

# Ubiquitous equatorial accretion disc winds in black hole soft states

G. Ponti,<sup>1</sup>★ R. P. Fender,<sup>1</sup> M. C. Begelman,<sup>2,3</sup> R. J. H. Dunn,<sup>4</sup> J. Neilsen<sup>5</sup>  
and M. Coriat<sup>1</sup>

<sup>1</sup>*School of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ*

<sup>2</sup>*JILA, University of Colorado and National Institute of Standards and Technology, Boulder, CO 80309-0440, USA*

<sup>3</sup>*Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309-0391, USA*

<sup>4</sup>*Excellence Cluster ‘Universe’, Technische Universität München, Boltzmannstrasse 2, D-85748 Garching, Germany*

<sup>5</sup>*MIT Kavli Institute for Astrophysics and Space Research, Cambridge, MA 02139, USA*

Accepted 2012 January 19. Received 2012 January 19; in original form 2011 October 30

## ABSTRACT

High-resolution spectra of Galactic black holes (GBHs) reveal the presence of highly ionized absorbers. In one GBH, accreting close to the Eddington limit for more than a decade, a powerful accretion disc wind is observed to be present in softer X-ray states and it has been suggested that it can carry away enough mass and energy to quench the radio jet. Here we report that these winds, which may have mass outflow rates of the order of the inner accretion rate or higher, are a ubiquitous component of the jet-free soft states of all GBHs. We furthermore demonstrate that these winds have an equatorial geometry with opening angles of few tens of degrees, and so are only observed in sources in which the disc is inclined at a large angle to the line of sight. The decrease in Fe xxv/Fe xxvi line ratio with Compton temperature, observed in the soft state, suggests a link between higher wind ionization and harder spectral shapes. Although the physical interaction between the wind, accretion flow and jet is still not fully understood, the mass flux and power of these winds and their presence ubiquitously during the soft X-ray states suggest they are fundamental components of the accretion phenomenon.

**Key words:** accretion, accretion disc – blackhole physics – methods: observational – techniques: spectroscopic – quasars: absorption lines – X-rays: binaries.

## 1 INTRODUCTION

The feedback of liberated gravitational potential energy by accreting black holes is determined by the combination of accretion states and outflow modes. In galactic black holes (GBHs), hysteresis is observed between the X-ray state of the accretion flow, which is strongly coupled to the presence of a relativistic jet, and the luminosity of the source (Fender et al. 2004). The jet is always present in ‘hard’ X-ray states, which can be observed at all luminosities. However, at the highest luminosities, sources can enter into a ‘soft’ X-ray state in which the jet is switched off, and kinetic feedback therefore appears to be strongly suppressed. Once the soft state is entered, GBHs remain in this state until they decline to  $\sim 1$  per cent of the Eddington rate, at which point they return to the hard state. Interestingly, it has been suggested that similar states also apply to AGN (Koerding et al. 2006).

Recent high-energy-resolution observations of several GBHs showed the presence of winds (Lee et al. 2002; Miller et al. 2004; 2006a,b), indicating that these objects drive outflows in the form of not only jets, but also winds (Díaz Trigo et al. 2011). There

