Narrow Line Region Dynamics and Photoionization in NGC 4151

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Overview

Observations: Narrow Line Region gas in NGC 4151 accelerates out to $r \sim 100$ pc followed by slow deceleration (Das et al. 2005).
Questions: What accelerates this Narrow Line Region (NLR) outflow? Can a simple thermal wind be responsible? Can a Parker wind (e.g., Chelouche & Netzer 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 ($v \sim 700$ km s^{-1}) outflows have been observed in [O III] in both NGC 1068 (Crenshaw & Kraemer 2000) and NGC 4151 (Das et al. 2005). These observations constrain the outflow:

- The NLR emission is roughly restricted to particular quadrants 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.

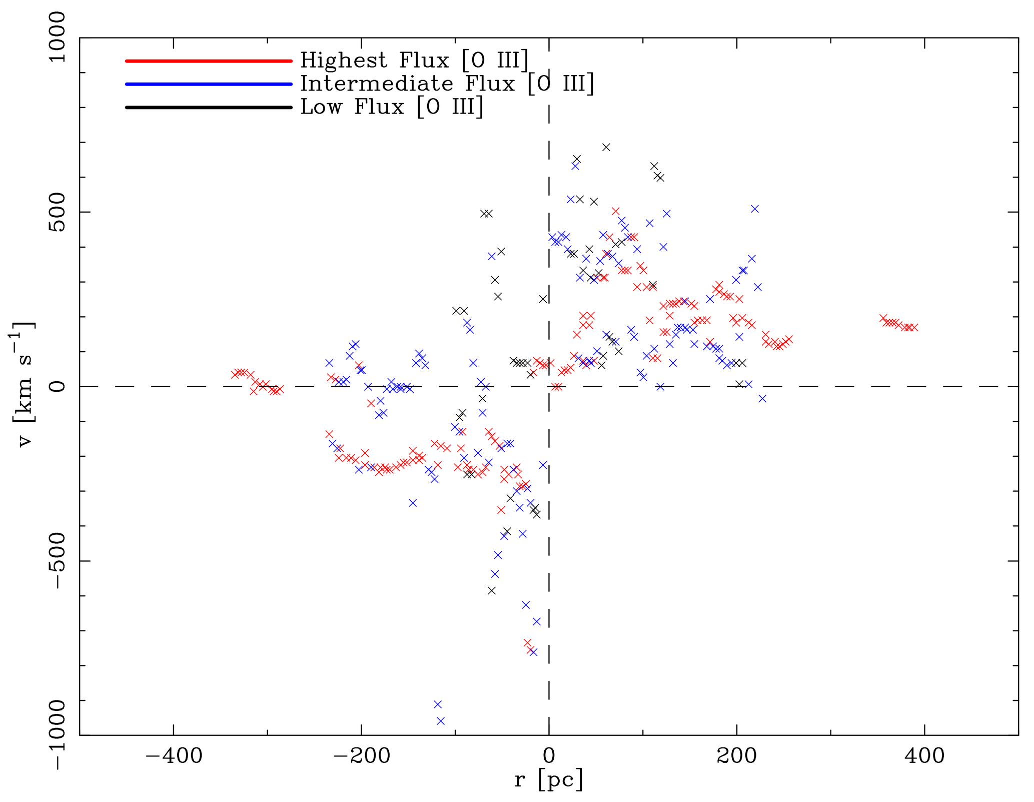

Figure 1: One set of [O III] emission velocities from *HST*/STIS observations. The three different colors show velocities from up to three flux components of the [O III] line (data from Das et al. 2005).

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), which is compared with multiwavelength observations in Figure 2. We then run photoionization simulations to check if $c_s > v_{\rm escape}$ for that central continuum and a range of densities in Figure 3.

