Revealing an Energetic Galaxy-Wide Outflow in a \( z \approx 2 \) Ultraluminous Infrared Galaxy

D. M. Alexander\(^1\), A. M. Swinbank\(^2\), I. Smail\(^2\), R. McDermid\(^3\), and N. P. H. Nesvadba\(^4\)

\(^1\)Department of Physics, Durham University, Durham, DH1 3LE, UK
\(^2\)Institute for Computational Cosmology, Durham University, Durham, DH1 3LE, UK
\(^3\)Gemini Observatory, 670 N. A’ohoku Place, Hilo, HI 96720, USA
\(^4\)Institut d’Astrophysique Spatiale, Université Paris Sud 11, Orsay, France

Abstract. Leading models of galaxy formation require large-scale energetic outflows to regulate the growth of distant galaxies and their central black holes. However, current observational support for this hypothesis at high redshift is mostly limited to rare \( z > 2 \) radio galaxies. Here we present Gemini-North NIFS Integral Field Unit (IFU) observations of the [O III]λ5007 emission from a \( z \approx 2 \) ultraluminous infrared galaxy (ULIRG; \( L_{\text{IR}} > 10^{12} L_\odot \)) with an optically identified Active Galactic Nucleus (AGN). The spatial extent (\( \approx 4–8 \) kpc) of the high velocity and broad [O III] emission are consistent with that found in \( z > 2 \) radio galaxies, indicating the presence of a large-scale energetic outflow in a galaxy population potentially orders of magnitude more common than distant radio galaxies. The low radio luminosity of this system indicates that radio-bright jets are unlikely to be responsible for driving the outflow. However, the estimated energy input required to produce the large-scale outflow signatures (of order \( \approx 10^{59} \) ergs over \( \approx 30 \) Myrs) could be delivered by a wind radiatively driven by the AGN and/or supernovae winds from intense star formation. The energy injection required to drive the outflow is comparable to the estimated binding energy of the galaxy spheroid, suggesting that it can have a significant impact on the evolution of the galaxy. We argue that the outflow observed in this system is likely to be comparatively typical of the high-redshift ULIRG population and discuss the implications of these observations for galaxy formation models.

1. Introduction

Modern-day cosmology is a rich cocktail of observations and theory. Hard observational constraints guide the theoretical models, which then provide more detailed insights into the potential physical mechanisms that drive the growth of galaxies and their massive central black holes. One area where theoretical models have been particularly successful is in highlighting that star formation must have been truncated in the most massive galaxies at high redshifts (\( z \approx 2–3 \); e.g., Benson et al. 2003; Di Matteo et al. 2005; Bower et al. 2006). The leading candidates to cause this truncation are galaxy-wide outflows and winds, associated with either star-formation activity (e.g., supernovae winds) or active galactic nuclei (AGNs; e.g., winds and jets initiated from the black-hole accretion disk). If energetic enough, these winds could heat the cool galactic gas and/or eject...
it from the gravitational potential of the host galaxy, effectively shutting down any further significant star formation.

Integral field units (IFUs) are the ideal tool to identify galaxy-wide energetic outflows as they provide spectro-imaging over several arcsecond fields of view (e.g., Swinbank et al. 2005, 2006). The typical expected signature of an outflow is a broad emission-line gas component kinematically distinct from the narrow-emission line gas in the host galaxy (velocity offsets of several hundreds of kilometers/second) that is extended over kpc-scales. IFU observations of the [O III] (rest-frame 5007 ang) emission in a handful of massive radio-loud AGNs at $z \approx 2–3$ have indeed revealed the signatures of galaxy-scale energetic outflows (e.g., Nesvadba et al. 2006, 2007, 2008). The outflows from these systems appear to be driven by radio jets initiated by AGN activity. While these data provide evidence that energetic outflows can be identified in distant galaxies, radio-loud AGNs are rare beasts and it is far from clear how typical these outflows are in the typical distant massive galaxy population. To throw light on whether outflows are ubiquitous in the distant Universe, we have used the Gemini NIFS IFU to search for galaxy-wide energetic outflows in more typical radio-quiet systems. Here we present our initial results from this program on the $z \approx 2$ radio-quiet AGN SMM J1237+6203, which are published in Alexander et al. (2009).

SMM J1237+6203 is an optically bright $z = 2.07$ quasar that is also bright at submillimetre (850 µm), radio (1.4 GHz), and X-ray (0.5–8 keV) wavelengths (Alexander et al. 2003, 2005; Barger et al. 2003; Chapman et al. 2005). The estimated infrared luminosity of SMM J1237+6203 is of order $6 \times 10^{12} L_\odot$, indicating that it is a distant ultra-luminous infrared galaxy (ULIRG). The AGN in SMM J1237+6203 is luminous (X-ray luminosity $\approx 10^{44}$ erg s$^{-1}$) and undoubtedly contributes to a considerable fraction of the infrared luminosity (Alexander et al. 2005). However, given the bright submillimetre and radio emission, it seems likely that SMM J1237+6203 also hosts an ultra-luminous infrared starburst in addition to the luminous AGN activity. Previously published near-infrared spectroscopy shows that SMM J1237+6203 has bright, and possibly broad and extended, [O III] emission (Takata et al. 2006). These are the expected signatures of a galaxy wide outflow, although high-quality IFU observations are required to provide detailed constraints.

