Relativistic blue- and red-shifted absorption lines in AGNs

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Current, accumulating evidence for (mildly) relativistic blue- and red-shifted absorption lines in AGNs is reviewed. *XMM-Newton* and *Chandra* sensitive X-ray observations are starting to probe not only the kinematics (velocity) but also the dynamics (accelerations) of highly ionized gas flowing in-and-out from, likely, a few gravitational radii from the black hole. It is thus emphasized that X-ray absorption-line spectroscopy provides new potential to map the accretion flows near black holes, to probe the launching regions of relativistic jets/outflows, and to quantify the cosmological feedback of AGNs. Prospects to tackle these issues with future high energy missions are briefly addressed.

1 Introduction

Little is known about the flow patterns of gas in the innermost regions of black holes (BHs) in AGNs. Probing of the gas kinematics (velocities) and, most importantly, dynamics (accelerations) around black holes is a fundamental requisite if we want to understand the source’s geometry and energy generation mechanism, i.e. the accretion mode.

Surprisingly enough, there is little direct evidence yet for inward radial motions (e.g. infalling/inflowing material) down to a few gravitational radii where most of the energy is generated. Probably the most convincing evidence of accretion onto a relativistic black hole are, to date, the detections of broadened, redshifted FeK emission line in the X-ray spectra of an increasing number of bright Seyfert 1 galaxies (e.g. Tanaka et al. 1995, Fabian 2002, see contributions in these proceedings by Fabian et al., Guainazzi et al., and Nandra et al.). Nandra et al. (1999) discussed the detection of a redshifted Fe resonant absorption feature in the X-ray spectrum of the Seyfert 1 galaxy NGC3516. The *ASCA* data showed a sharp and narrow drop of counts at E∼5.9 keV (corresponding, for FeXXVI, to an energy/velocity shift of ~0.15 c) imprinted over a broad emission line profile, with indication of variability on time scales of ~20 ks. Being the line redshifted, the authors speculated its association with material free-falling onto the BH. Unfortunately, these early studies were strongly limited by the instrumental sensitivity in the 2-10 keV band. The low statistic combined with a complex underlying continuum thus prevented any detailed studies.

Several are, on the contrary, the evidences in AGNs of matter flowing outward. Fast winds/outflows/ejecta are seen in AGNs since a long time, i.e. the jets of radio-loud galaxies (Axon et al. 1989, Tadhunter 1991), the (absorbed) spectra of broad absorption line (BAL) QSOs (Weymann et al. 1991, Reichard et al. 2003) or the [OIII] ionization cones of Seyfert galaxies (Tadhunter & Tsvetanov 1989, Wilson & Tsvetanov 1994). Warm absorbers are also common among AGNs. Indeed, they have been detected in more than half of bright Seyfert galaxies (Reynolds 1997, George et al. 1997, Blustin et al. 2005). High resolution UV and soft X-ray observations have shown that warm absorbers have typical temperatures of ~10^5-6 K and outflowing velocities of a few 100 to a few 1000 km s^-1 (see Crenshaw, Kraemer & George, 2003 for a comprehensive review on AGN winds and warm absorbers).

With the superior sensitivity of *XMM-Newton* and *Chandra* between 2-10 keV, it has now been possible to probe these phenomena in more detail. In particular, more extreme cases of redshifted and blueshifted absorption structures have now been discovered in the spectra of a number of bright AGNs. This paper briefly reviews the latest results on these new, extreme phenomena. Specifically, recent data show strong evidence for outflowing gas with unprecedented kinematic and ionization properties (§2.1 and 2.2), and provide hints of redshifted absorbers that would indicate either infalling clouds or strong gravitational redshift (§2.3 and 2.4). Despite some remaining observational critical issues (Section 3), X-ray absorption spectroscopy with future observatories (Section 4) offers new potential to probe the dynamics of the accretion and ejection of material onto black holes.

2 X-Ray Absorption Lines

2.1 Blue-shifted Lines

From recent observations with *XMM-Newton* and *Chandra*, there is now overwhelming evidence of absorption lines at rest-frame energies ~7-10 keV in the spectra of several radio-quiet (RQ) AGNs and QSOs. They are found in both

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low-z and high-z sources (see Table 1). If interpreted as absorption lines by He-like and H-like Fe, these imply the existence of massive, high velocity (v \sim 0.1-0.4 c) and highly ionized outflows in AGNs, with rather extreme values of absorption column densities (\sim 10^{23-24} cm^{-2}) and ionization parameters (log \xi \gtrsim 3).