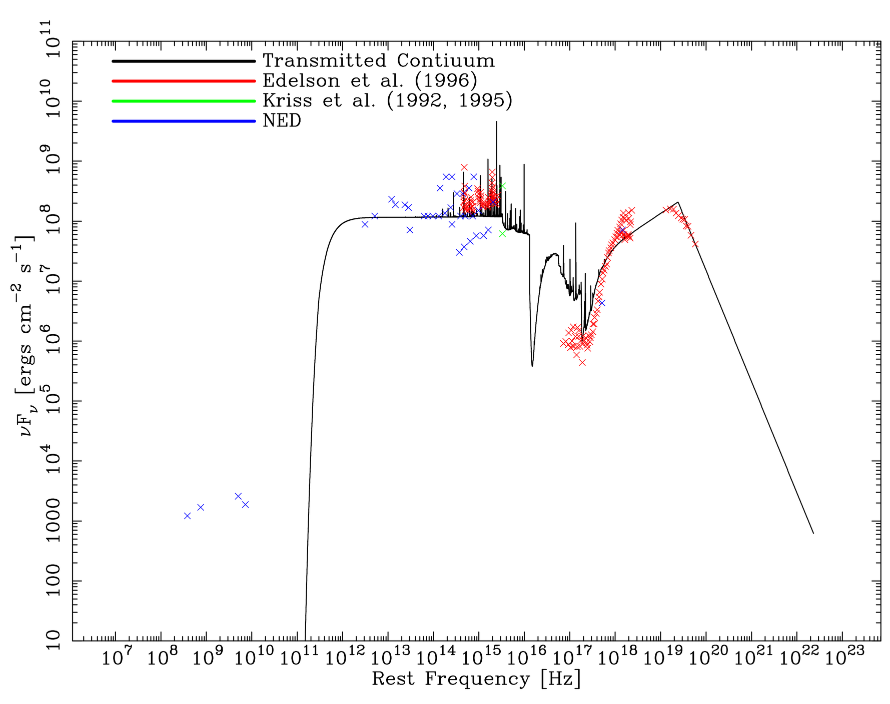

Figure 2: The assumed central continuum for photoionization simulations of NGC 4151 vs. multiwavelength observations of the same galaxy.

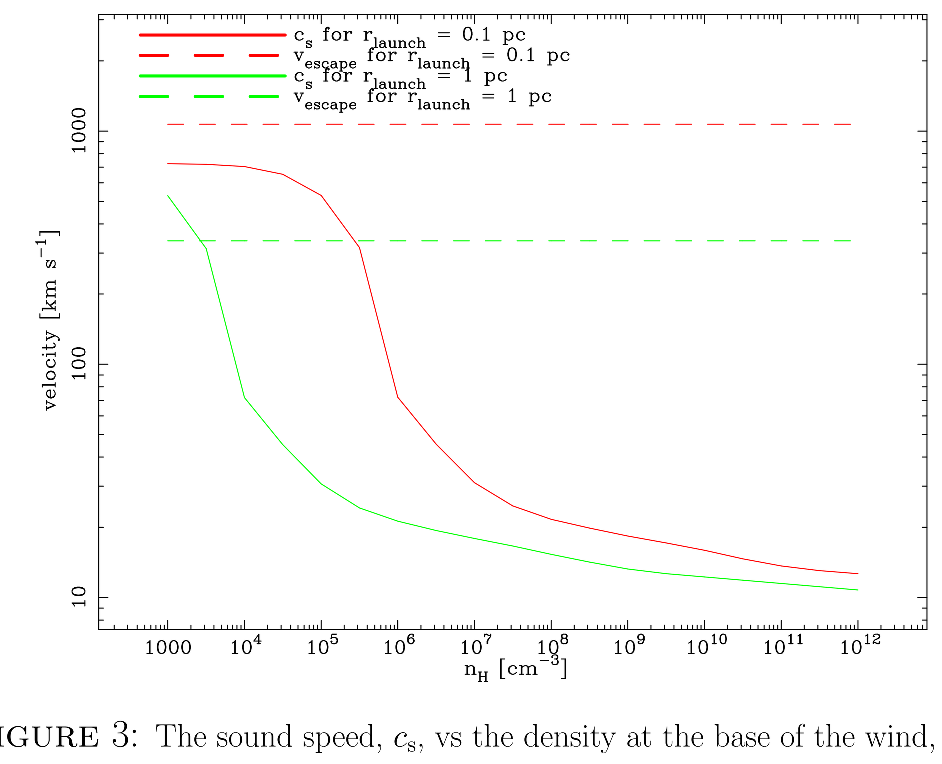

Figure 3: The sound speed, c_s, vs the density at the base of the wind, $n_{\rm H}$.

Figure 3 shows that, for winds launched from $r \sim 0.1$ pc, $c_s < v_{\rm escape}$. Winds launched from $r \sim 1$ pc would have $v = c_s \sim v_{\rm escape}$ but cannot match the observations: $c_s < v_{\rm observed}$. This shows that simple thermal winds cannot explain the NLR outflow observations.

Parker Winds

We now investigate a continuous Parker wind model, including:

- Enclosed mass vs radius, $M(r)$, from observations
- Adiabatic cooling (e.g., Chelouche & Netzer 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?

