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How the effects of resonant absorption on black hole reflection spectra can mimic high-velocity outflows

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ABSTRACT

Narrow absorption lines seen in the 2–10 keV spectra of active galaxies and Galactic black holes are normally attributed to iron in high-velocity outflows or inflows. We consider the possibility that such features could arise naturally in the accretion disc. Resonant absorption by highly ionized iron (e.g. Fe XXVI and Fe XXV) in an optically thin plasma that is located above the disc and rotating with it could reproduce narrow features in the reflection component of the spectrum as it emerges from the disc. Depending on the inclination of the disc and the exact geometry of the hot plasma (e.g. whether it blanket the disc or a ring), apparently narrow absorption features could be detected between 4 and 10 keV. Such an explanation requires no high-velocity outflow/inflow and is consistent with a reflection-based interpretation for accreting black holes systems.

Key words: accretion, accretion discs – black hole physics – line: formation – line: identification – relativistic processes – galaxies: active.

1 INTRODUCTION

The high energy resolution and signal-to-noise ratio provided by current X-ray telescopes have led to reports of narrow absorption lines in the spectra of black hole systems. These features, assumed to arise from iron ($E = 6.4$–6.97 keV), can be highly redshifted (e.g. Nandra et al. 1999, 2007; Turner et al. 2002; Pounds et al. 2003a, 2005; Turner, Kraemer & Reeves 2004; Dadina et al. 2005; Longinotti et al. 2007) or blueshifted (e.g. Pounds et al. 2003b; Dadina et al. 2005; Nandra et al. 2007; Reeves et al. 2009). Many of these features are transient and their actual existence have been called into question on statistical grounds (e.g. Vaughan & Uttley 2008). Others are persistent in that they have been identified in subsequent observations or with other instruments. These features are normally unresolved with current CCDs, constraining their widths to be less than a few hundred electron volts. The most common explanation is that these features originate in high-velocity outflows and inflows (see Cappi 2006, for a review), in some cases reaching speeds in excess of $0.1c$ (e.g. Reeves et al. 2009; Tombesi et al. 2010).

An alternative explanation for the redshifted features is resonant absorption lines due to highly ionized iron that arises naturally in the accretion disc (Ruszkowski & Fabian 2000). A hot and diffuse plasma located above the accretion disc will imprint resonant absorption lines on the reflection spectrum as it emerges from the disc. The medium is rotating with the accretion disc and thus experiences the same dynamical effects as material in the disc. Here we show that both redshifted and blueshifted features can occur and potentially shift features to apparently high velocities without the need to invoke high-velocity outflows.

This is a proof of concept work where we examine the possibility that resonant absorption by highly ionized iron could account for the narrow features over a wide range of energies by making use of the velocities already present in the disc. Detailed computational modelling is left to future work. It is certainly plausible that narrow absorption features close to 7 keV are due to highly ionized outflows. However, we consider that alternative explanations for the wide range of velocities reported need to be investigated. In the following section, we present the general picture and motivation for the study. In Section 3, we describe the potential features that would appear depending on the geometry of the system. We discuss our results in Section 4.

2 THE MODEL AND MOTIVATION

We adopt the standard accretion disc picture that has developed over recent years. The optically thick and geometrically thin accretion disc is illuminated by a primary power-law emitter that is located on the spin axis of the black hole (Fig. 1, left-hand panel). We note that the location of the primary emitter is arbitrary and does not need to be on the spin axis of the black hole; however, from recent X-ray studies (e.g. Wilkins & Fabian 2011) and gravitational microlensing observations of active galactic nuclei (AGNs; e.g. Chartas et al. 2009), we know the primary emitter must be compact and centrally concentrated.

