

# The origin of blueshifted absorption features in the X-ray spectrum of PG 1211+143: outflow or disc

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Accepted 2013 June 14. Received 2013 June 13; in original form 2013 May 30

## ABSTRACT

In some radio-quiet active galactic nuclei (AGN), high-energy absorption features in the X-ray spectra have been interpreted as ultrafast outflows (UFOs) – highly ionized material (e.g. Fe XXV and Fe XXVI) ejected at mildly relativistic velocities. In some cases, these outflows can carry energy in excess of the binding energy of the host galaxy. Needless to say, these features demand our attention as they are strong signatures of AGN feedback and will influence galaxy evolution. For the same reason, alternative models need to be discussed and refuted or confirmed. Gallo and Fabian proposed that some of these features could arise from resonance absorption of the reflected spectrum in a layer of ionized material located above and corotating with the accretion disc. Therefore, the absorbing medium would be subjected to similar blurring effects as seen in the disc. A priori, the existence of such plasma above the disc is as plausible as a fast wind. In this work, we highlight the ambiguity by demonstrating that the absorption model can describe the  $\sim 7.6$  keV absorption feature (and possibly other features) in the quasar PG 1211+143, an AGN that is often described as a classic example of a UFO. In this model, the 2–10 keV spectrum would be largely reflection dominated (as opposed to power law dominated in the wind models) and the resonance absorption would be originating in a layer between about 6 and 60 gravitational radii. The studies of such features constitute a cornerstone for future X-ray observatories like *Astro-H* and *Athena+*. Should our model prove correct, or at least important in some cases, then absorption will provide another diagnostic tool with which to probe the inner accretion flow with future missions.

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

## 1 INTRODUCTION

Blueshifted absorption features in the X-ray spectra of some radio-quiet active galactic nuclei (AGNs) have been attributed to resonant K-shell absorption lines of iron (Fe XXV and Fe XXVI) that are seen in outflow (e.g. Nandra et al. 1999, 2007; Turner et al. 2002; Dadina et al. 2005; Longinotti et al. 2007). Many of these features are transient, seen only at one epoch or during some part of an observation, and their existence is debated on statistical grounds (Vaughan & Uttley 2008). However, other detections are more robust and have been observed on multiple occasions and/or with different instruments (e.g. Pounds et al. 2003; Reeves et al. 2009).

To be associated with Fe XXV or Fe XXVI some of these features have to originate in very high velocity winds (e.g.  $v \gtrsim 10^4$  km s<sup>-1</sup>) or even moving at mildly relativistic velocities ( $v \gtrsim 0.1c$ ) (e.g. Reeves et al. 2009; Tombesi et al. 2010; see Cappi 2006 for a review). The claimed detection of such ultrafast outflows (UFOs) are widespread. Tombesi et al. (2010) suggest that as much as

$\gtrsim 35$  percent of radio-quiet AGN may contain a UFO. These UFOs can be very important in AGN feedback and thereby for understanding galaxy formation and the origin of the  $M$ – $\sigma$  relation (Kormendy & Gebhardt 2001; Merritt & Ferrarese 2001). Therefore, alternatives to UFOs need to be discussed and refuted (or confirmed).

Gallo & Fabian (2011; hereafter GF11) propose that some blueshifted absorption features could arise in a plasma that is located above and corotating with the inner accretion disc (Ruszkowski & Fabian 2000), and is optically thick at the energies of the resonance lines of iron. Depending on the inclination and geometry of the plasma, narrow absorption features attributed to Fe XXV and Fe XXVI could be imprinted anywhere between about 4 and 10 keV (GF11). Presumably, some features could be seen at even higher energies if originating from other transitions like Fe XXVI Ly $\beta$ , with a rest energy at  $E = 8.25$  keV. The appeal of this model is that the plasma is subjected to velocities that are already present in the disc, and does not require an additional launching mechanism. This is not to suggest that disc winds are not present, but simply that the diversity of such X-ray features need to be better understood.

