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High ionisation absorption in low mass X-ray binaries

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The advent of the new generation of X-ray telescopes yielded a significant step forward in our understanding of ionised absorption generated in the accretion discs of X-ray binaries. It has become evident that these relatively weak and narrow absorption features, sporadically present in the X-ray spectra of some systems, are actually the signature of equatorial outflows, which might carry away more matter than that being accreted. Therefore, they play a major role in the accretion phenomenon. These outflows (or ionised atmospheres) are ubiquitous during the softer states but absent during the power-law dominated, hard states, suggesting a strong link with the state of the inner accretion disc, presence of the radio-jet and the properties of the central source. Here, we discuss the current understanding of this field.

1 Introduction

Located at typical distances of few kilo-parsecs and with luminosities peaking at $L \sim 10^{38-39}$ erg s^{-1}, X-ray binaries are within the brightest X-ray sources of the sky, with the more extreme cases reaching fluxes of $F \sim 10^{-7}$ erg cm^{-2} s^{-1} (Bird et al. 2004; 2007; Remillard & McClintock 2006; Krivonos et al. 2007). Indeed, not surprisingly, the first extrasolar X-ray sources discovered were accreting X-ray binaries (Giacconi et al. 1962; 1974). These systems are composed of a compact object, either a neutron star (NS) or a black hole (BH), orbiting around a normal companion star from which they accrete material (van Paradijs 1983). The powerful X-ray emission originates from the accretion of such material that, because of the angular momentum, forms an accretion disc around the compact object (Shakura & Sunyaev 1973).

The mass of the companion star divides X-ray binaries in two main classes, the high mass and the low mass X-ray binaries (HMXB and LMXB, respectively). The geometry of the mass transfer from the companion star is one of the main macroscopic differences (of particular relevance here) between the two classes. In fact, HMXB accrete most of the material through the wind from the companion star, therefore the environment of such systems is filled with flows of highly and lowly ionised material from the companion star wind (Lubow & Shu 1975; Frank et al. 2002). The accretion in LMXB, instead, happens through Roche lobe overflow (Frank et al. 2002). The companion star fills its Roche lobe. Therefore, the material of the companion star at the internal Lagrangian point is in an unstable equilibrium and, in part, falls toward the compact object, generating a flow with high angular momentum (Lubow & Shu 1975; Shakura & Sunyaev 1973; Frank et al. 2002). Because of the high angular momentum of this material, an accretion disc extending up to a significant fraction of the Roche lobe is therefore formed.

The wind of the companion stars in HMXB typically generates an environment filled with outflowing plasma, potentially complicating the study of accretion disc winds. For this reason, most of the works on disc winds, that will be discussed here, have been performed in LMXB. Indeed, in LMXB the mass transfer from the companion star is supposed to be confined to the binary orbital plane and to be lowly ionised, leaving the other line of sights free from this confusing material.

1.1 Dipping phenomenon

The top and middle panels of Fig. 1 show the 3-10 keV light curve (with 50 s time bins) of AX J1745.6-2901 during two consecutive orbits, as a function of the orbital phase. AX J1745.6-2901 is an eclipsing (therefore high inclination) neutron star LMXB. All light curves in Fig. 1 show the presence of a drop at the time of the eclipse, at orbital phase 0.5. Moreover, the most evident features in the top panel of Fig. 1 are many narrow and intese drops of the source count rate, the so called dipping phenomenon. Such fea-

