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The Variable High-Velocity Outflows Seen in X-Ray Spectra

Shai Kaspi[1]

[1]Physics Department, Technion, Haifa 32000, Israel
and
School of Physics & Astronomy and the Wise Observatory
The Raymond and Beverly Sackler Faculty of Exact Sciences
Tel-Aviv University, Tel-Aviv 69978, Israel
Email: shai@wise.tau.ac.il

Abstract. Several AGNs have been reported to have ultra-high velocity (UHV) outflows (of order $0.3 \gtrsim v/c \gtrsim 0.05$) that are detected in their X-ray spectrum. Re-visiting these outflow observations reveal that the spectrum has changed along with the claimed outflows. The luminous quasar PDS 456 is the brightest AGN in which a UHV outflow has been claimed to be present in its grating spectrum. We report on an *XMM–Newton* observation of this source, as well as analysis of past observations, which reveal its variable nature and the variable nature of UHV outflows. In this object, as well as in a few others, repeated observations failed to reproduce the previous absorption spectra. This indicates that variability is common among the UHV winds. A discussion of the reality, significance, and the interpretation of the UHV outflow phenomenon is presented. If UHV outflows exist, they might be a transiting phenomenon, as indicated from repeated observations, and this has to be taken into account when studying the influence of these outflows on the surrounding galaxy.

Keywords. galaxies: active, galaxies: nuclei, quasars: absorption lines, X-rays: galaxies

1. Introduction

High-resolution UV and X-ray observations carried out in the past decade have demonstrated the existence of outflowing material from AGNs (for reviews see, e.g., Crenshaw *et al.* 2003; Turner & Miller 2009). This outflowing material is seen in absorption lines which are detected in about 70% of low-luminosity AGNs (i.e., Seyferts). A few dozen low-luminosity AGNs have been observed so far with the grating instruments on board *Chandra* and *XMM–Newton*. Many of them show narrow absorption lines from many ions in different ionization levels of all H-like and H-like ions from carbon and oxygen, through magnesium and neon, and up to sulfur and calcium. Also, many L-shell and M-shell lines of iron at different ionization stages (Fe XII thorough Fe XXIII) are seen in these spectra. A key characteristic of these absorption lines is that in many cases they are blueshifted (relative to the AGN rest frame) by a few hundreds up to a few thousands of kilometers per second. The hydrogen column density of these absorbers is of order of 10^{22} cm^{-2}. Such outflows indicate a moderate stream of order of one solar mass per year going from the AGN into the surrounding galaxy.

In the past few years, several studies claimed to find ultra-high velocity (UHV) outflows in the X-ray spectra of AGNs. These outflows are claimed to have outflow velocities from about 15,000 km s^{-1} up to about 100,000 km s^{-1}. Most claims for these UHV outflows are based on detections of absorption lines around 7–9 keV in *XMM–Newton*/EPIC and *Chandra*/ACIS observations. These absorption features, when interpreted as blue-shifted Fe Kα absorption, are relativistic velocities (e.g., Mrk 509 – Dadina *et al.* 2005; IC 4329A

– Markowitz *et al.* 2006; MCG-5-23-16 – Braito *et al.* 2007). These UHV outflows are potentially very interesting as their outflowing mass is about two orders of magnitude larger than in the low-velocity outflows, and the output of kinetic energy is comparable to the bolometric luminosity of the AGN.

Only very few objects with UHV absorption were claimed to be detected using the gratings of *XMM–Newton*/RGS. These objects are: PG 1211+143 (Pounds *et al.* 2003a, 2005) with an outflow of $\sim 24,000$ km s^{-1}, PG 0844+349 (Pounds *et al.* 2003b) with an outflow of $\sim 60,000$ km s^{-1}, and PDS 456 (Reeves *et al.* 2003) with an outflow of $\sim 50,000$ km s^{-1}. Detection of absorption lines in outflow with grating spectra is of vital importance as one can detect numerous lines in several ions, enhancing the statistical significance of the detection.

However, for the grating spectrum of PG 1211+143, Kaspi & Behar (2006a) suggested an alternative interpretation in which the outflow is only about 3000 km s^{-1}. This was done by identifying the eight features that were identified by Reeves *et al.* (2003) as coming from different lines and by fitting the whole spectrum with a full absorption and emission model which was built using an ion-by-ion fit. This lower outflow velocity suggests that the mass outflow is two orders of magnitude lower than in the UHV outflow interpretation.