We start with the **basic equation for a Parker wind**:

$$\left(v - \frac{c_s^2}{v}\right)\frac{dv}{dr} = \frac{2c_s^2}{r} - \frac{GM(r)}{r^2} \qquad (1)$$

where v is the radial velocity, r is spherical radius, and G is Newton's constant.

Next, we **embed clouds in that outflow** which are dragged along by the Parker wind. Assuming a spherical cloud with density $\rho_{\rm cl}$ and cloud radius $R_{\rm cl}$ embedded in a wind with density $\rho_{\rm wind}$, the acceleration for each cloud is:

$$a_{\rm drag,cloud} = \frac{\rho_{\rm wind}}{\rho_{\rm cl}}\frac{\frac{3}{4}(v_{\rm wind} - v_{\rm cl})^2}{R_{\rm cl}} = \frac{\rho_{\rm wind}}{N_{\rm H}m_{\rm p}}\left(\frac{3}{4}(v_{\rm wind} - v_{\rm cl})^2\right) \qquad (2)$$

Finally, the **wind is decelerated by dragging against the host galaxy's ISM**: ram pressure from the interaction with an external medium slows the outflow. The drag force is given by:

$$a_{\rm drag,ISM} = \frac{\rho_{\rm wind}}{\rho_{\rm ISM}}\frac{\frac{3}{4}v_{\rm wind}^2}{R_{\rm ISM}} = \frac{\rho_{\rm wind}}{N_{\rm H,ISM}m_{\rm p}}\left(\frac{3}{4}v_{\rm wind}^2\right) \qquad (3)$$

Equation 1 shows that **Parker winds place strict requirements on the thermal structure of the outflow.** In order to accelerate, $T(r)$ must decrease less quickly than $M(r)/r$ so that $\frac{dv}{dr} > 0$ for $v \geq c_s$ (see Eq. 1). One can look at this another way: if $T(r)$ decreases more quickly than $1/r$, the gas becomes a static atmosphere (Parker 1965). For example, with a point-source mass, this means that $T(r)$ must drop less quickly than $1/r$. This requirement is particularly important for large-scale winds in AGN, where $M(r)$ actually **increases** with radius. We model $M(r)$ with:

$$M(r) = M_\bullet + \frac{2r\sigma^2}{G}, \qquad (4)$$

where $M_\bullet = 1.33 \pm 0.46 \times 10^7\ M_\odot$ (Peterson 2004) and $M(r = 690\ {\rm pc}) = 4.77 \times 10^9\ M_\odot$ (Mundell et al. 1999). With this $M(r)$ function, at small distances, $T(r)$ must decrease slower than $1/r$, but for large distances, T must be roughly constant, since $M(r) \propto r$ for $r \gtrsim 2$ pc in NGC 4151. Since this is a very large-scale wind, for a first approximation, we apply an isothermal Parker wind model to the data.

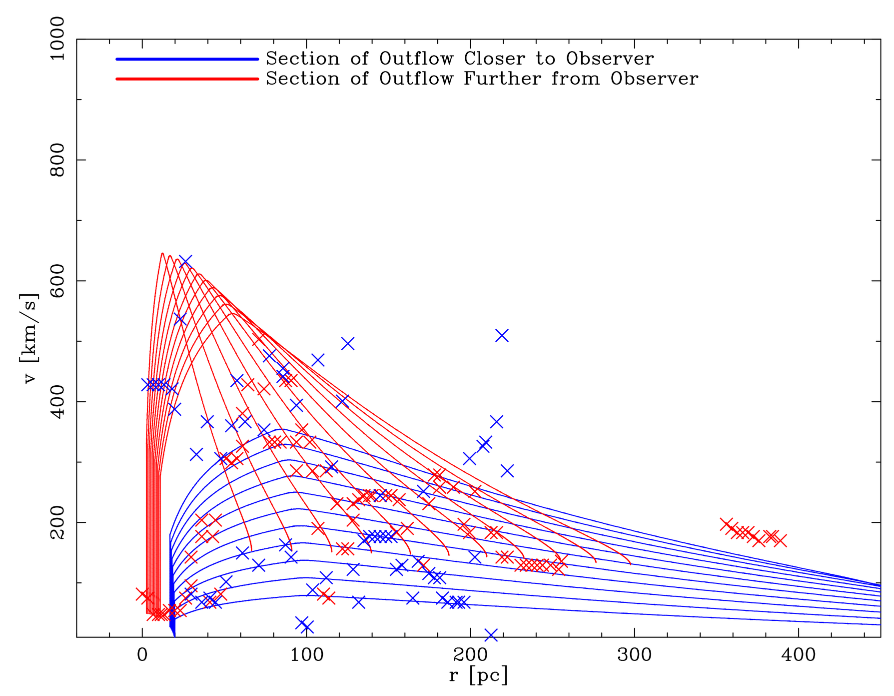

Figure 4: Cloud velocities for clouds dragged in an isothermal Parker wind.

