The Prevalence of Ionized Gas Outflows in Type 2 AGNs: 3-D models and IFU observations

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Part I. 3-D Model Simulations

Part II. IFU Observations
[O III] kinematics of ~39,000 type 2 SDSS-AGNs

Bae & Woo 14, Woo+16a
Observational Signatures of (Bi-)conical Outflows in AGNs

e.g., Pogge 88a,b, Schmitt & Kinney 96, Pogge+00, Fischer+10, ...
Applying Biconical Outflow Models
e.g., Crenshaw & Kraemer 00, Veilieux+01, Das+05, Storchi-Bergmann+10, Fischer+13

[O III] narrow-band image of Mrk 34

PV diagram

Bicone model

Fischer+13
Biconical Outflow Modeling  

3-D Model (f, v)  

3-D model for Mrk 34  
(based on Fischer+13)
Biconical Outflow Modeling  Bae & Woo 16a

3-D Model \((f, v)\)

\[
F(x, y) = \int f(x, y, z) dz,
\]

\[
f(x, y, z) = \begin{cases} f(x, y, z) & \text{if } z < z_{\text{dust}} \\ f(x, y, z) \times A & \text{if } z \geq z_{\text{dust}}, \end{cases}
\]

\[
V(x, y) = \frac{\int v_p(x, y, z) f(x, y, z) dz}{\int f(x, y, z) dz},
\]

\[
\sigma^2(x, y) = \frac{\int v_p^2(x, y, z) f(x, y, z) dz}{\int f(x, y, z) dz} - V^2(x, y).
\]

2-D Projection \((F, V, \sigma)\)

These 2-D maps can be compared with spatially resolved observations (IFU, long-slit, …)
3-D Model ($f, v$)

$$F(x,y) = \int f(x,y,z)dz,$$

$$f(x,y,z) = \begin{cases} f(x,y,z) & \text{if } z < z_{\text{dust}} \\ f(x,y,z) \times A & \text{if } z \geq z_{\text{dust}} \end{cases},$$

$$V(x,y) = \frac{\int v_p(x,y,z)f(x,y,z)dz}{\int f(x,y,z)dz} ,$$

$$\sigma^2(x,y) = \frac{\int v_p^2(x,y,z)f(x,y,z)dz}{\int f(x,y,z)dz} - V^2(x,y).$$

2-D Projection ($F,V,\sigma$)

$$v_{\text{int}} = \frac{\int \int V(x,y)f(x,y)dx dy}{\int \int f(x,y)dx dy},$$

$$\sigma_{\text{int}}^2 = \frac{\int \int V^2(x,y)f(x,y)dx dy}{\int \int f(x,y)dx dy} - v_{\text{int}}^2.$$

Integration ($v_{\text{int}}, \sigma_{\text{int}}$)

comparison

Observations ($v_{[\text{O III}]}, \sigma_{[\text{O III}]}$)
Model Parameter Test

$V_{\text{max}} = 1000 \text{ km/s}$

3 key parameters:
- Launching velocity
- Bicone inclination
- Dust extinction

No dust extinction = No velocity offset ($v_{\text{int}}$)

Higher bicone inclination = larger $\sigma_{\text{int}}$
Model Parameter Test

\[ V_{\text{max}} = 1000 \text{ km/s} \]

Negative velocity

Positive velocity

Larger extinction = Larger offset of \( v_{\text{int}} \), but smaller \( \sigma_{\text{int}} \)

Higher bicone inclination = Larger effect of dust extinction on \( v_{\text{int}} \) & \( \sigma_{\text{int}} \)
Simulated Emission-line Profiles

Examples of the observed [O III] profiles in AGNs
Model Grids on VVD Diagram + Observations
Monte Carlo simulation results with the observed VVD distribution show that models with a bicone opening angle of 40° and an inclination of 20° can reproduce the VVD of AGNs with a velocity dispersion of 130 km s\(^{-1}\) to 200 km s\(^{-1}\). These results imply that more energetic AGNs with a higher bicone opening angle and dust extinction at fixed inclination can reproduce the VVD of AGNs with a velocity dispersion larger than 400 km s\(^{-1}\). 

