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Quasar Feedback and Galactic-scale Outflows

Using the Gemini Multi-Object Spectrograph at Gemini North, an international team detected extended ionized gas nebulae around powerful radio-quiet quasars. These ground-breaking observations provide strong evidence that quasars in their most common mode can drive gas outflows engulfing an entire galaxy.

One of the most fascinating astronomical discoveries of the last several decades was the gradual realization that almost every massive galaxy, including our own Milky Way, contains a supermassive black hole in its center. Several lines of evidence suggest a fundamental connection between the black holes residing in galaxy centers and the formation and evolution of their host galaxies. One such observation is the tight correlation between the black hole masses and the velocity dispersions of their host bulges. Another is the close similarity of the black hole accretion history and the star formation history over the lifetime of the universe.

In addition to these observations, modern galaxy formation theory strongly suggests that black hole activity has a controlling effect on shaping the host galaxy's global properties. This is especially true for the most massive galaxies, whose numbers decline much more rapidly with luminosity than the predictions of large-scale dark matter simulations would suggest.

One possible explanation for this is that the black hole's energy output, in its most active ("quasar") phase, may be somehow coupled to the gas from which the galaxy's stars form. If the quasar launches a wind that entrains and removes gas from the galaxy, or reheats the gas, then it can shut off star formation in its host. Thus, quasars could be instrumental in limiting the maximal mass of galaxies.

In recent years, this type of feedback from accreting black holes has become a key element in modeling galaxy evolution. Feedback can, in principle, explain galaxy/black hole correlations and the lack of overly massive blue galaxies in the local universe. As significant as these achievements are, it has been challenging to find direct observational evidence of black hole/galaxy self-regulation and to obtain measurements of feedback energetics.

Quasar Winds

Quasars are so luminous ($L=10^{45}$ -10^{47} erg/s) that they should be able to launch powerful winds just by exerting radiation pressure on the surrounding gas. The gas near the quasar may be accelerated to thousands of kilometers per second (km/s); it then pushes on the gas further out, which in turn pushes on the gas at even larger distances from the quasar –– thus launching a large-scale (galaxy-wide) wind. Over the last few years, we and our collaborators have studied the distribution and kinematics of warm ionized gas around quasars to search for such winds.

Since the 1980s, several other groups have independently conducted similar types of observations. One of the most striking conclusions of these previous studies is that quasars with relativistic jets (and those without them) showed very different morphologies of ionized gas on galaxy-wide scales. Quasars without radio jets often showed no detectable extended emission at all. Objects with jets, both at low and high redshifts, routinely showed ionized gas emission on the scale of tens of kiloparsecs (kpc), with velocities of several hundred km/s – often well in excess of the escape velocity from the galaxy – and with high levels of turbulence.

Sometimes these outflows align nicely with the direction of the radio jet; sometimes, the extended ionized gas is oriented in a completely different direction. Some outflows, especially those observed in high-redshift radio galaxies, entrain a significant fraction of the entire galaxy's gas content. Thus, clear evidence exists that powerful radio jets exert a strong feedback effect on their hosts. The jet heads slam into the interstellar medium and drive shocks which engulf and accelerate at least some of the gas in the galaxy.

However, only a small fraction (~10 percent) of accreting black holes produce powerful jets at any given time — perhaps only some black holes are capable of launching them, or all black holes have them but for only a small fraction of their active lifetime. In either case, jet-driven feedback alone is probably insufficient to make the kind of impact necessary for establishing black hole/galaxy correlations and for limiting galaxy mass. Therefore, we decided to revisit observations of ionized gas around quasars without jets (so-called "radio-quiet" quasars) to see whether accreting black holes launch winds in their most common phase of activity.

In order to study this we made two key changes compared to the previous studies.

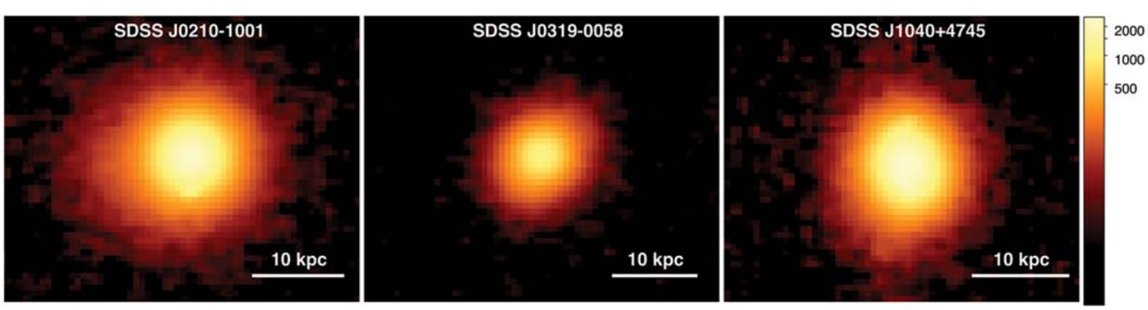

Figure 1.
Brightness distribution of [O III] emission in radio-quiet quasar nebulae on a logarithmic scale, as measured from our GMOS observations (in units of 10^{-17} erg $s^{-1}cm^{-2}$ $arcsec^{-2}$).

