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Jets from AGN Quench Star Formation in Shocking Ways

Gemini Multi-Object Spectrograph Integral field unit observations of the nearby lenticular galaxy NGC 1266 have shed light on a mysterious process that quenches star formation in galaxies. The data reveal how jets from an active galactic nucleus can shock and disrupt the interstellar medium, driving gas from the galaxy and exhausting the fuel necessary to create new stars.

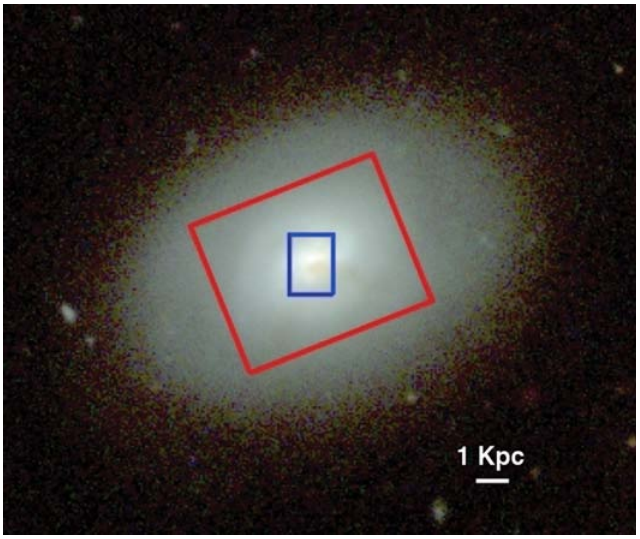

Figure 1.
B–V and R-band composite three-color image of lenticular galaxy NGC 1266. The white bar shows a linear scale of 1 kiloparsec; 65.94 arcseconds at an adopted distance of 29.9 Mpc. Overlaid is the total field-of-view of SAURON IFU (red) and GMOS IFU (blue) observations.
Image credit: SINGS Survey

Although galaxies come in all sizes and shapes, their colors appear strongly bimodal. Active star-forming galaxies have blue optical colors because bright young stars abound in their disks. On the opposite end of the spectrum, red light from cooler old stars tend to dominate the more quiescent systems. It is not, however, a uniform distribution from one color class to the other. In a diagram of galaxy color versus total galaxy brightness, we see not only a "blue cloud" of star-forming galaxies at one end, and a tight "red sequence" of quiescent objects at the other, but also what's known as a "green valley" of less numerous transition objects in between.

This strongly bimodal color distribution wouldn't appear so pronounced if blue-cloud galaxies are left to consume their gas via star formation and redden naturally. The color bimodality therefore implies that some galactic-scale process must actively quench star formation, removing its fuel from the environment in one violent episode.

Wind Power

Astronomers have long believed cold molecular gas provides the fuel for ongoing star formation. This phase of the inter-stellar medium (ISM) is cold and dense, thus tightly bound in galactic disks. Removing such gas requires vast amounts of energy. While strong starbursts can drive winds and strip gas on galaxy scales, this occurs only when star-formation rates run high.

Another way to input large amounts of energy into the ISM is by harnessing the power of an accreting super-massive black-hole (*i.e.* an active galactic nucleus, AGN). AGN can unleash powerful jets capable of directly driving gas from a galaxy, or output vast amounts of electromagnetic energy that can destroy or accelerate gas clouds.

Some tentative evidence links AGN to the quenching process that turns galaxies red. For instance, AGN seem to be more common in the transition region, between the red sequence and the blue star-forming galaxies. Astronomers have also detected outflows of ionized and neutral gas (detected in absorption) associated with powerful AGN. Direct evidence that AGN can drive the cold molecular gas from a galaxy, though, was scarce. This has all changed in the past few years, however, with a quick succession of discoveries of several large AGN-powered molecular outflows.

Notably, in 2011, an international team lead by K. Alatalo at University of California Berkeley discovered that the lenticular galaxy NGC 1266 (shown in Figure 1) has a large molecular outflow. Since the star-formation rate of NGC 1266 isn't high enough to power the outflow, the driving force most likely comes from the X-ray-emitting AGN lurking at the galaxy's core. The outflow is extremely powerful, accelerating over 20 million solar masses of cold molecular gas from the galaxy at such a rate that in 85 million years the entire system will be gas free.

This unusual galaxy is relatively nearby, allowing us to directly investigate the process of AGN feedback in action, and answer open questions: Is the outflow removing gas of all phases from the galaxy, not just the cold molecular gas? Is the AGN driving the outflow with radiation, or directly through radio jets? Is star formation outside the nuclear regions contributing to the outflow, or is only the AGN quenching the galaxy?

To help answer these questions, we combined observations from the Gemini Multi-Object Spectrograph (GMOS) Integral Field Unit (IFU) at Gemini North with data from the SAURON IFU on the William Herschel Telescope on La Palma to map the emission and absorption lines in the galaxy's central regions.

