Black Hole Winds at All Scales
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Constraining the driving mechanism of galaxy-scale winds with emission line spectra

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Abstract. Using hydrodynamic simulations and photoionization calculations, we demonstrate that quasar emission line spectra contain information on the driving mechanism of galaxy-scale outflows. Outflows driven by a hot shocked bubble are expected to exhibit LINER-like optical line ratios, while outflows driven by radiation pressure are expected to exhibit Seyfert-like line ratios. Driving by radiation pressure also has a distinct signature in the narrow UV lines, which is detected in an HST-COS spectrum of a nearby quasar hosting a large-scale wind.

Keywords. AGN, outflows, ISM: jets and outflows, Magneto-hyrdynamical simulations

1. Introduction

Quasar-driven galaxy-scale outflows, which are now routinely detected in emission and absorption line observations (e.g., Fiore et al. 2017), provide a potential mechanism for the central black hole to regulate star formation in the host galaxy. It is however unclear how the released black hole accretion energy couples to the host ISM and drives a large-scale outflow. Leading possibilities for this driving mechanism include direct radiation pressure from the accretion disk (e.g., Murray et al. 2005), an expanding hot bubble ($\sim 10^{10}$ K) produced when nuclear winds or jets shock against the ISM (Faucher-Giguère & Quataert 2012; Zubovas & King 2012), or pressure gradients in cosmic rays produced in the same shocks (e.g., Yusef-Zadeh et al. 2019). A method to distinguish between these possibilities would be highly beneficial for understanding the nature of these outflows and their impact on galaxy evolution (Krumholz et al. 2017; Veilleux et al. 2020).

Most existing constraints on the mass, momentum, and energy outflow rates of galaxy-scale winds are deduced from emission line spectra. *The same line spectra also contain information on the outflow driving mechanism, which has largely not been exploited.* This follows since the ionization structure of line-emitting clouds is sensitive to the confinement mechanism of the cloud's irradiated surface layer, and hence also to the wind driving mechanism.

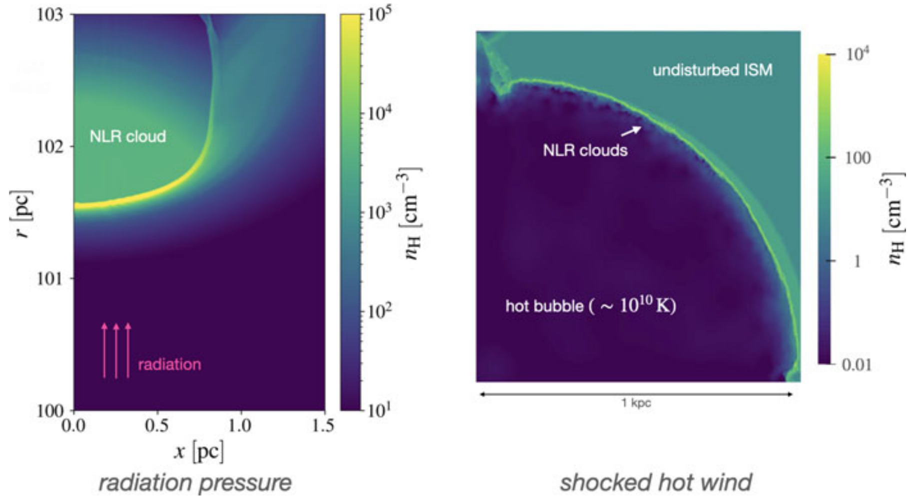

Figure 1. Simulations of NLR clouds subject to different wind-driving mechanisms. ***Left:*** an initially uniform density and spherical NLR cloud, 20 kyr after being exposed to quasar radiation (from Stern et al., in prep.). Radiation pressure both ablates the cloud and compresses the exposed surface layer, with the latter dominating the line emission. ***Right:*** Simulation of a hot bubble expanding through the host ISM (Richings & Faucher-Giguère 2018a,b). Line emission originates mainly in the compressed interface between the hot bubble and the undisturbed ISM.

