Astron. Nachr. / AN , No. , 1 – 7 () / **DOI *please set DOI!***

Accretion disk winds in active galactic nuclei: X-ray observations, models and feedback

F. Tombesi[1,2,⋆]

[1] X-ray Astrophysics Laboratory and, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[2] Department of Astronomy, University of Maryland and CRESST, College Park, MD 20742, USA

The dates of receipt and acceptance should be inserted later

Key words Galaxies: active – X-rays: galaxies – black hole physics – accretion, accretion disks – techniques: spectroscopic

Powerful winds driven by active galactic nuclei (AGN) are often invoked to play a fundamental role in the evolution of both supermassive black holes (SMBHs) and their host galaxies, quenching star formation and explaining the tight SMBH-galaxy relations. A strong support of this quasar mode feedback came from the recent X-ray observation of a mildly relativistic accretion disk wind in a ultraluminous infrared galaxy (ULIRG) and its connection with a large-scale molecular outflow, providing a direct link between the SMBH and the gas out of which stars form. Spectroscopic observations, especially in the X-ray band, show that such accretion disk winds may be common in local AGN and quasars. However, their origin and characteristics are still not fully understood. Detailed theoretical models and simulations focused on radiation, magnetohydrodynamic (MHD) or a combination of these two processes to investigate the possible acceleration mechanisms and the dynamics of these winds. Some of these models have been directly compared to X-ray spectra, providing important insights into the wind physics. However, fundamental improvements on these studies will come only from the unprecedented energy resolution and sensitivity of the upcoming X-ray observatories, namely ASTRO-H (launch date early 2016) and Athena (2028).

1 Introduction

Most galaxies host a supermassive black hole (SMBH) at their center, with masses ranging from a few million (e.g., for the one in our Milky Way) up to several billion times the one of the Sun. Surprisingly, the SMBH mass is found to correlate with several properties of the host galaxy. For instance, galaxies hosting more massive black holes also possess more massive bulges that contain on average faster-moving stars (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000). This suggests some sort of feedback mechanism(s) between a galaxy's black hole and the star-formation process. Yet there is still no adequate explanation for how a black hole's activity, which in principle may affect only a region of few times the size of our solar system, could actually influence a whole galaxy, which encompasses regions roughly a billion times larger.

During their active phases, accreting SMBHs can inject significant amounts of energy in their surroundings and they are called active galactic nuclei (AGN). Therefore, observations of AGN provide the key to directly study the feedback phenomenon in action. Radiation and jets from AGN can indeed interact with the interstellar medium leading to ejection or heating of the gas. However, they alone are not able to establish the intricate accretion/ejection feedback cycle linking the central SMBH to its host galaxy (e.g., Fabian 2012; Pounds 2014; King & Pounds 2015; Combes 2015). Increasing evidence point toward another promising player in AGN feedback: accretion disk winds. Observations in the X-ray band are particularly important because this radiation is produced very close to the central SMBH and it is energetic enough to pass through dense layers of absorbing material, therefore retaining a wealth of information about the AGN and the host galaxy environment.

This brief review paper is organized as follows: in §2 we describe the X-ray observations of disk winds, in §3 we compare the models that have been proposed for their characterization, in §4 we discuss the AGN feedback from these disk winds, and in §5 we show some of the fundamental improvements expected from upcoming X-ray observatories.

2 X-ray observations of disk winds

The first evidence of ionized absorption in the X-ray spectrum of an AGN was reported by Halpern (1984) comparing two spectra of the quasar MR 2251−178 taken in 1979 and 1980 with the *Einstein* satellite. The data showed a change in the soft X-ray band, which was interpreted as an ionized cloud crossing the continuum source.

The advent of the higher energy resolution grating spectrometers onboard *Chandra* and *XMM-Newton* provided a revolution in these studies, showing that the absorption is be composed of a number of lines and edges from different elements at different ionization states (e.g., Kaspi et

⋆ e-mail: francesco.tombesi@nasa.gov / ftombesi@astro.umd.edu

al. 2002). Importantly, the energies of these lines are found to be systematically blue-shifted compared to the expected values, indicating that the material is likely a wind outflowing from the central regions of these galaxies with velocities in the range of v_{out}~100–1,000 km s^{-1} (e.g., Kaastra et al. 2000; McKernan etal 2007; Gofford et al. 2011; Lobban et al. 2011; Detmers et al. 2011; Reeves et al. 2013; Kaastra et al. 2014). Overall, such warm absorbers (WAs) are detected in more than half of local Seyfert galaxies and have ionization and column densities in the range logξ~1–3 erg s^{-1} cm and N_H~10^{20}–10^{22} cm^{-2}, respectively (e.g., Crenshaw & Kraemer 2012).