First, because galaxy formation theory predicts strongest feedback effects at the high end of the galaxy luminosity function, we focused on the most luminous quasars. Second, we concentrated on so-called obscured quasars in which dusty gas close to the quasar blocks the line-of-sight to the observer, which enables us to observe extended emission line regions without the overwhelming glare of the quasar itself. Such objects are not easy to find in magnitude-limited astronomical surveys; due to the obscuration, they appear faint at optical wavelengths. Additionally, they have only been found in large numbers over the past decade or so.

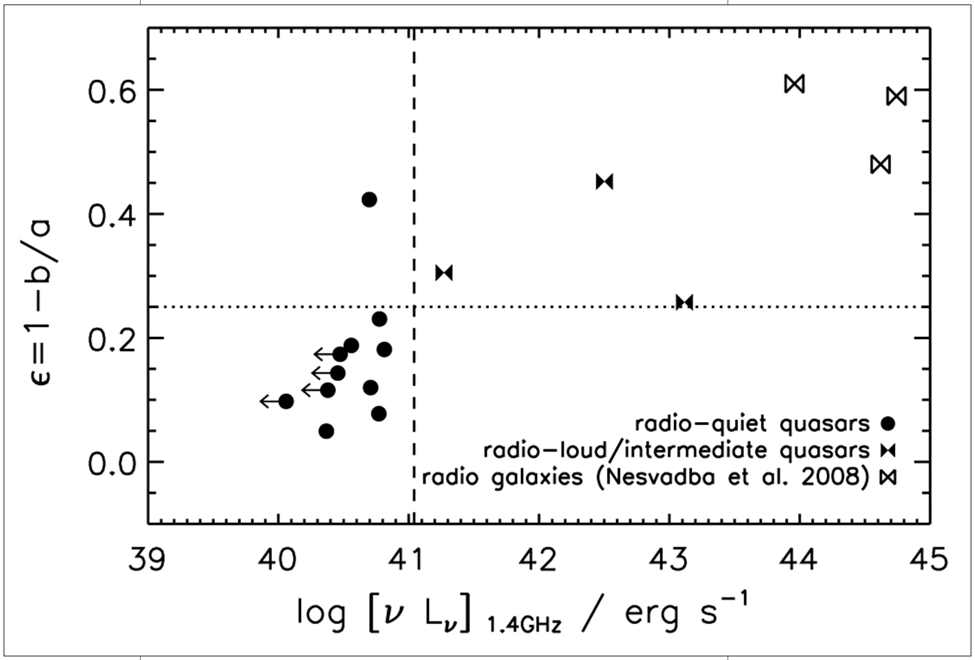

Figure 2.
Comparison of ellipticities of ionized gas nebulae around radio-loud (filled facing arrowheads) and radio-quiet (filled circles) quasars. Nebulae around radio galaxies and radio-loud quasars are universally more elongated than those around radio-quiet quasars from our sample.

Gemini Observations

The sample of obscured quasars we used in our work came from the spectroscopic database of the Sloan Digital Sky Survey. From about 900 known obscured quasars, we chose 11 very luminous ones at redshifts $z \sim 0.5$ for a detailed study with the Gemini North telescope. Using the Faint Images of Radio Sky at Twenty-Centimeters radio survey, we verified that our targets do not have powerful radio jets. We then used the Gemini Multi-Object Spectrograph in its integral field mode to measure spatial distributions, radial velocities, and velocity dispersions of the ionized gas around luminous obscured radio-quiet quasars.

The great advantage of the integral field mode is that it contains information on both the kinematics and morphology of the ionized gas in a single observation. For every element in the instrument's field-of-view, we obtain a spectrum that covers about $4100\,\text{Å} < \lambda < 5200\,\text{Å}$ in the source's rest-frame. This allows us to observe the most powerful optical emission line [O III] 5007 Å, as well as several weaker features such as Hβ and He II (4686 Å).

By measuring the observed centroid of the [O III] emission and the feature's width, we can determine the radial velocity, as well as the velocity dispersion of the gas producing this line. One hour of Gemini observations yields a root mean square surface brightness sensitivity of 1-2 x 10^{-17} erg s^{-1} cm^{-2} $arcsec^{-2}$ — one to two orders of magnitude deeper than typical previous narrow-band observations obtained from the ground or with the Hubble Space Telescope.