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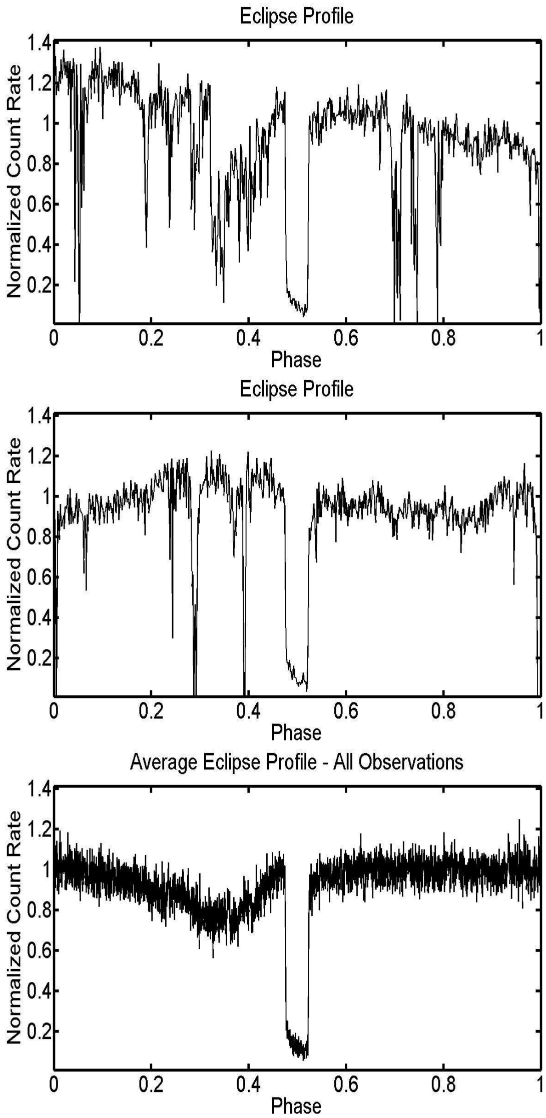

Fig. 1 *(Top and middle panels) XMM-Newton* light curve of AX J1745.6-2901 during two consecutive orbits, in the 3-10 keV band with 50 s time bins. The orbital phase is defined so that the mid eclipse happens at phase 0.5. Strong dipping activity is observed during one orbit, while almost no dipping is present in the following one. *(Bottom panel)* Stacked *XMM-Newton* light curve of all the orbits of AX J1745.6-2901 available in the *XMM-Newton* archive (for a total of 29). Although sporadic, the dipping phenomenon is periodic, peaking between orbital phases ~ 0.2 and 0.45.

tures almost completely disappear during the following orbit, suggesting that indeed they are sporadic and highly variable from orbit to orbit. The bottom panel of Fig. 1 shows the stacked light curve of all the orbits of AX J1745.6-2901 available in the *XMM-Newton* archive (see Ponti et al. 2015a,b,c). As typical in other sources, we show here for the first time that also for this source the dipping phenomenon, although sporadic, is periodic with maxima between orbital phase ~ 0.2 and 0.45.

It is well known that the dipping phenomenon is associated to high inclination systems (White & Mason 1985; Frank et al. 1987; Diaz-Trigo et al. 2006). It is believed that the turbulence, associated with the interaction between the stream of material from the companion star and the outer rim of the accretion disc, can substantially alter the height of the accretion disc rim with azimuthal angle, generating either a thick bulge where the stream hits the disc edge (White & Mason 1985) or an inner annulus where the remnant stream circularises (Frank et al. 1987). If so, erratic, but periodic, dips would be expected, around orbital phase 0.2-0.4, in high inclination systems, with maximum elevation of the material above the orbital plane of a few tens of degrees (Frank et al. 1987).

In agreement with this general interpretation, dipping sources are observed at high inclination (see e.g. Casares & Jonker 2014 and references therein). Therefore, the dipping phenomenon is a good tracer of inclination. It has also been confirmed that the dipping phenomenon is produced by transient obscuration of the primary X-ray source by a thick layer of lowly ionised material[1] (Parmar et al. 1986; Diaz-Trigo et al. 2006). Important column densities are typically observed with $N_H \gtrsim 10^{23}$ cm^{-2} (where N_H is the absorber column density) significantly modifying the X-ray spectrum below 2-4 keV (Parmar et al. 1986; Diaz-Trigo et al. 2006). Also confirmed is that, despite the dips being highly erratic in depth and duty cycle, they are recurrent showing periodicities equal to the system orbital period (e.g., see bottom panel of Fig. 1).