A more extreme type of outflows, often referred to as ultrafast outflows (UFOs), are instead observed mostly in the Fe K band through blue-shifted Fe XXV and Fe XXVI absorption lines (e.g. Chartas et al. 2002; Pounds et al. 2003; Dadina et al. 2005; Reeves et al. 2009; Cappi et al. 2009; Tombesi et al. 2010a, b; Giustini et al. 2011; Gofford et al. 2013; Tombesi et al. 2014; Nardini et al. 2015; Tombesi et al. 2015; but see also Gupta et al 2013, 2015 for UFO detections in the soft X-rays). The UFOs are highly ionized, with ionization parameter logξ~4–6 erg s^{-1} cm. They can have high column densities in the range N_H~10^{22}–10^{24} cm^{-2}. Most importantly, the implied outflow velocities are often mildly relativistic, in the range v_{out}~0.03–0.3 c, where c is the speed of light (e.g., Tombesi et al. 2011; Gofford et al. 2013).

The large dynamic range obtained when considering the WAs and UFOs together, spanning several orders of magnitude in ionization, column density, velocity and distance suggests that the closer is the absorber to the central black hole, the higher are the values of these parameters and consequently the mechanical power. This suggests that these absorbers could represent parts of a same large-scale outflow observed at different locations from the black hole. The UFOs are likely launched from the inner accretion disk and the WAs at larger distances, of the order of pc-scales or larger (e.g. Blustin et al. 2005; Tombesi et al. 2012a, 2013; Gofford et al. 2015).

3 Models of disk winds

The detailed acceleration mechanisms of disk winds in AGN are still matter of intense research. However, they can be classified in thermal, radiation and magnetohydrodynamic (MHD), depending on their main driving force.

Thermal-driven winds are accelerated by the thermal pressure of the gas and they can reach a maximum velocity of ~1,000 km s^{-1}. They are ejected from the outer accretion disk or obscuring torus at ~pc scales from the central SMBH. Some of the WA components in Seyferts may be associated with such winds (e.g., Chelouche & Netzer 2005).

Given the intense radiation field in most AGN, radiation pressure itself can be a very effective way to drive a disk wind (e.g., Elvis 2000; Sim et al. 2008, 2010, 2012; Ohsuga et al. 2009). The main source of opacity is due to

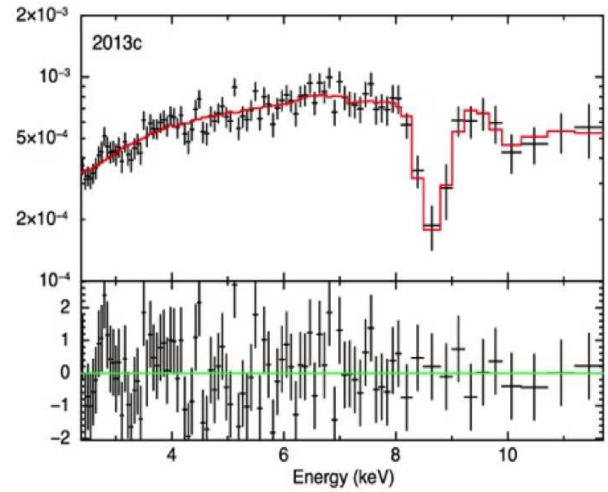

Fig. 1 Best-fit radiation-driven wind model of one *Suzaku* spectrum of PDS 456 observed in 2013, from Hagino et al. (2015).

UV absorption lines (e.g., Proga, Stone & Kallman 2000; Higginbottom et al. 2014). Compton scattering can also be effective if the luminosity of the source is close to Eddington (e.g., King & Pounds 2003). The wind is ejected from different locations on the accretion disk and can be accelerated to very high velocities, up to values of v_{out}~0.1c. This provides a very promising explanation for the observations of UFOs in luminous AGN.

For instance, a case study was recently reported for PDS 456 by Hagino et al. (2015), see Fig. 1. Using the *MONACO* radiation transfer code, they have been able to model the blue-shifted Fe XXV–XXVI absorption lines due to the disk wind in the *Suzaku* spectra of this source. They estimanted fundamental parameters of the wind, such as an inner launching radius of ~10r_s ($r_s = 2GM_{BH}/c^2$), inclination angle of ~48° and an outflow velocity of ~0.3c. The higher the inclination angle, the higher is the EW of the line due to the inclrease in column density. Instead, the inner radius mostly affects the velocity centroid and shape of the line. Thus, the smaller is the radius, the higher is the velocity and the broader is the high energy wing of the line (e.g., Fukumura et al. 2015).

