Winds in ultraluminous X-ray sources: new challenges

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Ultraluminous X-ray sources (ULXs) are the most extreme X-ray binaries shining above \(10^{39}\) erg/s, in most cases as a consequence of super-Eddington accretion onto neutron stars and stellar-mass black holes accreting above their Eddington limit. This was understood after the discovery of coherent pulsations, cyclotron lines and powerful winds. The latter was possible thanks to the high-resolution X-ray spectrometers aboard XMM-Newton. ULX winds carry a huge amount of power owing to their relativistic speeds (0.1-0.3 \(c\)) and are able to significantly affect the surrounding medium, likely producing the observed 100 pc ULX superbubbles, and limit the amount of matter that can reach the central accretor. The study of ULX winds is therefore quintessential to understand 1) how much and how fast can matter be accreted by compact objects and 2) how strong is their feedback onto the surrounding medium. This is also relevant to understand supermassive black holes growth. Here we provide an overview on this phenomenology, highlight some recent, exciting results and show how future missions such as XRISM, eXTP and ATHENA will improve our understanding.

KEYWORDS:
X-ray binaries, accretion, accretion discs, black hole physics, stars: winds, outflows

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are the most extreme among X-ray binaries (XRBs) with X-ray luminosities in excess of the Eddington limit for a standard 10 M\(_{\odot}\) black hole (BH), or \(10^{39}\) erg/s. Despite being discovered already 40 years ago with the Einstein observatory, it was only after the launch of powerful telescopes such as Chandra, XMM-Newton and NUSTAR that we began to understand their nature.

In the early 2000s, ULX extreme luminosities were thought to be mainly produced by intermediate-mass (\(10^2-4\) M\(_{\odot}\)) black holes (IMBHs) accreting well below their Eddington limit (e.g., Kaaret et al. 2001). Two alternative scenarios invoked either extreme geometrical beaming in Eddington-limited stellar-mass black holes (BHs, e.g., King, Davies, Ward, Fabbiano, & Elvis 2001) or super-Eddington accretion onto compact objects like BHs and neutron stars (NS), a common interpretation for the Galactic microquasar SS 433 UV emission (e.g., Begelman, King, & Pringle 2006). Both the IMBH and super-Eddington scenarios would be important to understand how it was possible to find fully-formed supermassive black holes (SMBHs) at high redshifts when the universe was young (e.g., Fan et al. 2003; Volonteri, Haardt, & Madau 2003).

Dedicated observations with XMM-Newton and, later on, NUSTAR have shown that ULXs are characterised by very soft spectra with a strong curvature below 10 keV, which would rule out highly sub-Eddington accretion and, therefore, IMBHs as compact objects (e.g., Bachetti et al. 2013; Gladstone, Roberts, & Done 2009). The so-called ultraluminous state is classified according to three main regimes depending on the spectral slope, \(\Gamma\): soft (SUL, \(\Gamma > 2\)) or hard (HUL, \(\Gamma < 2\)) ultraluminous. In the latter, if the X-ray spectrum has a single peak and a blackbody-like shape, it is called broadened disc regime (BD, Sutton, Roberts, & Middleton 2013).

The first masses inferred dynamically from optical data revealed two ULXs to be powered by compact objects with masses in the stellar-mass range (e.g., Liu, Bregman, Bai, Justham, & Crowther 2013; Motch, Pakuli, Soria, Grisé, & Pietrzyński 2014). This research field was significantly shaken...
after the first discoveries of pulsations in high-quality time series of ULXs (e.g., Bachetti et al. 2014; Fürst, Walton, Harrison, et al. 2016; Israel et al. 2017) and cyclotron lines in a few ULX spectra (Brightman et al. 2018; Walton et al. 2018). This showed that in many ULXs the compact object is actually a magnetised neutron star rather than a black hole.

