X-ray evidence for ultra-fast outflows in local AGNs

Francesco Tombesi

NASA/GSFC/CRESST, Greenbelt, MD (USA)
University of Maryland, College Park, MD (USA)

Main collaborators: M. Cappi, J. Reeves, R. Sambruna, C. Reynolds, V. Baito, G. Palumbo, M. Dadina, T. Yaqoob, R. Mushotzky

AGN Winds in Charleston, SC, Oct. 15-18 2011
• Spectral analysis of the radio-quiet AGNs sample (Tombesi et al. 2010a)

• Photo-ionization modeling and global parameters (Tombesi et al. 2011a)

• Location and energetics of ultra-fast outflows (Tombesi et al. 2011c, MNRAS submitted)

• Ultra-fast outflows in radio-loud AGNs (Tombesi et al. 2010b)

• Follow-up on 3C 111 (Tombesi et al. 2011b)

• Astro-H simulations

• Conclusions
Blue-shifted Fe XXV/XXVI absorption lines suggest presence of highly ionized and mildly relativistic X-ray outflows in radio-quiet AGNs (e.g. Chartas et al. 2002, 2003; Pounds et al. 2003; Dadina et al. 2005; Markowitz et al. 2006; Braito et al. 2007; Turner et al. 2008; Cappi et al. 2009; Reeves et al. 2009, …)

Possible direct connection with accretion disk winds/outflows and important contribution on AGN feedback

Need for a systematic analysis on a large sample of sources
The sample of local radio-quiet AGNs

- Selection of all NLSy1, Sy1 and Sy2 ($N_H < 10^{24} \text{cm}^{-2}$) in RXTE All-Sky Slew Survey Catalog (complete at 90% at 4$\sigma$ limiting flux $10^{-11} \text{erg s}^{-1} \text{cm}^{-2}$ in 4-10keV; Revnivtsev et al. 2004)

- Cross-correlation with XMM-Newton Accepted Targets Catalog (as of October 2008)

- Total of 42 sources for 101 pointed XMM-Newton observations

- Local ($z < 0.1$)

- X-ray bright ($F_{4-10\text{keV}} = 10^{-12} - 10^{-10} \text{erg s}^{-1} \text{cm}^{-2}$) (Tombesi et al. 2010a)
Fe K-shell absorption lines search

**Ultra-Fast Ouflows (UFOs):** highly ionized X-ray absorbers with outflow velocities $v \geq 10,000$ km/s (soft X-ray warm absorbers $v < 1000$ km/s)

**Uniform spectral analysis of EPIC pn:**
- Phenomenological baseline model in the 4-10keV: absorbed power-law + Gaussian Fe K emission lines
- Checked consistent results including more complex spectral components (e.g., reflection, warm absorption)

**Blind absorption/emission lines search:**
- Addition of narrow line to baseline model stepping energy in 4-10keV and recording $\Delta \chi^2$ deviations
- Visualization on energy-intensity contour plots (F-test significance >68% red, >90% green, >99% blue)
- Initial selection of narrow ($\sigma < 100$ eV) lines with F-test confidence levels >99%
- 14 absorption lines $E = 6.4-7.1$ keV and 22 at $E \geq 7.1$ keV
- Identification with Fe XXV/XXVI 1s-2p/1s-3p transitions and derived relative velocity shift
Global blue-shifted absorption lines significance

• Additional significance test on lines at E=7.1-10 keV with Monte Carlo simulations
• Selection of 22 with MC confidence level >95%
• Checked no contamination from EPIC pn background and calibration
• Only marginal model dependence results
• Detection of lines with blue-shift >10,000km/s (UFOs) in ~40%-60% of the sources
• Random probability detection in 21 observations out of 101 is <10^{-8} (>5σ)
• Consistency check and confirmation of 12/22 detections (>90%) with MOS, global random probability <10^{-7}
• Solved the claimed publication bias (Vaughan & Uttley 2008)
### Photo-ionization modeling Fe XXV/XXVI absorption lines

<table>
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<tr>
<th>Ion</th>
<th>ID</th>
<th>Transition</th>
<th>〈E〉 (eV)</th>
<th>Line</th>
<th>E (eV)</th>
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<td>Fe XXV</td>
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from NIST atomic database

- Curve of growth analysis of Fe XXV/XXVI absorption lines: EW vs. \( N_\text{H} \), \( \log \xi \), b (km/s)
- Fe ions populations derived from Xstar simulations and lines Voigt profile integration (Tombesi et al. 2011a)
Photo-ionization modeling Fe XXV/XXVI absorption lines

- Fe XXV dominates for \( \log \xi = 2.5 - 3.5 \), Fe XXVI dominates for \( \log \xi > 3.5 \) erg cm/s
- Calculated average Seyfert 1 SED from NED, \( \Gamma = 2 \) and cut-off \( E \sim 100 \text{keV} \)
- Calculated Xstar photo-ionization grids with Solar abundances and turbulent velocities of 1000, 3000, 5000 km/s
- Four absorption lines resolved with width \( \sigma \sim 5000 \text{km/s} \), others only upper limits
Photo-ionization modeling Fe XXV/XXVI absorption lines

\[ v = 0.092 \pm 0.04 \text{c}, \quad \log \xi = 4.19 \pm 0.23, \quad N_H = (1.9 \pm 1.2) \times 10^{23} \text{cm}^{-2} \]