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In this work, we examine the quasar PG 1211+143 to illustrate the ambiguity. PG 1211+143 is a classic example of a UFO candidate. *XMM-Newton* EPIC observations in 2001 revealed a significant absorption feature at a rest-frame energy of  $\sim 7.6$  keV (Pounds et al. 2003). Later observations in 2004 and 2007 found a consistent feature at slightly lower significance (Pounds & Reeves 2009; Reeves & Pounds 2012). The line was interpreted as blueshifted He- or H-like iron with an outflow velocity of either  $\sim 0.13c$  or  $\sim 0.08c$ , respectively (Pounds et al. 2003). There were indications of other absorption features in the 2001 data between 1 and 3 keV that were attributed to ionized species of Ne, Mg and S, also originating in a high-velocity outflow. These low-energy features were reported neither in the later *XMM-Newton* observations nor in the *Chandra* LETG observation (Reeves et al. 2005). The iron feature may also be variable as it was not detected in a 2005 *Suzaku* observation (Gofford et al. 2013; but see Patrick et al. 2012). The high velocity of the outflow was questioned by Kaspi & Behar (2006) who argued that a much lower velocity ( $\approx 3000 \text{ km s}^{-1}$ ) was sufficient based on the ion-by-ion modelling of the *XMM-Newton* RGS spectra. However, the authors did acknowledge the poor signal-to-noise ratio of their spectra and did not rule out a much higher velocity.

Most recently Tombesi et al. (2011) constructed photoionization models using *XSTAR* (Kallman & Bautista 2001) to describe a number of UFO candidates. Specifically, with respect to PG 1211+143 they modelled the 2001 EPIC-pn spectrum between 4 and 10 keV with a highly ionized absorber with an ionization parameter<sup>1</sup> of  $\log \xi \approx 2.87$  and a column density of  $N_{\text{H}} \approx 8 \times 10^{22} \text{ cm}^{-2}$  outflowing at  $v \approx 0.15c$ . The model was consistent with that produced by Pounds & Page (2006). Adopting a mass of  $\sim 10^8 M_{\odot}$  for PG 1211+143 results in an outflow mass rate of  $\sim 5 M_{\odot} \text{ yr}^{-1}$  (Pounds & Page 2006; Reeves & Pounds 2012). Reeves & Pounds (2012) further demonstrate how the kinetic power is a significant fraction of the quasar bolometric luminosity ( $>10$  per cent) and can be a strong source of mechanical feedback in the host galaxy.

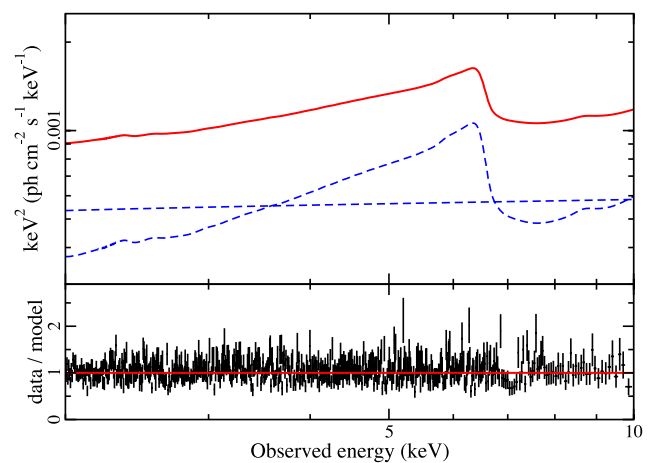
In this work, we present an alternative to the outflow model for PG 1211+143. Namely we describe the absorption feature as arising from resonance iron absorption close to the black hole where the plasma is subject to blurring effects (GF11).

## 2 A POSSIBLE MODEL FOR PG 1211+143

We modelled the 2001 *XMM-Newton* EPIC-pn spectrum of PG 1211+143 between 2 and 10 keV in order to focus on the significant absorption feature seen at about 7 keV ( $\sim 7.6$  keV in the AGN rest frame). The energy and width of the feature during other *XMM-Newton* observations are reported as being comparable to the 2001 measurements, but detected at lower significance. The works discussed above mainly fit this spectral region with an absorbed power law and, if necessary, a narrow, neutral Fe  $K\alpha$  emission line. Here, we fit the continuum with a blurred reflection plus power-law model (Ross & Fabian 2005). As with other works, for the time being, we ignore the spectrum below 2 keV where complications arise due to the soft-excess and distant ionized absorption/emission.

