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Density diagnostics of photoionized outflows in active galactic nuclei

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Abstract. Photoionized outflows in active galactic nuclei (AGNs) are thought to influence their circumnuclear and host galactic environment. However, the distance of the outflow with respect to the black hole is poorly constrained, which limits our understanding of the kinetic power by the outflow. Therefore, the impact of AGN outflows on their host galaxies is uncertain. If the density of the outflow is known, its distance can be derived. Density measurement via variability studies and density sensitive lines have been used, albeit not very effective in the X-ray band. Good measurements are rather demanding or challenging for the current generation of (grating) spectrometers. The next generation of spectrometers will certainly provide data with better quality and large quantity, leading to tight constraints on the location and the kinetic power of AGN outflows. This contribution summarizes the state-of-the-art in this field.

Keywords. atomic data – atomic processes – plasmas – techniques:spectroscopic – galaxies: active – galaxies: Seyfert

1. Introduction

The center of almost every galaxy but the smallest contains a supermassive black hole (SMBH) with $M_{\rm BH} > 10^5$ $\rm M_\odot$ (Netzer 2015). The growth of the supermassive black hole is realized via accretion of matter. When the accretion rate is above a certain limit ($\gtrsim 10^{-5}$ Eddington ratio), the galaxy is active and its central region is called an active galactic nucleus (AGN).

While AGNs are powered by accretion (or inflows) from the host galaxy, outflows that transport matter and energy away from the nucleus to the host galaxy and beyond are also observed (see Crenshaw *et al.* 2003) for a review. More importantly, since 1998 astronomers realized that AGN-driven outflows might be the key to understand the evolution of SMBHs and their host galaxies (Magorrian *et al.* 1998) and Silk & Rees (1998). This was triggered by the discovery of the tight correlation between the mass of SMBH and the velocity dispersion of the bulge component of the host galaxy. A similar correlation between the mass of SMBH and bulge luminosity of the host galaxy was also found later, supporting the need of AGN feedback (see Kormendy & Ho 2013 for a recent review).

Various forms of AGN outflows have been observed in the past two decades. In the radio band, relativistic particles (namely, jets), originating from the SMBHs, are powerful enough to reach to a distance scale up to Mpc (see Fabian 2012 for a recent review). In the infrared and optical band, relatively cold ($T \sim 10^{1-4}$ K) outflows traced by optical, near-infrared, and carbon monoxide (CO) emission lines (see Harrison *et al.* 2018 for a recent review). In the UV and X-ray band, relatively warm and hot ($T \sim 10^{5-7}$ K) outflows leave their finger prints as blueshifted absorption (mainly) and/or emission features in the high-resolution spectra (e.g., Arav *et al.* 2013 and Laha *et al.* 2014). The focus of this contribution is the warm and hot outflows observed in the X-ray band in the following.

Thanks to the current generation of high-resolution spectrometers aboard Chandra and XMM-Newton, in the past two decades, we have advanced our knowledge of AGN outflows observed in the X-ray band, including the line-of-sight column density ($N_{\rm H}$) and outflow velocity ($v_{\rm out}$), ionization stage (i.e. temperature) and so forth. Nevertheless, in only a rather limited number of studies, the distance with respect to the black hole is constrained (including upper or lower limits), such that the kinetic power ($L_{ki} \propto v_{\rm out}^3\, r^2$) carried by the warm and hot AGN outflows can be inferred. That is to say, the impact of the UV and X-ray outflows to the host galaxy and beyond is unknown or uncertain in most of the cases. Note that, the distance with respect to the SMBH also helps us to infer the origin of these outflows.

Direct measurement of the outflow distance with respect to the black hole is not available. This is simply due to the fact that the size scale is too small (ranging from a few light days to a few pc) and the system is too far away (at least a few tens of Mpc). In other words, it cannot be resolved via direct imaging. The distance can be indirectly constrained by measuring the number density of the ionized outflows. The two parameters are related via the definition of the ionization parameter (ξ),

$$\xi = \frac{L}{n_{\rm H} r^2}\ , \tag{1.1}$$

where L is the $1-1000$ Ryd (or 13.6 eV $-$ 13.6 keV) band luminosity of the ionizing source, $n_{\rm H}$ and r the hydrogen number density and distance of the outflow, respectively.

2. Density diagnostics

Two different approaches are commonly used to measure the density of AGN outflows observed as absorption troughs in the high-resolution X-ray spectra.

The first approach is to monitor the response of the outflow with respect to the changes of the ionizing continuum. The outflow is a plasma with finite density in photoionized equilibrium (Nicastro *et al.* 1999). For a variable incident ionizing continuum, it takes time to respond (via recombination) in order to reach an equilibrium state. The higher the density, the faster the plasma recombine.