- Blind search for Xstar solution(s) stepping redshift between 0.1 and -0.4, min \( \chi^2 \)
- Fits self-consistently take into account lines and edges from ions of all elements
- If two equivalent solutions, averaged parameters and included identification errors
- Fits significance >99% and only one Xstar component needed each time
Global parameters of UFOs in radio-quiet AGNs

- UFO detected in >40% of the sources, large covering fraction ~0.5
- Variability in EW and velocity on time-scales even of ~days, compact absorbers
- Mildly-relativistic outflow velocities, distribution ~0.03-0.3c, with mean ~0.14c
- Highly ionized, log \( \xi \)~2.5-6 erg s\(^{-1}\)cm, with mean ~4.2 erg s\(^{-1}\)cm
- Large column densities, \( N_\text{H} \)~\(10^{22}-10^{24}\)cm\(^{-2}\), with mean ~\(10^{23}\)cm\(^{-2}\)

(Tombesi et al. 2011a)
Location and energetics of UFOs in radio-quiet AGNs

- $r_{\text{max}} = \frac{L_{\text{ion}}}{\xi N_H}$, $r_{\text{min}} = \frac{2GM_{\text{BH}}}{v^2}$, $d \sim 0.0005-0.05 \text{pc} \sim (10^{-2}-10^{4}r_s)$, **accretion disk outflows**

- $M_{\text{out}}/C > M_{\text{acc}}$. For $M_{\text{out}} \sim M_{\text{acc}} \sim 0.2M_{\odot}/\text{yr}$, filling factor $\sim 10-20\%$, **clumpy and/or intermittent**

- Mechanical power $\sim 10^{43}-10^{44} \text{erg/s} \sim L_x \sim 5-10\% L_{\text{bol}}$, integrated $\sim 10^{59}-10^{60} \text{erg}$

- Potentially important for AGN energetic budget and cosmological **feedback**

- **Comparable/higher feedback than jets?** UFOs **massive, mildly-relativistic, wide angles, mechanical power \sim jets, \sim 40\% sources** and also in radio-loud AGNs

(Tombesi et al. 2011c, MNRAS sub.)
Broad Line Radio Galaxies are the radio-loud counterpart of Seyfert 1s.
Show relativistic radio jets, but $i \sim 20^\circ$ allows observation of the inner disk.
Limited long observations in X-ray archives to five local ($z<0.1$) sources:
- 3C 111
- 3C 390.3
- 3C 120
- 3C 382
- 3C 445

(Tombesi et al. 2010b)

Systematic 4-10keV spectral analysis Suzaku.
Same method for radio-quiet with XMM-Newton.
Search for blue-shifted Fe K absorption lines.
Blue-shifted Fe K lines at $E>7$keV in 3/5 sources.
Each absorption line significant at >99% with F-test and Monte Carlo simulations.
Background and XIS consistency checks.
Check broad-band XIS+PIN (0.5-50keV) including reflection and warm absorption.
Ultra-fast outflows in radio-loud AGNs

- **3C 111**: Fe XXVI Lyα, Lyβ, Lyγ, Lyδ series, v=0.041±0.004c. Random probability ~10^{-8}
- **3C 120**: Fe XXV Heα + Heβ and Fe XXVI Lyα + Lyβ, v=0.076±0.003c. Random probability ~10^{-4}
- **3C 390.3**: Fe XXVI Lyα, v=0.146±0.004c. Random probability ~10^{-3}
- Physically self-consistent photo-ionization modeling with Xstar, lines ratios suggest saturation
- High ionization log $\xi$=4-6 erg s^{-1}cm, mildly-relativistic v=0.04-0.15c, high columns $N_H > 10^{22} \text{ cm}^{-2}$
Ultra-fast outflows in radio-loud AGNs

Ultra-fast outflows in BLRGs:

• Common, detected in 3/5 sources
• Compact and close to the BH, d<0.01-0.1pc
• Covering fraction roughly ~0.5, similar to Seyferts
• Mildly relativistic, v~0.1c
• Massive, $M_{\text{out}} \sim 1 M_{\odot}$ yr$^{-1} \sim M_{\text{acc}}$
• Powerful, $E_k \sim 10^{44}-10^{45}$ erg/s ~ radio jet power
• Energetically significant, $E_k \sim L_x \sim 0.1L_{\text{bol}}$
• Possibly important contribution to AGN feedback
• $L_{\text{bol}}/L_{\text{Edd}} \sim 0.1-0.5$, wind/photon momenta $(M_{\text{out}} v_{\text{out}})/(L_{\text{bol}}/c) \geq 1$
• Acceleration through radiation and/or magnetic forces?
• Connection with ejection of knots in the jet? Outbursts?