Another ground-breaking discovery was the detection of ULX winds in the form of resolved rest-frame emission and blueshifted (0.1-0.3 c) absorption lines in deep (>100 ks) high-resolution X-ray spectra taken with the Reflection Grating Spectrometers (RGS) aboard XMM-Newton (e.g., Kosec et al. 2018; Kosec, Pinto, Fabian, & Walton 2018; Pinto et al. 2017; Pinto, Middleton, & Fabian 2016). These detections resolved and identified the nature of the spectral features previously spotted in low-resolution CCD spectra (e.g., Stobbart, Roberts, & Wilms 2006), which were attributed to the ULX rather than the host galaxy owing to their shape and variability (e.g., Middleton et al. 2015; Sutton, Roberts, & Middleton 2015). Chandra gratings confirmed similar outflows in a Galactic transient ULX (Swift J0243.6+6124, van den Eijnden et al. 2019). Further CCD work confirmed the presence of blueshifted absorption features (Walton et al., 2016; Wang, Soria, & Wang, 2019). These discoveries confirmed a major prediction of theoretical simulations of super-Eddington accretion discs in which radiation pressure is expected to launch mildly-relativistic winds (e.g., Kobayashi et al. 2018).

Despite important discoveries and progress in the last decade, several questions remained unanswered. Are the spectral transitions triggered by orbital variations in the accretion rate or by stochastic variations in the wind? What are the disc wind geometry and thermal structure? Does the wind regulate the growth of the compact object and inflate the interstellar cavities? To solve these issues a combination of accurate plasma modelling and spectral-timing studies is required.

### 2 WINDS: RECENT DEVELOPMENTS

Spectral lines are often searched for in high-resolution spectra focusing on well-known He- / H-like ionic transitions. Winds are expected to be photoionised by the source X-ray emission and, therefore, strong lines are to be found from the dominant ionic species such as O VII-VIII, Ne IX-X and N VII in the soft X-ray band (0.3-2 keV) where RGS operates (see Fig. 1).

Doppler shifts from plasma motions complicate the line detection and identification. The spectral scan with a moving gaussian line is a common procedure which indeed identified many lines in ULX RGS spectra (see Sect. 1). However, the issue of finding spurious features, the so-called look-elsewhere effect, requires thorough Monte Carlo (MC) simulations in order to estimate the false-alarm probability as F-test

![FIGURE 1 NGC 1313 ULX-1 XMM-Newton/RGS spectra of two fainter (HUL, top-middle) and one brighter (BD, bottom) epochs with overlaid the best-fit photoionised wind (red line) and the continuum models (black line, Pinto et al. 2020).](image)

is no longer valid (Protassov, van Dyk, Connors, Kashyap, & Siemiginowska, 2002). MC method consists of simulating a large number (~10,000) of featureless continuum spectra, which are then all searched with a gaussian line scan identical to the one used for the real data. This has been used extensively, providing robust significance estimates, but at a substantial computational cost (e.g., Kosec et al. 2018; Pinto et al. 2020).

It is possible to speed up the procedure by switching from a line scan (fit) to a cross-correlation (calculation) that compares a moving gaussian line (models) to the spectral residuals (both real and simulated data). This was successfully achieved in Kosec et al. (2021) who managed to decrease the computing time by four orders of magnitude. This enabled them to perform an accurate study for a sample of 19 ULXs with high-statistics RGS spectra and confirm the detection of narrow (≤ 1000 km/s) lines in the majority of the sample (> 60%, see Fig. 2).
2.1 Physical models: parameter-space scan

Owing to their distance (typically above 2 Mpc) and limited fluence ($\lesssim 10^{-12} \text{ erg/s/cm}^2$), ULXs can be difficult targets for current high-spectral-resolution detectors, due to their limited effective area. They are also commonly found in low-metallicity environments, which further implies weak lines. Each one is therefore detected at low significance ($\lesssim 3 \sigma$) except for nearby ULXs with exposure times above 300 ks. This is why lines were not detected in early observations.