To compare this trend with observations, we calculate the number ratio of AGNs with positive velocity (i.e., \(|v_{\text{int}}| > 1\)) to the number of AGNs with reliable velocity measurements (i.e., \(v_{\text{max}} > 500\) km s\(^{-1}\) and \(v_{\text{max}} > 1000\) km s\(^{-1}\)) for AGNs with a lower velocity dispersion (i.e., \(v_{\text{int}} = 500\) km s\(^{-1}\)) and a range of AGNs with a higher velocity dispersion (i.e., \(v_{\text{int}} = 2000\) km s\(^{-1}\)). These results indicate that more energetic AGNs with a higher bicone opening angle and dust extinction at fixed inclination can reproduce the VVD of AGNs with a velocity dispersion larger than 400 km s\(^{-1}\).
By comparing the observed VVD distributions of type 2 AGNs with the Monte Carlo simulations, we find that:

1) launching velocity: \( \sim 500-1000 \text{ km/s (} \sim 94\% \text{) up to 1500-2000 km/s} \)

2) Dust extinction < \( \sim 90\% \) (\( \sim 2.5 \text{ mag.} \))

3) Larger velocity dispersion
   = Larger outflow velocity
   = Higher luminosity of AGN
   = Larger bicone opening angle
   = Smaller covering factor
Part I. 3-D Model Simulations

Part II. IFU Observations
IFU studies on AGN outflows: Sample selection

Bae+16b (in prep.); See also Karouzos, Woo, & Bae 16a,b

- ~23,000 Type 2 AGNs at $z < 0.1$ selected from SDSS (Bae & Woo 2014, Woo+2016)

- ~3400 AGNs with a high $\text{[OIII]}$ luminosity (cor.) $> 10^{41.5}$ erg/s

- 491 AGNs with strong signatures of outflows: $V > 100 \text{ km/s}$, or $VD > 300 \text{ km/s for [OIII]}$ (~14% of the luminosity-limited sample)

- 6 AGNs with Gemini-N/GMOS-IFU — published (Karouzos+16a,b)

- 17 AGNs with Magellan/IMACS-IFU & 3 AGNs with VLT/VIMOS (Bae +16b)
Velocity maps of narrow- and broad comp. of line profiles

- Both [O III] and Hα broad component show outflow kinematics
- Hα narrow component reveals gas rotation in host galaxy (16/20)
Photometric size of the NLR & Size-Lum. relationship

The size-luminosity relationship of $S \propto L^{0.4}$ holds from low- to high luminosity of [O III] regardless of AGN types.
Size of AGN outflows & size-Lum. relationship

- Size of AGN outflows = distance where [O III] VD becomes smaller than the stellar VD (e.g., Karouzos+16a,b)
- The outflow size is ~1–2 kpc for the sample
Summary

• Simple models of bicone and a thin dust plane successfully reproduce the observed distribution of [O III] velocity and velocity dispersion of type 2 AGNs.

• The primary drivers of the integrated [O III] kinematics are the intrinsic velocity, the bicone inclination, and the amount of dust extinction.

• The simulated emission-line profiles based on the LOSVD well reproduce a narrow core and a broad wing components in the observed [O III] line profiles.

• We constrain the intrinsic outflow velocity ranging from ~500–1000 km/s for the majority of AGNs, up to ~1500–2000 km/s for extreme cases.

• The observed increase of the number ratio of AGNs with negative [O III] velocity with positive [O III] velocity is well reproduced by Monte Carlo simulations, suggesting that AGNs with higher intrinsic velocities then to have wider opening angles.

• We investigate large number of [O III] luminosity-limited sample of AGNs with strong signatures of gas outflows using IFUs. Stay tuned!