The mass outflow rates sensitively depend on the absorber’s distance from the ionization continuum source, on the assumed volume filling factor, and on other unknown values (such as the gas density for example), but can be comparable or even larger than the Eddington accretion rates.

Most interestingly, variability on timescales down to few 1000 s has been found among the brighter sources, two remarkable examples of which are shown in Figure 1 and 2. A measure of how these “hot” absorbers respond to flux variations in time allows to place some constraints on their geometrical properties and their origin (e.g. Risaliti et al. 2005, Dasgupta et al. 2005). Fitting with time-dependent photoionization models such as that calculated by Nicastro et al. (1999) will be a challenge for future observations.

These features are also reminiscent of the peculiar absorption structures found near 1 keV in some narrow line Seyfert 1 galaxies (Leighly et al. 1997, Dasgupta et al. 2005). First interpreted as oxygen absorption in a highly relativistic outflow (v \sim 0.2-0.3 c), alternative explanations have also been proposed since then (Nicastro, Fiore & Matt, 1999).

### 2.2 Models producing powerful outflows?

From a theoretical point of view, there are three main types of models which are generally called upon to explain AGN winds/outflows: i) thermally driven winds, ii) radiatively driven winds and iii) magnetically driven winds. Thermally driven models are generally most effective in producing slow winds and at large radii. Indeed the wind will arise when the gas sound speed is greater than the escape velocity, which decreases with radius. They have, for example, been called upon to explain the (large scale) warm reflector/absorber seen in the polarized light of Seyfert 2 galaxies (Miller and Antonucci 1983, Krolik & Begelman 1986, 1988; Balsara & Krolik 1993, Krolik & Kriss 1995, Woods et al. 1996).

Radiatively and magnetically driven models have instead been mostly proposed as the source of dense and fast winds from accretion disks. If the absorbing gas is not too highly ionized, winds can be driven vertically by radiation from the accretion disk and radially by radiation from the central source (e.g. Murray et al. 1995, Proga et al. 2000, and ref. therein). Alternatively rotating magnetic field lines can centrifugally accelerate gas above and away from the accretion
Fig. 1  XMM − Newton spectral residuals of the Seyfert galaxy NGC1365 by Risaliti et al. (2005). Strong (EW ~ 100 eV each) and variable, absorption structures are clearly detected around 7 keV (Kα of FeXXV/XXVI) and 8 keV (Kβ of FeXXV/XXVI). Their best-fit absorber model requires outflow velocities of ~5000 km/s, a column density of ~5 × 10^{23} cm^{-2} and a ionization parameter of log ξ = 3.

Fig. 2  Preliminary residual spectra obtained from multiple XMM − Newton observations of the bright Seyfert 1 galaxy Mrk509. Different absorption structures between 7.4 and 8.2 keV are clearly detected, they are indicated by arrows. The 6.9 keV (rest-frame) energy corresponding to the H-like Fe ionization level is marked for reference. A strong FeK emission line at 6.2 keV (6.4 keV rest-frame) is also clearly visible. Lower time-scale variations of these features is under investigation.

Fig. 3  One example of a magnetically-driven accretion flow, by Kato et al. (2004). Accumulated toroidal fieldlines emerging from the disk produce a magnetic tower, thereby driving an MHD jet. At the base of the flow, velocities as high as 0.4c are produced, as indicated by the color bar.

disk plane (Blandford & Payne 1982, Emmering, Blandford & Shlosman 1992, Kato et al. 2004). Hybrid models where clouds are magnetically elevated above the disk, and radiatively accelerated radially, are also being proposed and seem to be quite successful both theoretically (e.g. Proga 2003) and observationally (Elvis 2000). Most recent 2/3-dimensional, time-dependent, MHD simulations (Kato et al. 2004, Proga 2005) are able to account for dense and extremely fast (v few × 0.1 c, see Figure 3) flows but the large mass outflow rates (Section 2.1) may not be easy to accommodate within current models. One example of such a flow model by Kato et al. (2004) is shown in Figure 3.

