Narrow Line Region Dynamics and Photoionization in NGC 4151

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Observations:
Narrow Line Region gas in NGC 4151 accelerates out to \( r \approx 100 \) pc followed by slow deceleration (Das et al. 2005). The data requires that

**Questions:**
What accelerates this Narrow Line Region (NLR) outflow? Can a simple thermal wind be responsible? Can a Parker wind (e.g., Chevalier & Norman 2005) accelerate the outflow?

**Results:**
We apply models of thermal winds to this NLR, and find that neither thermal winds nor Parker winds can explain the observed kinematics.

**Observations**
Relatively low velocity (\( v < 700 \) km s\(^{-1}\)) outflows have been observed in [O III] in both NGC 1068 (Crenshaw & Krennrich 2000) and NGC 4151 (Das et al. 2005). These observations constrain the outflow:

- The NLR emission is roughly restricted to particular quads in velocity vs. radius, which helps constrain the outflow geometry.
- These data also exhibit resolved outflow acceleration and deceleration, particularly in the high-flux components.

**Figure 1:** One set of [O III] emission velocities from HST/STIS observations. The three different color-codes velocities from up to three flux components of the [O III] line (data from Das et al. 2005).

**Simple Thermal Wind**
First, can a simple thermal wind explain the kinematics?
To test this, we use the central continuum from Kraemer et al. (2000), and thermal winds cannot explain the observed outflows. We have developed thermal wind models to compare to observations of the NLR. We find:

- **Simple Thermal Wind:** Reaching the observed velocities requires launching far enough from the central source that \( v \approx 100 \) pc.
- At the distances where \( v \approx 10 \), the observed winds cannot fit the acceleration profile of the NLR in NGC 4151. We have used this for \( v \approx 10 \) pc and numerically solving the Parker wind equation for general initial conditions, photoionization-derived \( T(r) \), and such a wind decelerates at \( v \approx 5 \) pc.

Conclusions
We conclude that thermal winds cannot explain the NLR outflows. Parker winds can explain the observed kinematics, but the accretion luminosity varies with the wind.

References
Wilhite, E.J., in prep.

**Parker Winds**
We now investigate a continuous Parker wind model, including:

- Enclosed mass vs. radius, \( M(r) \), from observations
- Adiabatic cooling (e.g., Chevalier & Norman 2005)
- [O III] emitted from clouds embedded in the continuous wind
- Drag against the host galaxy’s ISM

Can a Parker wind model with these components successfully reproduce the NLR motion in NGC 4151?

**Figure 3:** The assumed central continuum for photoionization simulations of NGC 4151 vs. multiwavelength observations of the same galaxy.

**Figure 4:** Cloud velocities for clouds driven in an isothermal Parker wind.

**Figure 5:** \( T(r) \) for a range of densities at the base of the wind, \( n_b \).

**Figure 6:** Percent power-law exponents for \( T(r) \) vs. \( v(r) \) for a range of densities at the base of the wind.

**Equation 1:** \( \frac{m}{r^2} \frac{dv}{dr} = -\frac{GM(r)}{r^2} \)

**Equation 2:** \( \frac{dv}{dr} = -\frac{2GM(r)}{r^2} \) for \( v \approx 0 \) at \( r \approx 5 \) pc.

**Equation 3:** \( \frac{dv}{dr} = -\frac{2GM(r)}{r^2} \) for \( v \approx 10 \) pc.

**Equation 4:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \)

**Equation 5:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 5 \) pc.

**Equation 6:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 10 \) pc.

**Equation 7:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 50 \) pc.

**Equation 8:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 100 \) pc.

**Equation 9:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 500 \) pc.

**Equation 10:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 1000 \) pc.

**Equation 11:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 5000 \) pc.

**Equation 12:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 10000 \) pc.

**Equation 13:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 50000 \) pc.

**Equation 14:** \( M(r) = \frac{\rm dV}{\rm dt} - \frac{2\pi r^2 v^2}{C} \) for \( v \approx 100000 \) pc.