AGN Kinematics

• BLR profiles and kinematics
• Outflows seen in Absorption (AGN Winds)
• Emission-Line Outflows in the NLR
BLR Profiles and Kinematics

- Wide variety, many with bumps
- Many BLRGs have double-peaked profiles (after subtraction of NLR)

What is the BLR?
- bloated (irradiated) stars?
- surface of accretion disk?
- clouds in an outflowing wind?

Need more information on, size, geometry, and kinematics
➔ Use variability and reverberation mapping

(Peterson, p. 69)
Lags for Different Emission Lines


FWHM \approx r^{-0.5}

- Suggests gravitational motion (or at least 1/r² force)
- But radiation pressure could be important (Marconi et al. 2008)
Determining the kinematics directly $\rightarrow$ (Radial) velocity-dependent $\Psi$

$$L(v,t) = \int_{-\infty}^{\infty} \Psi(v,t)C(t-\tau)d\tau,$$

where $L(v,t)$ is the velocity-dependent profile


- Determine $\Psi(v,\tau)$ observationally and compare with models
- A few projects claim success, but no clear consensus yet
  (severe data requirements!)
Outflows in AGN: Types
1) Jets in Radio-Loud Galaxies and Quasars

- Highly collimated, low density plasma traveling at relativistic speeds
2) Broad Absorption-Line (BAL) Quasars

- Blueshifted absorption troughs extending up to ~0.2c
- Observed in ~10% of radio-quiet quasars
- Possibly occur in most quasars, covering ~10% of the AGN sky

3) Quasar “Associated Absorption”

- Discovered as excess absorption lines near z of quasar ($z_{\text{abs}} \approx z_{\text{emis}}$)
- Narrow absorption (FWHM < 300 km s$^{-1}$) within 5000 km s$^{-1}$ of $z_{\text{emis}}$
- Mostly blueshifted, which indicates outflow from nucleus

Not to be confused with absorption at $z_{\text{abs}} << z_{\text{emis}}$:

a) Ly$\alpha$ Forest - intervening clouds in the intergalactic medium

QSO1422+23, $z_{\text{emis}} = 3.62$

(Rauch, 1998, ARAA, 36, 267)

b) “Metal-line” systems - intervening galaxies and their halos

(Peterson, 1997, An Introduction to AGN, p. 201)
4) “Intrinsic Absorption” in Seyfert Galaxies


- Originally detected in optical spectra of NGC 4151 (Oke & Sargent 1968)
- Blueshifted He I and H I Balmer lines \( (n_e > 10^8 \text{ cm}^{-3} \rightarrow \text{rare in Seyferts}) \)
- UV absorption in resonance lines much more common (~50% of Seyferts)
Types of UV Absorption Lines - Summary

1. Galactic: Milky Way disk and halo (“high velocity clouds”)
2. Intervening ($z_{\text{abs}} << z_{\text{emis}}$)
   - Metal-line systems (“damped Ly$\alpha$”): galactic halos and disks
   - “Ly$\alpha$ forest”: IGM clouds (also some O VI, other high-ionization lines)
3. Seyfert “intrinsic” absorption lines
   - Mass outflow: up to ~4000 km s$^{-1}$ (probably related to QSO associated)
   - Intrinsic to host galaxy (very narrow, within 300 km s$^{-1}$ of galaxy $z$)
4. Quasar narrow absorption lines (“NALs”): FWHM $\leq$ 300 km s$^{-1}$
   - “Associated”: mass outflow up to 5000 km s$^{-1}$
   - “High-velocity NALS”: mass outflow up to 50,000 km s$^{-1}$
5. Quasar Broad Absorption Lines
   - Hi-BALs: velocity widths > 2000 km s$^{-1}$, outflow up to ~0.2$z$, high-ionization lines (C IV, N V, etc.)
   - Low-BALs: same as above, plus Mg II and other low-ionization lines
   - Mini-BALs: velocity widths between ~500 and 2000 km s$^{-1}$
IUE/HUT Observations of Intrinsic UV Absorption

IUE discovered absorption spanning a wide range in ionization (O I to N V)

HUT extended the ionization range to O VI, in the far-UV

Ulrich (1988) found that 3 - 10% of IUE Seyferts have intrinsic absorption

60% of Seyfert 1 galaxies show intrinsic absorption; those that show UV absorption also show X-ray absorption.

Global covering of the continuum source and BLR: $C_g = 0.5 - 1.0$

Most absorbers are highly ionized (C IV, N V); only 10% show Mg II
HST/STIS High-Resolution Spectra

NGC 4151

[Image of NGC 4151]

[Graph showing velocity versus different lines]

[Image showing high-resolution spectra]
Multiple outflowing components detected in UV and far-UV. Similar velocity coverage for X-ray absorbers; however X-ray absorbers have higher ionization parameters (U) and column densities (N$_H$). Comparison of UV doublets indicates partial covering of BLR in some cases. Mass outflow rates can be 10 to 1000x the accretion rates (Crenshaw et al. 2012)
5) X-ray “Warm Absorbers” in Seyferts

- Confirmed by ASCA detections of O VII and O VIII edges (see above)
- Mathur (1994) claimed a connection between X-ray and UV absorbers
- Blueshifted absorption lines seen by Chandra confirmed outflow