The model describes the spectrum rather well ( $\chi^2_{\nu} = 1.03$ ; Fig. 1). The power-law continuum has a photon index of  $\Gamma \approx 1.9$  and the ionization parameter of the disc is  $\xi \approx 290 \text{ erg cm s}^{-1}$  with an iron overabundance of  $\sim 5$  compared to solar. The blurring parameters

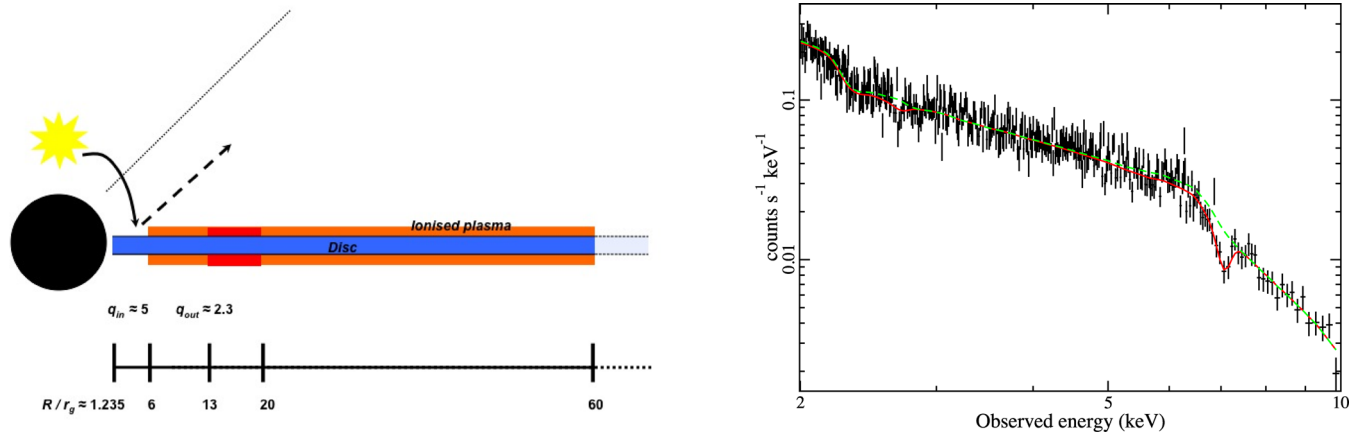
<sup>1</sup> The ionization parameter is  $\xi = L/nr^2$ , where  $L$  is the ionizing luminosity between 1 and 1000 Ryd,  $n$  is the number density of electrons and  $r$  is the distance of the gas from the ionizing source.



**Figure 1.** The 2–10 keV spectrum of PG 1211+143 is described with a blurred reflection plus power-law model. Upper panel: the model components (i.e. the power law and blurred reflector) are shown by the blue, dashed curves. The combined model is shown by the solid, red curve. Lower panel: the residuals (data/model) remaining when the model is fitted to the data. The model describes the spectrum well but does not account for the deviations at about 7 keV.

are typical compared to other type 1 AGN (e.g. Crummy et al. 2006; Walton et al. 2013). The disc is inclined at  $i \approx 35^\circ$  and the inner edge of the disc extends down to  $R_{\text{in}} \approx 1.5 r_{\text{g}}$  ( $1 r_{\text{g}} = 1 \text{ GM}c^{-2}$ ). The emissivity profile of the disc is represented by a broken power law where the inner profile is  $q_{\text{in}} \approx 5$  and flattens to  $q_{\text{out}} = 3$  beyond about  $6 r_{\text{g}}$ . Between about 2 and 10 keV the spectrum is dominated by the reflection component (Fig. 1, top panel). Despite the ionization parameter of the disc falling in the range where fluorescence is suppressed by resonant Auger destruction, the high iron abundance still allows production of a strong emission line and edge. The lower panel of Fig. 1 clearly shows the residuals remaining around 7 keV.

