Are ultrafast inflows in AGN truly rare - or just much harder to see?

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1 INTRODUCTION

X-ray spectra from an XMM-Newton observation of the luminous Seyfert galaxy PG1211+143 in 2001 first identified strongly blue-shifted absorption lines of highly ionized gas, corresponding to a sub-relativistic outflow with a velocity of 0.15±0.01c (Pounds et al. 2003; Pounds & Page 2006). A second example quickly followed with the detection of a powerful high velocity wind in PDS 456 (Reeves et al. 2003), with archival data from XMM-Newton and Suzaku subsequently showing that such ultra-fast, highly-ionized outflows (UFOs) are relatively common in nearby, luminous AGN (Tombesi et al. 2010, 2011; Gofford et al. 2013). While those archival searches typically reported a single velocity, in the few cases where an AGN was observed repeatedly, the wind velocity was often different. Mkn509 is the best example from the data archive, with wind velocities of ~0.173c, ~0.139c and ~0.196c, separated by 5 years and 6 months respectively (Cappi et al. 2009).

An extended 5-weeks XMM-Newton observation of PG1211+143 in 2014, covering 7 spacecraft orbits, showed a more complex velocity structure in the highly ionized wind, with three primary (high column density) outflow velocities of $v \sim 0.066c$, $v \sim 0.13c$ and $v \sim 0.19c$ (Pounds et al. 2016a), none being consistent with the wind velocity observed in 2001. In a review of continuum-driven or 'Eddington' winds, King and Pounds (2015) furthermore showed that the observability of an individual, short-lived wind ejection may be of order months or less, as an expanding shell presents a lower absorbing column to the nuclear x-ray source.

Considering the simultaneous observation of multiple expanding shells of absorbing gas in the context of super-Eddington accretion, Pounds, Lobban and Nixon (2017) noted that short-lived wind components might be a natural consequence of the way in which matter accretes in an AGN, typically falling from far outside the sphere of gravitational influence of the SMBH and with essentially random orientation. The resulting accretion stream will in general orbit in a plane misaligned to the spin of the central black hole (King & Pringle 2006, 2007), with the inner disc subject to Lense-Thirring precession around the spin vector, and orbits at smaller radii precessing sufficiently fast to cause the tearing-away of independent rings of gas.

Computer simulations by Nixon et al. (2012) furthermore showed that - as each torn-off ring precesses on its own timescale - two neighbouring rings will eventually collide, with the shocked material losing rotational support and falling inwards to a new radius defined by its residual angular momentum. A substantial increase in the local accretion rate might then allow a previously sub-Eddington flow to become briefly super-Eddington, with excess matter being ejected as a wind at or above the local escape velocity, as predicted in the classic paper on accretion disc theory by Shakura and Sunyaev (1973). For typical AGN disc parameters, Nixon et al. (2012) show the expected ‘tearing radius’ is of order a few hundred gravitational radii from the black hole - with predicted (escape) wind speeds in the range observed (King and Pounds 2015; fig 4a).

The detection of red-shifted X-ray absorption spectra during part of the same 2014 XMM-Newton observation of PG1211+143, corresponding to a substantial inflow of matter approaching the black hole at velocities up to ~0.3c (Pounds...
Figure 1. rev2659 soft x-ray spectral fit with continuum and photoionized emission features from the mean 2014 spectrum with the addition of: (top panel) blue-shifted absorption corresponding to a prevailing outflow velocity $v \sim 0.061c$; (mid-panel) red-shifted absorption from inflowing matter at $v \sim 0.096c$; (lower panel) combined blue- and red-shifted absorption components yielding an excellent overall spectral fit.
et al. 2018; hereafter Po18), offered the first observational support for the above accretion scenario. Simultaneous hard and soft X-ray spectra provided independent confirmation of the high inflow velocity, with the soft X-ray absorption indicating less ionized (higher density) matter embedded in the primary highly ionized flow. No further confirmed examples of an ultrafast AGN inflow have been reported, at least to this author’s knowledge, which is surprising in light of the above discussion. As noted in Po18, the probability of detecting such an extreme velocity inflow, close to the black hole, will be reduced both by a lower chance of a narrow converging flow being in the line of sight to the continuum source, and the likely short duration of the infall. Such considerations suggest a lower velocity, less highly ionized inflow, such as seen in PG1211+143, could offer a better opportunity for detection.

In the present paper we report a new analysis of the soft x-ray data from the Reflection Grating Spectrometer (RGS; den Herder et al. 2001) in the 2014 XMM-Newton observation of PG1211+143, separately identifying blue- and red-shifted absorption components. In addition to the relatively weak high redshift absorber (at $z = 0.43$), we confirm a stronger soft x-ray absorber at a redshift $z = 0.189$, corresponding to an inflow velocity $\sim 0.1 c$, and (free-fall) location at 200 R$_{g}$. We identify this absorption with matter lying ‘upstream’ of the ultrafast, highly ionized inflow reported in Po18, in the context of a line of sight along an accelerating flow converging on the black hole.