From the observational point of view, an AGN with suitable variability is essential, which is not necessarily guaranteed by nature. Both the AGN broad-band continuum (including optical, UV, and X-ray bands) and spectral features of the outflow need to be monitored frequently for a certain period of time. The length of this time period is limited by the visibility window of the target. For instance, the majority of the well studied nearby bright AGNs are visible less than six months in total (not necessarily continuously) each year with XMM-Newton (Table 1). If the monitoring were sparse, variability effects might be washed out. Furthermore, for each pointing in this time period, adequate exposure is required to ensure a high-level of signal to noise ratio in the high-resolution spectra so that changes of spectral features are indisputable. Since the observation is rather demanding, this approach has merely been applied to Mrk 509 (Kaastra *et al.* 2012), NGC 5548 (Ebrero *et al.* 2016), and NGC 4051 (Silva *et al.* 2016).

The alternative is to take advantage of the density sensitive metastable absorption lines (e.g., Mao *et al.* 2017). In a low density (photoionized) plasma, the level population of all the ions are concentrated in the ground level, so that only absorption from the ground levels are observed. As the plasma density increases, the collision between the free electrons and ions can populate the metastable levels, which leads to the presence of metastable absorption line(s) in the spectrum, slightly shifted toward the long wavelength side with respect to the ground level absorption line. The number of metastable lines

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Table 1. Visibility of some well-studied AGNs with outflows observed with XMM-Newton.

Target	Month[1]	Exposure[2]	Target	Month[1]	Exposure[2]
Ark 120	2,3,8,9	∼700 ks	Ark 564	1,5,6,7,11,12	∼600 ks
IRAS 13224-3809	1,2,7,8	∼2 Ms	MCG-6-30-15	1,2,7,8	∼700 ks
MR 2251-178	5,6,11,12	∼500 ks	Mrk 335	1,6,7,12	∼700 ks
Mrk 509	4,5,10,11	∼800 ks	Mrk 766	5,6,7,11,12	∼700 ks
NGC 3227	5,6,11,12	∼700 ks	NGC 3516	3,4,5,9,10,11,12	∼400 ks
NGC 3783	1,6,7,12	∼500 ks	NGC 4051	5,6,11,12	∼800 ks
NGC 5548	1,2,6,7,8,12	∼1 Ms	NGC 7469	5,6,11,12	∼800 ks

Notes: [1]The visibility window is provided by the HEASARC viewing tool. Note that the list of month is given in a conservative way because the target might be visible merely for a few days in a particular month. [2]The total archival exposure of XMM-Newton since 1999.

depends on the number of metastable levels for a given ion. As the total level population is conserved for each ion, the stronger the metastable absorption line(s), the weaker the ground absorption line. The rest frame wavelength of the metastable absorption lines from the cosmic abundance elements (including C, N, O, Ne, Mg, Si, and Fe) ranges from a few angstrom (X-ray) to ∼2000 angstrom (UV).

A spectrometer with an adequate spectral resolution and a large photon collecting area is essential. The form ensures that the metastable absorption lines are resolved, ideally with detailed line profiles. The latter ensures a high signal to noise ratio of the absorption features with reasonable exposure (up to a few hundreds of ks). The current generation of spectrometers are not very effective for the metastable absorption line studies, with Miller *et al.* (2008) put a tight constrain on the density of a disk wind in a stellar mass black hole GRO J1655-40, while Kaastra *et al.* (2004), King *et al.* (2012), and Mao *et al.* (2017) obtain upper or lower limits on density of AGN outflows.

Both the aforementioned density measurements rely on a photoionized plasma model with the underlying atomic database as accurate and complete as possible. Inaccurate recombination rates or metastable to ground level population ratios can lead to a biased measurement of density, thus, distance and kinetic power of AGN outflows. An accurate description of the incident broad band (optical to hard X-ray) ionizing continuum is also important for the photoionization modelling. This means that well coordinated multi-wavelength observational campaigns are required.

3. Future perspectives

Needless to say, the next generation of high-resolution X-ray spectrometers are essential to advance our knowledge of AGN outflows observed in the X-ray band. Future missions like Athena/XIFU Nandra *et al.* (2013) allow observers to easily detect ground metastable absorption lines below 20 angstrom for a large sample of X-ray outflows. These absorption lines are mainly from highly-ionized Fe ions. To detect ground and metastable absorption lines beyond 20 angstrom, Arcus Smith *et al.* (2016) is the only proposed mission (known to-date) to be the upgrade of the low energy transmission grating spectrometer (LETGS) aboard Chandra. Ground and metastable absorption lines from lowly-ionized C to S ions are located beyond 20 angstrom.

Depending on the properties of the targets, density (and distance) measurements via the aforementioned timing and/or spectral analyses need to be performed. The results of these two measurements on the same target ought to be cross-checked. Note that given the diversity of AGN outflows (e.g., Giustini & Proga 2019), observers need to investigate

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for different spectral features (at different wavelength ranges), which relates to different plasma density and temperature, as well as the distance with respect to the SMBH.

Last but not least, density measurements and the according astrophysical interpretations rely on the quality of (photoionized) plasma models. Since various detailed atomic processes (excitation, de-excitation, ionization and recombination) are involved, an extensive atomic database with level-resolved rates and cross sections for all the cosmic abundant ions in a wide density-temperature parameter space are highly needed. High quality theoretical calculations, preferably benchmarked by lab measurements, should be incorporated to the plasma models to reduce the systematic uncertainties.

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