In this summary we describe our efforts to infer the outflow driving mechanism from emission line spectra. We first derive quantitative predictions for line spectra assuming different driving mechanisms, and then compare these predictions with observed spectra.

2. Novel high-resolution simulations of NLR clouds subject to different outflow driving mechanisms

Figure 1 plots snapshots from the two types of hydrodynamic simulations we employ. On the left is a snapshot from a 2D axisymmetric PLUTO simulation of an ISM cloud, which is initially spherical and has a uniform density (from Stern et al., in prep.). The snapshot shows the cloud 20 kyr after being exposed to quasar radiation, which originates from the bottom of the plot. The radiation field is reduced as it proceeds within the cloud due to absorption by HI and dust grains, thus transferring both heat and momentum to the gas. The emitted radiation is derived using standard tables, and treated as an energy sink, neglecting further interactions with the gas. Spatial resolution is ≈ 0.01 pc, which is required to resolve the density structure of the cloud. The figure shows how radiation pressure both ablates the side of the cloud and compresses the surface layer against the shielded backside of the cloud. The gas pressure structure that forms in this compressed surface layer is consistent with a radiation pressure confined (RPC) slab – a 1D hydrostatic solution where the gas pressure gradient balances the pressure of the absorbed radiation (Dopita et al. 2002; Draine 2011; Stern et al. 2014; Baskin et al. 2014).

The right panel of Figure 1 plots a snapshot from the second type of simulations (from Richings & Faucher-Giguère 2018a,b), where a $\sim 10^{10}$ K bubble, as could be produced from shocks of small-scale BAL winds, expands into the host galaxy ISM. These simulations were run using the the Meshless Finite Mass hydro solver in the GIZMO code (Hopkins 2015), and have a mass resolution of ~ 30 $M_\odot$. In these simulations quasar radiation is a source of heat and ionization, radiation pressure is neglected, and radiation shielding is treated using a Sobolev-like approximation. The snapshot shows how the hot bubble compresses the ISM and drives an outflow.

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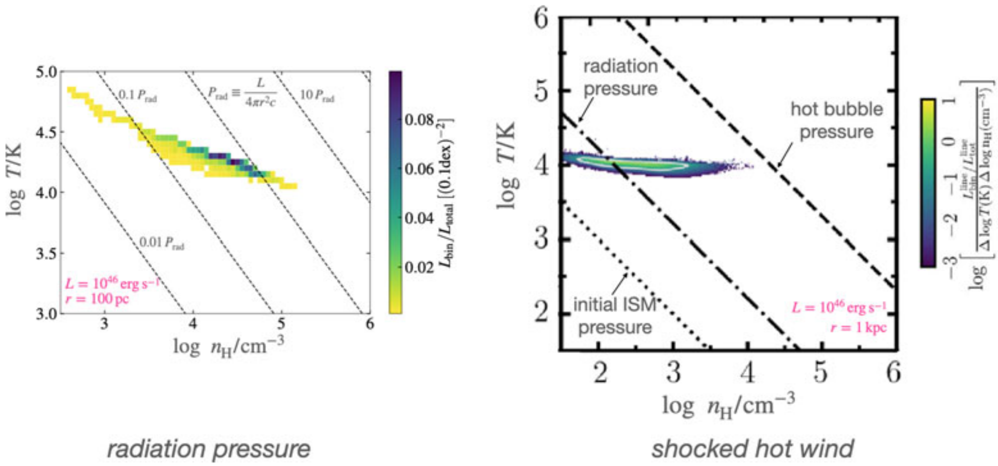

Figure 2. Density-temperature distributions weighted by Hα luminosity, in the two simulations shown in Fig. 1. Diagonal lines denote constant thermal pressures. Clouds subject to radiation pressure are compressed to $P_{\rm gas} \lesssim P_{\rm rad}$ (*left*), while in clouds subject to hot bubble pressure much of the Hα emission comes from gas with $P_{\rm gas} > P_{\rm rad}$ (*right*). Since the ratio $P_{\rm gas}/P_{\rm rad}$ sets the gas ionization level, the high $P_{\rm gas}/P_{\rm rad}$ when a hot bubble is present imply that strong low-ion lines are expected.