1.2 Transient, persistent LMXB and accretion states

LMXB are known to present fairly different behaviours on long time scales. Indeed, some systems are persistently bright, others, instead, are transient sources occasionally showing sporadic very luminous outbursts typically lasting months to years (sometimes decades). This transient-vs-persistent dichotomy is thought to be linked to a thermal-viscous disc instability generated by the ionisation of hydrogen (Meyer & Meyer-Hofmeister 1981; Lasota 2001). In this model, persistent sources are just like the transients, different only because the mass transfer from the companion star is so high that the temperature of the accretion disc never falls below the threshold for the hydrogen to recombine (Dubus et al. 2001; Coriat et al. 2012) .

Already the first spectral studies of X-ray binaries showed clear evidence that LMXB transit through clearly different states during an outburst. The initial notion of states in neutron stars was based primarily on colour-colour plots and to classifications according to the trail that the source draws into such plot, during an outburst (e.g., atols, z-sources).

[1] Having $log(\xi) \lesssim 3$; where ξ is the ionisation parameter defined as $\xi = L/(4\pi n R^2)$, where L is the source luminosity, n is the absorber density and R the source to absorber distance.

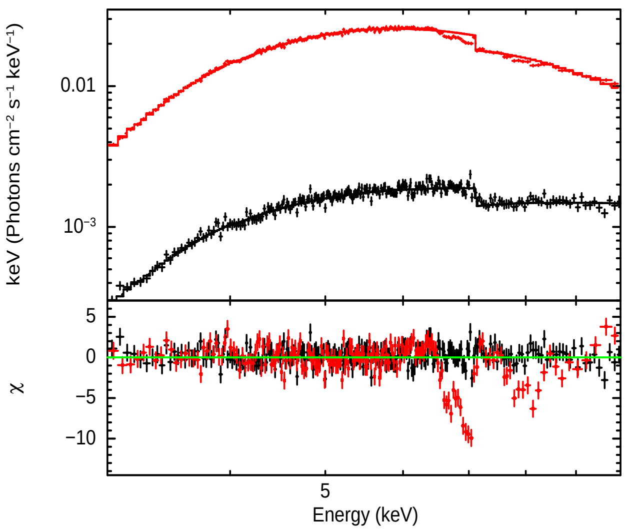

Fig. 2 *XMM-Newton* X-ray spectra of AX J1745.6-2901 during the soft (red) and hard (black) states. Strong features due to ionised absorption (e.g. Fe XXV and Fe XXVI Kα and Kβ) are present in the soft state and they disappear in the hard state (for more details see Ponti et al. 2015a).

The identification of the distinct accretion states, their hysteresis pattern, the link to the accretion geometry, optical depth and radiative efficiency as well as the link to outflows and patterns of variability has been developed first for BH systems (Fender et al. 2004; Belloni et al. 2011). During an outburst, a LMXB goes through an hysteresis pattern following a series of accretion states. Softer states are dominated by: i) the multi-temperature disc black body emission peaking around 1 keV (well described by an alpha-disc; Shakura & Sunyaev 1973); ii) low level of variability (integrated rms lower than ~ 5 %; Muñoz-Darias et al. 2011) and; iii) quenched jet emission (Fender et al. 1999). During harder states, instead: i) the disc emission is significantly weaker (the disc is, possibly, truncated) and the X-ray spectrum is dominated by a hard Comptonisation component peaking around ~ 100 keV; ii) the source is highly variable and; iii) a compact jet is always observed (Fender et al. 2004; Belloni et al. 2005). Interestingly the source moves, during an outburst, through the various states following a clear hysteresis pattern, rising in the hard state, eventually transiting to the soft state, then declining down to a few percent of the Eddington limit and transiting back to the hard state (see Fender & Belloni 2012, for a recent review). Very recently it has been realised that, once the complicating contribution from the boundary layer is removed, the same states observed in BH are present in NS too (Muñoz-Darias et al. 2014).