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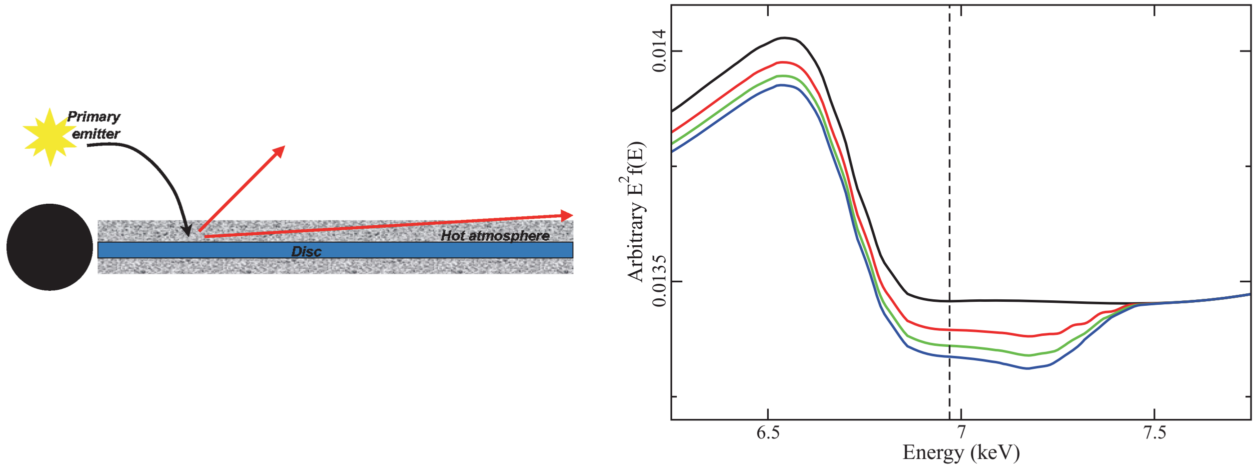

Figure 1. Left: the assumed geometry of the inner accretion disc. The primary emitter is located on the spin axis of the black hole and illuminates the standard accretion disc. The reflection spectrum (red curves) transverses the absorbing atmosphere above the disc. Various paths through the hot atmosphere can modify the depth of the absorbing features on the reflection spectrum. Right: the modification to the blurred reflection spectrum due to Fe XXVI absorption. The black curve is the unabsorbed spectrum. The red, green and blue curves correspond to optical depths of 0.1, 1 and 10, respectively.

