X-ray Observations of Ultra Fast Outflows in AGN

James Reeves (UMBC/Keele)
Main Collaborators: - Emanuele Nardini (Arcetri), Michele Costa, Andrew Lobban (Keele), Valentina Brainto, Gabi Matzeu (Brera), Jane Turner (UMBC), Francesco Tombesi (GSFC/UMD), Stuart Sim (Belfast), Ken Pounds (Leicester)
Outflows from Active Galactic Nuclei

**Introduction** – Observations of winds in Active Galactic nuclei and the discovery of ultra fast outflows.

**Case Study 1** – The powerful, wide angle, disk wind in the luminous quasar PDS 456. What are the outflow energetics? Revealing the outflow variability and structure. Possible driving mechanism

**Case Study 2** – The large XMM-Newton campaign on the nearby narrow line quasar, PG 1211+143. Observations of a rapidly variable accretion disk wind. The soft X-ray signature of the fast wind.

**Discussion** – statistics and occurrence. Energetics and role in feedback. What are the signatures of the fast outflow? Driving mechanism and acceleration.
Discovery of Accretion Disk Winds in AGN

- Initial discovery in PG 1211, PDS 456 and APM 08279 (Chartas et al. 2002).
- Disk winds simulations of Sim et al. (2010), Proga & Kallman (2004). Produces blue-shifted Fe K absorption
- Also MHD wind models (Ohsuga & Mineshige 2011, Fukumura et al. 2015).

![Graph showing ratio vs. observed energy (keV) and channel energy (keV)]

- PG 1211+143, z=0.0809 (Pounds et al. 2003)
- PDS 456, z=0.184, (Reeves et al. 03)
Powerful disc winds are naturally expected at high accretion rates:

\[ \dot{M}_{\text{out}} v_{\text{out}} \sim \frac{L_{\text{Edd}}}{c} \]

\[ v_{\text{out}}/c = 0.1 \]

\[ P_{\text{kin}} \sim 0.05 L_{\text{Edd}} \]
16/47 objects found to have significant Fe K absorption (in 20/61 spectra). => 4 have absorption in more than one obs, w/ evidence for variability (e.g. PDS456)

<table>
<thead>
<tr>
<th>Lines No.</th>
<th>Fe XXV+Fe XXVI (same V out)</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe &lt;XXV</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Fe XXVI only</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

| Multi V out systems | 2 |

Mrk 766 (NLS1, z=0.0129)

Suzaku Outflow Sample (Gofford et al. 2013)

Note - statistical significance of absorption lines in all cases tested from Monte Carlo simulations
Outflow velocity of $0.25-0.30c$, if associated with Fe XXV/XXVI resonance lines (at 6.7-6.97 keV).
Suzaku Outflow Sample (Gofford et al. 2013, 2015)

• 20/51 AGN found to have significant iron K absorption (18/51 at >99% significance from Monte Carlo).

• This corresponds to 28/73 of the fitted X-ray spectra (or 40%). The absorption line systems break down as follows:
  - 9/28 systems likely associated with Fe XXVI Lyα
  - 4/28 with Fe XXV or lower ionization.
  - 12/28 associated with at least 2 lines due to Fe XXV and Fe XXVI.
  - 3/26 may have multiple velocity systems.

• Overall 12/20 of the AGN have outflow velocities >10000 km/s of which 8 have v>0.1c. Only 3/19 are consistent with no-net velocity-shift.

• Mean ionization parameter, log $\xi=4$, column log $(N_H/\text{cm}^{-2})=23$
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<table>
<thead>
<tr>
<th>v_{out}/c</th>
<th>Number of sources</th>
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<tr>
<td>0.00</td>
<td>10</td>
</tr>
<tr>
<td>0.05</td>
<td>8</td>
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<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>0.35</td>
<td>1</td>
</tr>
</tbody>
</table>

1 at >99%

Fe XXVI.

n/s of velocity-
How powerful are disk winds?

$\log(\dot{M}_{\text{out}} / \dot{M}_{\text{edd}})$

Major uncertainties: launch radius + solid angle

Gofford et al. 2015, Sample of iron K outflows with Suzaku
How powerful are disk winds?

