The Importance of Mass Outflows for AGN Feedback

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Why do we think AGN outflows are important?

• AGN feedback is thought to play a crucial role in:
  – formation of large-scale structure in the early Universe (Scannapieco & Oh 2004; Di Matteo et al. 2005).
  – chemical enrichment of the intergalactic medium (Khalatyan et al. 2008).

• **AGN winds**: wider angles than jets with lower velocities (up to ~4000 km/s in nearby AGN, up to ~0.1c in BAL QSOs).

• Do AGN winds provide effective feedback?

• Here we concentrate **UV/X-ray absorbers** and **narrow-line region (NLR) outflows** in moderate luminosity \((10^{43} - 10^{45} \text{ erg s}^{-1})\) Seyfert galaxies.
UV and X-ray Absorbers

- Blueshifted UV (C IV, N V) absorption components detected in ~60% of Seyfert 1 galaxies at outflow velocities up to 4000 km s\(^{-1}\).
- The same AGN typically show X-ray “warm absorbers” with higher ionization lines (O VII, O VIII).
Absorbers show variable ionization (U).

- Space Telescope Imaging Spectrograph (STIS) UV spectra
- Measure ionic columns, use photoionization models to get U, N\(_H\)
- Variable ionization \(\rightarrow\) recombination time \(\rightarrow\) density \(\rightarrow\) location
Result: Most absorbers are between the BLR and NLR

How do the absorbers contribute to AGN feedback?

- Compute detailed photoionization models for each absorption component.
- Determine radial locations (or limits) for components from variability and/or excited-state absorption.
- Determine mass outflow rates and kinetic luminosities for each component, then add them up.

\[
M_{\text{out}} = 4\pi r N_H \mu m_p C_g v_r \quad (C_g = 0.5, \mu = 1.4)
\]

\[
L_{KE} = \frac{1}{2} M_{\text{out}} v_r^2
\]

\[
\dot{M}_{\text{acc}} = \frac{L_{\text{bol}}}{\eta c^2} \quad (\eta = 0.1)
\]
Most of the outflowing gas must originate outside of the inner accretion disk (or the disk would quickly dissipate.)

These outflows are not accretion disk winds (although we have not included ultrafast outflows [UFOs], Tombesi et al. 2011, 2013).

Result: Mass Outflow Rates >> Mass Accretion Rates

Result: Kinetic luminosity up to ~5% bolometric luminosity.


Most are close to $L_{\text{KE}} = 0.5\%$ to $5\% \ L_{\text{bol}}$, which is required by AGN feedback models (Hopkins & Elvis 2010).

$\rightarrow$ Absorbers contribute significant feedback in moderate luminosity AGN.
$\rightarrow$ They may not be effective at low luminosities ($< 10^{43}$ ergs s$^{-1}$).
Large-Scale Outflows in the Narrow Line Region (NLR) → What is their impact?

They occur on the same scales as nuclear star formation ($\leq 1 \text{ kpc}$), so could be crucial for $M_* - \sigma_*$ relation.
How do we model the NLR outflows? (based on HST STIS spectra)

(Das, et al. 2005)
How do we determine mass outflow rates in the NLR?

- STIS long-slit, low-dispersion spectra of emission lines along the slit.

- Photoionization models also give density law: \( n \sim r^{-1.7} \) for NGC 4151 (Kraemer et al. 2000).
Prescription for Mass Outflow in the NLR of NGC 4151


- **Mass ~ L [O III]/n_H** (Osterbrock & Ferland 2006). Use long-slit spectra to get the scale factor).

- Determine **mass** in each bin and sum along each annulus.

- STIS moderate-dispersion spectra and kinematic models to determine **velocity** law.

- $v \sim r$ to a turnover point at ~100 pc, followed by a linear decrease provides a good fit (Das et al. 2005, AJ, 130, 945).
Mass Outflow in the NLR of NGC 4151 (preliminary)

\[
M_{\text{out}} = \frac{\Delta M v(r)}{\Delta r},
\]
(where \(\Delta r = 8.6\) pc)

\[
L_{KE} = \frac{1}{2} M_{\text{out}} v^2
\]

- Evidence for in situ acceleration/mass loading of gas in the NLR.
- **Mass outflow rate** at peak is \(~5\) times that of the UV/X-ray absorbers (\(~200\) times the accretion rate).
- **Kinetic luminosity** at peak = \(2.5 \times 10^{41}\) erg s\(^{-1}\) cm\(^{-2}\) \(\approx 0.4\% L_{\text{bol}}\), comparable to that of the UV/X-ray absorbers.

New project: STIS spectra and WFCP2/WFC3 images of 10 Seyferts in HST archives
Conclusions

- UV/X-ray absorbers and NLR clouds are outflowing in nearby AGN on scales of 0.1 – 1000 pc.
- Absorber mass outflow rates can be 10 – 1000 times the accretion rates.
  - Most of the outflow originates outside the accretion disk. Most of the infalling gas likely gets blown out.
- Kinetic luminosities of the absorbers can be 0.5% to 5% of the bolometric luminosities.
  - They likely provide significant feedback in these AGN.
- NLR outflows may provide even more feedback.
  - at scales appropriate for termination of star formation.
The End
Direct evidence for feedback?

In situ acceleration of gas off host disk

Fischer et al. 2010
Near-infrared Integral Field Spectrometer (NIFS)

- Only available on Gemini North
- Spectral Resolving Power ~ 5000 over 3” x 3” at ~ 0.1” angular resolution
- Spectra in Z (0.9 – 1.1µm), J (1.1 – 1.3µm), H (1.5 – 1.8µm), and K (2.0 – 2.4 µm) bands
- Works with adaptive optics system ALTAIR using natural or laser guide stars
- For AGN, access to:
  - [S III] emission in Z band to map ionized gas in the NLR
  - H₂ emission lines in K band to map warm molecular gas
  - CO bandheads in H and K bands to map stellar kinematics and determine gravitational component of motion.
NGC 4151: NIFS Velocity-Channel Maps

[S III] emission: → Outflows

H₂ emission: → Reservoir of fueling flow

(Storchi-Bergmann et al. 2010)
Mrk 3: [S III] Observations with NIFS (preliminary)

(Fischer et al., in preparation)

→ Slightly greater inclination than predicted by STIS model.
Using NLR kinematics to determine AGN inclinations
Column density increases with polar angle

- Ionized column increases with $\theta$ up to $\sim45^\circ$.
- Smooth transition to neutral column from “torus”.
  - Connection between wind and torus?

Fischer et al., in preparation.
Mid-IR color changes with polar angle.

Spitzer IRS $F(5\mu m)/F(30\mu m)$ increases with decreasing $\theta$, as hot throat of torus becomes more visible.
Absorbers show variable column densities ($N_H$)

Some absorbers show bulk motion across the BLR with transverse velocities up to several thousand km s$^{-1}$. 
from T. Fischer

$0^\circ$

from pole on
from T. Fischer

20° from pole on

- Blue

+ Red

Top

Bottom
from T. Fischer

40° from pole on
60° from pole on

from T. Fischer
80° from pole on

from T. Fischer
Narrow-Line Region Kinematics: NGC 1068

(Das, et al. 2006)