Accretion disc atmospheres and winds in low-mass X-ray binaries

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In the last decade, X-ray spectroscopy has enabled a wealth of discoveries of photoionised absorbers in X-ray binaries. Studies of such accretion disc atmospheres and winds are of fundamental importance to understand accretion processes and possible feedback mechanisms to the environment. In this work, we review the current observational state and theoretical understanding of accretion disc atmospheres and winds in low-mass X-ray binaries, focusing on the wind launching mechanisms and on the dependence on accretion state. We conclude with issues that deserve particular attention.

1 Introduction

The presence of highly ionised plasma in low-mass X-ray binaries (LMXBs) was first observed in the microquasars GRO J1655−40 (Ueda et al. 1998) and GR 1915+105 (Kotani et al. 2000) thanks to the X-ray observatory ASCA. Their spectra showed narrow absorption lines that were identified with absorption from Fe XXV and Fe XXVI. Those first detections paved the way for a myriad of discoveries of photoionised plasmas in LMXBs (see Table 1) following the launch of the X-ray observatories Chandra, XMM-Newton and Suzaku. Soon after the first handful of detections was it realised that photoionised absorbers could be ubiquitous to all X-ray binaries (e.g., Parmar et al. 2002). However, only recently has it been recognized that photoionised plasmas may be a key ingredient for our understanding of X-ray binaries (XRBs). The reason is that the amount of mass that leaves the XRB when the plasmas are outflowing is of the order of or larger than the mass accreted into the system (e.g., Ponti et al. 2012), and could therefore lead to instabilities in the accretion flow (Begelman et al. 1983, hereafter BMS83) or even trigger accretion state changes (Shields et al. 1986).

In this work, we review the current observational state and theoretical understanding of accretion disc atmospheres and winds in LMXBs. High mass X-ray binaries are not discussed because their winds are often dominated by the contribution from the companion star. As a diagnostic tool for this study we focus on the presence of narrow absorption lines in the spectra, with or without blueshifts.

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2 Observational properties of accretion disc atmospheres and winds

To date, 19 LMXBs have shown narrow absorption lines from highly ionised ions situated in a “local” absorber inside the system as opposed to the interstellar medium: 11 neutron star (NS) and 8 black hole (BH) systems (Table 1). The majority of these systems are dippers (16/19 or 84% in Table 1) see also Boirin et al. 2004; Díaz Trigo et al. 2006; Ponti et al. 2012). These sources are viewed relatively close to edge-on, i.e., at a high inclination angle of 60−80° (Frank et al. 1987). The three systems not showing dips in Table 1 are suspected to have a relatively high, >45−50°, inclination. The preferential detection of absorbing plasmas at inclinations ≥50° points to a distribution of the ionised plasma close to the accretion disc. This suggests an equatorial geometry or a flared geometry exhibiting a stratification of density and/or ionisation (Higginbottom & Proga 2015).

With the aid of photoionised plasma models produced by XSTAR (Kallman & Bautista 2001) or CLOUDY (Ferland 1997), the relative depths of the absorption lines detected in a spectrum give access to the column density of the photoionised plasma and to its degree of ionisation, defined as ξ = L/nω2 (Tarter et al. 1969), where L is the luminosity of the ionising source, n the electron density of the plasma and ω the distance between the plasma and the ionising source. On the other hand, a blueshift of the lines with respect to the theoretical wavelengths indicates that the plasma is outflowing.

The ionised plasmas detected in LMXBs have column densities ranging between 0.5×1021 and 1024 cm−2. There is no obvious difference between the column densities observed for NSs and BHs. Among the sources for which log ξ was estimated, the vast majority (16/18 or 89%) in Table 1 have shown very highly ionised plasmas with log ξ≥3. All
these sources have indeed shown absorption lines from Fe XXV at 6.70 keV and/or from Fe XXVI at 6.97 keV. Four sources have shown both high (log $\xi \geq 3$) and low (log $\xi < 3$) ionisation plasmas. Two sources have only shown plasmas with log $\xi < 3$: MAXI J1305−704 and GX 339−4. MAXI J1305−704 has actually shown lines that may be modeled by two absorbers, among which the most ionised one could still have a log $\xi$ close to 3 (2.9 in $\xi$ in Shidatsu et al. 2013). GX 339−4 is the only source left showing only one low ionisation plasma (log $\xi = 1.8$, Miller et al. 2004) with no accompanying absorber detected with a higher degree of ionisation. Interestingly, GX 339−4 does not show dips, suggesting that there could be stratification of the ionised plasma as a function of inclination. On the other hand, most of the low ionisation plasmas have been detected in systems that show a relatively low column density of interstellar absorption, indicating that the number of systems with low ionisation plasmas may be actually larger.