The detection of narrow, blueshifted X-ray absorption lines does not provide any solid constraint on the total energetics of a wind

\[ \dot{M}_{\text{out}} \sim \Omega N_H m_p v_{\text{out}} R_{\text{in}} \]

★ Solid angle: frequency of BH wind signatures among local AGN

★ Column density: modelling of absorption by photo-ionised gas

★ Outflow velocity: line’s energy shift following identification

★ Launch radius: ionisation state of the gas and escape velocity

It is still unclear whether disk winds have sufficient mechanical energy to power feedback on galactic scales
**PDS 456: the Rosetta Stone of AGN disk winds**

Most luminous radio-quiet AGN in the local Universe

\[ M_B \sim -27 \quad L_{\text{bol}} \sim 10^{47} \text{ erg s}^{-1} \quad M_{\text{BH}} \sim 10^9 M_\odot \]

Systematic detection of a deep trough above 7 keV rest-frame: evidence for a large column of highly ionised matter outflowing at about one third of the speed of light

Ideal target for studying BH winds in the Eddington-limited regime

2013/14 campaign: 5 simultaneous *XMM* + *NuSTAR* observations
The Wide Angle UFO is the Quasar PDS 456

- **XMM-Newton**
- **NuSTAR**

Rest-frame energy (keV) vs. Flux (10^{-12} erg s^{-1} cm^{-2})

- Kβ
- K edge

Nardini+15, Science
A persistent, wide-angle wind

P-Cygni-like profile resolved at any epoch (aperture > 50° from FWHM)

Apparent response to continuum changes over 7-10 days
Some relevant numbers

\[ \dot{M}_{\text{out}} \sim \frac{\Omega}{4\pi} \times \frac{N_H}{10^{23} \text{ cm}^{-2}} \times \frac{v_{\text{out}}}{c} \times \frac{R_{\text{in}}}{10^{15} \text{ cm}} \ M\odot \text{ yr}^{-1} \]

All the information can now be determined from the data

The solid angle is obtained from the emitted/absorbed luminosity ratio, and the launch radius from the variability timescale

\[ \dot{M}_{\text{out}} \sim 10 \ M\odot \text{ yr}^{-1} \Rightarrow P_{\text{kin}} \sim 2 \times 10^{46} \text{ erg s}^{-1} \sim 0.2 \ L_{\text{bol}} \]

The deposition of a few % of the total radiated energy is enough to prompt significant feedback on the host galaxy (Hopkins & Elvis 10). Over a lifetime of \(10^7\) yr the energy released through the accretion disk wind likely exceeds the binding energy of the bulge

\[ E_{\text{wind}} \sim 10^{61} \text{ erg} \sim 3 \times M_{\text{bulge}} \sigma^2 \]
One Year in the Life of PDS 456… (Matzeu et al. 2016)

XMM/NuSTAR 2013 Obs A (Aug 2013)

XMM/NuSTAR 2014 Obs E (Feb 2014)

(Feb-March 2013)

Suzaku 2013a - Exp 190 ks

Suzaku 2013b - Exp 164 ks

Suzaku 2013c - Exp 108 ks

Energy (keV)

$E_{\text{F}}$ Flux (keV cm$^{-2}$ s$^{-1}$)
Variability of Wind velocity in PDS 456 (Matzeu et al. 2017)

Centroid energy of iron K absorption appears to increase with increasing luminosity over 12 XMM/NuSTAR/Suzaku observations from 2001-2014.

Wind velocity increases with ionizing luminosity (as $L_X^{1/4}$)

May be explained in terms of radiative driving in the Eddington limited regime.
Signatures of fast (0.15c) “BAL” like profiles in soft X-rays with XMM-Newton/RGS. Velocity widths $\sigma \approx 10000$ km/s.
Soft X-ray absorbing gas the likely signature of an inhomogeneous wind, partially obscuring the AGN. Velocities of up to 0.2c. Absorption primarily due to highly ionized Fe (Fe XX-XXIV) as well as NeIX/X.
Figure 2: Comparison between the two HST observations of PDS 456. The red one was taken in May 2000 with STIS, the blue one in April 2014 with COS. There is a remarkable flux variability over this decade. Notably, in the lower state the broad Lyα absorption trough looks much shallower. The behavior of the optical/UV flux is therefore fundamental to understand the properties and fate of the SMBH X-ray wind at larger scales.