2. Gemini NIFS IFU Observations

We obtained the NIFS IFU observations of SMM J1237+6203 on 2008 May 22 and 2008 May 30, with a total on-source integration time of 7.8 ks (600s individual exposures obtained in a standard ABBA configuration). The observations were taken in excellent photometric conditions with $\approx 0.3$ arcsec seeing. The NIFS IFU uses an image slicer to take a $3 \times 3$ arcsec field with a pixel scale of 0.043 arcsec and divides it into 29 slices of width 0.103 arcsecs. The collapsed one-dimensional spectrum is shown in Fig 1. The [O III] emission line has a blue asymmetric profile, which is fitted with two underlying Gaussian profiles: the offset between the narrow emission line (FWHM $\approx 210$ km s$^{-1}$) and the broad emission line (FWHM $\approx 820$ km s$^{-1}$) is $\Delta V \approx -250$ km s$^{-1}$. The luminosity of the broad and narrow components are comparable ($\approx 10^{43}$ erg s$^{-1}$). The luminous [O III] emission is the result of photoionisation by the AGN, although it is
less certain what is responsible for the production of the kinematically complex [OIII] component.

To provide spatial information of the [OIII] emission, we constructed intensity, velocity, and FWHM maps of the [OIII] emission from the IFU data cube. A $\chi^2$ minimisation procedure was used to fit each spectrum within the datacube, taking into account the greater noise at the positions of the sky lines. The spectra were averaged in increasingly larger spatial bins until a significant emission-line component was identified. To detect an emission line we required a $>5\sigma$ improvement over a simple continuum fit, and to detect an additional broad component we required a $>4\sigma$ improvement over a single narrow emission-line fit. The basic [OIII] properties derived from the IFU datacube are shown in Fig 2.

3. Evidence for an Energetic Galaxy-Wide Outflow

Narrow [OIII] emission is detected across $\approx 14$ kpc, which is blue-shifted and red-shifted (with respect to the systemic redshift) to the South-East and North-West of the nucleus, respectively; see Fig. 2. The velocity field of this narrow [OIII] emission may be dominated by the host-galaxy rotation, although it is not clear that this is the only plausible explanation; see Fig 1. The spheroid mass estimated from the velocity dispersion of the narrow [OIII] emission ($\approx 200$ km s$^{-1}$) is of order $\approx 10^{11} M_\odot$, and is consistent with that expected from the estimated black-hole mass ($M_{\text{BH}} \approx 2 \times 10^8 M_\odot$; Alexander et al. 2008), given the local black-hole–spheroid mass relationship.
Broad [O III] emission is detected over ≈ 4–8 kpc at the nucleus and to the South-East of the nucleus; see Fig. 2. The radial extent, velocity offset, and FWHM of the broad [O III] emission is shown in Fig. 3. The broadest [O III] components clearly correspond to those with the largest velocity offset. These characteristics are similar to those found in some distant radio-loud AGNs (e.g., Nesvadba et al. 2006, 2007, 2008) and are consistent with those expected for an energetic galaxy-wide outflow. Assuming that the broad [O III] emission is due to an energy-conserving bubble expanding into a uniform region, the kinetic energy required to produce the broad [O III] features is of order ≈ (0.6–3) × 10^{44} erg s^{-1} over 4–8 kpc (calculated using Eqn. 3 in Nesvadba et al. 2006). Over a typical AGN/starburst lifetime of ≈ 30 Myrs, the total injection of energy into the outflow would be of order ≈ (0.3–3) × 10^{59} ergs, which is comparable to the estimated binding energy of the galaxy spheroid (≈ 10^{59} erg s^{-1}). This analysis is based on a simple model and should only be considered illustrative with uncertainties at the level of an order of magnitude but, given the limited constraints available for high-redshift systems, a more complex model is not yet warranted. However, it does indicate that the large-scale outflow in SMM J1237+6203 may be energetic enough to unbind at least a fraction of the gas from the host galaxy.