Another promising possibility to explain the origin of disk winds in AGN (and possibly also X-ray binaries) is offered by MHD models (e.g., Kazanas et al. 2012). Magnetic fields are fundamental for the onset of accretion and the formation of relativistic jets, therefore it is plausible that they may have an effect in the production of disk winds as well. In this case the wind is accelerated by the centrifugal force of the magnetic field lines anchored on the disk and the magnetic pressure (e.g., Blandford & Payne 1982; Konigl & Kartje 1994; Proga 2000; Everett & Ballantyne 2004; Everett 2005; Fukumura et al. 2010a). The wind is ejected from different regions of the disk. This causes a stratification, with increasing column density, ionization and velocity closer to the central SMBH. In particular, the resultant

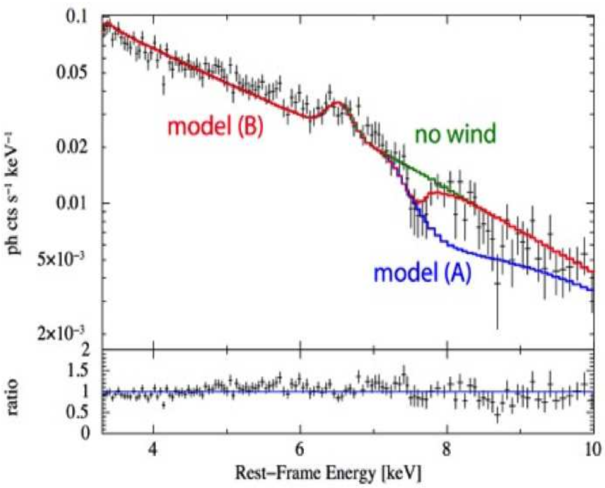

Fig. 2 Best-fit MHD-driven wind model of the 2001 *XMM-Newton* spectrum of PG 1211+143, from Fukumura et al. (2015). The green, blue, and red lines indicate the case without wind model, with inner wind radius fixed to the innermost stable circular orbit, and the best-fit model with an inner wind radius of $\simeq$30r_s, respectively.

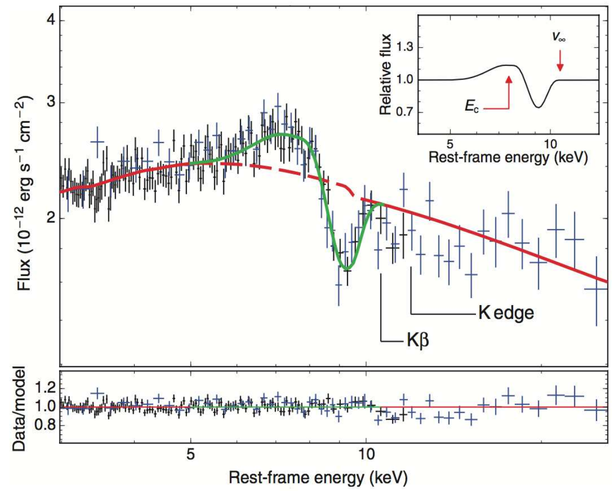

Fig. 3 Simultaneous *XMM-Newton* and *NuSTAR* spectra of PDS 456 in the Fe K band showing a clear P-Cygni profile from a disk wind with velocity $\simeq$0.3c, from Nardini et al. (2015).

wind velocity is proportional to the disk rotational velocity at each radius and it can reach up to relativistic values (e.g., Fukumura et al. 2010b, 2014). The wind possibly originates from just a few r_s from the SMBH up to the outer disk or torus.

The first MHD modeling of an AGN disk wind observed in the X-rays was recently reported by Fukumura et al. (2015) for the quasar PG 1211+143, see Fig. 2. Using the *mhdwind* model in XSPEC the authors have been able to successfully parameterize the blue-shifted Fe K absorption line in the 2001 *XMM-Newton* spectrum of this source. They estimate an inner wind launching radius of $\sim$30r_s, an inclination angle of $\sim$50° and an outflow velocity of $\simeq$0.1–0.2c.