At the same time, these observations will allow us to derive a preliminary slope for the power spectral density of PDS 456. Together with the already available Swift and XMM–Newton data, the coverage in frequency space could be enough to test for a broken power law shape. The break energy is known to correlate with the SMBH mass (McHardy et al. 2006, Nature, 444, 730), no measure of which is available for PDS 456 to date.

3. Justification of Requested Observing Time, Feasibility, and Visibility

The simultaneous monitoring of optical/UV and X-ray fluxes is fundamental to understand the relation between the accretion disk and the X-ray corona in AGN, and Swift is unrivalled to perform this kind of study. The recent Suzaku and XMM–Newton/NuSTAR programs have proven that one week is the typical timescale to detect significant spectral changes. On top of that, all the historical X-ray light curves of PDS 456 exhibit plenty of sharp flares, during which the flux increases by factors of \( \sim 3–5 \) in about a day. These flares have an undoubtedly intrinsic origin (Matzeu et al. 2015, submitted). By the light-crossing time argument, the steep flux rise observed in a flare poses stringent constraints on the size of the X-ray corona, which should not exceed a few tens of gravitational radii. Since the absorption-induced

Figure 3: In spite of the very different range of flux variability observed over weeks/months in the optical/UV and X-ray bands (\( \sim 10% \) against 600%), the emission from the accretion disk and from the X-ray corona in PDS 456 are clearly related. Even the most extreme X-ray states are consistent with the optical/UV emission once corrected for absorption, returning the correct accretion rate (\( \sim 0.8 \)). The combined data sets are from XMM–Newton/OM (blue, August 2013), Suzaku (black, March 2013) and NuSTAR (red, February 2014) observations, fitted with the energetically self-consistent optxagn model by Done et al. (2012).

and intrinsic variations occur with clearly different timescales, the best approach to disentangle the two effects is to combine short- and long-term monitoring into a single campaign.

During cycle 12, PDS 456 is not visible for Sun constraints from October 28, 2016 to January 28, 2017. This leaves a continuous visibility window of more than 6 months from April 2016. We then request to perform the proposed monitoring during this period, for a total span of 26 weeks. We request a 2-ks snapshot every week with (reasonably) exact spacing, plus a more intense sampling over two consecutive weeks with two additional pointings (separated by 2 or 3 days) in order to better explore the frequent short-term flares. As the flares are almost ubiquitous, there is a large chance of finding at least one of them with 7 visits over any period of 14 days, which can be chosen freely according to the mission schedule. In summary, the campaign will consist of 30 observations (26 plus 4) of 2-ks exposure each. Moon constraints are fully compatible with the suggested monitoring strategy.

Considering the average flux state of PDS 456, we expected at least 400 counts per observation in the X-ray spectrum, which are enough to determine with good accuracy the spectral slope and reveal the presence of the X-ray wind.

Very broad UV emission profiles, e.g. Lyα / C IV 12000-15000 km/s. Highly blueshifted, CIV=5000 km/s.

Broad absorption trough bluewards of Lyalpha or highly blueshifted CIV?
The XMM-Newton Large Programme on PG1211+143
(Lobban et al. 2015, 2016; Pounds et al. 2016a, b)

PG 1211+143, luminous ($L_{\text{bol}} \sim 10^{46}$ erg/s), nearby, narrow-lined type I quasar (z=0.0809), the initial proto-type example of an ultra fast outflow (Pounds et al. 2003).

Ultra Fast Fe K Outflow in The Quasar PG 1211+143

600ks observation of PG 1211 from XMM/2014 campaign.

Spectrum shows a wealth of high ionization absorption lines from Fe XXV and Fe XXVI.

The line profiles are fitted with a disk wind model (Sim et al. 2008, 2010), with two streamlines at different radii/velocities:

Wind launch radius of $R_{\text{min}} = 64R_G$ and $250R_G$

Resultant wind terminal velocities of $v = 0.07c$ and $0.14c$ (consistent with analysis in Pounds et al. 2016).