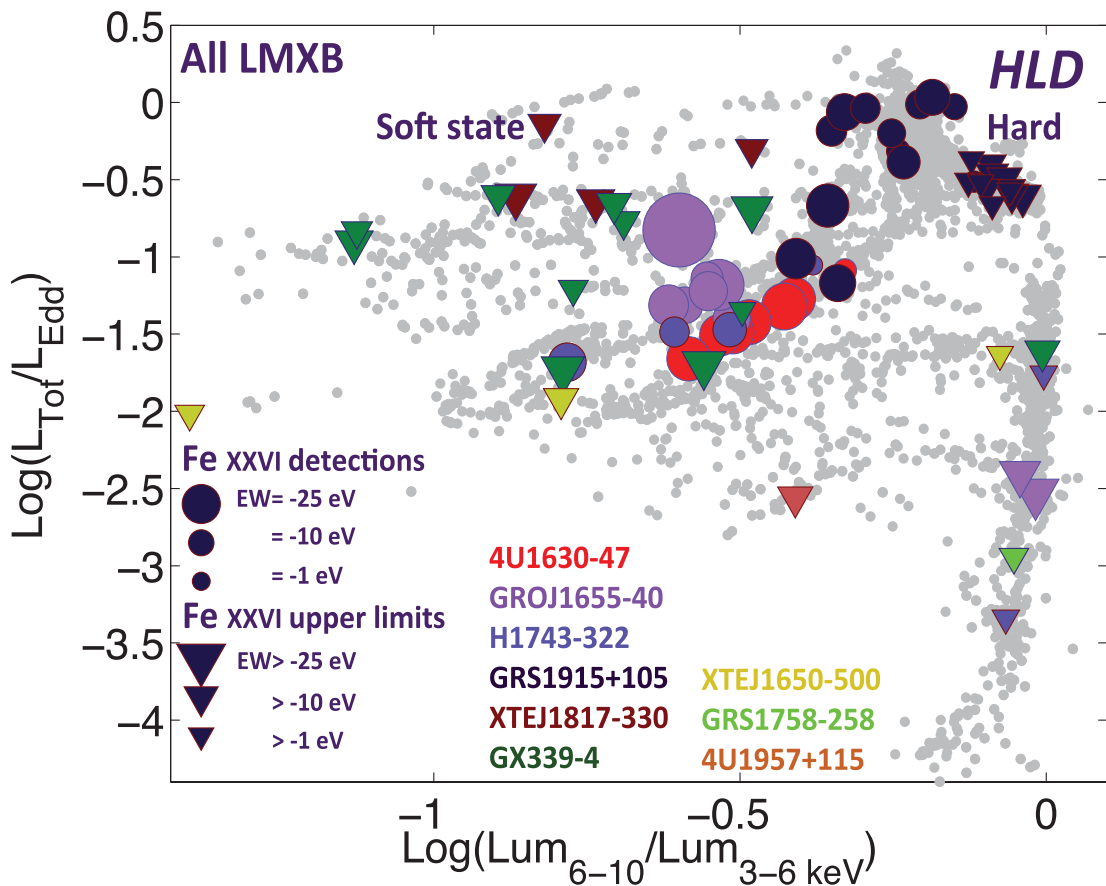
are three main mechanisms that can launch a wind from the surface (the atmosphere) of the accretion disc: thermal, radiation and magnetic pressure. In each case, a wind will be launched only if the pressure can overcome gravity. As a rule of thumb, the closer the launching point is to the BH, the higher the wind terminal velocity is.

In GRS 1915+105, a peculiar GBH accreting close to the Eddington rate for more than a decade (Fender & Belloni 2004), an accretion disc wind appears to be present in softer X-ray states and to be so powerful and to carry away so much mass as to halt the flow of matter into the jet (Neilsen & Lee 2009).

## 2 WIND-STATE-JET CONNECTION

We have performed a comprehensive study of ionized X-ray winds in GBHs. To do this, we analysed the X-ray spectra of all the *Chandra*, *XMM-Newton* and *Suzaku* observations of black hole low-mass X-ray binaries (LMXBs; which are GBHs accreting by Roche lobe overflow) with well-studied outbursts (Dunn et al. 2010) and at least one deep (exposure  $>5$  ks) grating spectroscopy observation. An effective way to separate the observations during the soft and hard states is to plot the hardness–luminosity diagram (HLD). We

\*E-mail: ponti@iasfbo.inaf.it



**Figure 1.** The presence or absence of ionized winds in a sample of GBHs. The grey (background) points show the HLD of all LMXBs studied. The hardness is computed from *RXTE* data as  $\log(L_{6-10}/L_{3-6})$ , where  $L_{6-10}$  and  $L_{3-6}$  are the source luminosity in the 6–10 and 3–6 keV bands, respectively. Circles indicate *Chandra*, *XMM-Newton* and *Suzaku* observations during which a high-ionization wind is detected through the observation of the Fe xxvi absorption line. The size of the symbol is directly proportional to the EW of the Fe xxvi absorption line. Triangles show, instead, the non-detections. Their size is proportional to the upper limit on the Fe xxvi EW. The different colours indicate data results from different sources. In soft states, during which the jet is always quenched, sometimes a wind is observed. However, other soft state observations show stringent upper limits on the presence of the wind.