2.3 Red-shifted Lines

Following upon the seminal work by Nandra et al. (1999) on NGC3516, several results are now reporting on the detections of absorption structures at rest-frame energies between ~4–6 keV in the spectra of several RQ AGNs and QSOs. These have been found in both Seyfert and RQ QSOs (see Table 1). The two most significant detections to date, PG1211+143 and Mrk509, are shown in Figures 4 and 5, respectively. As for the blueshifted absorption lines illustrated above (Section 2.1), the most natural explanation for such absorption components is in terms of resonant absorption by highly ionized (H-like or He-like) iron. In this case however the measured energy shifts correspond to receding velocities v ~ 0.1-0.4 c. It is unlikely that the lines result from a lower ionization state than Fe XXV, as in this case a series of strong L-shell Fe lines and edges would have been detected at lower energies. Furthermore, the absorption lines cannot be due to near-neutral Fe (Fe I–XVII) at 6.4 keV, because no strong Kα absorption line would be observed, as the L shell would be fully populated.

Modeling of the absorption-line systems with theoretical models such as XSTAR (Kallman et al. 1996) or SIABS (Kinkhabwala et al. 2003) require large column densities (typically greater than 10^{23} cm^{-2}), very large ionization parameters (greater than ~1000), and mass flow rates of the order of a fraction of M_{⊙} yr^{-1} (e.g. Dadina et al. 2005, Reeves et al. 2005). These should be considered order-of-
Two absorption features are apparent at 4.22 and 4.93 keV, corresponding to 4.56 and 5.33 keV in the rest frame of PG 1211+143 (z=0.0809).

Two possible causes for those (mildly) relativistic redshifted lines have been proposed: either gravitational redshift of photons near the massive black hole or infall of matter onto the black hole. In the former scenario, the absorbing matter would have to be located very near the black hole, at a few $R_g$. It could be in the form of a rotating absorbing corona, located on top of the source-plus-disk system, as proposed by Ruszkowski & Fabian (2000), or a kind of “self-absorption” effect at the inner edge of a nuclear outflow/jet (Yaqoob & Serlemitsos 2005). Alternatively, the matter may be infalling onto the black hole with a diffuse (wind) or clumpy (blobs) structure. The fact that both Mrk509 and PG1211+143 do also possess fast outflows (Section 2.1) suggests that inflows may be linked to outflows. One possibility is that part of the outflow does not escape the gravitational potential of the black hole. For instance in PG1211+143 the material launched with $v = 0.1c$ from a radius of $R < 100 R_g$ would not escape the system. This would naturally produce both red- and blueshifted lines. A similar situation is predicted by several theoretical models. The “failed disk wind” model proposed by Proga (2005, see Figure 7), the “thundercloud” model (Merloni & Fabian 2001), and the “aborted jet” model by Ghisellini,
Therefore, statistical significance (and a "blind" search in the time and energy parameter space. The analysis thus requires attention and are detected at energies which are shifted with respect to expected atomic values. The analysis thus requires account on proper Monte-Carlo simulations (i.e. Protassov et al. 2002, Porquet et al. 2004, Yaqoob & Serlemitsos 2005, Reeves et al. 2005). The statistical significance of (single) blue-shifted lines is, to date, robust (typically ~3–5 \( \sigma \)), while it is weaker for red-shifted lines (typically ~2–4 \( \sigma \)).

Another issue is the difficulty to distinguish, sometimes, between emission and absorption lines. For instance, Turner et al. (2002) have shown that the claimed redshifted Fe K-shell absorption in the ASCA spectrum of the Seyfert 1 galaxy NGC 3516 (Nandra et al. 1999) was probably due to a strong narrow K\( \alpha \) core at 6.4 keV and variable emission lines at E<6.4 keV which were better visible only with the superior XMM-Newton sensitivity. Similar difficulties were encountered by Longinotti et al. (2003) and Dadina & Cappi (2004) in fitting their data.

The analysis could also be complicated by the difficulty to unambiguously identify (i.e. model) absorption lines in the FeK shell energy band (see Kaspi et al. 2006 and Pounds & Page 2006 in the case of PG1211+134). Indeed, (photoionization) modelling of FeK absorption spectra depend sensitively on details of energy levels, transition probabilities, and photoionization cross sections (i.e. Kallman et al. 2004), hereby potentially affecting the astrophysical interpretation of absorption features in the 7–9 keV energy band.