Recent, more sophisticated, techniques perform a full and uniform search of the parameter space using physical models of winds that fit multiple lines simultaneously. The simplest case adopts gas in collisional ionisation equilibrium (CIE) and implies searching through line of sight velocity ($v_{\text{LOS}}$), velocity dispersion ($\sigma_v$) and electron temperature ($kT_e$). The normalisation or emission measure ($n_H n_e V$) can be a free parameter. This makes sense when shocks between the wind and the surrounding medium or a thermal contribution from the jet are expected as in SS 433 (Marshall, Canizares, & Schulz, 2002). Metallicity is kept to Solar to decrease the computing time. Besides, ULX lines are rather weak and metallicity might be unconstrained. This was successfully applied to NGC 5204 ULX-1 and SS 433 (Kosec et al., 2018; Pinto et al., 2021).

Winds are most likely to be photoionised due to the strong radiation field, at least before impacting the surrounding medium or the companion star. The variability of the spectral features and the underlying continuum suggests that these wind components come from the inner disc ($10^{-2.5} R_G$, see e.g. Alston et al. 2021; Kara et al. 2020). Here accurate modelling of the spectral energy distribution (SED) is necessary in order to calculate the photoionisation equilibrium (PIE) and the ionisation parameter, $\xi = L_{\text{ion}}/n R^2$. Then $\xi$, $v_{\text{LOS}}$ and $v_e$ constitute the backbone of the parameter space. The column density, $N_{H}$, is a free parameter. PIE scans unveiled winds in almost all ULXs with deep observations (each one lasting $t_{\text{exp}} \gtrsim 100 \text{ ks}$ or a full $XMM-Newton$ orbit, Pinto et al. 2017, 2020; Kosec et al. 2018). In Fig. 3 we show the remarkable example of the detection of a photoionised absorber in the supersoft NGC 247 ULX-1 (Pinto et al. 2021), blowing at 17% of the speed of light ($c$). The comparison between the best-fit $\xi$ solution and the stability curves ($kT$ or $\xi$ versus the ratio between thermal and radiation pressure) has showed that ULX winds are likely stable to thermal perturbations (Pinto et al. 2020).

As expected, the simultaneous modelling of multiple lines by means of physically-motivated models, significantly improves the significance, reaching peaks of $5 \sigma$ in the deepest observations of ULXs with soft X-ray spectra ($\Gamma > 2$). In HUL spectral lines are significantly fainter and more difficult to detect (Kosec et al. 2021) although deep ($\gtrsim 100 \text{ ks}$) observations of nearby targets have confirmed strong detections in the HUL spectra of NGC 1313 ULX-1 and the pulsating NS NGC 300 ULX-1 (Kosec et al. 2018; Pinto et al. 2020).

The velocities of the winds (0.1-0.3 $c$) and the ionic species (O VII-VIII and Ne IX-X) are compatible with the predictions from theoretical simulations (Kobayashi et al., 2018).

3 DISCUSSION

3.1 Super-Eddington disc-wind structure

Super-Eddington accretion predicts the disc to thicken and launch powerful winds which give the system the shape of a funnel. We therefore expect at low inclinations (i.e. face on) to see the innermost, very bright, disc region and a hard spectrum (HUL or $\Gamma < 2$). Along this LOS the wind should be highly ionised and have a low density. At progressively higher inclinations the wind scatters more photons out of the LOS and the source appears softer. The outer wind portions are expected to
be cooler as a consequence of a softer SED and slower if their speed is associated to the escape velocity $v_{\text{esc}} = \sqrt{2GM/R}$. This was confirmed, albeit with a limited source sample, by Pinto et al. (2020) in the form of a positive correlation between the wind velocity, the ionisation parameter and the ULX spectral hardness (see Fig. 4). This is also validated by the spectra taken at different epochs for a few ULXs.

The scenario is likely more complex as the opening angle of the funnel depends on the mass accretion rate. Thus, the observed wind properties depend on a combination of the inclination angle and the Eddington ratio.