compute the HLD from data obtained with the *Ross X-ray Timing Explorer (RXTE)* by first fitting each spectrum of each source with two components, a multitemperature disc blackbody component for the disc and a power-law component for the corona (see Dunn et al. 2010, for more details). The grey (background) points in Fig. 1 show the total luminosity (in Eddington units) versus the hardness for each *RXTE* observation. The hardness is computed as  $\log(L_{6-10}/L_{3-6})$ , where  $L_{6-10}$  and  $L_{3-6}$  are the observed source luminosity in the 6–10 and 3–6 keV bands, respectively. During observations in the hard state, the spectrally hard power-law component dominates the emission; thus,  $\log(L_{6-10}/L_{3-6\text{keV}})$  is close to 0.

Circles in Fig. 1 correspond to each of the *Chandra*, *XMM-Newton* and *Suzaku* observations during which a high-ionization wind is detected through the observation of the Fe xxvi absorption line. In particular, the size of the symbol is directly proportional to the equivalent width (EW) of the Fe xxvi absorption line. Triangles, instead, report wind non-detections (symbol size proportional to the Fe xxvi upper limit).

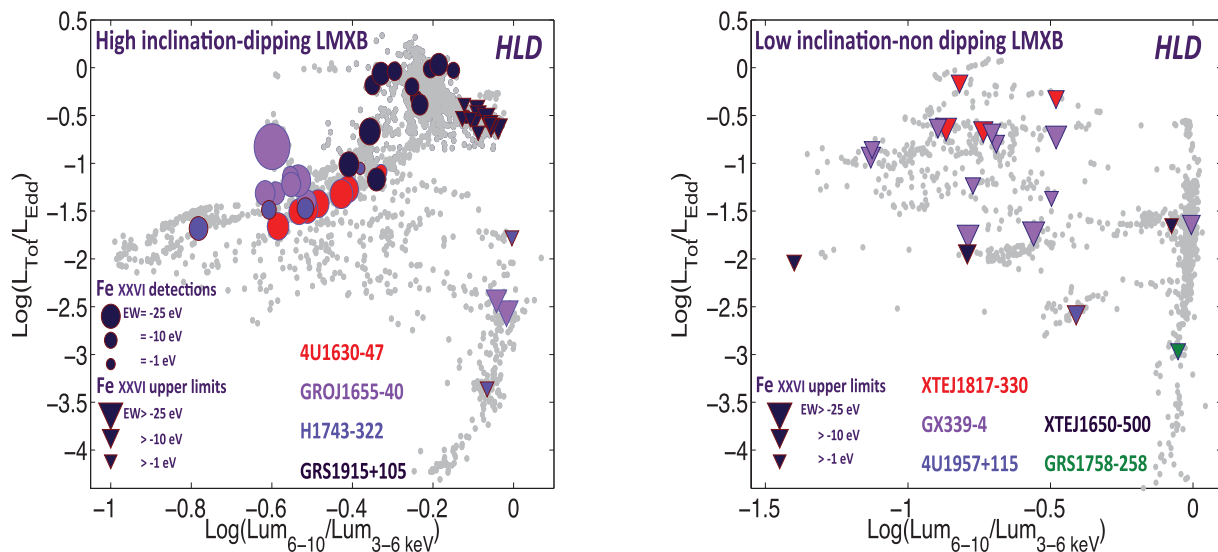
Analysing just 11 GRS 1915+105 *Chandra* observations, Neilsen & Lee (2009) already measured a strong anticorrelation between the presence of the (radio) jet and of the winds, with the wind being present primarily during the jet-free soft states and disappearing during hard states (see also Miller et al. 2008). The addition of the *XMM-Newton* and *Suzaku* data, which more than

doubles the number of observations, confirms and strengthens the anticorrelation (now with a total of 26 good-quality spectra) in this peculiar LMXB.

However, when we consider other LMXBs, the picture appears to be more complex. In fact, stringent upper limits are set during 17 soft state (jet-quenched) observations. In the next section, we suggest that this may be an effect of viewing geometry.