We note that as deeper observations become available, the need to include more than one ionised plasma while modelling a given spectrum is increasing due to the co-existence of lines with significantly different outflow velocities or different ionisation equilibria (e.g., Kallman et al. 2009; Xiang et al. 2009). This suggests that studies of absorption measurement distributions as done for AGN (e.g., Stern et al. 2014) could soon be needed also in XRBs.

We consider that a given system shows an outflow if the absorption lines show a significant blueshift or a P-Cygni profile. Conversely, we call atmospheres those plasmas for which no blueshift is detected with the high resolution gratings on board Chandra and XMM-Newton. Typically, these gratings enable to derive upper-limits on velocity shifts of $\sim 250$ km s$^{-1}$ (e.g., Juett & Chakrabarty 2006) while CCD instruments like the pn camera on board XMM-NEWTON give upper-limits of $\sim 1000$ km s$^{-1}$ (e.g., Boirin et al. 2005). Roughly half of the sources in Table 1 show an outflow (8 among the 15 systems showing lines clearly attributed to a local absorber and whose wavelength was measured with gratings). This includes all the BH LMXBs showing dips and the BH IGR J17091−3624 not showing dips. In contrast, a significant blueshift in the absorption lines could only be measured for $\sim 30\%$ (3/11) of the NS LMXBs showing an ionised absorber. The overwhelming presence of outflows in BHs as opposed to NSs could be mostly due to the size of the systems since the NSs showing an outflow are precisely those with large orbital periods of the order of those found in BHs. Line blueshifts are moderate, between $\sim 400$ and $3000$ km s$^{-1}$, for the majority of systems that show an outflow. There is an indication for an ultra fast outflow in IGR J17091−3624 (a single line detected at $4\sigma$ significance blueshifted by $\sim 9300$ km s$^{-1}$, not found in a second observation of the same source during a similar soft state, King et al. 2012). In MAXI J1305−704, Miller et al. (2014) reported the detection of a rich absorption complex in the Fe-L band redshifted by 540 to 14390 km s$^{-1}$, indicating an infall of the photoionised plasma that may correspond to a failed wind.

One important difference between systems showing static atmospheres and outflows is that only the latter will undergo mass loss. Mass-loss rates are of the order of 1−20 times the mass accretion rates in the black hole systems (e.g., King et al. 2012; Lee et al. 2002; Neilsen et al. 2011; Ponti et al. 2012), implying that the wind presence or absence along the outburst (see Sect. 4) could be key to understand the outburst evolution (Shields et al. 1986).

3 The wind launching mechanism

The wealth of data collected on photoionised plasmas in LMXBs (see Table 1) allows us to investigate the launching mechanism of winds in these sources. The successful mechanism should be able to reproduce the observed plasma characteristics (density, column density, outflow velocity or degree of ionisation) for single observations from the same source or from different sources. In addition, if there is a universal mechanism for the formation of winds in LMXBs, it should be able to explain the properties of the sample, i.e. why some systems show static atmospheres and others outflows and why the plasmas are preferentially observed at high inclinations or “soft” accretion states (see Sect. 4).

Accretion disc winds can be driven via thermal, radiative and/or magnetic pressure. In what follows we examine the possibility that winds in LMXBs are launched via thermal pressure. However, it should be kept in mind that the dominant mechanism could change as a system evolves through an accretion outburst. For example, Proga & Kallman (2002) demonstrated that, in general, radiation pressure due to lines cannot drive a wind in LMXBs due to the strong irradiation of the “UV-emitting disk” but radiation pressure due to electron scattering assists thermal expansion to drive a hot wind if the luminosity rises above the Eddington limit.