2 Highly ionised (Fe K) absorption in LMXB

Being located along the Galactic plane, LMXB are typically absorbed by significant column densities of Galactic neutral material. Indeed, LMXB are generally used as lighthouses to trace the distribution of the cold and warm matter in the Galaxy through absorption imprinted in their spectra and their dust scattering halo (Predehl & Schmitt 1995; Juett et al. 2004; 2006; Costantini et al. 2005).

In addition to this component, the latest generation of X-ray telescopes, equipped with improved spectral resolutions detectors, brought to the discovery of narrow absorption lines, due to highly ionised material (such as Fe XXV and Fe XXVI), a new component in the spectra of LMXB (Brandt & Schulz 2000; Lee et al. 2002; Parmar et al. 2002; Boirin et al. 2004, 2005; Jimenez-Garate, Schulz & Marshall 2003; Ueda et al. 2004; Miller et al. 2006a,b). Such absorption lines were observed to be variable, produced by very high ionisation plasma and in several cases in outflow. All these characteristics indicate that they originate locally in the X-ray binary. A very high ionisation state characterise these absorbers, with typical values in the range $log(\xi) \sim 3.5 - 5$. At such high ionisations, the strongest lines are the Kα and Kβ transitions of Fe XXV and Fe XXVI (see Fig. 2 for an example). For this reason, we will refer to this component as Fe K absorption, hereinafter.

We note that, initially it was not well appreciated the deep link between this newly discovered component and the source properties and accretion state. Indeed, at a first glance, these absorption lines appear as un-impressive narrow (with typical broadening of the order of $\sim 500 - 1000$ km s^{-1} or lower) lines with relatively small equivalent widths of $EW \sim 10 - 40$ eV (see Fig. 2). Remarkable similarities are observed between the highly ionised absorption observed in NS and BH systems. However, also some outstanding differences are seen.

2.1 Soft state, equatorial disc winds in BH

Since the beginning of this century, high resolution spectroscopy has allowed to carefully detail the kinematic of highly ionised absorbers. Up to the present day, all the high ionisation absorption lines in BH systems are observed to be in outflow, therefore they are signatures of winds (but see Miller et al. 2014). The typical outflow velocities are in the range $v_{\rm out} \sim 100 - 2000$ km s^{-1}. Interestingly, Fe K absorption is not observed in all BH systems. Thanks to a compilation of all the BH LMXB observed with *Chandra*, *XMM-Newton* and *Suzaku*, it has been recently realised that the Fe K wind is present only in high inclination systems (Ponti et al. 2012). This is a clear evidence that the wind has an equatorial geometry and it has a limited covering factor (e.g. few tens of degrees above the accretion disc, similar to the dipping phenomenon). Indeed, this is in agreement with the lack of evidence for the wind re-emission lines, expected for fully covering absorbers (Lee et al. 2002). The link between the dipping phenomenon and the highly ionised material appears therefore to be just coincidental (simply the product of the high inclination of the system). Indeed, the narrow absorption lines are present also during non-dipping periods and, differently from the dipping phenomenon, no clear modulation with orbital phase is observed (Boirin et al. 2005; Diaz-Trigo et al. 2006; Ponti et al. 2014; 2015a).

One of the most peculiar properties of these winds, that underlines the deep link with the inner accretion process, is that they are observed primarily and consistently in the so called soft states (Neilsen et al. 2009; Ponti et al. 2012). The presence of the wind at all times in the soft state indicates a high filling factor, e.g., higher than the one producing the dipping phenomenon. For example, if the wind were patchy in the azimuthal angle, then we would expect to see some soft state spectra with no wind. On the other hand, the Fe K lines, signatures of the wind, disappear during the hard state (Ponti et al. 2012). The strong connection between winds and source states requires an explanation. One obvious reason would be that the wind is over-ionised in the hard state. Indeed, when present, the wind appears to increase its ionisation state with luminosity, as expected (Ueda et al. 2010; Diaz-Trigo et al. 2012; Ponti et al. 2012). However, it has been shown that over-ionisation fails at explaining the disappearance of the Fe K lines in the hard state, at least in the few cases when detailed photo-ionisation computations have been performed (Miller et al. 2012; Neilsen et al. 2012; Ponti et al. 2015a). This suggests that disc winds are actually missing in the hard state, with the wind being present when a standard accretion disc is present and the jet is absent.