### 3 THE WIND ANGULAR DEPENDENCE

To study the wind angular dependence, we aim at dividing the sources into two samples, based on inclination. Thanks to extensive campaigns at other wavelengths, we know that GRO J1655–40 and GRS 1915+105 are high-inclination sources, close to edge-on, with similar disc inclinations of  $\sim 70^\circ$  (van der Hooft 1998; Greiner et al. 2001). GRO J1655–40 is also known to experience frequent dips (Tanaka et al. 2003). The dipping phenomenon is thought to be produced by clumps of low-ionization material along the line of sight, which are temporarily obscuring the X-ray source. The intervening material is probably related to the transfer of matter from the companion star to the disc, and it generally occurs in sources observed at high inclination (Frank, King & Raine 2002). Therefore, we also added H1743–322 and 4U 1630–47, known to experience frequent dips (Tomsick et al. 1998; Homan et al. 2005), to represent a



**Figure 2.** Left-hand panel: HLD of the high-inclination (dipping) LMXBs studied and of all the low-inclination (non-dipping) LMXBs. Right-hand panel: high-inclination (dipping) sources show Fe xxvi absorption every time they are in the soft state and upper limits in the hard states. In low-inclination (non-dipping) LMXBs, the Fe xxvi absorption line is never detected. We interpret these as due to a ubiquitous equatorial disc wind associated with soft states only. We note that high-inclination sources tend to show a more triangular HLD, while the low-inclination sources exhibit a boxy one.

population of sources which are close to edge-on. Fig. 2 (left-hand panel) shows the HLD of all the high-inclination LMXBs and reports the measured Fe xxvi absorption-line EW. These sources show clear evidence for a high-ionization disc wind ( $v_{\text{out}} \sim 10^{2.5-3.5} \text{ km s}^{-1}$ ) during all 30 observations in the soft state.<sup>1</sup>

On the other hand, whenever these sources are observed in the hard X-ray state, they show only upper limits. We, in fact, observe stringent upper limits for 16 out of 17 observations and just one detection of a weak wind quasi-contemporaneous with a weak jet (Lee et al. 2002; Neilsen & Lee 2009). This demonstrates that for this set of sources, the presence of the disc wind is deeply linked to the source state. In particular, the wind is present during spectrally soft states, when the jet emission is strongly quenched.

The right-hand panel of Fig. 2 shows the HLD for the non-dipping LMXBs, GX 339-4, XTE J1817-330, 4U 1957+115, XTE J1650-500 and GRS 1758-258, which have accretion discs which are inclined more face-on to the observer. None of these source has a detection of a highly ionized wind in any state. Several spectra have a signal-to-noise ratio good enough to measure upper limits as small as a few eV, even during the soft state. For this reason, we confidently state that these sources do not present the signatures of highly ionized Fe K winds.<sup>2</sup>

This difference in behaviour can be easily understood if both the high- and low-inclination sources have the same wind present in soft states and absent in the hard states, but the wind is concentrated in the plane of the disc; thus, our line of sight intercepts the wind only in high-inclination sources. If this idea is correct, we expect that deeper observations of low-inclination sources may reveal the

presence of the wind through the detection of weak ionized emission lines.

Is it theoretically plausible for the disc winds to have a strong angular dependence? Indirect evidence for an angular dependence of the wind in GBH was already inferred from the lack of emission lines associated with the X-ray absorption lines (Lee et al. 2002; Miller et al. 2006b). This suggests that the wind subtends a small fraction of  $4\pi$  sr. Moreover, disc wind models and magnetohydrodynamic simulations predict a strong angular dependence of the wind (Begelman et al. 1983a,b; Melia et al. 1991; 1992; Woods et al. 1996; Proga et al. 2002; Luketic et al. 2010). In fact, if the disc wind is produced by X-ray irradiation (i.e. Compton heating, line driving), it is expected to be stronger in edge-on sources simply because once the material is lifted from the disc, it will experience an asymmetric push from the radiation field of the central source. Flattened disc winds have also been assumed to explain the winds of broad absorption-line QSO and other AGN outflows (e.g. Emmering et al. 1992; Murray et al. 1995; Elvis 2000).