Also, repeated *XMM–Newton*/RGS and *Chandra*/LETG observations of PG 1211+143 did not show a relativistic absorber. Indeed, no absorption seemed to be reproduced in spectra from the different epochs, as was illustrated in detail by Kaspi & Behar (2006b). Pounds & Page (2006), however, claim that the outflow exists in repeated EPIC observations, and Reeves *et al.* (2005) claim that infall is indicated by the Fe Kα absorption line in one of the three consecutive LETG observations.

In a repeat study of the spectrum of PG 0844+349, Brinkmann *et al.* (2006) did not detect the claimed absorption lines, and a re-analysis of the same data set with the most recent detector calibrations did not confirm the earlier results.

Thus, the only reliable detection of UHV outflow with a grating instrument remains the observation of PDS 456. In order to confirm this detection, we carried out a second observation with *XMM–Newton* on PDS 456 during 2007 September. In the following section, I will describe the results from this new observation, and in §3 I will describe several issues related to the detection of UHV outflows and their consequences.

2. New X-Ray Observations of PDS 456

PDS 456 ($z = 0.184$) is the most luminous radio-quiet quasar in the local universe. Rapid X-ray variability was detected in this quasar in *RXTE* observations (Reeves *et al.* 2000), which indicates a very compact source of a few gravitational radii. The first *XMM–Newton* observation of 40 ks was carried out in 2001 February, and a UHV outflow with velocity of $\sim 50,000$ km s^{-1} was detected in the RGS spectrum by Reeves *et al.* (2003).

During 2007 September, PDS 456 was observed with *XMM–Newton* for two observations of 90 ks each. The two observations were taken in consecutive revolutions, so they are separated by two days. Comparison of the EPIC spectra of the two observations shows that PDS 456 varied significantly between the two observations. The average flux in the second observation is about half that of the first observation. Also, there is a spectral variation between the two observations in that the spectrum of the second observation is softer than the first observation (see Figure 1). Thus, this object demonstrates strong variations on time scales of days.

A comparison of the RGS spectra from the two new observations (Figure 2) reveals a flux variation of a factor of two over two days. Both spectra show narrow features that

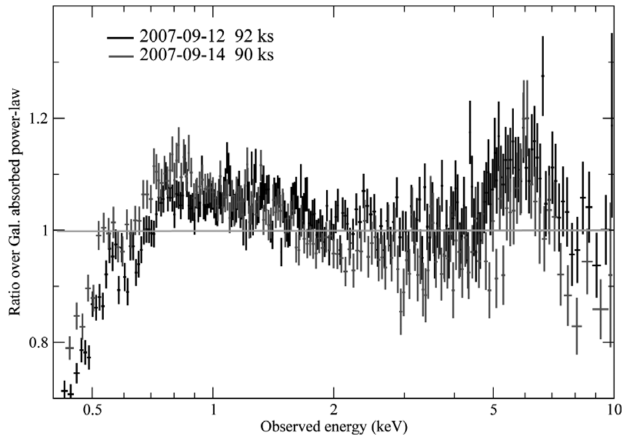

Figure 1. Ratio of the *XMM–Newton*/EPIC-pn 2007 X-ray spectra of PDS 456 to a power law with a spectral index of 2.

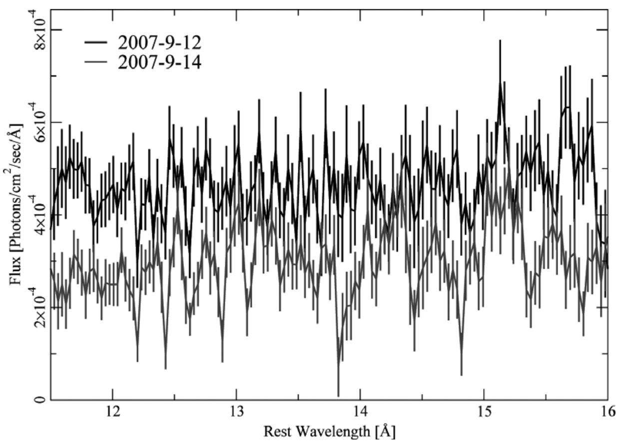

Figure 2. Comparison of the two RGS spectra of PDS 456 from 2007. The flux decreased by a factor of two between the two observations, which were separated by only two days. Each spectrum shows possible narrow features, but most of them are not reproduced in the other spectrum.

can be considered to be absorption lines. However, most of the features in one spectrum do not reproduce in the other spectrum and vice versa. Also, no identification for these features was possible with known ionic lines. Thus, either these are fast varying features, or that they are statistical fluctuations in the spectrum and are not real.