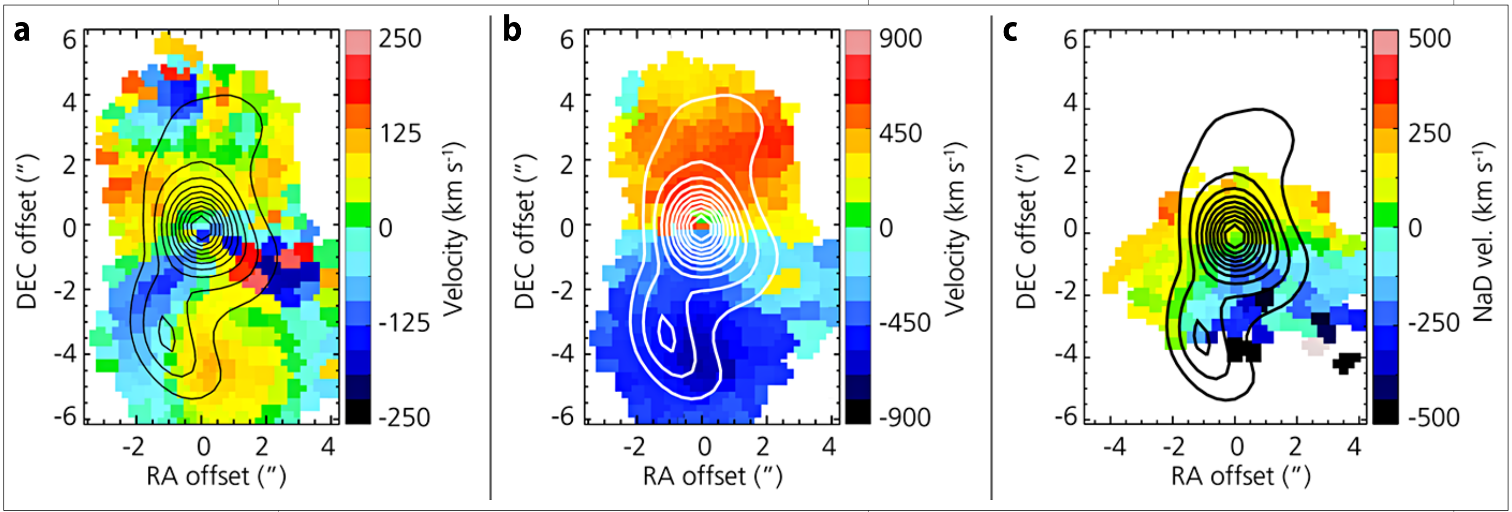

Figure 2.
Ionized and atomic gas kinematics derived from the GMOS IFU data. In panels a and b we display the kinematics of the ionized gas in the bound component, and the outflow, respectively. Bins where only one ionized gas component is required are also shown in panel a. Panel c shows the neutral gas kinematics derived from the sodium absorption. The 1.4 gigahertz radio-emission contours (from observations by the VLA) are overlaid.

The SAURON IFU data for this object were taken as part of the wider ATLAS^{3D} which attempts to understand the formation and evolution of red-sequence galaxies (Cappellari *et al.*, 2011). The SAURON data only provide H-beta, [O III] and faint [N I] lines — insufficient to securely characterize the ionized gas properties. We therefore used the GMOS IFU (2-slit mode) to obtain complementary data around the H-alpha line, making a mosaic of four pointings. The coverage of the two IFU data sets can been seen in Figure 1.

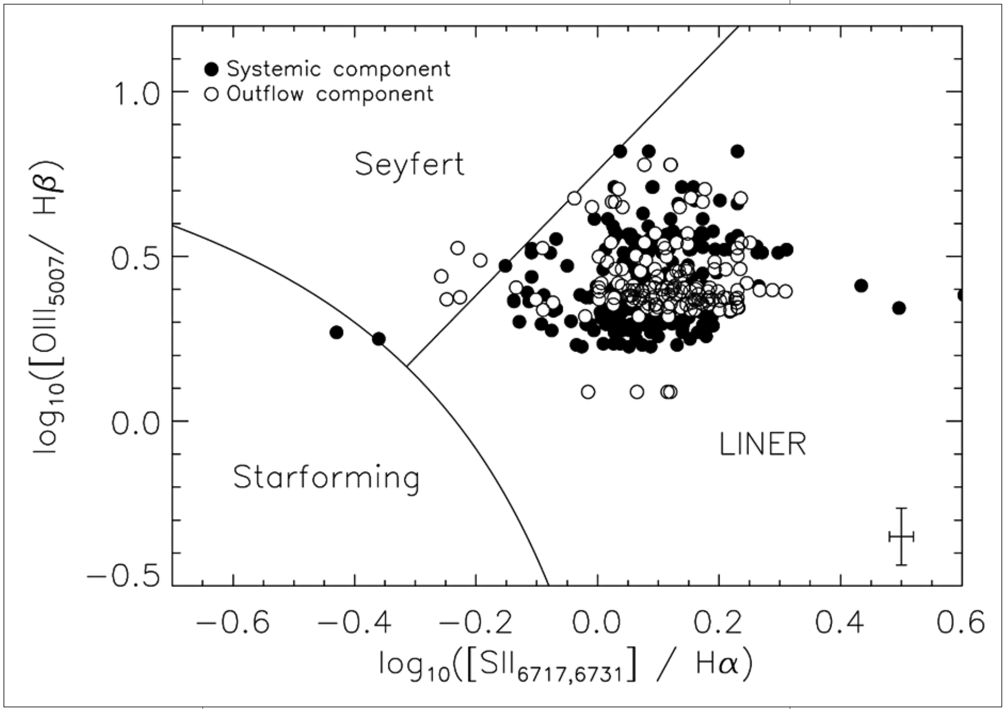

Figure 3.