#### 4 IONIZATION EFFECTS

The strong connection between winds and source states requires an explanation. Ueda et al. (2010), during oscillating X-ray states of GRS 1915+105, observe the ionization parameter of the wind to vary with the source luminosity, suggesting the importance of ionization. Can an overionization effect explain the disappearance of the wind during hard states? If the absorber is in the form of ‘static’ clouds with approximately constant density  $n$  and distance  $R$  from the ionizing source and assuming that the spectral shape changes have a minor impact on the ionization state of the wind, then the absorber ionization parameter  $\xi$  will be directly related to the source luminosity:<sup>3</sup>  $\xi = LnR^2$ . The left-hand panel of Fig. 2 shows that *at the same luminosity*, the winds are present in the soft but not in hard states (see also Lee et al. 2002; Miller et al. 2006b;

<sup>1</sup> One observation of GRS 1915+105 with lower luminosity and Compton temperature does not show any Fe xxvi but only Fe xxv absorption, thus suggesting the importance of ionization effects.

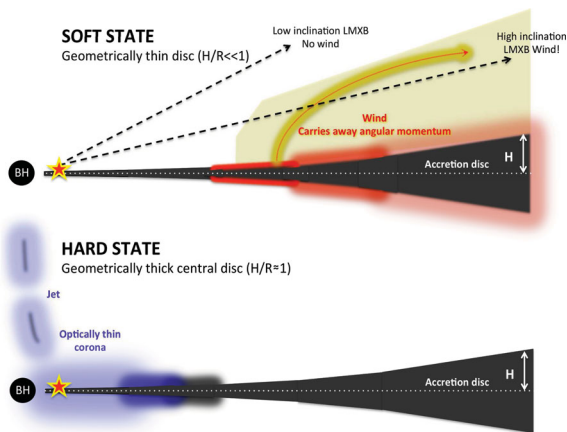
<sup>2</sup> The majority of the low-energy absorption lines detected in these LMXBs (Miller et al. 2004) are consistent with being produced by the interstellar medium (Juett et al. 2004; 2006; Nowak et al. 2008). Most of the remaining structures are consistent with being at rest, thus unlikely associated with the Fe K wind (Juett et al. 2006).

<sup>3</sup> Where  $L$  has been computed as the integral of the disc emission (in the 0.001–100 keV band) plus the power law (1–100 keV) one.

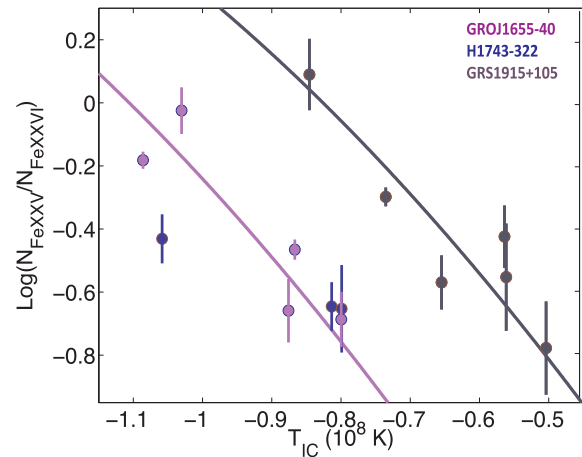
Blum et al. 2010; Neilsen et al. 2011b). Thus, the ‘static absorber’ interpretation may be unlikely.

Early works on accretion disc theory (Shakura & Sunyaev 1973) already predicted the formation of winds from the outer disc. Compton-heated winds (see Fig. 3) can be launched if the inner disc is geometrically thin and thus the central source can illuminate and heat the outer disc, creating a hot outflowing disc atmosphere with temperature  $T \sim T_{\text{IC}} = \int_0^\infty h\nu L_\nu d\nu / 4kL \sim 10^{7-8}$  K (Krolik et al. 1981; London et al. 1981; Begelman et al. 1983a,b; Woods et al. 1996; Shields et al. 1986) whose ionization parameter is expected to be primarily linked to the spectral energy distribution (SED; characterized by  $T_{\text{IC}}$ ) of the illuminating source.