(Ohsuga et al. 2009)
Accretion disk-outflow connection in 3C 111 with Suzaku

Follow-up on 3C 111: 3x60ks Suzaku observations in Sep. 2010 to monitor predicted UFO variability on ~7 days (Tombesi et al. 2011b)

- 30% flux variability between Obs1 and Obs2
- 4-10 keV XIS spectral analysis, power-law continuum $\Gamma \sim 1.7$ and 6.4keV Fe K
- Detection emission line $E=6.88$keV in Obs1, absorption line $E=7.75$keV in Obs2
- High significance, >99.9% from F-test and Monte Carlo simulations
- Constancy emission/absorption lines excluded at 99.7% and 99.9%
Accretion disk-outflow connection in 3C 111 with Suzaku

**Obs1**
- Ionized relativistic disk line (relline profile)
- Emission from Fe XXV/XXVI
- Bulk reflection accretion disk at ~20-100rg
- Inclination ~18°

**Obs2**
- Ultra-fast Outflow (Xstar modeling)
- Velocity $v_{\text{out}} = 0.106\pm0.006c$
- $\log \xi = 4.32\pm0.12 \text{ erg s}^{-1}\text{cm}$, Fe XXV/XXVI
- $N_H = (7.7\pm2.9)\times10^{22} \text{ cm}^{-2}$
Accretion disk-outflow connection in 3C 111 with Suzaku

• Variability ~7 days, d<0.006 pc (compact absorber)
• Ionized reflector, ~20-100 $r_g$, Compton-thick

Ultra-fast Outflow $v \sim 0.1c$, $M_{out} \sim 1M_{\odot} \text{yr}^{-1} \sim M_{acc}$

$E_K \sim 5 \times 10^{44} \text{erg/s} \sim 0.5 L_x \sim 0.06 L_{bol}$, ~radio jet power

$L_{bol}/L_{Edd} < 0.3$, $(M_{out} v_{out})/(L_{bol}/c) \sim 1$

Evidence accretion disk-outflow connection

• Disruption/over-ionization inner accretion disk
• Outflow lifted at ~100 $r_g$, acceleration by radiation pressure?
• Superluminal and ~18°, possible plasma additional magnetic acceleration?

Under investigation

• Connection with radio jet? External layers, collimation, shocks? (e.g., Chattergee et al. 2011)
  (X-ray spectroscopy potentially capable study jet related phenomena on distances <0.1 milliarcsec resolution of VLBA images)
• Coupling between accretion disk, outflows and jets? (e.g., GRS 1915+105 Neilsen & Lee 2009)
• Role on AGN cosmological feedback? Additional monitoring required!
Astro-H micro-calorimeter simulations

3C 120 Astro-H 100ks (v_turb=1000km/s, Feb 2006)

3C 111 Astro-H 100ks (v_turb=1000km/s, Aug 2008)

3C 111 Astro-H 100ks (Obs1 Sept. 2010)

3C 111 Astro-H 100ks (Obs2 Sept. 2010)
Conclusions

- Highly ionized and mildly-relativistic outflows are common (>40%) in both radio-quiet and radio-loud AGNs
- Directly connected with accretion disk winds
- High outflow rate suggest a synergy between accretion and ejection processes
- Large covering fraction (~0.5), clumpy and/or intermittent (filling factor ~10-20%)
- Mechanical power ~5-10% $L_{bol}$, potentially important for AGN feedback
- Important improvements from higher effective area and energy resolution in Fe K band from Astro-H and especially Athena

Several still open questions, such as:

- What is the duty cycle and actual filling factor of UFOs?
- What triggers the ejection of UFOs? Similar to jets? Need long-term monitoring and different wavebands, X-ray, Optical-UV, radio (e.g., Chatterjee et al. 2011)
- What is their main acceleration process, radiation and/or magnetic? The same in RL and RQ?
- What is their connection with the jet in radio-loud sources?
- What is their detailed feedback impact on the surrounding environment?
- What is the possible connection with outflows in other bands? e.g., Soft X-ray, UV
Thank you
Check on EPIC pn absorption lines significance

- **Sigma vs. counts distribution** UFO absorption lines means they are fake? (Assuming constant EW) (LEFT)
- **Abs** E=6.4-7.1keV (green dots), E>7.1keV (red stars), Emi ionized E=6.5-7keV (blue triangles)
- **Simulation** 4-10keV counts 3-300x10^3, randomly variable EW=20, 40, 60eV and E=7,8,9keV (black squares)
- **The three distributions are consistent and agree with the simulations!** (RIGHT)
- **No problem** with E>7.1keV (UFO) absorption lines, it means they are variable in EW and E, as observed.
Consistency check on EPIC pn and MOS

- Systematic more significant detection UFO abs lines in EPIC pn w.r.t. MOS means they are fake? (LEFT)
- Abs 6.4-7.1keV (green dots), >7.1keV (red stars), Emi 6.4keV (black dots), ionized 6.5-7keV (blue triangles)
- **All the four distributions are consistent and show more significant pn detections compared to MOS!** (RIGHT)
- No problem with E>7.1keV (UFO) absorption lines.
- MOS lower effective area: combined effective area MOS 1+2 is ~20% pn at E>7keV
- MOS higher background: background/source ratio MOS is ~10x higher pn at E>7keV