Figure 4 shows that an isothermal Parker wind can fit the observational spread of velocities with distance in NGC 4151. The data requires that the model parameters take on the values given below.

Quantity	*Value*
Launch Radius, $r_{\rm launch}$	0.1 pc
ISM Gas Radius, $r_{\rm ISM}$	100 pc
Wind Temperature, T	3×10^6 K
$\frac{\rho_{\rm wind}}{N_{\rm H,ISM}m_{\rm p}}$	4×10^{-3} cm^{-1}
$\frac{\rho_{\rm wind}}{N_{\rm H,cl}m_{\rm p}}$	2×10^{-2} cm^{-1}
Inclination of Outflow Cone	45°
Inner Cone Opening Angle	12°
Outer Cone Opening Angle	38°

Would such a wind be isothermal, though?

But first, a word from our sponsor:

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Parker Wind Photoionization Simulations

To model the thermal structure of the wind, we run photoionization simulations using Cloudy (Ferland et al. 1998). We start the simulations with a range of densities, $n_{\rm H,0}$, at the base of the wind, using the incident continuum from Kraemer et al. (2000, see Fig. 2), and plot the radial dependence of both $T(r)$ and α for $T(r) \propto r^\alpha$.

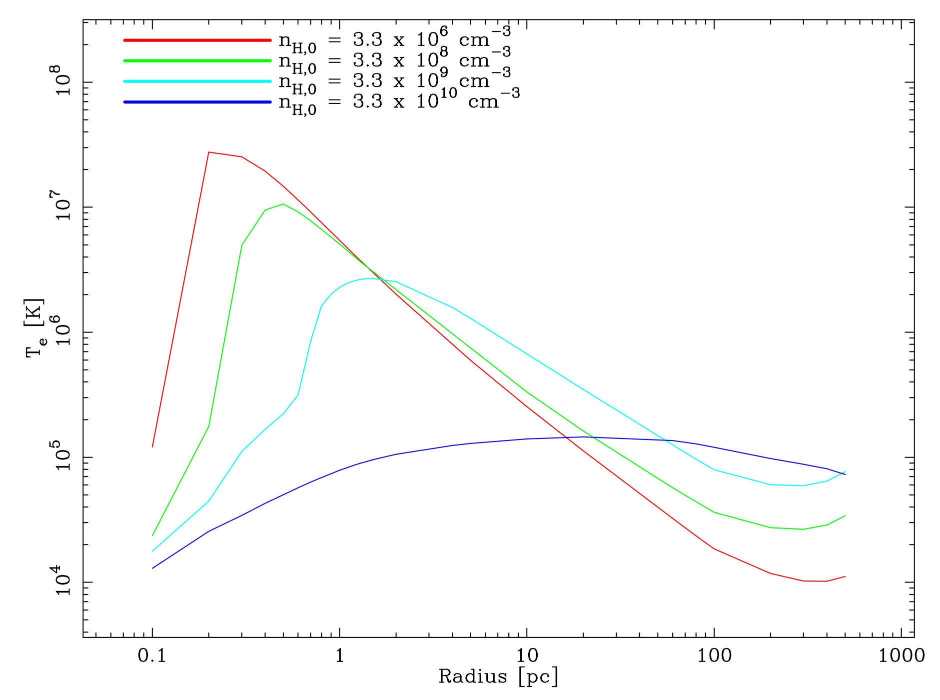

Figure 5: $T(r)$ for a range of densities at the base of the wind, $n_{\rm H,0}$.

Figures 5 shows that only winds with $n_{\rm H,0} \lesssim 3.3 \times 10^9$ cm^{-3} can reach the high temperatures ($T \sim 10^6$ K) required.