These models provide a very good starting point for the study of disk winds in AGN. However, it is important to note that the real situation can be much more complex. In fact, accretion and ejection physics should be considered together in a self-consistent way. Therefore, the accretion disk, the wind and the jet should be studied simultaneously (e.g., Ohsuga et al. 2009; Tchekhovskoy et al. 2011; Sadowski et al. 2013, 2014; McKinney et al. 2014; Yuan & Narayan 2014). Moreover, the different acceleration mechanisms can also be present at the same time or some of them may dominate for certain wind launching radii. Bright radio galaxies are promising candidates for these studies, as they simultaneously show the disk, the wind and the jet (e.g., Marscher et al. 2002; Tombesi et al. 2012b, 2014).

4 AGN wind feedback

There are several indications of relations between SMBHs and their host galaxies. For instance, the M_{BH}–σ relation shows that the bigger the mass of the SMBH, the higher is the velocity dispersion of stars in the galaxy bulge (e.g., Kormendy & Ho 2013). Moreover, large-scale computer simulations of galaxy evolution show that the high mass end of the galaxy stellar mass function is over-predicted and some phenomena should be responsible for the quenching of the star formation. One promising possibly being feedback from the central SMBH (e.g., Bower et al. 2012).

Therefore, a fundamental question is, *how do SMBHs affect galaxy evolution?* The typical radius of a SMBH is $\sim$10^9 times smaller than that of a galaxy. Considering the volume, the SMBH is $\sim$10^{27} times smaller! Moreover, the typical mass of a SMBH is only $\sim$1% of the stellar bulge mass (e.g., Magorrian et al. 1998). However, it is important to note that there is an huge amount of gravitational energy "released" by SMBHs, which in total can be comparable to the binding energy of the entire galaxy bulge! Therefore, if there is a way to tap into this energy, SMBHs may have a strong impact on the host galaxy.

Indeed, the conversion of gravitational energy into radiation or jets and winds can have a profound impact on the AGN host galaxy. Here, we focus more on the winds, which are thought to be responsible for the so-called "quasar-mode feedback" (e.g., Silk & Rees 1998; Fabian 2012; King Pounds 2015). In this regard, two recent papers reported compelling evidence for the presence of powerful disk winds in quasars.

Combining simultaneous X-ray spectra collected with *XMM-Newton* and *NuSTAR*, Nardini et al. (2015) showed the clear presence of a P-Cygni line profile in the Fe K band of the luminous quasar PDS 456, see Fig. 3. This is due to a powerful, large opening angle disk wind with an outflow velocity of $v_{out}$$\sim$0.3c. This X-ray wind is observed close to the accretion disk, but it is very likely to have a strong effect at much larger scales in the host galaxy.

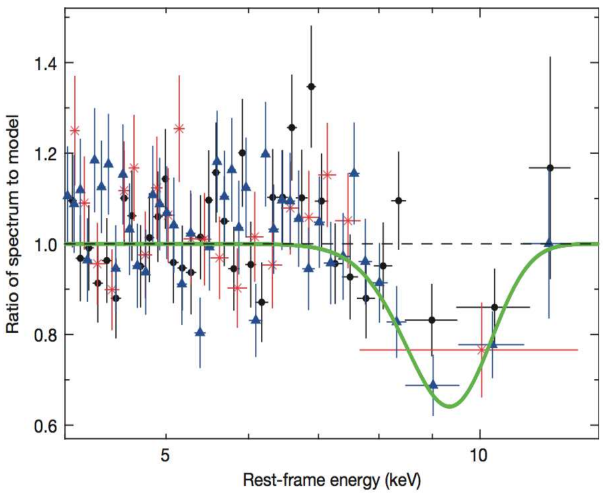

Fig. 4 Ratio between the *Suzaku* XIS0 (black), XIS1 (red) and XIS3 (blue) spectra of IRAS F11119+3257 in the Fe K band showing a clear broad and blue-shifted absorption line from a disk wind with velocity of ≃0.25c, from Tombesi et al. (2015).