We assume a cosmological redshift for PG1211+143 of $z = 0.0809$ (Marziani et al. 1996), with a black hole mass of $4 \times 10^{7} M_{\odot}$ (Kaspi et al. 2000) indicating the historical bolometric luminosity is close to Eddington. All velocities are corrected for the relativistic Doppler effect. The spectral analysis is based on the software package described in XSPEC (Arnaud et al. 1996).

2 SOFT X-RAY ABSORPTION COINCIDENT WITH THE HARD X-RAY INFLOW IN PG1211+143.

In order to quantify the strong red-shifted absorption unique to the second orbit (rev2659) of the 2014 campaign, we start with the mean 2014 soft x-ray spectral profile of PG1211+143 published in Pounds et al. 2016b (Po16b), based on the sum of RGS1 and RGS2 data from all 7 XMM-Newton orbits (for a combined exposure of 1.27 Ms). Fitting the data over the 11-28 Â waveband, where the data are of highest statistical quality, the continuum is modelled by power law and black body components, both attenuated by the Galactic column. Strong positive and negative residuals were matched in Po16b with photoionized emission and absorption attributed to a circumstellar outflow. Details of the multiplicative absorption and additive emission grids used are also given in Po16b.

Here, we substitute the composite 7-orbit RGS data with that from rev2659, and repeat the spectral fit, retaining continuum and photoionised emission, with only the normalisation of each component left free. The blue-shifted absorption reported in Po16b is initially excluded, though we expect it to be present at some level throughout all 7 orbits. The fit is now quite poor, with $\chi^2$ of 554/436 over the 11-28 Â waveband.

In a second spectral fit (Figure 1; top panel), blue-shifted absorption is added, finding the primary (high column) outflow velocities of $\sim 0.06 c$ and $\sim 0.13$ reported in Po16b, with column density and ionization parameters listed in Table 1. This addition recovered a much improved fit, with $\chi^2$ of 485/432.

The data from rev2659 are next examined in the same way for red-shifted absorption. All 3 components mentioned in Pounds et al. 2018 are found, with column density, ionization parameter and redshifts listed in Table 1, together with their individual significance. The fit statistic has $\chi^2$ of 525/427, weaker than for the blue-shifted absorption alone, but still highly significant.

Finally, re-fitting the 7-orbit baseline emission model with both red- and blue-shifted absorption yields an excellent spectral fit ($\chi^2$ of 455/421), with the combined flows provide a better match, in particular to the complex of inner-shell Fe absorption lines (or UTA; eg Behar et al. 2001). For visual clarity in Figure 1 we confine the blue- and red-shifted spectral plots to the dominant flow component in each case.

In the context of the present paper we speculate that previous analyses of the soft x-ray spectra may well have missed a short-lived inflow in the presence of a stronger, more persistent outflow. We acknowledge that was the case in our analysis of the variable soft x-ray wind in PG1211+143 (Reeves et al. 2018), carried out before the highly ionised inflow detection at 0.3c was made.

3 DISCUSSION

The discovery of ultra-fast highly ionized outflows (UFOs) in early x-ray spectra of the narrow line Seyfert galaxy PG1211+143 (Pounds et al. 2003) and the luminous QSO PDS 456 (Reeves et al. 2003) opened up a new field of study of AGN, well suited to the uniquely high throughput of x-ray spectrometers on ESA’s XMM-Newton, launched in late 1999. King and Pounds (2003, 2015) noted that such winds are a natural result of a high accretion ratio, with excess matter being driven off by radiation pressure when the accretion rate exceeds the local Eddington limit (Shakura and Sunyaev 1973).

While this picture provided a satisfactory explanation of most UFOs, where a single detection yielded a unique wind velocity, the extended study of PG1211+143 in 2014 found a more complex outflow profile, with velocities of $\sim 0.06c$, $\sim 0.13c$ and $\sim 0.18c$ detected in the stacked data set. Such complexity was clearly inconsistent with a wind profile launched from a flat axi-symmetric disc (SST3), suggesting some intrinsic disc instability or rapidly variable accretion rate being introduced to the inner disc.