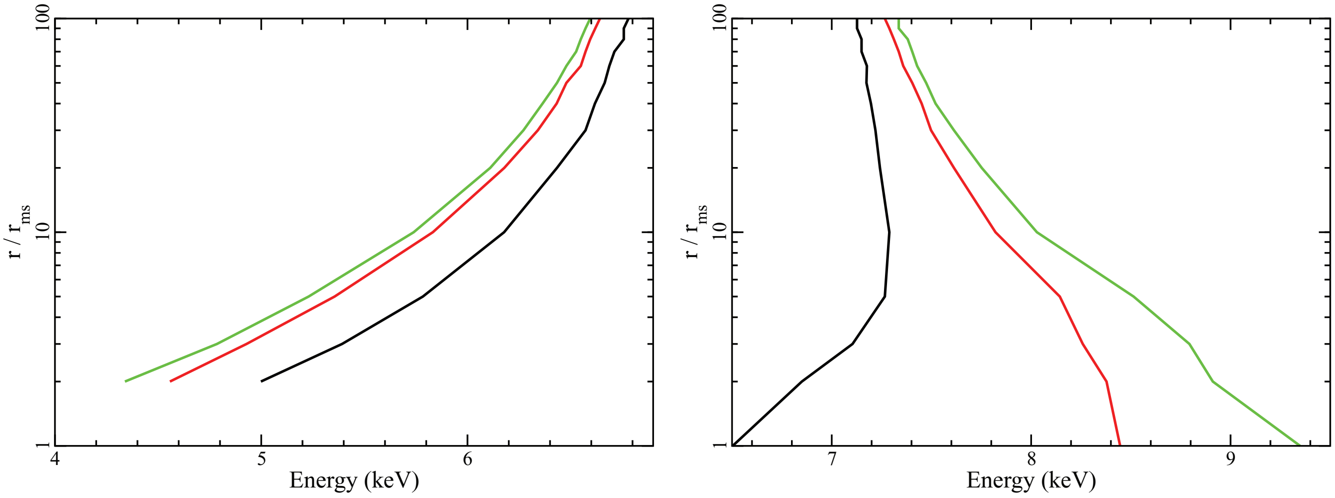

Figure 2. Left: the peak energy of the red wing of a narrow 6.97 keV line blurred by motions in the accretion disc as a function of distance at which the absorption originates from a black hole with a spin parameter of $a = 0.7$. The distance is given relative to the radius of marginal stability ($r_{\rm ms}$). The black, red and green lines correspond to disc inclinations of 30°, 60° and 85°, respectively. The measurements are cut-off below $2r_{\rm ms}$ as it is not possible to isolate the peak of the red wing. Right: same as the left-hand panel, but for the peak of the blue wing.

Located above the accretion disc is an optically thin, highly ionized plasma that is corotating with the disc. The reflection spectrum (i.e. reflection continuum and fluorescent lines; Ross & Fabian 2005) emitted from the disc will cross through the plasma and may be subject to resonant absorption as it emerges from the disc. Since the absorbing material is corotating with the disc, the resonant absorption features are subject to the same kinematic and gravitational effects influencing the reflection spectrum.

Various lines of sight could influence the significance of the resonant features as the optical depth through the absorbing medium changes (Fig. 1, left-hand panel). This will alter the depth of the feature as is shown in Fig. 1 (right-hand panel).

As a simple test to examine if such a model could reproduce narrow absorption features in the appropriate energy band, we considered the observed energies of the red and blue peaks of an intrinsically narrow absorption profile (Gaussian) at the rest energy of H-like iron (Fe XXVI Lyα, 6.97 keV). The line is broadened by Doppler and relativistic effects using the `kerrconv` model in XSPEC (Brenneman & Reynolds 2006) for a black hole spin parameter of $a = 0.7$ (Fig. 2). Depending on the inclination of the disc, features attributed to narrow Fe XXVI absorption could appear anywhere from ~4 to over 9 keV. The energy range could expand to even lower energies if one considers absorption by Fe XXV ($E = 6.7$ keV) or higher energies if one considers Fe XXVI Lyβ ($E = 8.25$ keV).

3 SIMULATIONS

In this section, we consider various geometries of the model in Section 2 and examine the appearance of the absorption imprinted on the reflection spectrum. The direct component of the primary emitter viewed by the observer is not absorbed by the plasma. We assume the hot atmosphere is highly ionized and consider resonant absorption only from hydrogen-like (Fe XXVI Lyα) and helium-like (Fe XXV) iron. The scattering is treated as simple line absorption, that is once the photon is scattered out of the line of sight, it is