Figure 3 shows the RGS spectrum of the 2001 observation and illustrates the absorption from Fe L-shell absorption lines around rest-frame wavelength of 11–12 Å (Reeves *et al.* 2003). Superposing the first observation from 2007 shows that the deep absorption is not seen in the new observation. Although the two spectra are consistent overall, they differ in the small narrow features that do not seem to be reproduced after six years. The second observation from 2007 also does not show the absorption trough that was present in 2001. Since the absorption trough from 2001 is very strong and clear, it does not seem plausible that it is a result of low signal-to-noise ratio S/N or an identification error.

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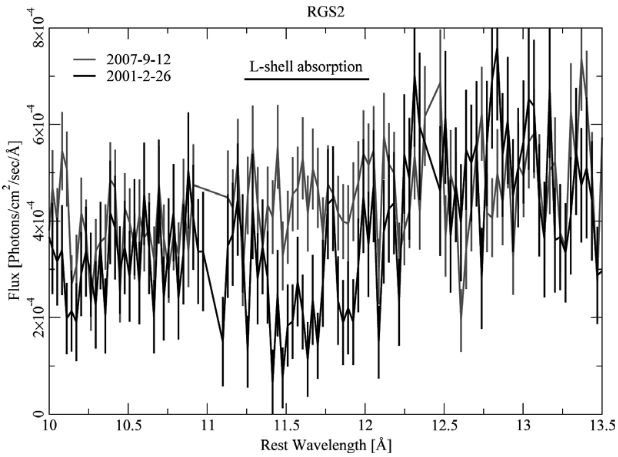

Figure 3. A comparison of two RGS spectra of PDS 456 taken 6 years apart. While the 2001 observations show strong Fe L-shell absorption, such absorption is absent in the 2007 observations, indicating the variable nature of this object.

The most plausible explanation is that PDS 456 varied in time and the strong Fe L-shell absorption lines that were present in 2001 have disappeared in the 2007 observations.

Figure 4 shows all X-ray observations of PDS 456 over the past decade with different observatories and instruments. Very clear spectral variation is seen in this object, as in every observation it has a different spectral shape. Behar *et al.* (2010) checked if all spectra can be explained by a partial covering outflow model that both absorbs and reflects the central source. This kind of model is flexible enough to produce a wide variety of spectra. The overall spectral curvatures of the different spectra can be reproduced by changing the partial coverage of the source between zero and one. However, this model is only partially successful as none of the spectral fits is statistically acceptable, and narrow features that are predicted by the models differ from the observed spectra. The viability of the partial covering model therefore remains inconclusive.

PDS 456 was observed with *Suzaku* at the beginning of 2007 for 190 ks, six months before the *XMM–Newton* observations (Figure 4). This *Suzaku* observation is described by Reeves *et al.* (2009), who find two statistically significant absorption features around 9 keV in the quasar rest frame. If these features are plausibly interpreted as blueshifted Fe XXVI Lyα lines at 6.97 keV in the rest frame, then this may indicate that the UHV outflow in PDS 456 is moving at near relativistic velocities ($0.26c$ and $0.31c$). These authors suggest that the iron K-shell absorption in PDS 456 is associated with a thick, possibly clumpy, outflow covering about 20% of the source. This model suggests that the kinetic power of the outflow may be similar to the bolometric luminosity of this quasar, and thus, such a powerful wind should have a significant effect on the co-evolution of the host galaxy and its supermassive black hole.

This absorption seems to be reproduced in some of the historical observations of PDS 456, but in some of them it is not seen (e.g., the 2007 *XMM–Newton* observations described above). Thus, it seems that the outflow, if it exists, has a varying nature (as also described above and by Kaspi & Behar 2006b for PG 1211+143), and this has to be taken into account when calculating the amount of matter that outflows over time and whether it is significant for influencing the AGN environment.