Assuming that the Fe xxv and Fe xxvi absorption lines are unsaturated and are on the linear part of the curve of growth, we can estimate the Fe xxv and Fe xxvi ion abundances (see formula 1 of Lee et al. 2002). Fig. 4 shows the Fe xxv-to-Fe xxvi ion abundance ratio as a function of  $T_{\text{IC}}$  for all the observations in which the two lines are detected. For all sources, we systematically observe the lower ionization states (Fe xxv) at low  $T_{\text{IC}}$ , with the ratio Fe xxv/Fe xxvi decreasing for harder spectral shapes (higher  $T_{\text{IC}}$ ), as expected if the ionization parameter ( $\xi$ ) increases linearly with  $T_{\text{IC}}$  (see solid lines in Fig. 4). This result suggests that, during the soft states, ionization effects might play an important role in determining the properties of the wind. However, this conclusion is based on the ionization balance for a low-density gas illuminated by a  $\Gamma = 2$  power law; in order to verify the disappearance of the wind in hard states as due to overionization, a detailed study of the actual ionizing spectra and wind densities would be required. Although important, this is beyond the scope of this Letter. Alternatively, the wind disappearance in the hard state might arise from the fact that illumination of the outer disc is critical for the production of Compton-heated winds or from some other phenomenon (e.g. organization of magnetic field) which is related to the accretion states. Irradiation only occurs when the outer disc subtends a larger solid angle than the inner flow. Thus, the formation of thermal winds might be prevented if harder states are associated with thick discs that, even if optically



**Figure 3.** Several physical mechanisms can explain the properties of the observed equatorial disc winds. Here the thermal winds scenario is sketched. In soft states, associated with geometrically thin discs, the central source does probably illuminate the outer disc and thus it might heat it, increasing the thermal pressure that then drives away a wind, which is flattened above the disc. Thus, only in high-inclination sources our line of sight to the central source crosses the wind, allowing us to detect it. In hard states, a geometrically thick and optically thin corona and the jet are present, while no wind is observed. [Correction added after online publication 2012 April 4: figure colours fixed]



**Figure 4.** The Fe xxv-to-Fe xxvi ion abundance ratio as a function of  $T_{\text{IC}}$ . For each source, the Fe xxv/Fe xxvi ion abundance ratio is decreasing with  $T_{\text{IC}}$  (which is a tracer of the spectral hardness). This suggests that the wind ionization increases with spectral hardness, thus suggesting that ionization effects play an important role here. The solid lines show the expected relation between ion ratios and  $T_{\text{IC}}$ , assuming a linear relation between  $\xi$  and  $T_{\text{IC}}$  ( $\xi = \Xi \times T_{\text{IC}} / 1.92 \times 10^4$ , where  $\Xi = F_{\text{ion}} / nkTc$ ,  $F_{\text{ion}}$  is the ionizing flux between 1 and  $10^3$  Rydberg; Krolik et al. 1981) and the ion fraction versus  $\xi$  as computed by Kallman & Bautista (2001; see their fig. 8) for an optically thin low-density photoionized gas ( $\Gamma = 2$ ).

thin at the centre, have an optically thick region with  $H/R \sim 1$  or have a significant optical depth as seen from the outer disc (see also Neilsen et al. 2011b). Alternatively, if the disc ionization instability is at work in these transient sources, the Compton radius of the wind might lie in a low-temperature, and thus unflared, part of the outer disc (Dubus et al. 2001).

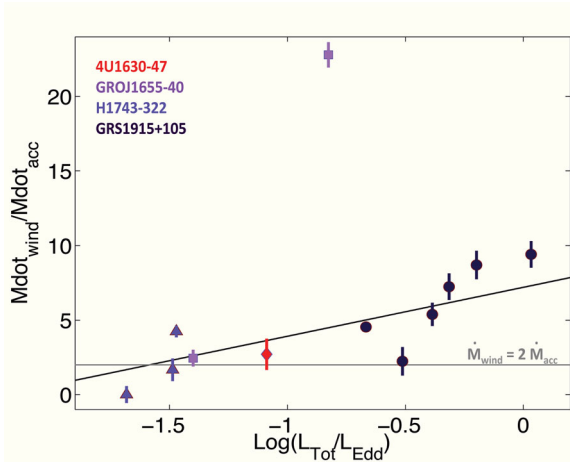
## 5 DISCUSSION

How important are these winds for the accretion phenomenon? We estimate the wind mass outflow rate using the equation