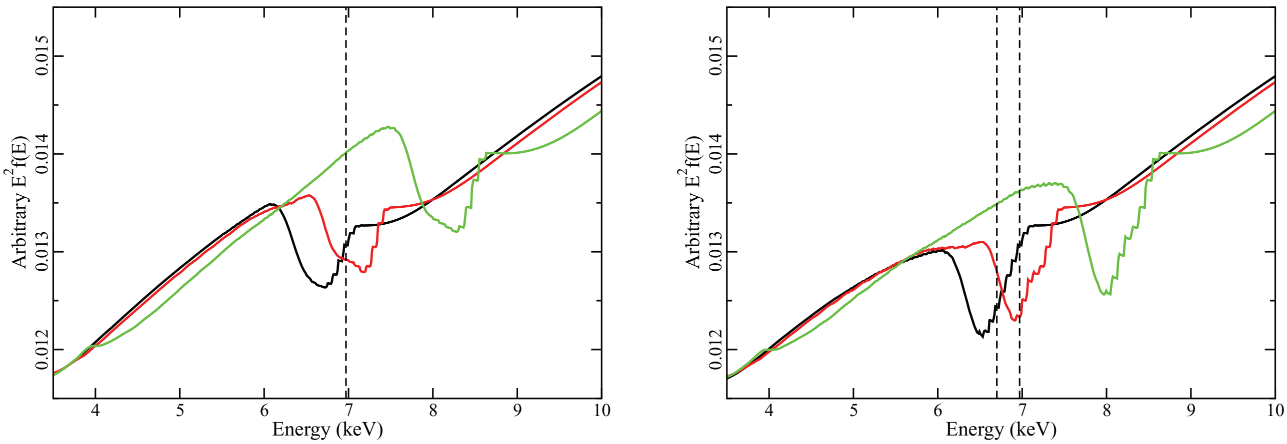

Figure 3. Left: the modification of the reflection spectrum due to Fe XXVI absorption that covers the entire disc. The black, red and green curves correspond to inclination angles of 0°, 30° and 60°, respectively. Right: same as the left, but with the absorption originating from Fe XXVI and Fe XXV. The vertical dashed lines mark the position of Fe XXV (6.7 keV) and Fe XXVI (6.97 keV).

neglected. When considering two lines, for simplicity we treat both features as equally strong.

We adopt a modest AGN spectrum for our trials. The power-law photon index is $\Gamma = 2$. The disc is ionized with $\xi = 100\,\mathrm{erg\,cm\,s^{-1}}$ and solar iron abundances (Morrison & McCammon 1983). The inner and outer disc edges are set at $r_{\mathrm{in}} = 1.25\,r_{\mathrm{g}}$ ($=1.25\,GMc^{-2}$) and $r_{\mathrm{out}} = 100\,r_{\mathrm{g}}$, respectively, and the emissivity index for the disc is $q = 3$. For each case considered, we simulate the appearance the spectrum could have when viewed during a 100 ks exposure with the *XMM–Newton* pn detector. The 2–10 keV flux is $\sim 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The simulated spectra and models are shown in the AGN rest frame.

3.1 Fully covered disc – blanket absorption

The first case examined builds on the situation in Fig. 1. We consider an accretion disc that is blanketed by the ionized plasma. The plasma has a line optical depth of $\tau = 1$ at all radii and is irradiated with the same emissivity profile as the disc. Fig. 3 depicts the spectrum for a plasma made up of H-like iron (left-hand panel) and both H- and He-like iron (right-hand panel) resonant absorption at different line-of-sight inclinations.

As seen in the left-hand panel of Fig. 3, such features can be shifted and appear significantly broad and deep as they blend with the iron absorption edge at 7.1 keV. In the case of Fe XXVI absorption viewed at 60° inclination, the feature can be redshifted well over 8 keV in the rest frame. In Fig. 4, we demonstrate how such a feature may appear in an *XMM–Newton* pn observation after one has presumably modelled the reflection spectrum correctly.

If absorption were attributed to Fe XXVI and Fe XXV, the situation would resemble the right-hand panel of Fig. 3. The lines would be blended due to relativistic broadening of each and would not be distinguished as two features.

3.2 Absorption in an annulus – variable inclination

In this section and in Section 3.3, we still adopt the lamppost model described above, but consider the situation in which the absorption is enhanced in a certain region above the disc effectively forming an annulus of absorbing material. This could originate from a hotspot above the disc illuminating a certain region, or anisotropies in disc leading to increased concentration of hot plasma, or enhanced structure in the disc that amplifies the reflection continuum. In the simulations shown in Fig. 5, the absorption is localized between 5 and 7 r_{g} from the black hole and viewed at different inclinations. Depending on the inclination, significant absorption lines can be seen between ∼5 and 8.5 keV in the rest frame. Detectable features are predicted in the *XMM–Newton* pn simulation (Fig. 6).