We now consider that this emission is exposed to resonance absorption as it emerges from the disc in a layer of highly ionized plasma that is corotating with the disc (GF11). The plasma is thus experiencing the same blurring as the reflection spectrum (Fig. 1). A reasonable model is found with continuum parameters that are similar to those described above. The power-law photon index is now  $\Gamma \approx 1.84$  and the ionization parameter of the disc is  $\xi \approx 284 \text{ erg cm s}^{-1}$ . Iron is still overabundant to the same degree (approximately five times solar), and the disc inclination is  $i \approx 45^\circ$ . The values of  $R_{\text{in}}$ ,  $q_{\text{in}}$  and the break radius ( $R_{\text{b}}$ ) remain comparable. The model also predicts a 15–50 keV flux of  $\approx 5.5 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ , which is comparable to that reported by Patrick et al. (2012) from *Suzaku* HXD measurements. The 7 keV absorption feature can be described as arising from Fe xxvi that is corotating with the disc beyond the break radius where the emissivity profile flattens. A cartoon illustrating the situation is presented in the left-hand panel of Fig. 2. The model overlaid on the spectrum is shown in the right-hand panel of Fig. 2. As can be seen, the feature is broad with absorption in the red wing extending down to  $\sim 5$  keV. Adding another absorption line at  $\sim 2.63$  keV and blurring it in the same environment can describe the deviations from the continuum at those energies. This particular feature would originate in a ring between about 13 and  $20 r_{\text{g}}$  from the central black hole. The line energy corresponds to absorption by H-like sulphur.

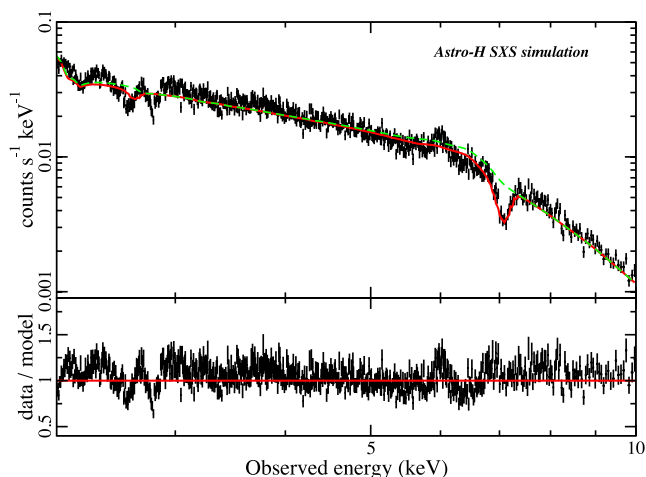


**Figure 2.** Left-hand panel: a cartoon illustrating the potential geometry of the inner accretion disc that could reproduce the 2–10 keV spectrum (right-hand panel). The disc is illuminated by the compact, primary emitter (i.e. the corona). Some light bending is occurring as evident by the steeper emissivity profile in the inner part of the disc. The emissivity profile flattens beyond about  $6r_g$  at which point a highly ionized plasma, that produces the Fe xxvi absorption, forms above the disc and extends several 10s of gravitational radii. A ring between 13 and  $20r_g$  could be the origin of the S xvi that produces the absorption at  $\sim 2.6$  keV. The black, dashed line is at a  $45^\circ$  angle and marks the line of sight of the observer. Right-hand panel: the spectral model (solid, red curve) resulting from the geometry described in the left-hand panel is overlaid on the 2001, 2–10 keV spectrum of PG 1211+143. The dashed, green curve shows the model without the resonance absorption features (effectively just the model shown in Fig. 1).

### 3 FUTURE OBSERVATIONS WITH *Astro-H*

The exercise in Section 2 demonstrates how a resonance scattering toy model can describe the 2–10 keV spectrum of PG 1211+143, a quasar that is often referred to as a classical example of a UFO AGN. The large effective area of current telescopes like *XMM-Newton* and *Suzaku* generates the required signal to detect such features, but the CCD resolution of the detectors does not typically provide the sufficient spectral resolution to distinguish various models. Specifically, the features in the outflow models are much narrower than the broad features in the absorption model.