Thermal pressure or Compton-heated winds are expected to arise in systems in which the accretion disc is subject to X-ray irradiation from the central part such as X-ray binaries or quasars (BMS83). In these systems, the X-rays illuminating the disc can heat the gas to temperatures exceeding $10^7$ K predominantly through the Compton process. The heated gas will then form an atmosphere or corona above the disc (BMS83; Jimenez-Garate et al. 2002; Shakura & Sunyaev 1973). The upper boundary of the atmosphere is the Compton temperature corona, which is less dense and hotter than the underlying atmosphere. The evaporated photoionised plasma will remain bound to the disc as an atmosphere/corona or be emitted as a thermal wind, depending on whether the thermal velocity exceeds the local escape velocity (BMS83; Proga & Kallman 2002; Woods et al. 1996). Importantly, the radial extent of the corona is determined only by the mass of the compact object and the Compton temperature and is independent.
Table 1  List of low-mass X-ray binaries for which a photoionised plasma local to the source has been detected in absorption. The first columns indicate the source name, the orbital period, the galactic column density towards the source after Kalberla et al. (2005), whether the compact object is a neutron star (NS) or a black hole, whether it shows dips (D), and, if not, the source inclination (i). See Liu et al. (2007) for the references on the period and inclination, unless otherwise noted. The last columns indicate if the degree of ionization of the photoionised absorber(s) detected during persistent intervals (outside dips) is $< 3$ or $\geq 3$ in log $\xi$, whether the absorber seems to flow outwards (out), inwards (in) or to be bound as an atmosphere (atm), based on the velocity shifts of the absorption lines detected with Chandra HETGS or XMM-Newton RGS. “no grat.” means that no contraints were published on the velocity shifts from these gratings.

| Source               | $P_{orb}$ | $N_{\text{Gal}}^{\text{HI}}$ | NS Dips | $i$ (°) | log $\xi$ | Flow | References on the warm absorbers |
|----------------------|-----------|-------------------------------|---------|---------|-----------|------|----------------------------------|
| XB 1916–053          | 0.83 h    | 2.3                           | x x atm |         |           |      | Boirin04, Juett06, Díaz Trigo06, Iaria06, Zhang14 |
| 1A 1744–361          | 1.62 h    | 3.1                           | x atm   |         |           |      | Gavriil12 |
| 4U 1323–62           | 2.93 h    | 12 NS D                       | x x no grat.  | Boirin05, Church05, Balucinska-Church09 |
| EXO 0748–676         | 3.82 h    | 1.0                           | x x atm | Díaz Trigo06, van Peet09, Ponti14 |
| XB 1254–690          | 3.93 h    | 2.0                           | x atm   | Boirin03, Díaz Trigo06/09, Iaria07 |
| MXB 1658–298         | 7.11 h    | 1.9                           | x atm   | Siodi01, Díaz Trigo06 |
| XTE J1650–500        | 7.63 h    | 4.2                           | $> 50$ | ab, e | Miller02/04 |
| AX J1745.6-2901      | 8.4 h     | 12 NS D                       | x no grat.  | Hyodo09, Ponti15 |
| MAXI J1305–704       | 9.74 h    | 1.9                           | D x in  | Shidatsu13, Miller14 |
| X 1624–490           | 20.89 h   | 20 NS D                       | x atm   | Parmar02, Díaz Trigo06, Iaria07b, Xiang09 |
| IGR J17480–2416      | 24.27 h   | 6.5                           | D x out | Miller11 |
| GX 339–4             | 1.76 d    | 3.6                           | $> 45$ | x | Miller04, Juett06 |
| GRO J1655–40         | 2.62 d    | 5.2                           | D x out | Ueda98, Yamaoka01, Miller06b/08, Netzer06, Sala07, Díaz Trigo07, Kalman09, Luketic10, Neilsen12 |
| Cir X–1              | 16.6 d    | 16 NS D                       | x x out | Brandt00, Schulz02, D’A07, Iaria08, Schulz08 |
| GX 13+1              | 24.06 d   | 13 NS D                       | x out   | Ueda01/04, Siodi02, Díaz Trigo12, Madeje14, D’A14 |
| GRS 1915+105         | 33.5 d    | 13 D                          | x out   | Kotani00, Lee02, Marcocchio06, Ueda09/10, Neilsen09/11/12 |
| IGR J17091–3624      | $> 4$ d   | 5.4                           | $> 53$ | x | King12 |
| 4U 1630–47           | 17        | D x out | Kubota07, Díaz Trigo13/14, King13/14, Neilsen14 |
| H 1743–322           | 6.9       | D                             | x out   | Miller06a |