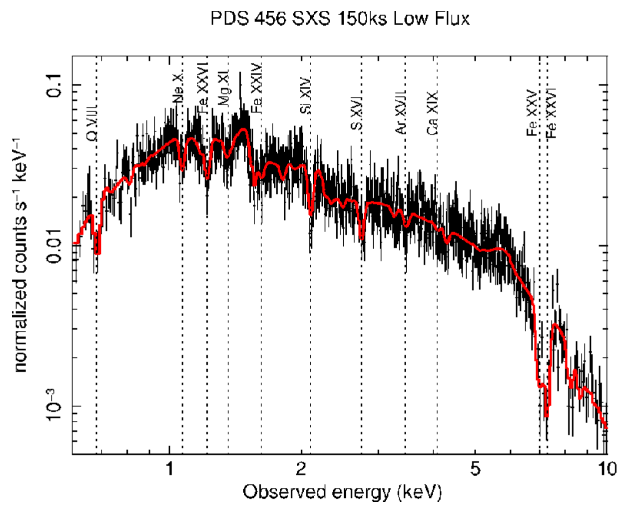

Fig. 5 Simulated *ASTRO-H* microcalorimeter spectrum of PDS 456 in the interval E=0.5-10 keV. A 150ks exposure and the low flux case are assumed. The vertical dotted lines indicate the expected blue-shifted absorption lines from the UFO with velocity v_{out}≃0.23c. Both Fe K and several lower-Z element lines will likely be detected with high significance.

On the other hand, Tombesi et al. (2015) reported, for the first time, the connection between a powerful accretion disk wind detected in the X-ray band with *Suzaku* and a large-scale molecular outflow detected in the IR with *Herschel* in IRAS F11119+3257, see Fig. 4. This is a local ($z = 0.189$) ULIRG hosting a quasar in the center with a luminosity of L≃10^{46} erg s^{-1} (Veilleux et al. 2013). This source, as most ULIRGs, is likely the result of a previous merger between two galaxies. Therefore, the study of this type of objects is very important for the connection with galaxy evolution and whether the merger process is an effective way to feed the central SMBH to very high rates (within the uncertainties, this source is accreting at ∼5 times the Eddington limit).

The OH 119μm line profile in IRAS F11119+3257 shows a prominent P-Cygni profile, indicating a molecular outflow with maximum velocity of 1,000 km s^{-1} at a scale of >300 pc from the SMBH. This corresponds to a very high mass outflow rate of ∼800 M$_\odot$ yr^{-1}. The X-ray spectrum shows a broad and blue-shifted absorption line at the energy of ≃9 keV. The best-fit XSTAR model (Kallman & Bautista 2001) indicates a highly ionized wind with outflow velocity v_{out}≃0.255c, column density N_H≃6×10^{24} cm^{-2} and covering fraction >0.85. The mechanical energy of the disk wind and the molecular outflow are log$\dot{E}_K = 45.4^{+0.4}_{-0.5}$ erg s^{-1} and log$\dot{E}_K = 44.4\pm0.5$ erg s^{-1}, respectively. These corresponds to ≃15% and ≃3% of the AGN luminosity, respectively. The two values are consistent considering an efficiency f=0.22 ± 0.07 derived from the ratios of the two convering fractions. This result is in agreement with the "quasar-mode feedback" model in which the mildly-relativistic disk wind produces a strong shock in the interstellar medium, which then expands adiabatically as a hot bubble and drives the molecular outflow at galaxy-scales (e.g., Zubovas & King 2012; Faucher-Giguère & Quataert 2012; Wagner et al. 2013; Zubovas & Nayakshin 2014).

5 Future missions

Currently, only the CCD instruments onboard *XMM-Newton*, *Suzaku* and *NuSTAR* have provided enough sensitivity to study the crucial Fe K band in detail. In particular, they allowed the detection of UFOs at E>7 keV in local AGN and to estimante their parameters. However, there are still uncertainties, mostly from the fact that the width of the lines is often unconstrained and the limited sensitivity to higher order Fe K line features. The improved energy resolution of the microcalorimeters onboard *ASTRO-H* and *Athena* will allow to study such Fe K features with unprecedented detail.

The *ASTRO-H* X-ray observatory (Takahashi et al. 2014), with a launch date planned for early 2016, will have a microcalorimenter with a unprecedented combination of high energy resolution of ≃5 eV and high sensitivity in the broad energy range between E=0.5–10 keV. Moreover, *ASTRO-H* will have three other instruments, which will allow to simultaneously cover whole X-ray band, from 0.5 keV up to 500 keV.

As a case study we consider the simulated *ASTRO-H* observation of PDS 456 (for more details, see the AGN winds White Paper by Kaastra et al. 2014). This is one of the quasars with the most powerful UFO detected in the X-rays. The UFO in PDS 456 was observed having a variable column density in the range N_H≃1×10^{23}–8×10^{23} cm^{-2}. The column density appears to be higher