Finally, it has also been claimed that some of these outflows may not exist if absorption features that are really local to our Galaxy have been misidentified as being at the redshift of the AGNs (McKernan et al. 2004, 2005). This is a caveat that should be beared in mind, in particular for sources located near the Galactic plane, though certainly not the case for most of the sources discussed here.

### 4 Future Prospects

The question arises as to whether we are actually seeing only the “tip of the iceberg”. Despite red- and blue-shifted FeK absorption lines are of indisputable importance and interest, there has been, unfortunately, up to now a number of biases against their detections. First there is an “observational bias” against the highest-velocity blueshifted features (at E>7 keV) in that orbiting X-ray telescopes are of limited spectral and sensitivity capabilities at these energies. Then the apparently sporadic nature of the features, inherent to this type of extreme phenomena, has also generated another bias, a “detection bias”. Finally diagnostic of gas with the greatest velocities and, thus, ionization properties will ever only be possible through its FeK lines emission/absorption (the lower-Z elements being too weak and/or completely ionized), i.e. somewhat a “physical bias” against its detectability.

This, combined to the fact that transient blue- and red-shifted absorption lines are naturally expected in several theoretical models (Section 2.4) suggests that the parameter space for new discoveries is large and important under this topic. In particular, two type of measurements are addressed below which may bring in the future to relevant breakthroughs in this area: to track the flow dynamics on

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**Fig. 7** Map of logarithmic density of the AGN failed disk wind by Proga (2005). Note that high density (10^{-12}-10^{-14} g cm^{-3}) flows can develop vertically, and with large (up to few 10000 km s^{-1}) velocity radial components both inward and outward. Allowing for a smaller inner radius than used in this computational domain, the velocities amplitudes would likely become significantly higher (Proga, private communication).

Haardt & Matt (2004) all predict episodes of matter ejecta and infalls. Other recent models such as that proposed by Gierlinski & Done (2004) to explain the soft X-ray excess of type-1 AGNs do invoke extreme versions of the “failed disk wind” model, where the absorption structures suffer a huge (\( \gamma \sim 0.2-0.3 c \)) velocity smearing that is characteristic of a complex velocity structure in the flow (Proga & Kallman 2004).

The current indications that the red-shifted lines are transient on relatively short (~10000 s) time-scales (Dadina et al. 2005, Reeves et al. 2005, Yaqoob & Serlemistos 2005) favor absorbing systems made of a single dense clump of matter or an ensemble of clumps, rather than a diffuse (i.e. wind or corona) structure. It also calls for the interesting possibility to track the infall of one or more blobs toward the black hole, i.e. dispose of “test-particles” to probe general relativity (GR) in strong field. Regardless of the mechanism, the large redshifts involved, the high covering factor and the sporadic nature of the lines imply that the absorber is most likely located within a few \( R_g \) of the black hole.

### 3 Critical Issues

The calculation of the statistical significance of these absorption lines is often a matter of debate. Indeed, both blue-shifted and red-shifted absorption lines appear to be transient and are detected at energies which are shifted with respect to expected atomic values. The analysis thus requires a “blind” search in the time and energy parameter space. Therefore, statistical significance (and \( \chi^2 \) results) must either correct for the number of trials performed or account for few 10000 km s^{-1}) time-scales (Dadina et al. 2005).
very short time-scales, and to probe the highest velocity outflowing gas.

4.1 Gas Dynamics (not only kinematics) around Black Holes

What are the frequency and duty cycle of this phenomena, what are the typical densities, velocities, covering factors and ionization states involved? These are still open issues. Despite our lack of detailed understanding, the case is settled for the study of gas inflows and outflows in AGNs to give insights into the accretion and ejection processes at work around black hole systems. They may offer unprecedented ways of probing/mapping GR under the strong field limit and help understand how earth-like quantities of matter (as estimated in Dadina et al. 2005) are accelerated up to relativistic velocities and kept collimated. The most important goals would thus be to characterise the geometry, the kinematics (measure of velocities, v) and, most importantly, the dynamics (measure of velocity variations, ∆v/∆t) of the absorbing material, either inflowing or outflowing. For example, one wish to track the absorption lines from, say, ~1 Rs(=2 Rg) to 10 Rs, with intervals of ~1 Rs. Assuming a velocity of v~0.2 c, these correspond to time-scale intervals of ~5000 s for a black hole of mass 10^8 M⊙ and ~50 s for a 10^9 M⊙ black hole. Assuming an equivalent width of ~−100 eV for the Fe absorption line and a bright source with 2-10 keV flux of 2×10^{-11} erg cm^{-2}s^{-1} (as measured in Mrk509, Dadina et al. 2005), simulations show that XEUS could detect such line at any energy between 4–10 keV and on a time-scale as short as 100 s. Inflowing, outflowing, accelerating and/or decelerating absorption lines could then be tracked (as illustrated in Figure 8) on few tens of AGNs on a few 100 s time-scale. Clearly, very high throughput between 4–10 keV is mandatory for this type of measurements.