*a* not estimated; absorption lines from Ne IIx and of a Ne II (Miller et al. 2004). *b* estimated; absorption feature near 7 keV possibly due to Fe xxvi (Miller et al. 2002). *c* Detection of an unshifted line from Ne IIx and of a Ne II line blueshifted by $\sim 510 \pm 60 \text{ km s}^{-1}$ possibly due to a local absorber (Miller et al. 2004). An interstellar origin was attributed to a similar Ne II line in GX 339–4 (see below). *d* Shidatsu et al. 2013. *e* Papitto et al. 2011. *f* using the lower limit on the mass of the companion star estimated by Muñoz-Darias et al. 2008 and assuming that the black hole mass is less than 15 $M_{\odot}$ (Shidatsu et al. 2011). *g* Detection of several lines (Ne II, O VII, and Ne) with blueshifts in the range 50–160 km s$^{-1}$ and of lines from Ne II–III blueshifted by $510 \pm 20 \text{ km s}^{-1}$ (Miller et al. 2004). While the Ne II line is produced mainly by a local absorber, the Ne II–III lines are consistent with being produced by the hot interstellar medium (Juett et al. 2006). *h* Wijnands et al. 2012. *i* Rao & Vadawale 2012.

of luminosity (BMS83; Woods et al. 1996). BMS83 determined that a wind would be launched by thermal pressure at radii larger than 0.1 $r_{IC}$ (where $r_{IC}$ denotes the Compton radius or distance at which the escape velocity equals the isothermal sound speed at the Compton temperature $T_{IC}$). Proga & Kallman (2002) found that for very luminous systems, including the radiation force due to electrons could lower the effective gravity and subsequently the escape velocity and allowed a hot robust disc wind to be already produced at $\sim 0.01 r_{IC}$, well inside the Compton radius and previous estimates by BMS83 and Woods et al. (1996).

It is already apparent from Table 1 that outflows are only present in systems with “long” orbital periods. This could indicate that the capability to launch a wind is related to the size of the disc, consistent with the expectations of thermal winds. The disc size can be approximated as $r_{\text{disc}} \sim 0.8 r_L$, where $r_L$ is the radius of the Roche lobe for the compact object and can be estimated from the orbital period, the mass of the compact object and the mass ratio following Eggleton (1983) and Kepler's third law (see equations 4.2 and 4.6 from Frank et al. 2002). We list in Table 2 the disc sizes for all the sources from Table 1 for which there are reliable estimates of the mass ratio and (for BHs) of the mass of the compact object. We then compare these values to the radius at which Compton-heated winds could be launched, $\sim 0.1 r_{IC}$ (see above). It follows that small systems like GX 1916–053 will be incapable of launching winds via the thermal mechanism. In contrast, large systems like GRO J1655–40 and GRS 1915+105 will be able to launch thermal winds (regardless of whether additional mechanisms are in play). If the Compton temperature is well above $10^7 \text{ K}$, the Compton radius would proportionally

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decrease allowing the launch of winds in smaller systems. However, \( T_{\text{JC}} \sim 10^7 \text{ K} \) seems a fair assumption given that winds are preferentially launched during “soft” states (see Sect. 4).

In conclusion, Table 2 shows that at the extremes of small and large disc sizes, the expectations of thermal winds are fulfilled in the sense that small systems show atmospheres and large systems show winds (see also Fig. 1 from \textit{Díaz Trigo & Boirin} (2013) for a comparison of the estimated position of the plasma and source luminosity for NS LMXBs with the expectations of thermal winds from \textit{Woods et al.} 1996). In contrast, for systems of medium sizes this test is inconclusive since sources like XB 1254–690 or MXB 1658–298 could in principle show mild thermal winds but only static atmospheres have been reported.

