Inflows, Outflows, and Rotation in the Narrow-Line Regions of Seyfert Galaxies

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Figure 4. The Astrophysical Journal
Before *HST*, the NLR was mostly unresolved.


In the past, investigators claimed infall, rotation, outflows, parabolic orbits, etc.
HST images resolved the NLR, and we used HST/STIS to study the kinematics with biconical outflow models.

- Kinematic models from HST/STIS medium-dispersion spectra to get velocity profile: $v(r)$.
- Photoionization models of STIS low-dispersion spectra to get density profile: $n_{HI}(r)$.
- Measure [O III] luminosities from HST images to get mass as a function of position (in ellipsoidal annuli).

$$\Delta M \propto L_{[O\text{ III}]} n_{HI}$$

$$v_{\text{out}} = \frac{\Delta M}{v(r) \Delta r}$$

(NGC 4151: Das+ 2005, AJ, 130, 945)

- However, a single long-slit spectrum may be misleading.
- Kinematic maps of the NLR are needed $\Rightarrow$ IFUs.
IFUs (+ AO) can map the NLR kinematics.

- **Integral Field Units (IFUs):** image slicers, lenslets, and/or fibers obtain spectra over a field of view. **Adaptive optics (AO)** resolves NLR structure.
- **Ex) Gemini’s Near Infrared Field Spectrometer (NIFS):**
  - $\lambda/\Delta\lambda \approx 5000$, $\sim 0.1''$ resolution, 0.9 – 2.4 µm coverage, 3'' x 3'' FOV.
  - $\rightarrow$ 3600 spectra in one observation
  - Z band: [S III]; J band: [Fe II], Pβ; K band: Brγ, H₂, CO stellar.
- **Other IFU Observations of AGN NLRs:**
  - Gemini GMOS: Storchi-Bergmann+, Rupke+
  - Keck OSIRIS: e.g., Hicks+
  - ESO VLT SINFONI: e.g., Davies+
What can kinematic mapping of the NLR tell us?

- Is the gas in the NLR rotating, infalling, or outflowing?
- What is the origin of NLR outflows?
- Can NLR outflows provide significant AGN feedback?
- How are AGN fueled on NLR scales (1 – 1000 pc)?

Let’s look at some examples →
Mrk 509 (Seyfert 1) is being fueled by a minor merger.

rotation and inflow

- Liu, Arav, & Rupke (2015) also find outflows to \( \sim 1.2 \) kpc \( (\sim 1.7'') \) using GMOS.
- Emission properties similar to those of UV absorption outflows.

Mrk 573 (Seyfert 2): Dust spirals are lit up by AGN.

Dust spirals in NLR are ionized as they enter the ionizing bicone (~vertical in figure).

Gemini NIFS contours show correspondence of [S III] with [O III] and H$_2$ with dust lanes.
Mrk 573 NLR shows \textit{in situ} acceleration of ionized and warm molecular gas from rotating dust/molecular spirals.

Outflows extend to \(~750\) pc, beyond which the ionized gas is rotating. → Not sufficient to clear the entire bulge
As the *inner* dust spirals enter the radiation bicone, gas is ionized and accelerated away from the AGN.
The extended NLR (ENLR) is rotating and extends out to ~17” (~ 6 kpc).

*Apache Point Observatory DIS (Fischer+ 2017)*
Conclusions (somewhat preliminary)

- Is the gas in the NLR rotating, infalling, or outflowing?
  - Yes. Depends on geometry, ionization state, AGN luminosity, distance from SMBH, etc. *(Gnilka talk, Machuca poster)*

- What is the origin of NLR outflows?
  - Primarily *in situ* acceleration of local material - e.g., rotating dust/molecular spirals *(Fischer et al. 2017)*

- Can NLR outflows provide significant AGN feedback?
  - Need *spatially resolved* mass outflow rates and kinetic luminosities over a range of luminosities. *(Revalski talk, Fischer talk)*

- How are AGN fueled on NLR scales (1 – 1000 pc)?
  - Along nuclear dust spirals/bars seen in *HST* images? Need kinematic maps of warm H$_2$ (*JWST*?) and likely cold molecular gas (*ALMA*).
Mrk 573: Composite X-ray, Optical, Radio
Dynamics of the emission-line clouds in Mrk 573

Enclosed mass profile and photoionization models give equation of motion (radiative driving and gravitational decelerations):

\[
v(r) = \sqrt{\int_{r_1}^{r} \left[ 6840L_{44} \frac{M}{r^2} - 8.6 \times 10^{-3} \frac{M(r)}{r^2} \right] dr},
\]

→ Nearly all of the clouds originated near dust/molecular gas lanes and traveled only tens of parsecs from their origins.

(Fischer+ 2017)