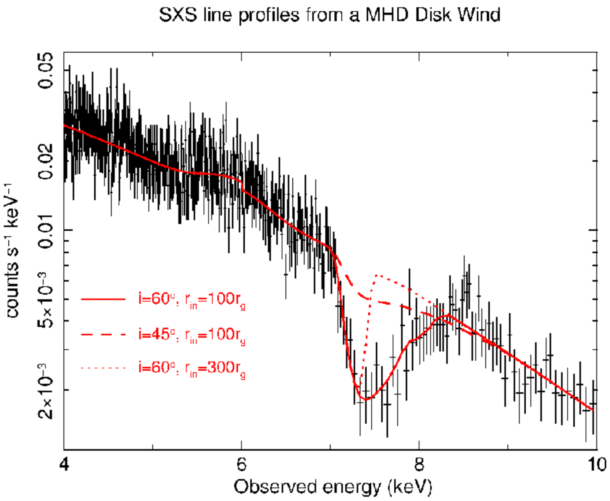

Fig. 6 Simulated *ASTRO-H* microcalorimeter spectrum of PDS 456 in the Fe K band (E=4–10 keV). The lines illustrate the simulated MHD disk wind profiles using the model of Fukumura et al. (2010) and the high flux continuum of PDS 456. Three representative profiles are shown for different values of the wind inclination angle (i) and launching radius (r_{in}). The microcalorimeter will allow to explore the geometry and acceleration of the wind.

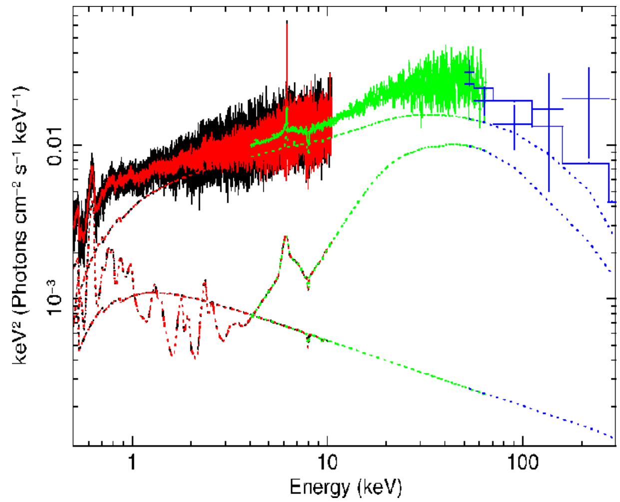

Fig. 7 Simulated 100 ks *ASTRO-H* broad-band spectrum of 3C 120 in the energy range $0.5 - 300$ keV, corresponding to the state in which the jet knot is ejected and the inner disk is disrupted (the inner disk radius recedes from $r_{in} \simeq r_g$ up to $r_{in} \simeq 38\,r_g$). The microcalorimeter SXS spectrum is shown in black, the SXI in red, the HXI in green, and the SGD in blue.

for lower flux states. We assume two representative cases, a high flux (3.6×10^{-12} erg s^{-1} cm^{-2} in the 2–10 keV) / low column ($N_H = 1 \times 10^{23}$ cm^{-2}) and a low flux (1.5×10^{-12} erg s^{-1} cm^{-2} in the 2–10 keV) / high column ($N_H = 5 \times 10^{23}$ cm^{-2}), respectively. We assume the baseline model of Gofford et al. (2014). The exposure time required to detect the UFO at $\geq 6\sigma$ significance in both low and high flux cases is 150 ks.

The microcalorimeter observation will allow to estimate the UFO parameters with unprecedented accuracy (N_H at 5-15%, logξ at 1-5% and v_{out} at 0.5-1%). This is fundamental to decrease the uncertainties on the mass outflow rate and mechanical power of these winds and therefore to quantify the impact of the SMBH on the host galaxy through AGN feedback. From Fig. 5 we see that several other absorption lines due to lower-Z elements at E<6 keV (mainly H/He-like Ar, Ca, S, Si, Ne, O, Mg) may likely be observed in the spectrum. This will provide an additional strong support for the existence of the UFO than the Fe XXV-XXVI lines alone.

Moreover, for the first time, the microcalorimeter will allow to resolve the line width with an accuracy of less than 10%. This will allow to measure the turbulent velocity of the plasma. Moreover, the two Fe XXV Heα and Fe XXVI Lyα lines will be distinguishable. Thus, the *ASTRO-H* observation will allow to explore different line broadening mechanisms. It will also be possible to investigate a distinction between radiation pressure and MHD acceleration mechanisms (e.g., Sim et al. 2008; Fukumura et al. 2010). In fact, the shape of the magnetic field lines in MHD winds and the more equatorial geometry of the radiation driven case will strongly affect the absorption line profile (e.g., Giustini & Proga 2012). In Fig. 6 we show the representative case of an MHD disk wind profile using the model of Fukumura et al. (2010). Three representative profiles are shown for different values of the wind inclination angle (i=45°–60°) and launching radius (r_{in}=100–300 r_g).