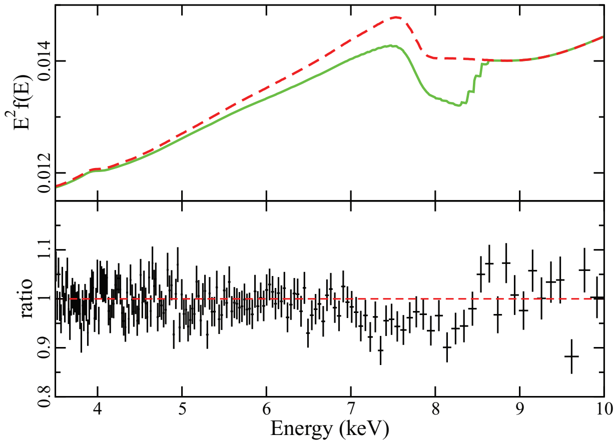

Figure 4. Upper panel: the green curve is the model corresponding to Fe XXVI absorption that covers a disc with an inclination of 60° (same as green curve in Fig 3). The red dashed curve is the absorption-removed model. Lower panel: the ratio between the two curves in the upper panel based on a 100 ks *XMM–Newton* simulation.

3.3 Absorption in an annulus – variable distance

The final situation examined corresponds to an absorbing annulus at various distances from the black hole. At distances less than ∼5–7 r_{g}, the absorption profile is rather blurred (see also Section 3.2), but as the distance increases and general relativistic effects are less dominant, Doppler effects prevail and the line profiles begin to take on the inverted disc line appearance. In Fig. 7, we examine a disc inclined 30° with absorption coming from different distances. The double-peaked profile becomes apparent at distances beyond ∼12 r_{g}. The blue edge of the profile is driven by the inclination of the disc and is shifted to higher energies as the disc inclination increases (see Fig. 2). The simulation in Fig. 8 depicts Fe XXVI

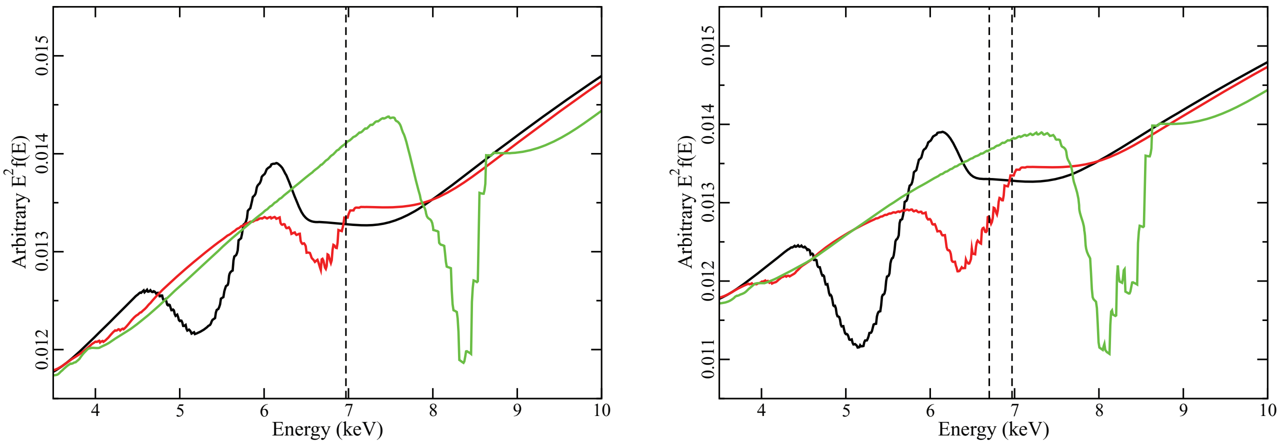

Figure 5. Left: the modification of the reflection spectrum due to Fe XXVI absorption that originates in a ring of material between 5 and 7 r_g. The black, red and green curves correspond to inclination angles of 0°, 30° and 60°, respectively. Right: same as the left, but with the absorption originating from Fe XXVI and Fe XXV. The vertical dashed lines mark the position of Fe XXV (6.7 keV) and Fe XXVI (6.97 keV).