$$\dot{M}_{\text{wind}} = 4\pi R^2 n m_p v_{\text{out}} \frac{\Omega}{4\pi} = 4\pi m_p v_{\text{out}} \frac{L_X}{\xi} \frac{\Omega}{4\pi}, \quad (1)$$

where  $m_p$  is the proton mass,  $v_{\text{out}}$  the wind outflow velocity and  $\Omega$  is the solid angle subtended by the wind. *Chandra* observations provide reliable measurements of the outflow velocities; the detection of the wind in each soft state spectrum suggests a high filling factor; moreover, we measured a wind opening angle of  $\sim 30^\circ$ . Thus, once the ionization parameter is estimated, we can measure the mass outflow rate and compare it to the mass inflow rate (assuming an efficiency  $\eta = 0.1$ ). We estimate the ionization parameter  $\xi$  from the Fe xxv/Fe xxvi ion ratio and assume the ion versus  $\xi$  distribution computed by Kallman & Bautista (2001) and obtain values between  $\log(\xi) \sim 3.5$  and 4.2. However, we caution the reader that these values might change significantly once (instead of assuming the ion abundances of Kallman & Bautista 2001) the ion abundances versus  $\xi$  are computed using the properly tailored ionization balances from the self-consistent SED.<sup>4</sup> Fig. 5 shows that the mass outflow

<sup>4</sup> For example, under various assumptions about the gas density, different authors studying the same data set found ionization parameters that vary by  $\sim 2$  orders of magnitude (Miller et al. 2006a, 2008; Netzer 2006; Kallman et al. 2009). However, our estimated ionization parameters here are within the typical range of measured values, and we believe they are useful for our purposes here.



**Figure 5.**  $\dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$  versus luminosity. Apart from the one observation at the lowest luminosity, all detected winds carry away at least twice more mass than the one accreted into the central object. This implies that these winds are major players in the accretion phenomenon. The largest  $\dot{M}_{\text{wind}}$  is measured for the GRO J1655–40 observation during which a magnetically driven wind was detected (Miller et al. 2006a, 2008; Kallman et al. 2009). [Correction added after online publication 2012 April 4: figure colours fixed]

rates carried away by these winds are generally several times, up to 10–20 times, higher than the mass accretion rates as found by Neilsen et al. (2011a). This indicates that these winds are fundamental components in the balance between accretion and ejection, and that disregarding such winds would mean overlooking the majority of the mass involved in the accretion phenomenon. Such massive winds suggest a higher mass transfer rate from the companion than is generally assumed. This might imply, for example, more rapid evolution of the binary orbit than we expect.

Such winds should have a major impact on the physics of the inner accretion disc. For example, it is expected that the onset of the wind would reduce the local accretion rate. After a viscous time, this would modulate the accretion rate in the inner disc and, thus, the source luminosity, ultimately producing oscillations (Shield et al. 1986; Melia et al. 1991). Interestingly, a *Suzaku* observation caught GRS 1915+105 in transition from the hard ( $\chi$  state) to the soft state (Ueda et al. 2010, but see also Neilsen et al. 2011a) and, in agreement with this interpretation, both the rise of the wind and oscillations ( $\theta$  state) are observed. We note that Compton-heated winds are predicted to be powerful only at luminosities higher than few per cent of the Eddington limit. This corresponds to the only range of luminosities in which the soft states are observed, suggesting a strong connection. We speculate that the wind might have an effect in keeping the thin disc stable and the source firmly in the soft state, basically preventing the transition back to the hard state until the wind is not powerful anymore. This would lead to a more or less constant luminosity for soft to hard state transitions, which is observed (Maccarone 2002). It is critical to establish in the future whether these winds really are driven by Compton heating and what their influence is on the inner accretion flow, to better understand how they are linked to the accretion state and/or the formation/suppression of the jet.

## ACKNOWLEDGMENTS

The authors wish to thank L. Calvillo, M. Giustini, E. Koerding, C. Knigge and G. Dubus for discussion. This research has made

use of data obtained from the *Chandra*, *XMM-Newton*, *Suzaku* and *RXTE* satellites. GP acknowledges support via an EU Marie Curie Intra-European Fellowship under contract no. FP7-PEOPLE-2009-IEF-254279. MCB acknowledges support from NASA ATP grant NNX09AG02G and NSF grant AST-0907872. JN acknowledges additional support from the National Aeronautics and Space Administration through the Smithsonian Astrophysical Observatory contract SV3-73016 to MIT for support of the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-03060.