However, regardless of whether a system could launch Compton-heated winds due to its size, we should actually prove that the location of the plasma that is outflowing is outside the Compton radius for that system. Unfortunately, this is currently challenging for the majority of the observed winds due (mainly) to the uncertainty in the density of the plasma. As an example, a plasma with \( \log \xi \sim 3 \) subject to a ionising luminosity of \( 10^{36} \text{ erg s}^{-1} \) would be located at \( 10^{10} \text{ cm} \) for a plasma density of \( 10^{15} \text{ cm}^{-3} \) and therefore be able to outflow (using \( \xi = L/n_{\text{H}} \), see Sect. 2). For a larger density of \( 10^{17} \text{ cm}^{-3} \) the plasma would be instead located at \( 10^{7} \text{ cm} \) and therefore bound to the system. To date the direct measurements of plasma density are rare (for two sources densities of \( 10^{13} - 10^{15} \text{ cm}^{-3} \) have been determined: \textit{Kallman et al.} 2009, \textit{Schulz et al.} 2008). Based on the density measured for GRO J1655–40, \textit{Kallman et al.} 2009 derived a radius of \( 7 \times 10^{9} \text{ cm} \) for the location of the plasma and concluded that the wind could not be thermally launched, in agreement with previous claims of a magnetic nature for this wind (\textit{Miller et al.} 2006a, 2008, but see \textit{Netzer} 2006). \textit{Luketic et al.} (2010) performed hydrodynamical simulations and also concluded that the wind could not be thermally launched, since they could not find a space in their simulations which showed simultaneously a high density (> \( 10^{12} \text{ cm}^{-3} \)) and velocity outflow, as detected in the \textit{Chandra} observation (but note that it remains to be proven that magnetic pressure can generate such a dense, fast wind, see e.g. \textit{Chakravorty et al.}, this proceedings). To date this is the only claim of a disc wind driven by magnetic pressure and is therefore important to understand its launching conditions and the differences with respect to other epochs of the same system or different systems. \textit{Díaz Trigo & Boirin} (2013) pointed out that the luminosity of the system could have been severely underestimated for the measured plasma column densities (~ \( 10^{24} \text{ cm}^{-2} \), \textit{Miller et al.} 2008) by not including Compton scattering in spectral modelling. The fact that the optical flux was increasing monotonically around the epoch of the \textit{Chandra} observation, while the X-ray flux started decreasing 10 days before suggests that the wind was optically thick to Compton scattering and that the X-rays were scattered and absorbed by the wind, giving further support to the idea that the luminosity was underestimated (\textit{Shidatsu et al.}, these proceedings). Interestingly, \textit{Higginbottom & Proga} (2015) succeeded in simulating thermal winds that are faster and denser than found by \textit{Luketic et al.} (2010) by increasing the ionising luminosity or reducing line cooling while increasing X-ray heating. Clearly, the issue of wind opacity and potential underestimation of luminosity deserves further studies before we can discard a thermal launching mechanism for this wind. Different Compton temperatures, obtained by fitting plausible continuum models to broadband spectra, should also be considered when calculating the allowed radii since the non-modelling of Compton scattering could introduce significant changes in the Spectral Energy Distribution (SED).

In summary, the potentially magnetically driven wind from GROJ1655–40 should be studied further due to its uniqueness. However, given that all other sources and even other stages of the wind from GROJ1655–40 could be explained as generated by thermal pressure (e.g. \textit{Neilsen & Homan} 2012), we conclude that Compton heating is an excellent candidate as the dominant launching mechanism of winds in LMXBs. This is also supported by the fact that both winds and atmospheres are only detected in high-inclination sources (see Table 1), consistent with the geometry predicted for a thermal wind that will be preferentially observed close to the equatorial plane, since at polar angles, \( \lesssim 45^{\circ} \), the low density and the high ionisation of the gas prevent its detection.