Overall wind parameters in 2014:-
Mass outflow rate $M_{\text{out}} / M_{\text{Edd}} = 0.72 \pm 0.13$
Ionization $L_X / L_{\text{Edd}} = 3\%$, inclination = 57°.
Is there evidence for the fast outflow in the soft X-ray spectrum of PG 1211? Mean RGS spectrum (June 2014, 600ks exposure)

Blue-shifted absorption profiles revealed in deep RGS exposure of PG 1211+143, e.g. from N, O, Ne, Fe. Systematic velocity shift of 0.06-0.07c.
Note position of low ionization UTA component and strong emission (OVII/OVIII).
Comparison between XMM-Newton (RGS) spectra of the QSOs PG 1211+143 (z=0.0809) vs MR 2251-178 (z=0.064)
MR 2251–178 (z=0.064)

Slow Wind (<0.01c)

Rest Wavelength (Å)
PG 1211+143 (z=0.081)

Soft band comparison – note also the presence of broad soft X-ray emission lines (e.g. OVII and OVIII) in addition to the blueshifted absorption.
MR 2251−178 (z=0.064)
Rapid Variability of Ultra Fast Outflow in PG 1211+143

Soft X-ray absorber not a conventional warm absorber. Fast (0.07c) and rapidly variable on timescales of < 1 week. Implies absorber is compact, on scales of 10s Rs, likely part of clumpy disk wind.
Variability of PG 1211 wind seen in RGS spectrum

![Graph showing variability of PG 1211 wind seen in RGS spectrum with Rest Wavelength (Å) on the x-axis and ratio on the y-axis.]
Variability of PG 1211 wind seen in RGS spectrum

Rest Wavelength (Å)

ratio

Ne IX/X  Fe UTA  O VIII  O VII  N VII

REV 2659
Variability of PG 1211 wind seen in RGS spectrum

Rest Wavelength (Å)

ratio

1.5
1
0.5

Ne IX/X  Fe UTA  O VIII  O VII  N VII

REV 2661

Rest Wavelength (Å)
Variability of PG 1211 wind seen in RGS spectrum

Ne IX/X  Fe UTA  O VIII  O VII  N VII

Rest Wavelength (Å)
Variability of PG 1211 wind seen in RGS spectrum

Rest Wavelength (Å)

ratio

Ne IX/X  Fe UTA  O VIII  O VII  N VII

REV 2664
Variability of PG 1211 wind seen in RGS spectrum

Rest Wavelength (Å)

Ratio

Ne IX/X  Fe UTA  O VIII  O VII  N VII

REV 2666
Variability of PG 1211 wind seen in RGS spectrum

![Graph showing variability in the RGS spectrum of PG 1211. The graph plots ratio against rest wavelength (Å), with peaks at Ne IX/X, Fe UTA, O VIII, O VII, and N VII labeled. The graph includes a line at ratio 1.0 labeled REV 2670.](image-url)
Variability of Soft X-ray Wind Zones in PG 1211 vs XMM orbit.

abs 1
$\nu \sim 0.062c$
$log \xi \sim 1.2$

abs 1a
$\nu \sim 0.062c$
$log \xi \sim 3.1$

abs 3
$\nu \sim 0.13c$
$log \xi \sim 0.7$
Absorber rapidly responds to the level of the soft X-ray excess below 2 keV on timescales of ~2 XMM orbits (about 300ks). Opacity is inversely proportional to the continuum. Wind is clumpy and multi-phase, lowest ionization phase is most compact ($\Delta R \sim 10^{14}$ cm) on scales of $R \sim 10^{17}$ cm.
Innermost highly ionized wind launched from within 100 $R_g$ ($10^{16}$ cm) of black hole – ultra fast iron K absorption (0.3c).

Inhomogeneous soft X-ray absorber $R \approx 10^{17}$-$10^{18}$ cm, $n_e \approx 10^7$-$10^8$ cm$^{-3}$, with thickness $\Delta R \approx 10^{15}$ cm. Filling factor $f \approx 10^{-3}$.

UV BLR emission (absorption) profiles $R \approx 10^{18}$ cm – high velocity CIV in UV.
Discussion

What is the statistical occurrence of the outflows. Is their still any doubt about their detection and origins?

How can we measure accurately the energetics of the winds and are they likely to be significant for feedback?

What is the evidence for the ultra fast outflows aside from at iron K?

What is the driving mechanism for the disk wind? Radiation, Magnetic driving or both? What is the role of the clumpy gas, is it needed to accelerate the gas?

Future - What is the occurrence of the winds amongst the higher luminosity (or higher redshift) QSOs.