Another case study is the *ASTRO-H* observation of the radio galaxy 3C 120 (for more details, see the Broad-band White Paper by Coppi et al. 2014). This is one of the most relevant and promising targets for exploring disk winds in the context of the disk-jet coupling. Previous X-ray observations, augmented by the high-resolution radio data, hinted at a close link between the inner disk state transitions, the jet formation processes and possibly also UFO ejections (e.g., Marscher et al. 2002; Chatterjee et al. 2009; Tombesi et al. 2012b; Lohfink et al. 2013).

We consider the combined disk-jet model of Lohfink et al. (2013), in which the jet X-ray emission is parameterized with a steep power-law with the photon index of $2.5 - 4$, while the disk (disk corona) continuum is represented by a power-law component with the photon index of $1.7 - 2.4$ and the high energy cut-off at 150 keV. In the first case, the disk extends down to the ISCO. This is modeled in XSPEC with a relativistically blurred ionized reflection component with $q \simeq 7$, inclination $i \simeq 15°$, and the ionization $\xi \simeq 200$ erg s^{-1} cm. The neutral distant reflector (pexmon) is included with a reflection fraction $R \simeq 2$. In the second case, which is related to the launch of the jet knot, the inner disk is disrupted and the inner radius recedes to $r_{\rm in} \simeq 38\,r_g$. The relativistic blurred reflection has now a more standard value of $q \simeq 3.5$ and the neutral reflection fraction is $R \simeq 0.26$. In this latter case, a UFO with the velocity $v_{out} \simeq 0.16\,c$

was detected by Tombesi et al. (2014). This outflow is modeled with an XSTAR table assuming a turbulent velocity of 3,000 $\mathrm{km\,s^{-1}}$, ionization $\log\xi \simeq 4.9\,\mathrm{erg\,s^{-1}}$ cm, and column density $N_{\rm H} \simeq 5\times10^{22}\,\mathrm{cm^{-2}}$. If modeled with an inverted Gaussian absorption line, this is equivalent to the energy of $E \simeq 8.23$ keV, line width of $\sigma \simeq 110$ eV, and EW $\simeq -20$ eV.

The simulated 100 ks *ASTRO-H* broad-band spectrum of 3C 120 is shown in Fig. 7. The source will be detected at high significance with all the four instruments, from 0.5 keV up to 300 keV. This will allow to simultaneously constrain the corona continuum, the jet emission, and the neutral/ionized reflection. In addition, the inner disk radius will be measured with 15% accuracy. Moreover, the presence of the disk wind will be determined by means of the detection of the Fe K UFO. In combination with an multi-wavelength monitoring, will allow for a direct comparison between the activity level of the intermittent jet, the state of the accretion disk, and the energetics of the disk wind.

The very high effective area (more than ∼10x of *ASTRO-H*) of the microcalorimeter onboard the future (launch date 2028) *Athena* X-ray observatory (Nandra et al. 2013) will allow to extend the study of AGN wind feedback to higher redshifts ($z \simeq$2–3), where the peak of the AGN population is expected. Moreover, it will be possible to study not only the kinematics but also the dynamics of disk winds in local Seyfert galaxies, thereby directly comparing the data with detailed simulations (Cappi et al. 2013).

6 Conclusions

Powerful winds driven by active galactic nuclei can play a fundamental role in the evolution of both supermassive black holes and their host galaxies, quenching star formation and explaining the tight SMBH-galaxy relations. A strong support of this quasar mode feedback comes from X-ray observation of mildly relativistic accretion disk winds in active galaxies.The unprecedented energy resolution and sensitivity of the upcoming X-ray observatories, namely *ASTRO-H* and *Athena*, are expected to provide revolutionary improvements in this field.

Acknowledgements. FT would like to thank Chris Done and Norbert Schartel for organizing the very interesting and productive workshop "The Extremes of Black Hole Accretion" held at ESAC, Madrid, Spain on June 8-10 2015.