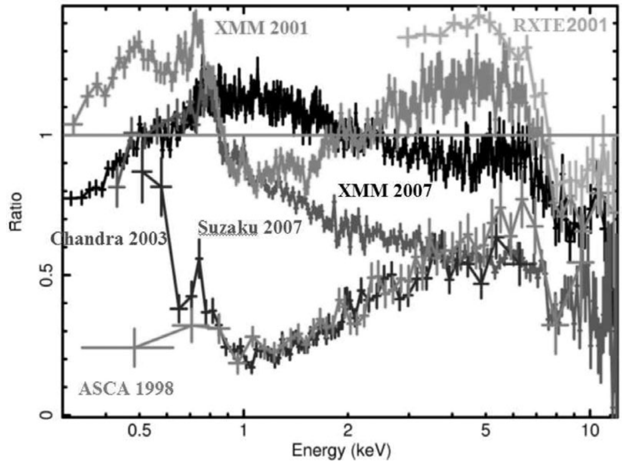

Figure 4. All X-ray observations of PDS 456 over the past decade with different observatories and instruments. Spectra are plotted as the ratio of the data to a Galactic absorbed power-law spectrum with photon index $\Gamma = 2$. For the *XMM–Newton* observation from 2007, an average of the two observations is shown. The strong spectral variation of this object is clearly seen.

3. Ultra-High Velocity Outflows?

As mentioned above in §1, many UHV outflows are detected in the X-ray using CCD spectra where absorption is seen around 7–9 keV. This absorption is interpreted as coming from the Kα line of highly ionized iron, and thus, UHV are found.

Vaughan & Uttley (2008) tried to study the significance of the reported detections of highly redshifted or blueshifted narrow spectral lines, both emission or absorption, in the X-ray spectra of AGNs. Their literature search revealed 38 reported detections of strongly shifted ($v \geqslant 0.05c$) X-ray lines. When they plotted the estimated line strength versus its uncertainty they found a linear relation in the sense that better observations (with smaller uncertainties) always show the smallest lines. This result is consistent with many of the reported lines being false detections that result from random fluctuations. Thus, they concluded that the reality of many of these features is in question.

In some EPIC observations, the background subtraction from the source needs special care, as it can have strong instrumental narrow emission lines at energies around 1.5 and 8 keV. These lines could introduce, by subtraction from the source, artificial absorption lines. Freyberg *et al.* (2004) investigated this background and found it is composed of a continuum and X-ray fluorescence lines, mostly at 1.5, 7.7, 8.0, 8.6, and 17.4 keV, which are due to Kα line emission of Al, Ni, Cu, Zn, and Mo, respectively (e.g., see discussion in Behar *et al.* 2010). The lines show strong spatial inhomogeneities correlated with the structure of the electronics board mounted below the EPIC CCDs. Thus, one needs to take extra care when dealing with such data so that no spurious lines will be introduced into the data at the energies in question for K-shell iron lines as UHV outflows.

Kallman *et al.* (2004) calculated the efficiency of iron K-shell emission and absorption lines in photoionized models using a new set of atomic data. They demonstrated that the effects of the many strongly damped resonances below the K ionization thresholds conspire to smear the edge, thereby potentially affecting the astrophysical interpretation of absorption features in the 7–9 keV energy band. Their model suggests many absorption lines in that energy band. It is plausible to postulate a scenario in which the broad and narrow Fe Kα emission lines around 6.4 keV are filling in the main absorption trough of iron around this energy, while the absorption detected in the 7–9 keV energy band is coming from Fe Kβ lines of highly ionized iron, thus requiring no outflow velocity. For example, Figure 14b of Kallman *et al.* (2004) shows that absorption in the Fe Kβ region is stronger than the absorption in Fe Kα. This is due to the proximity of the Fe Kα lines to different ions on one hand, and the spread of the Fe Kβ lines from different ions on the other hand.

Combining all above three factors put in question the reality, interpretation, and significance of many of the absorption lines in the 7–9 keV energy band. These lines, if they exist, should be a great challenge to modelers.

4. Summary

While moderate low-velocity outflows of order hundreds to thousands of kilometers per second are common in low-luminosity AGNs, the nature of the claimed UHV outflows remains unclear. Repeated grating observations of objects with detected UHV outflows do not reproduce, in most cases, the same results, as shown above for PDS 456 (Behar *et al.* 2010) and in the case of PG 1211+143 (Kaspi & Behar 2006b). Currently there are no good repeated grating observations that indicate an UHV outflow in any object. Also, the claimed detections of lines at energies around 7–9 keV, which are interpreted as coming from Fe Kα and thus yielding relativistic velocities, may come from a different line and/or ion, which might not indicate such high velocity. High-resolution spectroscopy is urgently needed in that energy band in order to resolve the interpretation of the absorption and the existence of UHV outflows. Even if UHV outflows exist, they seem to be a transient phenomenon, as indicated from the repeated observations, and this should be taken into account when studying the influence of these outflows on the surrounding galaxy.

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