An example BPT-type diagram — which demonstrates how LINERs can be distinguished from normal H II regions and normal AGNs — for the inner part of NGC 1266. The Y-axis shows the [O III]/H-beta ratio derived from SAURON data, and it is plotted versus the [S II]/H-alpha line ratio from GMOS observations. In the bottom right of the plot is the typical error bar associated with each point. Overplotted are diagnostic lines, which indicate the dominant line excitation mechanism.

A Surprise Finding

While analyzing the data, we encountered our first surprise: the ionized gas lines had strange profile shapes, implying that at least two ionized gas components exist along each line of sight. After carefully separating these lines to ensure a robust determination of the ionized gas kinematics of each component, we found that one of them traced the outflow, which emerges in the galaxy's polar plane. The ionized gas in this outflow pushes outwards at speeds of up to 800 kilometers per second (kms), ensuring it will leave its host galaxy entirely, enriching the intergalactic medium with metals.

The second ionized gas component extends to larger radii, and appears bound to the galaxy, but its origin is unclear. It may simply reflect unrelated gas components at different locations along the line of sight, or it may be a coherent rotating structure that has been disturbed by the outflow. Figure 2 shows the GMOS view of these components.

In addition to the ionized gas, the GMOS data also shed light on the kinematics of the neutral atomic gas in this system — thanks to the detection of absorption lines caused by sodium atoms in the gas phase, visible after careful subtraction of the stellar absorption spectrum. Alatalo *et al*. (2011) detected atomic hydrogen in absorption in NGC 1266, and our GMOS observations confirmed that the outflow is indeed expelling neutral gas from the galaxy at speeds up to 500 kms.

As we view the gas projected against the galaxy's starlight, we were able to use the observed sodium (Na D) absorption profiles to set constraints on the size and orientation of the outflow. The results show well-correlated neutral and molecular outflows along a slightly different axis to the ionized gas. The cause of this effect is unclear.

High-resolution radio observations of NGC 1266 reveal it to have a small asymmetric double radio jet. Alatalo *et al.* (2011) hypothesized that the AGN is driving this nascent structure into the extremely dense molecular ISM surrounding it, causing the outflow.

With the benefit of the GMOS IFU data, we were able to confirm that this jet correlates with the morphology of the ionized and atomic gas (see Figure 2), leaving little room for doubt that the jet itself is driving the outflow.

In optical diagnostic diagrams (see Figure 3), NGC 1266 is classified as a LINER (low-ionization nuclear emission region). This is a controversial class of objects. Some authors claim their characteristic ionized gas line emission ratios arise from AGN activity, while others believe shocks or old stars can cause them. By combining the SAURON and GMOS IFU emission line diagnostics, we showed that, although NGC 1266 undoubtably hosts an AGN, the line emission in this object is extended, and is most consistent with excitation from fast shocks caused by the interaction of the radio jet with the ISM.

These shocks have velocities of up to 800 kms, which match well with the observed velocity of the outflow. It thus seems that within the inner parts of this galaxy, star-formation has ceased to be an important energy source, as gas is driven from the galaxy by jets that shock and disrupt the ISM. Eventually this process would be expected to entirely quench the already low levels of ongoing star formation.

NGC 1266 is one of the few currently known galaxies in which we can witness ongoing active feedback, where a central AGN is disrupting its star-forming reservoir. The GMOS IFU observations have shed light on this mysterious process. However, further work is clearly required to understand all the subtleties of the violent processes at work in this galaxy.

The fact that NGC 1266 is relatively nearby and bright in most wavebands means we will be able to study it in-depth, with high spatial and spectral resolution. It is clear that understanding the processes removing the ISM will have widespread implications to both theoretical and observational attempts to understand AGN feedback, its effect on the ISM, and its role in building up the red sequence.

For more information:

Atlas^{3D} website:
www.astro.physics.ox.ac.uk/atlas3d/

Alatalo, K., Blitz, L., Young, L. M., *et al.*, *The Astrophysical Journal*, **735**: 88, 2011

Cappellari, M., Emsellem, E., Krajnovič, D., *et al.*, *Monthly Notices of the Royal Astronomical Society*, **413**: 813, 2011

Davis, T.A., Krajnovič, D., McDermid, R.M., *et al.*, *Monthly Notices of the Royal Astronomical Society*, **426**: 1574, 2012

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