Chandra HETG observations of Fe K winds allow an accurate measurement of the wind outflow velocity ($v_{\rm out}$) and a characterisation of the ionisation state of the absorber. From these quantities, assuming, from statistical arguments, that the wind opening angle is $\sim 30^\circ$ (Ponti et al. 2012), it is possible to estimate the wind mass outflow rate using the equation

$$\dot{M}_{wind} = 4\pi m_p v_{\rm out} \frac{L}{\xi}\frac{\Omega}{4\pi} \quad (1)$$

where m_p is the proton mass and Ω is the solid angle subtended by the wind. The measured values are generally either of the order of, or higher, than the mass accretion rates (Lee et al. 2002; Ueda et al. 2004; Neilsen, Remillard & Lee 2011; Ponti et al. 2012). This strongly indicates that these winds are a fundamental component in the balance between accretion and ejection and they are major ingredients in the accretion process. Disregarding such winds would mean overlooking the majority of the mass involved in the accretion process. In particular, a higher mass transfer rate from the companion star, compared to what is generally assumed, might be required. This might lead to a more rapid evolution of the binary orbit than we expect. Indeed, eclipse timing studies of eclipsing LMXB typically fail to reproduce the observed orbital evolution through conservative mass transfer (see Ponti et al. 2015d and references therein).

From the mass outflow rate we can compute the wind kinetic luminosity as: $L_{kin} = \frac{1}{2}\dot{M}_{wind} v_{\rm out}^2$. We note that despite such winds can carry away the majority of the transferred mass, their relatively small outflow velocity generates

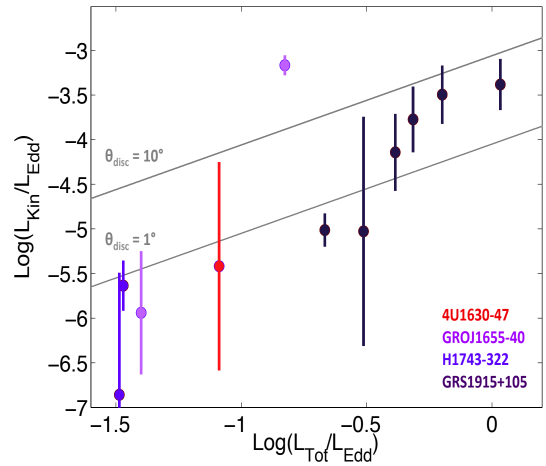

Fig. 3 Kinetic luminosity of the wind as a function of the source central luminosity for several BH LMXB with *Chandra* HETG observations (see Ponti et al. 2012 for more details). The grey lines show the expected relation for disc flared by $\theta_{\rm disc} = 1^\circ$ and 10°, assuming a conversion between the luminosity intercepted by the disc into kinetic luminosity of 0.01.

very small kinetic luminosities. Indeed, the wind kinetic luminosities are observed to span the range $L_k \sim 10^{-3.5-6}$ of the Eddington luminosity (see Fig. 3). Even if the same type of rather low velocity wind is present in active galactic nuclei, it would have no significant contribution for the feedback phenomenon or impact for the evolution of the host galaxy (Fabian et al. 2012). Much higher outflow velocities, such as the ones observed in ultra fast outflows (Tombesi et al. 2010; 2013) would be required in this case.

2.2 Highly ionised absorption in NS

NS LMXB also show highly ionised absorption, with a similar range of ionisation states and column densities as in BH. Again, as in BH, in NS also, ionised absorption is observed only in dipping LMXB, suggesting an equatorial geometry (Diaz-Trigo et al. 2006).