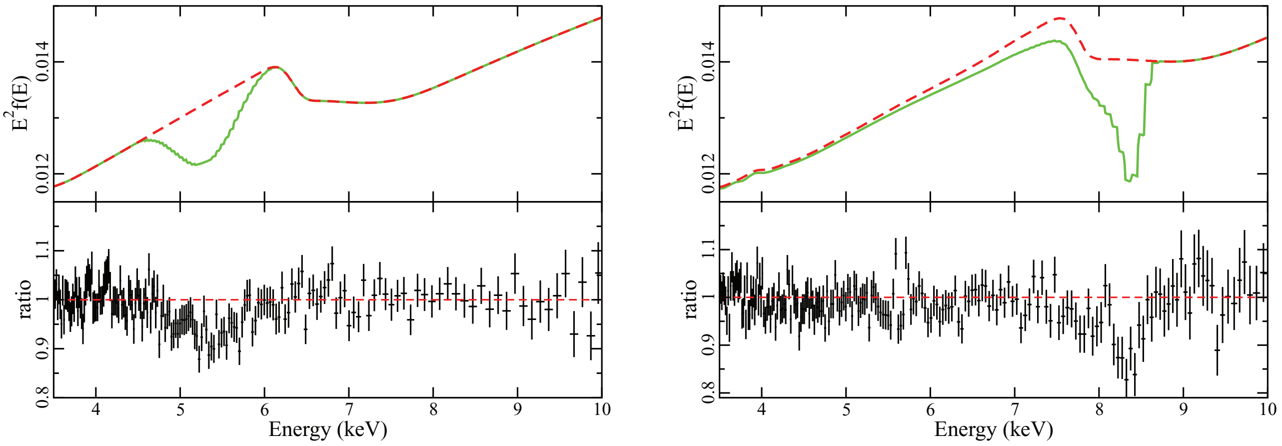

Figure 6. Left: in the top panel, the green curve is the model corresponding to Fe XXVI absorption from a ring between 5 and 7 r_g. The disc has an inclination of 0° (same as the black curve in Fig. 5, left). The red dashed curve is the absorption-removed model. In the lower panel, the ratio between the two curves based on a 100 ks *XMM–Newton* simulation is shown. Right: same as left, but for a disc inclination of 60°.