*Astro-H* (Takahashi et al. 2012), to be launched in 2015, will be the first X-ray observatory to operate a microcalorimeter [Soft X-ray Spectrometer (SXS); Mitsuda et al. 2012] that will provide high spectral resolution in the 0.3–10 keV band. In Fig. 3, we present an SXS simulation of the outflow in PG 1211+143. The UFO model



**Figure 3.** Upper panel: simulated *Astro-H* SXS data of the UFO model from Tombesi et al. (2011) specifically for PG 1211+143. The solid and dashed curves represent the resonance absorption models, as in Fig. 2, overlaid on the simulated spectrum. Lower panel: the residuals (data/model) highlight the difference between the sharp, narrow features in the data and the broader features in the model.

is that of Tombesi et al. (2011) as described in Section 1 (the *xstar* model was kindly provided by F. Tombesi). The spectrum is a power-law continuum modified by outflowing wind. The turbulent velocity in the wind is  $5000 \text{ km s}^{-1}$ . A narrow ( $\sigma = 100 \text{ eV}$ ) Fe K $\alpha$  emission line is also included at  $\sim 6.5$  keV. Overlaid on the simulated data is the resonance absorption model from Fig. 2. The narrow features predicted by the wind model can be distinguished from broader features. In addition, *Astro-H* will have high-energy imaging between 5 and 80 keV that will allow us to accurately constrain the broad-band continuum that would differ between the blurred reflection and absorption models.

### 4 DISCUSSION AND CONCLUSIONS

The prospect of UFOs in AGN is exciting. In most cases, the estimated mass and energy output by the system are considerable, and if confirmed would have a prominent role in galaxy evolution. The nature of X-ray UFOs is diverse. In many cases, the signatures are marginally detected and transient. In some others, the perceived outflows are inconsistent with data at other wavelengths. Understanding the complex nature of outflows is necessary given the importance of these winds.

GF11 proposed that at least some UFO candidates could be explained by absorption (or scattering) of resonance lines in a plasma located above and corotating with the disc. In this way, the imprinted features would be subjected to blurring from motions of the disc. A priori, the existence of an ionized layer above the disc is as reasonable as a wind. The models are distinguishable in a number of ways. The blurred resonance absorption features would be broader than lines from an outflow. We would not expect to detect high velocities from discs at low inclinations, whereas an outflow might show high velocities at low inclinations unless it is equatorial. In addition, both models predict different continuum shapes and fluxes above 10 keV.

We show that this model can describe the features in PG 1211+143 very well, an AGN that is often referred to as a classic UFO example. The blurring and shifting is done with velocities that are already present in the disc itself. The feature in PG 1211+143

is rather pronounced compared to absorption features in other UFO candidates. This could indicate that the optical depth in the line is rather high and consequently could necessitate the inclusion of an absorption edge. However, precise measurement of the optical depth would depend on various factors like the column density, iron abundance and covering fraction of the absorber. Alternatively, the absorber could be arranged in ‘clumps’ of different densities and temperatures. This could help explain the different location of the sulphur feature inferred by the model. We fully realize that our model needs to be developed further and we are unable to make robust predictions at this time. These are all factors that are being considered in current work. Moreover, understanding the variability and transient behaviour is an open question for both the outflow and disc model. If the ionized plasma is tenuous, clumpy or occupies a small region of the disc then one may expect variability on dynamical time-scales.

In the near future, observations of UFO candidates with *Astro-H* will provide the means to distinguish the proposed models. Should our model prove correct then absorption will provide another diagnostic tool with which to probe the inner accretion flow with *Astro-H* and eventually *Athena+*.

## ACKNOWLEDGEMENTS

We would like to thank Francesco Tombesi for providing his outflow model for PG 1211+143. LCG would also like to thank Sherry Hurlburt and Dominic Walton for providing data. We thank the referee for providing a helpful report. ACF thanks the Royal Society for support.

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