4.2 Highest Velocity Outflows as Source of Cosmological Feedback from AGNs

It is well established in literature that ‘slow’ (non-relativistic) AGN winds may have an important cosmological impact in that they may provide an important source of energy feedback (see the review by Elvis 2006 and references therein). Their effect on a number of astrophysical areas (such as the AGN-host galaxies co-evolution, the heating of galaxies, groups and cluster of galaxies, the disruption of cooling flows, the ISM and IGM metal enrichment, etc.) is not yet established because of the remaining large (order of magnitudes) uncertainties in the total mass, energy and momentum released into the ISM and IGM (Blustin et al. 2005, Crenshaw et al. 2003, Chartas et al. 2004, Elvis 2006.). Likely, their impact would be even more relevant if extreme outflows like the ones presented here are considered (Pounds et al. 2003, King & Pounds 2003). The remarkable detections in at least a few high-z BAL QSOs (Chartas et al. 2003) have then set the ground for quasar massive outflows to have a very significant impact in the evolution of their own host galaxies (Chartas, Brandt & Gallagher 2004; Lapi, Cavaliere & Menci 2005). How ubiquitous are these massive outflows in high-z BAL and non-BAL QSOs has yet to be understood and will necessitate further observations.

As stated in Section 4, we may have been missing most of the highest-velocity gas because of a number of biases against its detection. These are precisely the outflows that are most interesting and potentially most important because they could transport outward most of the mechanical energy emerging from the black holes. Good sensitivity and energy resolution are needed at all energies from ~7 up to ~15 keV to be able to detect and constrain absorption lines and edges from the highest ionization Fe (up to 9 keV rest-frame), at the highest plausible velocities (up to, say, 0.9c). Much improvement with respect to XMM-Newton will be obtained with the planned franco-italian mission Simbol-X (see simulations in Figure 9). More detailed, time-resolved, spectroscopy on shorter time-scales and/or fainter sources shall wait the hard X-ray detector planned on-board XEUS (see ESA’s XAWG Report: Parmar et al. 2004).

5 Conclusion

Recent Chandra and XMM-Newton observations of bright Seyfert galaxies and QSOs have revealed the presence of massive outflows of ionized material driven from a few gravitational radii from the black holes with velocities up to ~0.4c. Other recent observations show evidence for redshifted iron Kα absorption lines, which require either pure gravitational redshift or matter infalling directly onto the...
black hole. The two phenomena (relativistic outflow and inflow) may possibly be linked together and there are observational and theoretical evidence for this to be true. Both phenomena are of outstanding interest because they offer new potential to probe the dynamics of innermost regions of accretion flows, to tackle the formation of ejecta/jets and to place constraints on the rate of kinetic energy injected by AGNs into the ISM and IGM. Future high energy missions (such as the planned Simbol-X and XEUS) will likely allow an exciting step forward in our understanding of the flow dynamics around black holes and the formation of the highest velocity outflows.

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Fig. 9 Simulations of a 50 ks observation with Simbol-X (dark and red curves for two different mirror configurations), compared to a simulated 50 ks XMM-Newton observation (green curve). The model consists in a power-law with $\Gamma=1.9$ and $F(2-10)=10^{-11}$ erg cm$^{-2}$ s$^{-1}$, plus 2 narrow emission lines (at 5 and 6.4 keV, with EW=100 eV), plus 4 absorption lines at 7, 9, 12, and 15 keV ($\sigma < 50$ eV, EW=100 eV). The XMM-Newton simulations would (barely) detect the two absorption lines below 10 keV, while Simbol-X would detect them all, up to $\sim 15$ keV.

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