It is important to notice that optical spectroscopy reveals the presence of strong lines from H- and He- transitions in many ULXs. The lines are very similar to those observed in SS 433 and have been associated with the cool, outer, photosphere of the super-Eddington disc wind ($10^5-6 R_G$, see e.g. Fabrika, Atapin, Vinokurov, & Sholukhova 2021; Vinokurov, Fabrika, & Atapin 2018) and further confirm that SS 433 is most likely a highly obscured ULX that is being seen almost edge-on as shown by Fe K time lags (Middleton et al. 2021).

3.2 Feedback and growth rate

Owing to their extreme velocities, ULX winds are expected to have a significant impact on their environments. Many ULXs, including NGC 1313 ULX-1, are indeed surrounded by huge interstellar cavities or bubbles with supersonic expansion (80-250 km/s, Gurpide, Parra, Godet, Contini, & Olive, 2022). The bubbles are young ($10^5-6$ yr) and their H α luminosities require a mechanical power of $10^{39-40}$ erg/s (Pakull & Mirioni, 2002).

The kinetic power of the winds can be written as follows: $L_w = 0.5 \dot{M}_w v_w^2 = 2 \pi m_p \mu \Omega C L_{\text{ion}} v_w^3 / \xi$ where $\dot{M}_w = 4 \pi R^2 \rho v_w \Omega C$ is the outflow rate, $\Omega$ and $C$ are the solid angle and the volume filling factor (or clumpiness), respectively, $\rho = n_H m_p \mu$ is the density and $R$ is the distance from the ionising source. The fraction of ULXs with wind detections is $> 60%$ (Kosec et al. 2021) which implies a solid angle $\Omega / 4\pi \geq 0.3$ in agreement with theoretical simulations. The typical ionisation parameters found in ULX winds ($\log \xi \sim 2-4$) would correspond to a clumping factor between 0.01-0.1 (Kobayashi et al., 2018). This yields a kinetic power $L_w = 10^{39-40}$ erg/s, which is likely enough to inflate the superbubbles.

ULX winds also take away of lot of momentum and matter from the system. Comparing their kinetic power with the bolometric luminosity we estimate that about 50% of the energetic budget is lost to launch the winds. The maximum outflow rate $\dot{M}_w$ is $\sim 90%$ (assuming standard accretion efficiency, i.e. $\eta = 0.1$). However accounting for advection and photon trapping we estimate a more realistic mass loss rate of 10-50% (Mushtukov, Ingram, Middleton, Nagirner, & van der Klis, 2019). The compact object would still grow fast but at a milder super-Eddington rate.

3.3 Current limitations and prospects

There are some limitations in the current facilities that hamper a full understanding of the ULX phenomenology. We know that spectral lines vary over the time and in response to the variability of the underlying continuum, showing higher fluxes and significance in softer spectra (Kosec et al. 2021; Pinto et al. 2020). Accurate physical modelling has shown that the wind is cooler and slower in softer spectra perhaps due to a larger launching radius at higher accretion rates (Pinto et al. 2021). The picture is more complex as the emission lines become stronger and require multiple components likely from different regions (Pinto et al. 2020). It is difficult to distinguish among different processes (variable accretion rate, precession, stochastic variability, etc.) because current facilities require to integrate well over 100 ks of exposure thereby preventing us from resolving the variability timescales which can be as short as 100 s (e.g. Alston et al. 2021; Kara et al. 2020; Kobayashi et al. 2018). Another issue is the lack of sensitivity and resolution in the Fe K band (6-9 keV) which limits our capability of detecting hot wind components from the inner disc expected for ULXs with hard spectra (HUL). Presently, the only Fe K detections are those for NGC 1313 ULX-1, NGC 300 ULX-1 and NGC 4045 HLX-1 (Brightman et al., 2022; Kosec et al., 2018; Walton et al., 2016). Of course, deep observations of other ULXs would help to increase the Fe K line sample.