What is driving this large-scale energy outflow? Both AGN activity and star formation are plausible candidates. Assuming that ≈ 10% of the mass accreted onto the black hole is also liberated as an accretion-disk outflow (as motivated by observations of similar distant AGNs; e.g., Chartas et al. 2007), the initial energy input into the accretion-disk wind would be of order ≈ (0.3–3) × 10^{45} erg s^{-1}. Therefore, so long as ≈ 2–100% of this energy can be coupled to the host-galaxy gas, an accretion-disk wind in SMM J1237+6203 could drive the outflow over ≈ 4–8 kpc. Similarly, assuming a typical star-formation rate for submillimeter-emitting galaxies of ≈ 1000 M_{\odot} yr^{-1}, the predicted energy injection from supernovae winds would be of order ≈ 3 × 10^{44} erg s^{-1}. If ≈ 20–100% of this energy...
can be coupled to the host-galaxy gas, then star-formation activity could also drive the large-scale outflow. We cannot distinguish between these two different scenarios on the basis of the current data. However, given the comparatively modest radio luminosity from SMM J1237+6203, we can rule out that the outflow if driven by radio jets, in contrast to that found in distant radio-loud AGNs; the gas coupling efficiency in SMM J1237+6203 would need to be unphysically high (≈ 10,000%), assuming typical radio-jet models. See §4 of Alexander et al. (2009) for more details.

SMM J1237+6203 is the first high-redshift ULIRG with spatially extended broad [O III] emission to be mapped with IFU observations. Previous IFU studies of high-redshift ULIRGs have typically focused on the Ly α or H α emission line, and the majority of the objects observed have not shown evidence for AGN activity at optical wavelengths (e.g., Swinbank et al. 2005, 2006). However, three pieces of indirect evidence suggest that SMM J1237+6203 could be rela-
tively typical of the high-redshift ULIRG population: (1) broad [O \text{III}] emission-line components have been identified with rest-frame optical spectroscopy in several high-redshift ULIRGs to date (e.g., Takata et al. 2006), (2) $\approx 50\%$ of nearby ULIRGs hosting optical AGN activity have [O \text{III}] components with FWHM $> 800$ km s$^{-1}$, comparable to that found for SMM J1237+6203 (e.g., Veilleux et al. 1999; Zheng et al. 2002), and (3) high-quality IFU data have been published for a number of nearby ULIRGs showing that they host broad and extended [O \text{III}], providing evidence for large-scale energetic outflows in at least some ULIRGs in the local Universe (e.g., Wilman et al. 1999; Lípari et al. 2009).

It therefore seems likely that the outflow processes seen in SMM J1237+6203 are comparatively common in the distant Universe. Since ULIRGs are orders of magnitude more common than radio-loud AGNs at $z \approx 2$, their global contribution to the injection of energy into the host galaxy could therefore be very significant and even dominant. The NIFS IFU observations for the other targets in our distant AGN–ULIRG sample should provide at least the first steps toward addressing this issue.

Acknowledgments. We would like to thank the following organisations for support: Royal Society (DMA), the Philip Leverhulme Prize Fellowship (DMA), the Royal Astronomical Society (AMS), and the Science and Technology Facilities Council (STFC).

References

Alexander, D. M., et al. 2003, AJ, 126, 539
Alexander, D. M., et al. 2005, ApJ, 632, 736
Alexander, D. M., et al. 2008, AJ, 135, 1968
Alexander, D. M., Swinbank, A. M., Smail, I., McDermid, R., & Nesvadba, N. P. H. 2009, in press [arXiv:0911.0014]
Barger, A. J., et al. 2003, AJ, 126, 632
Benson, A. J., Bower, R. G., Frenk, C. S., Lacey, C. G., Baugh, C. M., & Cole, S. 2003, ApJ, 599, 38
Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, MNRAS, 370, 645
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, ApJ, 622, 772
Chartas, G., Brandt, W. N., Gallagher, S. C., & Proga, D. 2007, AJ, 133, 1849
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nat, 433, 604
Lípari, S., et al. 2009a, MNRAS, 392, 1295
Nesvadba, N. P. H., Lehner, M. D., Eisenhauer, F., Gilbert, A., Tecza, M., & Abuter, R. 2006, ApJ, 650, 693
Nesvadba, N. P. H., Lehner, M. D., De Breuck, C., Gilbert, A., & van Breugel, W. 2007, A&A, 475, 145
Nesvadba, N. P. H., Lehner, M. D., De Breuck, C., Gilbert, A. M., & van Breugel, W. 2008, A&A, 491, 407
Swinbank, A. M., et al. 2005, MNRAS, 359, 401
Swinbank, A. M., Chapman, S. C., Smail, I., Lindner, C., Borys, C., Blain, A. W., Ivison, R. J., & Lewis, G. F. 2006, MNRAS, 371, 465
Takata, T., Sekiguchi, K., Smail, I., Chapman, S. C., Geach, J. E., Swinbank, A. M., Blain, A., & Ivison, R. J. 2006, ApJ, 651, 713
Veilleux, S., Kim, D.-C., & Sanders, D. B. 1999, ApJ, 522, 113
Wilman, R. J., Crawford, C. S., & Abraham, R. G. 1999, MNRAS, 309, 299
Zheng, X. Z., Xia, X. Y., Mao, S., Wu, H., & Deng, Z. G. 2002, AJ, 124, 18