The detection of red-shifted X-ray absorption spectra during part of the same 2014 XMM-Newton observation of PG1211+143, where the extreme redshift ($\sim 0.48$) in highly ionized matter indicated absorption in a substantial inflow approaching the black hole at a velocity of $\sim 0.3c$ (Po18), offered the first observational support for such rapidly variable accretion. While the inflow observation was of high significance in only one of seven individual observations, inflows of lower column density and smaller redshift were detected in 5 of the other 6 EPIC pn observations, with redshifts
Table 1. Parameters of 3 red- and 2 blue-shifted soft x-ray absorption components from a spectral fit to the RGS data from rev2659. Each absorber is further defined by its ionisation parameter $\xi$ (erg cm s$^{-1}$) and column density $N_H$ (cm$^{-2}$).

| $\log \xi$ | $N_H$ (10$^{20}$) | redshift | $v_{in}$ | $\Delta \chi^2$ |
|-----------|-----------------|----------|---------|----------------|
| 2.58±0.15 | 11±4            | 0.189±0.001 | 0.095±0.001 | 17/3 |
| 3.42±0.18 | 40±43           | 0.172±0.001 | 0.080±0.001 | 12/3 |
| 0.76±0.23 | 8±4             | 0.433±0.002 | 0.28±0.01  | 9/3  |
| 0.85±0.18 | 4.2±2.1         | -0.052±0.001 | -0.131±0.001 | 13/3 |
| 1.32±0.08 | 8±4             | -0.0168±0.0005 | -0.0611±0.0005 | 65/3 |

ranging from 0.20 to 0.36 (and line-of-sight inflow velocities from 0.1 – 0.23c).

As noted in the Introduction, periods of highly variable accretion to the inner disc are a likely consequence of the way in which AGN accrete, where gas initially falls towards the SMBH with essentially random orientation. Lense-Thirring precession would cause misaligned orbits to precess around the black hole spin vector, with the innermost ring(s) warping and potentially breaking off. Collision between neighbouring rings, rotating at different rates, would then shock, with loss of rotational support leading to matter falling freely to a new radius defined by its residual angular momentum, where it may form a new disc (Nixon et al. 2012).

Our new soft x-ray analysis, reported here, shows both blue- and red-shifted photoionized absorption strongly affecting the soft x-ray spectrum of PG1211+143 during the 2014 XMM-Newton observations. The higher significance of the outflow components is in part due to the 7-fold greater exposure for a wind that persists throughout the XMM-Newton observation, with the outflow at $\sim 0.061c$ particularly strong (see also Reeves et al. 2018). In contrast, red-shifted absorption is limited to rev2659 and much diluted in the overall 2014 data.

We identify the soft x-ray inflow component at $\sim 0.433c$ with higher density matter surviving close to the primary, highly ionised inflow reported in Po18. While providing independent support of the primary $\sim 0.3c$ inflow, the accretion mass rate remains dominated by the highly ionised flow.

The strongest soft x-ray inflow component, at $\sim 0.095c$, is the most interesting and here we identify that slower moving and less highly ionized absorber with matter ‘upstream’ from the 0.3c inflow, with the correlation of ionization parameter and velocity being also indicative of a converging and accelerating inflow approaching the SMBH. In this important respect we differ from Reeves et al. (2018), where the absorption in rev2659 was discussed as a random cloud or filament crossing the line of sight. Assuming, as before, a free-fall velocity determined solely by the black hole’s gravity, the strong soft x-ray inflow is located at 200 R$_g$.

Splitting the $\sim$100ks observation into 5 equal time intervals finds both high and low ionisation absorbers present at similar strength throughout rev2659, showing the flow mass rate is maintained throughout the rev2659 observation. However, the high ionization, high column inflow is not detected in either preceding (rev2652) or following (rev2661) spacecraft orbits.

Po18 estimate an accretion rate during rev2659 for the highly ionized inflow of $\sim 10^{23}$ gm s$^{-1}$, yielding a luminosity of $\sim 10^{43}$ erg s$^{-1}$ for a mass/energy conversion efficiency $\eta \sim 0.1$, and lasting for $\sim 10^5$ s. In comparison, the mean bolometric luminosity of PG1211+143 is $\sim 10^{45}$ erg s$^{-1}$, with $\sim 10^{42}$ erg s$^{-1}$ arising from the inner disc region relevant here, suggesting a small number of infall events - similar to that observed - would make a significant contribution to the inner disc accretion rate, while remaking out of sight.

While the lower column density of a soft x-ray counterpart of the 0.3c inflow is of less significance to the overall accretion rate, detection of co-moving, higher density matter in the higher resolution RGS spectra provides valuable confirmation of that extreme velocity. In addition, the strongest red-shifted absorber provides an upstream measure of an accelerating stream of matter as it converges and becomes more highly ionized on close approach to the SMBH in PG1211+143. Most relevant in the context of the present paper, the slower and broader upstream inflow is likely to be easier to detect. A search for such soft x-ray inflows in new or archival XMM-Newton observations is highly recommended.

4 DATA AVAILABILITY

The data underlying this article are available in the XMM archive at http://nxsa.esac.esa.int/nxsa-web.

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