References

Blandford, R. D., & Payne, D. G. 1982, MNRAS , 199, 883
Bower et al. 2012, MNRAS , 422, 2816
Blustin et al. 2005, A&A, 431, 111
Cappi et al. 2009, A&A, 504, 401
Cappi, M., Done, C., Behar, E., et al. 2013, arXiv:1306.2330
Chartas, G. et al. 2002, ApJ , 579, 169
Chatterjee, R., et al. 2009, ApJ, 704, 1689
Chelouche, D., & Netzer, H. 2005, ApJ , 625, 95
Combes, F. 2015, IAU Symposium, 309, 182
Coppi et al. 2014, arXiv:1412.1190
Crenshaw, D. M., & Kraemer, S. B. 2012, ApJ , 753, 75
Dadina et al. 2005, A&A, 442, 461
Detmers et al. 2011, A&A, 534, A38
Elvis, M. 2000, ApJ , 545, 63
Everett, J. E., & Ballantyne, D. R. 2004, ApJ , 615, L13
Everett, J. E. 2005, ApJ , 631, 689
Fabian, A. C. 2012, ARA&A , 50, 455
Faucher-Giguère, C.-A., & Quataert, E. 2012, MNRAS , 425, 605
Ferrarese, L., & Merritt, D. 2000, ApJ , 539, L9
Fukumura, K., et al. 2010a, ApJ , 715, 636
Fukumura, K., et al. 2010b, ApJ , 723, L228
Fukumura et al. 2014, ApJ , 780, 120
Fukumura et al. 2015, ApJ , 805, 17
Giustini et al. 2011, A&A, 536, A49
Giustini, M., & Proga, D. 2012, ApJ, 758, 70
Gofford et al. 2011, MNRAS , 414, 3307
Gofford et al. 2013, MNRAS , 430, 60
Gofford et al. 2014, ApJ , 784, 77
Gofford et al. 2015, MNRAS , 451, 4169
Gupta et al. 2013, ApJ , 772, 66
Gupta et al. 2015, ApJ , 798, 4
Hagino et al. 2015, MNRAS , 446, 663
Halpern, J. P. 1984, ApJ , 281, 90
Higginbottom et al. 2014, ApJ , 789, 19
Kaastra et al. 2000, A&A, 354, L83
Kaastra et al. 2014, Science, 345, 64
Kaastra et al. 2014, arXiv:1412.1171
Kallman, T., & Bautista, M. 2001, ApJS , 133, 221
Kaspi et al. 2002, ApJ , 574, 643
Kazanas et al. 2012, The Astronomical Review, 7, 92
King, A. R., & Pounds, K. A. 2003, MNRAS , 345, 657
King, A., & Pounds, K. 2015, arXiv:1503.05206
Konigl, A., & Kartje, J. F. 1994, ApJ , 434, 446
Kormendy, J., & Ho, L. C. 2013, ARA&A , 51, 511
Lohfink et al. 2013, ApJ , 772, 83
Lobban et al. 2011, MNRAS , 414, 1965
Magorrian et al. 1998, AJ , 115, 2285
Marscher et al. 2002, Nature, 417, 625
McKernan et al. 2007, MNRAS , 379, 1359
McKinney et al. 2014, MNRAS , 441, 3177
Nandra et al. 2013, arXiv:1306.2307
Nardini et al. 2015, Science, 347, 860
Ohsuga et al. 2009, PASJ , 61, L7
Pounds et al. 2003, MNRAS , 345, 705
Pounds, K. 2014, SSRv, 183, 339
Proga, D. 2000, ApJ , 538, 684
Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ , 543, 686
Reeves et al. 2013, ApJ , 776, 99
Sądowski et al. 2013, MNRAS , 436, 3856
Sądowski et al. 2014, MNRAS , 439, 503
Silk, J., & Rees, M. J. 1998, A&A, 331, L1
Sim et al. 2008, MNRAS , 388, 611
Sim et al. 2010, MNRAS , 404, 1369
Sim et al. 2012, MNRAS , 426, 2859
Takahashi et al. 2014, SPIE, 9144, 914425
Tchekhovskoy et al. 2011, MNRAS , 418, L79
Tombesi et al. 2010a, A&A, 521, A57
Tombesi et al. 2010b, ApJ , 719, 700
Tombesi et al. 2011a, ApJ , 742, 44
Tombesi et al. 2012a, MNRAS , 422, L1
Tombesi et al. 2012b, MNRAS , 424, 754
Tombesi et al. 2013, MNRAS , 430, 1102
Tombesi et al. 2014, MNRAS , 443, 2154

Tombesi et al. 2015, Nature, 519, 436
Veilleux, S., Meléndez, M., Sturm, E., et al. 2013, ApJ , 776, 27
Wagner, A. Y., et al. 2013, ApJ , 763, L18
Yuan, F., & Narayan, R. 2014, ARA&A , 52, 529
Zubovas, K., & King, A. 2012, ApJ , 745, L34
Zubovas, K., & Nayakshin, S. 2014, MNRAS , 440, 2625