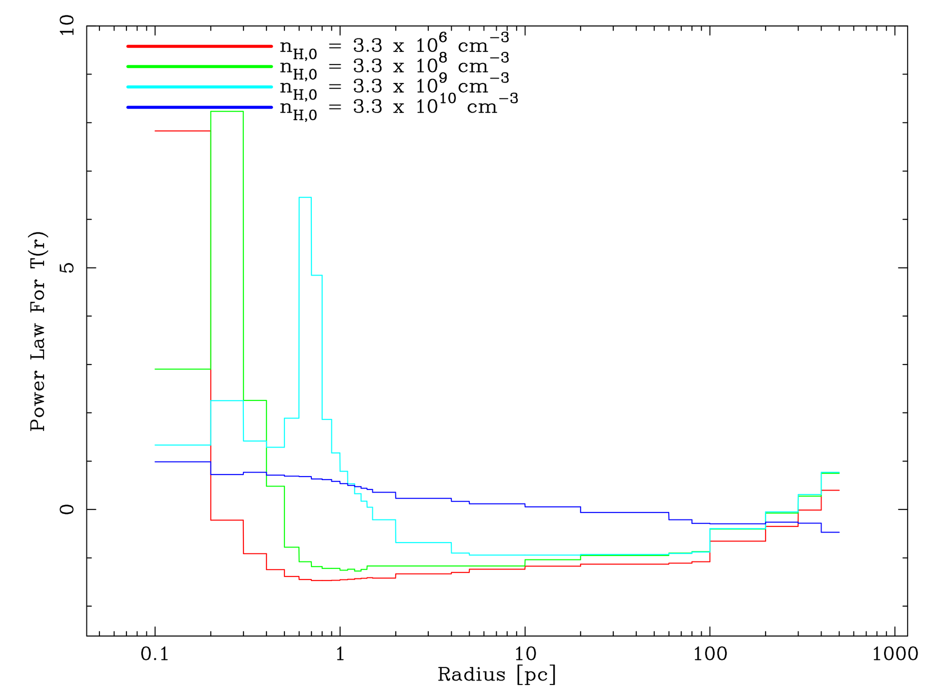

Figure 6: Piecewise power-law exponent α for $T(r) \propto r^\alpha$ for a range of densities at the base of the wind.

Figure 6 shows that for Parker wind models that achieve $T > 10^6$ K, adiabatic cooling dominates photoionization heating for $r \gtrsim 1$ pc. Therefore, none of the resultant temperature profiles leads to acceleration out to $r \sim 100$ pc. Parker winds cannot fit the acceleration profile in the NLR of NGC 4151. We have verified this for $n_{\rm H,0} = 3.3 \times 10^9$ cm^{-3} by numerically solving the Parker wind equation for a general, piecewise, photoionization-derived $T(r)$: such a wind decelerates at $r = 5.5$ pc.

Conclusions

We have developed thermal wind models to compare to observations of acceleration and deceleration in NGC 4151's NLR. We find:

- **Simple Thermal Wind**: Reaching the observed velocities requires launching far enough from the central source that $c_s \sim v_{\rm escape}$. But at the distances where $c_s \sim v_{\rm escape}$, $c_s < v_{\rm observed}$. Thermal winds cannot explain this NLR outflow.
- **Parker Wind**: Adiabatic cooling dominates photoionization heating at large scales: such a Parker wind cannot accelerate with the photoionization-derived $T(r)$ and observationally-constrained $M(r)$.

References

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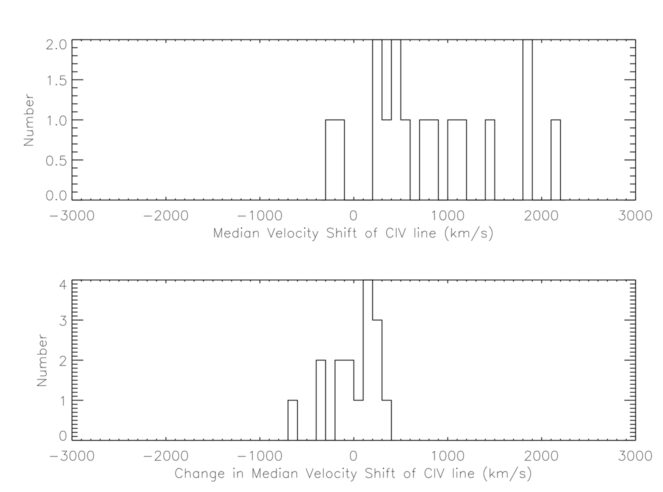
"And now for something *completely* different..."



Wilhite et al. (2006; Accepted to ApJ) find no observable change in C IV blueshift with quasar luminosity variations. *This is an important constraint for understanding the origins of the* C IV *blueshift!*