Striking Finds

The first striking conclusion of this work is that we detect an ionized nebula in every quasar we look at (Figure 1). These gas nebulae extend over the entire quasar host galaxy, with a mean diameter of ~90,000 light-years.

Another major finding is that nebulae around radio-quiet quasars are round and featureless, in contrast to those around radio galaxies which tend to be lumpy or elongated (Figure 2). This difference in morphology is the key piece of evidence and suggests

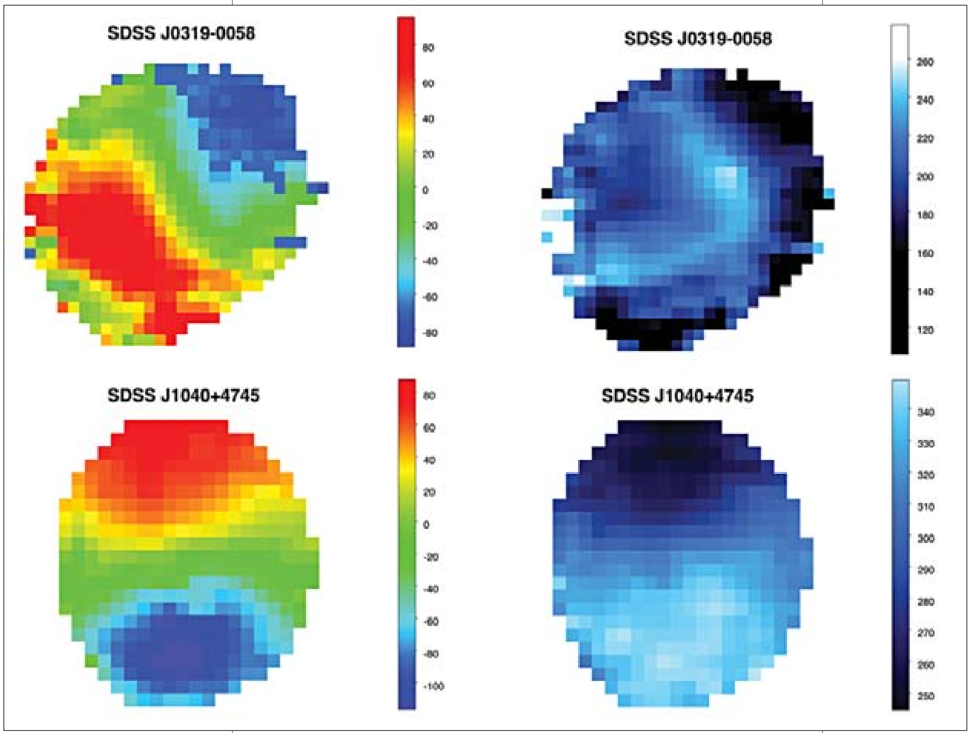

Figure 3.
Line-of-sight velocities (left panels) and velocity dispersions (right panels) of the gas comprising the nebulae (in units of km/s).

that in these two different types of objects we see two fundamentally different mechanisms of producing ionized gas on galaxy-wide scales. However, the mere fact that the gas is distributed over the entire galaxy does not imply that the gas is outflowing.

The second piece of the puzzle is the kinematic measurements (Figure 3). The Doppler effect allows us to determine the average line-of-sight velocity of the gas at every spatial element in the field-of-view. If the outflow is completely isotropic, then the average radial velocity at any point is in fact zero; thus, our measurements critically rely on the intrinsic anisotropy of quasar winds.

Fortunately, such anisotropies seem to be common. Indeed, in Figure 3 we see in both SDSS J0319-0058 and SDSS J1040+4745 that one side predominantly shows blue-shifted emission, while the other side is mostly red-shifted. This means that the gas on one side is moving towards us (and away from the galaxy, which is in the center of each image); the gas on the other side is moving away from us (and the galaxy).

Our interpretation of the GMOS observations is that we have finally observed the long-sought evidence of radiation-pressure-driven quasar winds. We are conducting further analysis of our dataset to construct kinematic models of quasar outflows and determine their energetics. This will allow us to estimate the effects of such winds on galaxy evolution. Furthermore, this semester we are obtaining new Gemini observations of a comparison sample of unobscured quasars to determine the effects of quasar orientation, and perhaps evolutionary stage on the observed properties of the outflows. We are grateful for the opportunity to use world-class Gemini data to reveal the critical details of the process of quasar feedback.

The first of the papers describing these results will be published in the *Monthly Notices of the Royal Astronomical Society*.

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