The enhanced X-ray Timing and Polarimetry (eXTP) mission (2027-, Zhang et al. 2019) will provide a high effective area in the hard X-ray band (> 2 keV) which together with a low background due to the low Earth orbit could significantly improve the detection of the Fe K wind component with respect to XMM-Newton. This is showcased in Fig. 5 with our 80 ks
FIGURE 5 Pulsating NGC 300 ULX-1 eXTP/SFA simulation (80 ks, top panel) adopting the best-fit continuum plus wind model from Kosec et al. (2018). For the residuals plot (bottom panel) the wind component was removed from the model.

simulation of NGC 300 ULX-1 using the Spectroscopic Focusing Array (SFA). We estimate that the Fe XXV absorption line may be detected at $5\sigma$. Physical models gathering multiple lines will achieve this at much shorter exposure times.

Microcalorimeter spectrometers will boost our sensitivity to weak lines. This can be defined as the product between effective area and resolving power or $A_{\text{eff}}/\Delta E$. The X-Ray Imaging and Spectroscopy Mission (XRISM, 2023-, Guainazzi & Tashiro 2018) will bear the Resolve microcalorimeter ($\Delta E \sim 5$ eV and PSF $\sim 1'$) which, similarly to Hitomi/SXS, is 10 times more sensitive than the gratings aboard XMM-Newton and Chandra above 4 keV, and even more above 7 keV. In Fig. 6 (bottom panel) we show a physical model scan of a 100 ks XRISM/Resolve spectrum that we have simulated for NGC 1313 ULX-1 using the best-fit continuum model plus multiphase photoionised wind. Both cold/slow and warm/fast components are detected at very high significance. For the brightest, nearby, ULXs exposures of a few 10 ks should be sufficient to achieve $3\sigma$ detections and enable studies of line variability within half a day, which is currently impossible.

A groundbreaking improvement would be provided by the X-ray Integral Field Unit (X-IFU) aboard the Advanced Telescope for High-ENergy Astrophysics (ATHENA, 2035-, Barret et al. 2022). At the time of writing, X-IFU is designed to achieve an exquisite combination of high effective area (1m$^2$) and spectral resolution ($\lesssim 2.5$ eV), small PSF ($5-10'$), and low background. This would provide a 2-orders-of-magnitude improvement with respect to the current instruments, about 10 times better than XRISM/Resolve or above given that ULXs are often found in crowded areas. In Fig. 6 (top panel) we show a similar simulation for the bright state of NGC 1313 ULX-1 using ATHENA/X-IFU and adopting an exposure time of just 1 ks. This snapshot would be sufficient to detect the wind components at very high significance de-facto enabling, for the first time, the simultaneous study of the variability in the wind and the underlying spectral continuum. This can be extended to other ULXs and is the key to answer the main question regarding the nature of the ULX regime transitions (SUL $\leftrightarrow$ BD $\leftrightarrow$ HUL), the role of the wind, its location and launching radius.

The codes will have to be adapted to the size and complexity of the response matrices of future detectors and parameter space. The use of cross-correlation and machine learning may provide a viable solution. Recently, it was also shown that the slope of the histogram of the $\Delta C$-stat or $\Delta \chi^2$ remains constant above a certain number of simulations (Pinto et al. 2021), which may therefore be extrapolated and used to estimate higher values of significance at low computational costs.
4 | CONCLUSIONS

We have provided a brief overview on the properties of winds in ULXs. As the most valuable candidates of super-Eddington accreting systems, ULXs are predicted to blow powerful winds that slow down the accretion onto the compact object and affect the surrounding medium. Current instruments, primarily XMM-Newton/RGS, enabled to obtain highly significant detections and a qualitative view of the wind structure and general properties. An intimate connection between the wind and the source state is suggested, potentially unveiling the detailed accretion and variablity mechanism. However, a larger statistical sample of ULX winds and more observations per target are required to place more quantitative constraints. Our understanding is also limited by the variability timescales that are too short to be sampled with the current instruments. Future missions such as XRISM, eXTP and ATHENA will boost our sensitivity to such timescales and to different thermal phases of the wind, providing a better coverage of its parameter space.

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