## REFERENCES

- Begelman M. C., McKee C. F., 1983, *ApJ*, 271, 89  
 Begelman M. C., McKee C. F., Shields G. A., 1983, *ApJ*, 271, 70  
 Blum J. L. et al., 2010, *ApJ*, 713, 1244  
 Díaz Trigo M., Miller-Jones J., Migliari S., Parmar A., Boirin L., 2011, *A&A*, 528, A150  
 Dubus G., Hameury J.-M., Lasota J.-P., 2001, *A&A*, 373, 251  
 Dunn R. J. H., Fender R. P., Körding E. G., Belloni T., Cabanac C., 2010, *MNRAS*, 403, 61  
 Elvis M., 2000, *ApJ*, 545, 63  
 Emmering R. T., Blandford R. D., Shlosman I., 1992, *ApJ*, 385, 460  
 Fender R., Belloni T., 2004, *ARA&A*, 42, 317  
 Fender R. P., Belloni T. M., Gallo E., 2004, *MNRAS*, 355, 1105  
 Greiner J., Cuby J. G., McCaughrean M. J., 2001, *Nat*, 414, 522  
 Homan J. et al., 2005, *ApJ*, 623, 383  
 Juett A. M., Schulz N. S., Chakrabarty D., 2004, *ApJ*, 612, 308  
 Juett A. M., Schulz N. S., Chakrabarty D., Gorczyca T. W., 2006, *ApJ*, 648, 1066  
 Kallman T., Bautista M., 2001, *ApJS*, 133, 221  
 Kallman T. R. et al., 2009, *ApJ*, 701, 865  
 Krolik J. H., McKee C. F., Tarter C. B., 1981, *ApJ*, 249, 422  
 Lee J. C. et al., 2002, *ApJ*, 567, 1102  
 London R., McCray R., Auer L. H., 1981, *ApJ*, 243, 970  
 Luketic S., Proga D., Kallman T. R., Raymond J. C., Miller J. M., 2010, *ApJ*, 719, 515  
 Maccarone T. J., 2002, *MNRAS*, 336, 1371  
 Melia F., Zylstra G. J., Fryxell B., 1991, *ApJ*, 377, L101  
 Melia F., Zylstra G. J., Fryxell B., 1992, *ApJ*, 396, L27  
 Miller J. M. et al., 2004, *ApJ*, 601, 450  
 Miller J. M. et al., 2006a, *Nat*, 441, 953  
 Miller J. M. et al., 2006b, *ApJ*, 646, 394  
 Miller J. M. et al., 2008, *ApJ*, 680, 1359  
 Murray N., Chiang J., Grossman S. A., Voit G. M., 1995, *ApJ*, 451, 498  
 Neilsen J., Lee J. C., 2009, *Nat*, 458, 481  
 Neilsen J., Remillard R. A., Lee J. C., 2011a, *ApJ*, 737, 69  
 Neilsen J., Petschek A. J., Lee J. C., 2011b, *MNRAS*, preprint (arXiv:1112.1066)  
 Netzer H., 2006, *ApJ*, 652, L117  
 Nowak M. A. et al., 2008, *ApJ*, 689, 1199  
 Proga D., Kallman T. R., 2002, *ApJ*, 565, 455  
 Shakura N. I., Sunyaev R. A., 1973, *A&A*, 24, 337  
 Shields G. A., McKee C. F., Lin D. N. C., Begelman M. C., 1986, *ApJ*, 306, 90  
 Tanaka Y., Ueda Y., Boller T., 2003, *MNRAS*, 338, L1  
 Tomsick J. A., Lapshov I., Kaaret P., 1998, *ApJ*, 494, 747  
 Ueda Y. et al., 2010, *ApJ*, 713, 257  
 van der Hoof F., Heemskerk M. H. M., Alberts F., van Paradijs J., 1998, *A&A*, 329, 538  
 Woods D. T., Klein R. I., Castor J. I., McKee C. F., Bell J. B., 1996, *ApJ*, 461, 767

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.