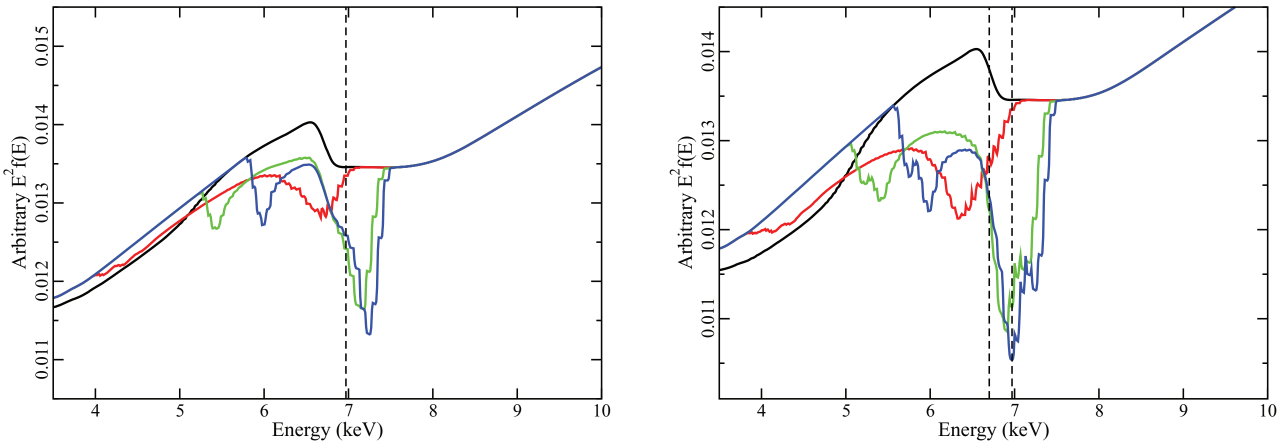

Figure 7. Left: the modification of the reflection spectrum due to Fe XXVI absorption in a ring of plasma arising at various distances along the disc. The black, red, green and blue curves correspond to rings at 1.25–3, 5–7, 12–13 and 20–21 r_g, respectively. The disc is inclined at 30°. Right: same as left, but with absorption arising from Fe XXVI and Fe XXV.

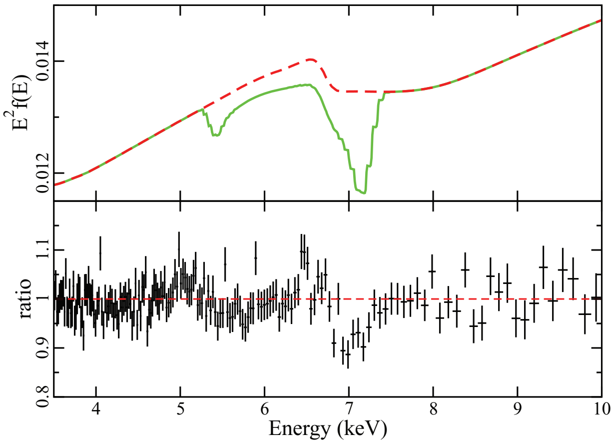

Figure 8. Upper panel: the green curve is the model corresponding to Fe XXVI absorption arising in a ring between 12 and 13 r_g and a disc inclination of 30° (green curve in Fig. 7). The red dashed curve is the absorption-removed model. Lower panel: the ratio between the two curves in the upper panel based on a 100 ks *XMM–Newton* simulation.

absorption from a ring between 12 and 13 r_g. The single feature could easily mimic multiple absorption features.

4 DISCUSSION AND CONCLUSIONS

We examine the possibility that narrow absorption features regularly observed in the spectra of AGN and attributed to fast, ionized inflows and outflows could arise naturally from resonant absorption of the reflection spectrum making use of velocities already present in the disc. We consider various geometries (e.g. rings and blankets) for the hot plasma that is corotating with the accretion disc and subject to the same kinematic and relativistic effects as the reflection spectrum. In all cases, we demonstrate that absorption features could be easily detected between ~4 and 9 keV in typical *XMM–Newton* observations. We note that the observed energy range could be significantly expanded by adding the contribution of other transitions (e.g. Fe XXVI Lyβ at $E = 8.25$ keV).

Notable from the simulations in Section 3 is that the absorption features are not genuinely narrow, but have significant width. However, the CCD resolution provided by current instruments limits our ability to distinguish features narrower than a few hundred eV. Calorimeter observations with *Astro-H* and *Athena* will likely be capable of resolving such features and thereby distinguishing models.

The work here is highly simplified and we only consider resonant absorption by Fe XXVI and Fe XXV. More complicated situations, in which elemental abundances are non-solar (or variable) and/or there exists greater diversity in composition of the plasma, are easy to envision. Line-of-sight effects are also treated simply here. If there is a composition gradient in the atmosphere, then long sightlines through the hot plasma (e.g. low inclinations) can produce very complicated spectra with many features (e.g. the spectrum of the X-ray binary GRO J1655−40; Miller et al. 2008). Long sightlines will also mean that different species experience different blurring effects and a specific species will be associated with a specific distance from the black hole. The purpose of this work was to demonstrate a concept, leaving more complex situations for further study.

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