4 Dependence on accretion state

To date, disc winds have been predominantly observed in the “high/soft”, thermal-dominated, state of BH transients, when the jet emission is absent. Conversely, in observations of the “low/hard” state of the same transients, with typical jet emission, winds were excluded. In particular, blueshifted absorption lines were observed in the soft state spectra of GROJ1655–40 (\textit{Díaz Trigo et al.} 2007, \textit{Miller et al.} 2006b), GRS 1915+105 (\textit{Ueda et al.} 2009, 4U 1630–47 (\textit{Díaz Trigo et al.} 2014, \textit{Kubota et al.} 2007) and H 1743–322 (\textit{Miller et al.} 2006a). In contrast, observations of the hard state of GROJ1655–40 (\textit{Takahashi et al.} 2008) and H 1743–322 (\textit{Miller et al.} 2012) excluded the presence of such lines down to equivalent widths of 20 and 3 eV, respectively. For GRS 1915+105, disc winds are predominantly observed during soft states (\textit{Neilsen & Lee} 2009, \textit{Ueda et al.} 2009) but there is also one detection of a weak wind in a “hard” (or “C”) state (\textit{Lee et al.} 2002). The winds appear to be absent also in the “very high state” (VHS) of 4U 1630–47 (\textit{Díaz Trigo et al.} 2014) and H 1743–322 (\textit{Miller et al.} 2006a). The presence of FF XXV and FF XXVI lines as a function of accretion state has been recently investigated for two NS XRBs, EXO 0748–676 and AX J1745.6–2901, by \textit{Ponti et al.} (2015, 2014) who
Table 2  LMXBs for which a photoionised absorber local to the source has been detected and for which there are good estimates for the period, the mass ratio \( q \) and (for BHs) the mass of the compact object (\( M_j \)). We include NSs for which their mass has not been estimated if the period and the mass ratio are known and fix the NS mass to 1.4\( M_\odot \). We estimate \( r_{IC} = 10^{11} \, T_{IC}^{8} \left( M_{1}/M_\odot \right) \) cm (eq. 2.7 from BMS83) and assume \( T_{IC} = 0.1 \) (or \( 10^{-7} \) K).

| Source       | Period [hrs] | \( M_1 \) [M\(_\odot\)] | \( q \)  | Reference                  | \( 0.8 \, r_L \) [10\(^{15}\) cm] | \( 0.1 \, r_{IC} \) [10\(^{10}\) cm] |
|--------------|-------------|--------------------------|--------|---------------------------|--------------------------------|--------------------------------|
| XB 1916–553  | 0.83        | 1.2–1.6                  | 0.046  | Heinke et al. (2013)      | 0.43–0.47                     | 1.2–1.6                        |
| EXO 0748–676 | 3.82        | 1.0–2.4                  | 0.11–0.28 | Muñoz-Darias et al. (2009) | 1.5–2.7                     | 1.0–2.4                        |
| XB 1254–690  | 3.93        | 1.2–1.8                  | 0.33–0.36 | Cornelisse et al. (2013)  | 2.3–2.8                     | 1.2–1.8                        |
| MXB 1658–298 | 7.11        | 1.4                      | 0.18–0.64 | Cominsky & Wood (1984)    | 3.0–4.7                     | 1.4                            |
| IGR J17480–2446 | 21.27   | 1.4                      | 0.3–1.1\( ^k \) | Papitto et al. (2011) | 7.4–12.0                     | 1.4                            |
| GRO J1655–40 | 62.92       | 6.6 ± 0.5                | 0.42 ± 0.03 | Casares & Jonker (2014)  | 27.3–30.2                   | 6.1–7.1                        |
| GRS 1915+105 | 81.12       | 10.1 ± 0.6               | 0.042 ± 0.024 | Casares & Jonker (2014) | 69.6–100.5                  | 9.5–10.7                       |

\( ^j \) The mass ratio has been estimated assuming a NS of 1.4\( M_\odot \) and the companion mass estimated by Cominsky & Wood (1984) of 0.25–0.9\( M_\odot \). \( ^k \) The mass ratio has been estimated assuming a NS of 1.4\( M_\odot \) and the companion mass estimated by Papitto et al. (2011) of 0.42–1.5\( M_\odot \).

Concluded that the dichotomy observed for BH transients was also present for NSs.