Chandra 900 ks Spectrum of NGC 3783

How do we get more Info? → Variability Monitoring

- Nearly all Seyfert 1 galaxies with intrinsic UV absorption show components with variable equivalent widths (EWs)
- Sources of EW (or ionic column density) variations:
  1) Variations in the ionizing continuum flux (variable U)
  2) Transverse motion of cloud across the BLR + continuum (variable N_H or covering factor in the line of sight)
- **Variable ionizing continuum**: can determine density (n_e) and distance from source (r) from time scale of variability (t)
  \[ n_e \approx \frac{1}{\alpha \ t_{\text{rec}}} \]
  \[ U = \frac{\int_{v_0}^{\infty} L_v / h \nu \ dv}{4\pi r^2 c \ n_e} \] (U from photoion. models)

- **Transverse motion**: can determine the transverse velocity
  \[ v_T = \sqrt{C_{\text{BLR}} \ d_{\text{BLR}} / t}, \] where C_{BLR} is the los covering factor
NGC 4151 - Variability in Ionizing Flux

- Low-ionization lines “appear at low continuum $\rightarrow$ variable U
NGC 3783 – Variability due to Transverse Motion

Comp. 1 transverse velocity: \( v_T = \sqrt{C_{BLR} d_{BLR}} / \Delta t \geq 550 \text{ km s}^{-1} \)
Why are AGN outflows important?

- Quasar outflows have likely:
  1) contributed to the heavy-element abundance of the IGM (Hamann & Ferland, 1999, ARA&A, 37, 487)

- Seyfert galaxies are the best AGN for probing the machinery of mass outflow in the form of AGN winds.
  1) Of all AGN, they have the largest apparent brightness.
  2) They are nearby ($z < 0.1$), and offer the best hope of directly resolving the outflowing gas.
Emission-Line Outflows in the NLR

- Previous ground-based studies have claimed infall, rotation, parabolic orbits, outflow, etc.
- The problem: they relied on spatially integrated line profiles, since the NLR is only a few arcsecs across.
- HST/Space Telescope Imaging Spectrograph has angular resolution $\sim 0.1^\prime$.
- Large ground-based telescopes + adaptive optics (AO) + integral-field units (IFUs) also approach this resolution
NGC 1068: NLR – [O III] Image

continuum “hot spot”

4.0"
(290 pc)
NGC 1068: STIS Long-Slit Spectrum (Hβ, [O III])

outflow
Biconical Outflow Model for the NLR in NGC 1068

\[
\begin{align*}
\text{incl} &= 5^\circ, \\
\theta_{\text{max}} &= 40^\circ, \\
\theta_{\text{min}} &= 26^\circ, \\
v_{\text{max}} &= 1300 \text{ km/sec}, \\
r_t &= 137 \text{ pc}
\end{align*}
\]

- Outflow matches the general trend.
- Radial acceleration followed by deceleration.

(Das et al. 2006, AJ, 132, 620)
Kinematics of the Narrow-Line Region in NGC 4151

\[ \text{incl} = 45^\circ, \ \theta_{\text{max}} = 33^\circ, \ \theta_{\text{min}} = 15^\circ, \ v_{\text{max}} = 800 \text{ km/sec}, \ r_t = 96 \text{ pc} \]

(Das et al. 2005, AJ, 130, 945)
Mrk 573 – Ionized Spirals in the NLR

(Fischer et al. 2010, AJ, 140, 577)

- NLR geometry due to intersection between host disk and ionizing bicone.
- Kinematic indicate “in situ” acceleration of gas from the dust spirals.
What is the importance of NLR outflows?

• Provide AGN feedback on scales of hundreds of parsecs
  → may regulate black hole growth, terminate star formation, and explain black-hole mass/bulge correlations
• Provide alternate explanation for double-peaked NLR emission lines (Fischer et al. 2011)
  → Often used to claim double SMBHs in distant merging galaxies
• Kinematic models can determine the *inclination* of the AGN system (bicone, torus, and presumably accretion disk)
  → Investigate how intrinsic properties (SED, BLR velocities, absorber column densities) change with polar angle
NLR Studies: Integral Field Units

• Spectrum for every position in a field of view

• Three Basic Types
  – Lenslets: microlens array can be tilted around the optical axis so that spectra do not run into each other (allowed length of spectra is small) Ex) WHT Sauron
  – Fiber Optics: fibers transfer light to the spectrograph slit (there are gaps between the fibers) Ex) Gemini GMOS
  – Image Slicers: instrument mirror segmented into thin vertical slices that are slightly tilted with respect to each other (difficult to fabricate) Ex) Gemini NIFS

• Best used with adaptive optics (AO) on large telescopes to give angular resolution of ~0.1”
Integral Field Unit – Image Slicer

Gemini North and NIFS

Data Cube
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
  - $H_2$ emission lines in $K$ band to map warm molecular gas
  - CO bandheads and other stellar features in $H$ and $K$ bands to map stellar velocities and dispersions for determining black hole masses.
Currently observed in nearby galaxies, while still maintaining an average bulge radius, scenarios must be much smaller than typical kpc-scale bulge radii. This is because AGN at the time it is evacuated in quenching feedback via AGN outflows are successful in the local universe. Therefore, for negative feedback, housing an AGN radiating near Eddington, such as Mrk 573, it is unlikely that the AGN can fully evacuate a bulge. With AGN feedback unable to fully evacuate a bulge, the interaction between this AGN and its host galaxy, this is the mechanism by which gas in dusty molecular spirals is ionized and radiatively driven outward.

- Gas in dusty molecular spirals is ionized and radiatively driven outward.
- Mass outflow rate peaks at ~3 M_{Sun}/yr (Revalaski et al. 2018).