However, there are also outstanding differences. Indeed, it was soon realised that two families of highly ionised absorbers are present in NS LMXB. In fact, some sources show absorption features with outflow velocities of the order of $v_{\rm out} \sim 10^{2-3}$ km s^{-1} and are, therefore, called winds, others, show no outflow velocities. The ionised structures in these latter sources are sometimes called ”disc atmospheres”.

2.3 A connection between state and Fe K absorption also in NS?

After the discovery of the clear connection between the presence of the wind and the accretion state in BH systems (Ponti et al. 2012), we investigated if the same connection is present in NS (Ponti et al. 2014; 2015a). We first checked the entire sample of NS LMXB with *Chandra* or *XMM-Newton* observations (allowing a good characterisation of the properties of the Fe K lines) and we realised that only two sources were standing out for their extensive monitoring campaign. One, EXO 0748-676, has been observed more than 20 times because it was a calibration source for *XMM-Newton*, while the second, AX J1745.6-2901, has more than 40 observations because it falls in the same field of view of Sgr A* (Genzel et al. 2010; Ponti et al. 2015b,c).

EXO 0748-676 was discovered by *EXOSAT* in 1985 (Parmar et al. 1985) and it has been active for 23 years, when it finally returned to quiescence in 2008 (Hynes & Jones 2008). EXO 0748-676 spent most of the outburst in the hard state. Using both the hardness intensity diagrams and measuring the source variability, from nearly simultaneous *RXTE* observations, Ponti et al. (2014) classified the state of the source within each *XMM-Newton*, *Chandra* and *Suzaku* observation. Not one of the 20 X-ray spectra obtained in the hard state reveal any significant Fe K absorption line. On the other hand, intense Fe XXV and Fe XXVI (as well as rarely observed Fe XXIII plus S, Ar, and Ca transitions) lines are clearly detected during the only soft state observation.

Ponti et al. (2015a) analysed all the *XMM-Newton* observations of AX J1745.6-2901 available as of 2014 May 14. Eleven observations caught the source in outburst of which nine in the soft state and two in the hard state. Significant Fe XXV and Fe XXVI Kα and Kβ lines are observed during all the nine soft state observations, while stringent upper limits are observed during the hard state observations (see Fig. 2). The column density ($N_H \sim 2 \times 10^{23}$ cm^{-2}) and ionisation state ($Log(\xi) \sim 4.1$) of the highly ionised absorber are consistent with being constant within the soft state observations. Nearly simultaneous *NuSTAR* observations allowed Ponti et al. (2015a) to well characterise the source spectral energy distribution both in the soft and hard state. This allowed the authors to check that the Fe K absorption does not disappear because of over-ionisation in the hard state. These findings strongly support the idea that the same connection between Fe K absorption and states is also valid in the two best monitored NS systems, therefore it is not a unique property of BH, but a more general characteristic of accreting sources.

3 Wind launching mechanisms

Many different mechanisms have been invoked to launch winds from accreting sources. Among these, some of the most popular have at their core: i) the extreme radiation pressure present when the source is either at, or over, the Eddington limit; ii) the large opacities of the UV transitions generating line driven winds (Castor et al. 1975; Murray et al. 1995; Arav et al. 1995) or; iii) the photo-evaporation instability producing winds from irradiated molecular clouds (such as the torus in AGN; Krolik & Kriss 2001; Blustin et al. 2005). None of these mechanisms is thought to be at work in the case of LMXB. Indeed, i) no major difference is typically observed in the wind properties of sources spanning a wide range of Eddington ratios, down to luminosities of a few per cent Eddington, when the first mechanism is expected to be negligible (but see Miller et al. 2006); ii) line driven winds are expected to be inhibited by the very hard X-ray radiation typical of LMXB, that is very quickly over-ionising the plasma (Proga et al. 2002); iii) the reservoir of accreting matter is in the companion star and not stored in large molecular clouds, therefore also the last mechanism is inhibited. LMXB are, therefore, simplified laboratories to study the generation of disc winds.