At this stage it is important to establish if the absence of atmospheres/winds can be derived from the absence of absorption from Fe XXV or Fe XXVI. While there is only one case where absorption from Fe XXVI has been found during a hard state (Lee et al. 2002; see above), the presence of a photoionised plasma during hard states has been inferred from a broadened Pa\( \beta \) emission line in GX 339–4 (Rahoui et al. 2014) and from absorption troughs below 2 keV in EXO 0748–676 (Díaz Trigo et al. 2006, van Peet et al. 2009). The plasma had a low degree of ionisation in both cases. Therefore, it might be that atmospheres/winds are present during states other than the soft but their degree of ionisation or density is such that no lines are expected from highly ionised iron.

Clearly, if photoionised plasmas in LMXBs are the result of disc irradiation, then we expect important changes in such plasmas as the systems transit from a soft to a hard state due to the change of the SED, which determines the Compton temperature (see Sect. 3). However, it remains to be determined if the change of SED is the decisive factor for the existence of winds or if other components such as the jet play a significant role. Based on GRS 1915+105 observations, Nielsen & Lee (2009) proposed that the wind observed during the soft state carries enough mass away from the disc to halt the flow of matter into the radio jet. Chakravorty et al. (2013) invoked instead the thermal instability present during the hard state of XRBs as a plausible inhibitor of winds in that state. Díaz Trigo et al. (2014) followed the evolution of the wind in 4U 1630–47 as the luminosity increased along the soft state and the transition to a VHS. They observed a decrease in the column density and an increase of ionisation of the wind as the SED became harder towards higher luminosities and concluded that the disappearance of the wind in the VHS was a consequence of over-ionisation (note that both the increase of Compton temperature, due to the hardening of the SED, and luminosity play a role). In contrast, Hori et al. (2014) compared observations of 4U 1630–47 from two outbursts and argued that ionisation was important but not enough to make the wind disappear during the VHS. Other authors have pointed to the possibility of density (Hori et al. 2014) or geometrical (Miller et al. 2006a; Ueda et al. 2010) changes to explain the presence of atmospheres/winds in some accretion states and their absence in others.

Most likely several of the effects above play a role in producing an “observable” atmosphere/wind. For example, a change in luminosity could induce a change in the plasma density and leave its level of ionisation unchanged (Higginbottom & Proga 2015). Conversely, a hardening/softening of the spectrum implies a change of Compton temperature and consequently of the Compton radius. This could translate into a different wind formation region. In contrast, it is not clear that the presence of a thermal instability should inhibit the wind since the presence of ionised plasma is detected in simulations where gas was thermal unstable (Higginbottom & Proga 2015). In this context it is important to derive reliable SEDs including Compton scattering to infer the state of the plasma expected at different accretion states. For example, the discrepant conclusion about over-ionisation causing the disappearance of the wind in the VHS of 4U 1630–47 (see above) could be a result of using different SEDs. A realistic SED reconstruction might explain not only why winds are preferentially detected in some accretion states but also why a wind may disappear during a given accretion state (King et al. 2012).

5 Conclusions and prospects

There are excellent prospects for advancement in this field in the coming years. In the observational domain the launch of Astro-H, foreseen for 2016, will allow fine spectroscopy of photoionised plasmas with its X-ray Calorimeter Spectrometer and reliable determination of broad-band SEDs thanks to its hard X-ray Imaging System. In the theoreti-
cal and modelling domain, two issues deserve immediate attention to progress further. The first item is the inclusion of Compton scattering both in hydrodynamical simulations and modelling of photoionised plasmas since this determines how well we can infer the incident SED and luminosity that irradiates the disc. Moreover, the correlation between the evolution of the wind and the broad iron line observed in two LMXBs (Díaz Trigo et al. 2014, 2012) indicates that Compton scattering in the wind could actually account for a fraction of the broad iron lines that are observed in XRBs, having consequences for the measurement of black hole spin with methods that request the broad iron line to purely arise from disc reflection. The second issue is related to the (most likely) over-simplistic constant density models for photoionised plasmas that are used in the vast majority of the literature. While so far most of the sources included in Table 1 show one or at most two states of the plasma simultaneously, it is expected that this will change as the observations become more sensitive. In this context, it may be important to consider plasmas of different densities co-existing in the same state of a source (as it is the case for plasmas under constant pressure conditions) or a change in density between different accretion states.

Considering the above and bearing in mind that XRB winds could be the key missing ingredient to understand accretion state changes during an outburst we are expectant for discoveries in the next decade.

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