Figure 2 plots the density-temperature distribution of the line-emitting clouds in the two simulations, weighted by Hα luminosity. Diagonal lines denote constant thermal pressures, and specifically we mark the radiation pressure $P_{\rm rad} \equiv L/(4\pi r^2 c)$ where $L = 10^{46}$ erg s^{-1} is the bolometric luminosity and r is the cloud distance from the nucleus ($r = 100$ pc and 1 kpc in the radiation pressure and hot bubble simulations, respectively). Comparison of the two panels shows a difference in the predicted ratio of the gas pressure to the radiation pressure $P_{\rm gas}/P_{\rm rad}$. In the radiation pressure-dominated case $P_{\rm gas}/P_{\rm rad} \sim 0.3 - 1$, while in the hot bubble dominated case a higher ratio of $P_{\rm gas}/P_{\rm rad} \sim 0.5 - 10$ is evident. Compression by radiation pressure is limited to $P_{\rm rad}$, while when a dynamically important hot bubble is present clouds are compressed above this value. This result is robust to different choices of gas metallicity, spectral slope, and cloud distances.

3. Emission line predictions of different wind driving mechanisms

The relation between the driving mechanism and $P_{\rm gas}/P_{\rm rad}$ inferred above has important implications for observed emission line spectra. As discussed in Stern et al. (2016), the ratio $P_{\rm rad}/P_{\rm gas}$ sets the ionization level of the gas, and thus when a hot bubble is present and $P_{\rm gas} > P_{\rm rad}$ we expect relative strong emission from low-ionization species, in contrast with the higher-ionization lines when radiation pressure dominates and $P_{\rm rad} \lesssim P_{\rm gas}$. This difference is demonstrated in Figure 3, adapted from Richings et al. (2021). The figure shows that radiation pressure-dominated models predict relatively high ionization, Seyfert-like spectra, in contrast with lower-ionization, LINER-like spectra in hot bubble dominated models.

Emission lines from high ionization species observable in the UV provide another test of the wind driving mechanism. Radiation pressure-dominated models predict specific UV line ratios, and thus UV spectra provide a stringent test of the radiation pressure scenario. In Figure 4 (from Somalwar et al. 2020) we compare these predictions with HST-COS observations of SDSS J1356+1026 (PID: 15280, PI: Johnson), an obscured radio-quiet quasar at $z = 0.123$ which hosts a prototypical superwind. The observed line ratios are

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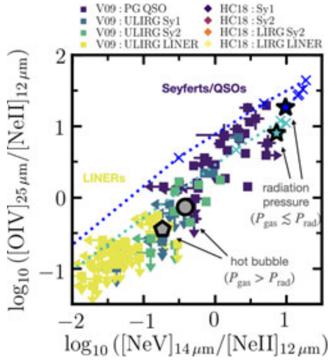

Figure 3. Predicted IR emission line ratios (markers with black borders) versus observed ratios (other markers), from Richings et al. (2021). Hot bubble models predict LINER-like spectra with strong low ions, due to the high $P_{\rm gas}/P_{\rm rad}$.