Only two mechanisms, either magnetic or thermal, are instead believed to be able to launch winds in LMXB. Thermal (or Compton heated) winds are generated in the outer part of a flared accretion disc. At large radii, because of irradiation from the central source, the surface of the disc can be heated to a point where the thermal velocity exceed the escape velocity. In this conditions, an outflow is continuosly generated (Begelman et al. 1983a,b; Woods et al. 1996; Luketic et al. 2010). The radius at which the thermal velocity is equal to the escape velocity is typically referred to as Compton radius. An ad hoc configuration of the magnetic field can also, of course, generate winds (Blanford & Payne 1982; see Fukumura et al. 2010; 2015, for the simulations of magnetic winds in AGN). No restriction on either the launching radius or the wind outflow velocity is present in this case. Therefore any wind in LMXB generated well inside the Compton radius is thought to have a magnetic origin.

3.1 Magnetic or thermal wind?

A significant effort has been undertaken to try to understand if winds in LMXB are magnetically or thermally driven. One observation of GROJ1655-40, during the so called anomalous state, shows exceptionally intense wind features, with an array of more than 90 absorption lines detected at more than 5 σ (Miller et al. 2006; 2008; Kallman et al. 2009). In particular, the detection of the metastable 2s2p^{3}P level of Fe XXII implies a narrow range of relatively high number densities ($n \sim 5 \times 10^{15}$ cm^{-3}) for the absorbing plasma. Given the observed ionisation state of the absorber and the source luminosity, then it can be derived the distance R of the absorber by $R = \sqrt{\frac{L}{4\pi n \xi}} \sim 5 \times 10^8$ cm$\sim 400\, r_g$, where $r_g = GM_{\rm BH}/c^2$ with $M_{\rm BH}$ being the BH mass, c the speed of light and G the gravitational constant. This location is well inside the Compton radius. This is a strong argument in favour of a magnetic launching mechanism for this wind. We note that in this case the wildly employed rule of thumb for which the wind outflow velocity is reminiscent of the launching radius of the disc, does not hold. Indeed, the observed wind outflow velocity $v_{\rm out} \sim 300 - 1500$ km s^{-1} is characteristic of outer regions of the disc (consistent with a thermal origin, although this does not exclude a magnetic origin). If indeed winds in LMXB have a magnetic origin, then the wind-jet anti-correlation (therefore the wind state connection) might be easily understood as the product of a reconfiguration of the magnetic field lines (first suggested by Neilsen et al. 2009). In fact, both jets and winds might be the product of the same magnetic outflow. When the magnetic field lines generate a collimated outflow, this appears as a jets, while it appears as a wind, when un-collimated.

Apart from the peculiar wind observed during the anomalous state of GROJ1655-40, no other metastable-density-sensitive lines are observed in other observations, therefore preventing us from a clear determination of the distance to the absorber and therefore to pin down the launching mechanism. Apart from a few outliers, typically derived from lines with lower significance, the wind outflow velocities are in the range $v_{\rm out} = 0$, for disc atmospheres, up to $v_{\rm out} = 100 - 2000$ km s^{-1}. These velocities are higher than the Keplerian, or local escape velocity, outside $2 \times 10^4\ r_g$. Therefore these relatively small outflow velocities are consistent and suggest a thermal origin for these winds. Since their first theorisation, it was predicted that the mass outflow rate in thermal winds could be up to many times higher than the mass accretion rate (Begelman et al 1983a,b). This, also, is in remarkable agreement with observations. In thermal winds, the power required to energise the wind is provided by the central source. Therefore, the maximum kinetic luminosity of the wind is expected not to exceed the central source luminosity intercepted by the outer disc and used to heat and launch the wind. For discs flared by less than $\sim 8 - 12°$, this corresponds to a kinetic power of $\sim 10^{-3} L/L_{\rm Edd}$ (assuming a conversion efficiency of 0.01 from incident luminosity into kinetic power) and expected to scale with the source central luminosity. Figure 3 shows that this is well consistent with observations.

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