30^\circ$  inclination,  $M_{\text{BH}} > 10 M_\odot$  over all periods up to 10 days.

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