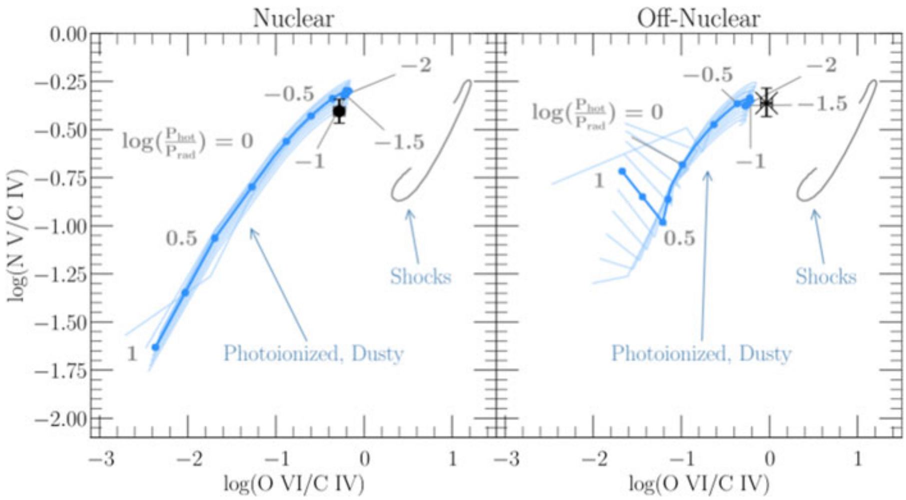

Figure 4. UV line ratios in J1356, an obscured $z = 0.1$ quasar with a prototypical superwind, compared to predictions from shock models and 1D hydrostatic photoionization models of the compressed surface layer (from Somalwar et al. 2020). The photoionization models span a range of assumed hot gas pressure to radiation pressure ratios in the range $0.01 - 10$ as marked. Different lines mark different choices for other parameters – metallicity, spectral slope and cloud distance. As $P_{\rm hot}/P_{\rm rad} \to 0$ the predicted line ratios approach asymptotic values. This limit is consistent with observed lines ratios (black markers) both in the nuclear spectrum (left) and the off-nuclear spectrum (right), *strongly suggesting radiation pressure dominates in this object.*

spot-on the predictions of the radiation pressure dominated models, strongly suggesting that radiation pressure dominates in this object. In contrast the hot bubble-dominated model predictions for high-ionization UV lines are somewhat uncertain, mainly due to the expected contribution of gas which is out of pressure, thermal and/or chemical equilibrium (Richings et al. 2021).

4. Summary and Future prospects

The above results suggest that (1) Radiation pressure driving can be identified using UV narrow line spectra; and (2) Systems with a dynamically important hot bubble are expected to have LINER-like optical and IR line ratios. It would be beneficial to search for these spectral signatures in additional objects with observed galaxy-scale winds, thus

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producing constraints on the wind-driving mechanism which are hard to obtain by other means. We have obtained seven additional HST-COS spectra of nearby obscured quasars for this goal (PID: 15935, PI: Johnson), and obtaining a larger sample is planned.

References

Baskin A., Laor A. & Stern J., 2014, *MNRAS*, 438, 604
Dopita M. A., Groves B. A., Sutherland R. S., Binette L. & Cecil G., 2002, *ApJ*, 572, 753
Draine B. T., 2011, *ApJ*, 732, 100
Faucher-Giguère C.-A. & Quataert E., 2012, *MNRAS*, 425, 605
Fiore F., et al., 2017, *A&A*, 601, A143
Krumholz M. R., Thompson T. A., Ostriker E. C. & Martin C. L., 2017, *MNRAS*, 471, 4061
Murray N., Quataert E. & Thompson T. A., 2005, *ApJ*, 618, 569
Richings A. J. & Faucher-Giguère C.-A., 2018a, *MNRAS*, 478, 3100
Richings A. J. & Faucher-Giguère C.-A., 2018b, *MNRAS*, 474, 3673
Richings A. J., Faucher-Giguère C.-A. & Stern J., 2021, *MNRAS*, 503, 1568
Somalwar J., Johnson S. D., Stern J., et al. 2020, *ApJL*, 890, L28
Stern J., Laor A. & Baskin A., 2014, *MNRAS*, 438, 901
Stern J., Faucher-Giguère C.-A., Zakamska N. L. & Hennawi J. F., 2016, *ApJ*, 819, 130
Veilleux S., Maiolino R., Bolatto A. D. & Aalto S., 2020, *A&AR*, 28, 2
Yusef-Zadeh F. & Wardle M., 2019, *MNRAS*, 490, L1
Zubovas K. & King A., 2012, *ApJL*, 745, L34

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