Spatially Resolved Spectroscopy to Confirm or Disprove Dual Active Galactic Nuclei

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Abstract. When galaxies merge, gas accretes onto both central supermassive black holes. Thus, one expects to see dual active galactic nuclei (AGNs) in a fraction of galaxy mergers. Candidates for galaxies containing dual AGNs have been identified by the presence of double-peaked narrow [O III] emission lines and by high spatial resolution images of close galaxy pairs. 30% of double-peaked narrow [OIII] emission line SDSS AGNs have two spatial components within a $3''$ radius. However, spatially resolved spectroscopy is needed to confirm these galaxy pairs as systems with double AGNs. With the Keck 2 Laser Guide Star Adaptive Optics system and the OSIRIS near-infrared integral field spectrograph, we obtained spatially resolved spectra for SDSS J095207.62+255257.2, confirming that it contains a Type 1 and a Type 2 AGN separated by 4.8 kpc ($=1.0''$). We performed similar integral field and long-slit spectroscopy observations of more spatially separated candidate dual AGNs and will report on the varied results. By assessing what fraction of radio-quiet double-peaked emission line SDSS AGNs are true dual AGNs, we can better constrain the statistics of dual AGNs and characterize physical conditions throughout these interacting AGNs.

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1. Introduction

One common explanation for active galactic nuclei (AGNs) invokes mergers of gas-rich galaxies; tidal forces can disturb the gas and funnel it into the centers of the merging galaxies, causing new bursts of star formation in the nuclear regions, increased fueling of the supermassive black hole(s), and their possible activation as an Active Galactic Nucleus (AGN) (Hernquist 1989; Kauffmann & Haehnelt 2000; Hopkins *et al.* 2008).

If galaxy mergers trigger AGN activity, the nuclei of both galaxies should be active in at least some galaxy mergers. Hundreds of AGN pairs are known at > 15 kpc separations (e.g. Hennawi *et al.* 2010; Green *et al.* 2010), while only $\sim$20 spatially and spectrally confirmed pairs of AGNs are known with separations < 15 kpc (commonly known as dual AGNs). At these separations, dual AGNs can be observed as double-peaked emission lines when the spectra are spatially unresolved (McGurk *et al.* 2012, Fu *et al.* 2012).

To <u>confirm</u> a potential dual AGN, spatially resolved spectroscopy is needed to prove that each resolved source has a unique AGN spectrum. Without spatially resolved
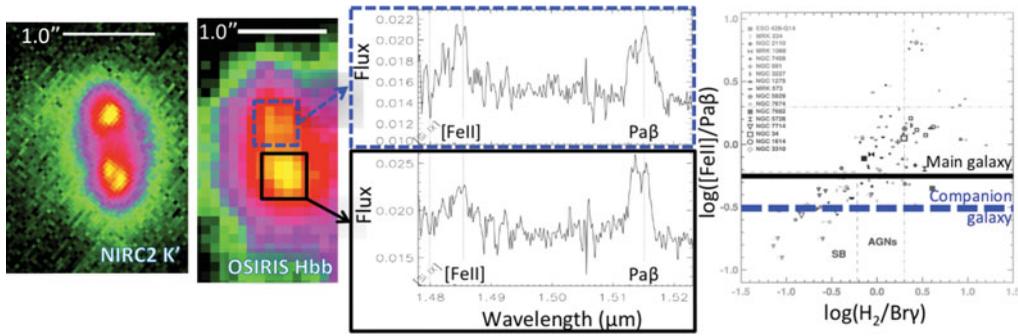
Figure 1. Keck NIRC2 and OSIRIS data for the galaxy and AGN J1108+0659 and its companion star-forming galaxy. *Far Left:* NIRC2 K' continuum image with the $1.0''$ scale bar showing 3.0 kpc at the AGN's redshift. The main galaxy (bottom) with the AGN shows 2 small clumps, perhaps a bulge bisected with a dust lane; the companion galaxy (top) is located $0.73''$ (2.2 kpc) away. *Middle Left:* OSIRIS H-band continuum image showing that the 100 milliarcsec pixel scale used does not spatially resolve the two clumps in the main galaxy. *Middle Right:* Extracted spectra: top dashed blue box shows the star-forming companion galaxy, and bottom solid black box shows the AGN. While emission lines are detected in both galaxies, there is insufficient signal-to-noise to determine accurate line centers and velocity differences, especially of the double-peaks suggested in the main AGN spectrum. *Far Right:* Rodríguez-Ardila *et al.* near-infrared AGN/star-formation emission line diagnostic diagram, similar to the optical Baldwin-Phillips-Terlevich diagram. Rodríguez-Ardila *et al.* (2008) plot the emission line flux ratios [Fe II] $\lambda 1.2570\mu$m/Paβ vs. H$_2$ $\lambda 2.121\mu$m/Brγ star-forming galaxies and Type 1 and 2 Seyfert AGNs; dotted lines show the star-forming, AGN, and inconclusive regions of the diagram. Over this, we have plotted the [Fe II] $\lambda 1.2570\mu$m/Paβ line ratios of the main AGN and companion galaxy as, respectively, solid black and dashed blue lines (since we do not have observations of the H$_2$ $\lambda 2.121\mu$m and Brγ lines). The original SDSS spectrum informs us that there is at least one AGN present in system, and the main galaxy appears to contain it. The companion galaxy appears to fall primarily in the star-forming region, so it is likely a star-forming galaxy.

spectroscopy to match the observed galaxies to their corresponding double-peaked emission lines, the double peaks of spectral lines may be due to a chance superposition of two objects, a recoiling SMBH (Bonning *et al.* 2007), jets interacting with the surrounding medium (Rosario *et al.* 2010; Veilleux *et al.* 2013), biconical or one-sided outflows from a single AGN (Fischer *et al.* 2011; Rupke & Veilleux 2013), or rings of star formation. Similarly, without spatially resolved spectroscopy, the multiple bright cores imaged in or around one galaxy may be any of the previously listed scenarios, gravitationally lensed sources (Hennawi *et al.* 2006), or starbursts. High-energy X-ray observations are another unambiguous way to confirm true dual AGNs at wide ($>1''$) separations, but they lack the spatial resolution to probe dual AGNs at smaller separations.

2. Overview

Recent studies have searched large extragalactic spectroscopic datasets such as the Sloan Digital Sky Survey (SDSS) to arrive at statistically useful samples of double-peaked emission line AGNs. The catalogs of Smith *et al.* (2010), Wang *et al.* (2009), and Liu *et al.* (2010) create a well-defined sample of 340 candidate dual AGNs by selecting SDSS DR7† spectroscopic AGNs that show a double-peaked [O III] $\lambda 5008$ line. Using the NIRC2 camera‡ and the Keck II Laser Guide Star Adaptive Optics (LGS AO) system

(Wizinowich *et al.* 2006), Rosario *et al.* (2011), Fu *et al.* (2011, 2012), and McGurk *et al.* (in prep) undertook near-infrared (NIR) imaging of these candidate double AGNs. In total, 140 SDSS AGNs with double-peaked [O III] were imaged with NIRC2; 42 objects (30%) have a companion within 3″ of the primary galaxy.

Unfortunately, the imaging discussed above proves little about how the double emission line structure relates to presence of a companion. Spatially resolved spectroscopy is needed to map the spatial separation of the double-peaked emission lines and distinguish outflows from dual AGNs. We used the OH Suppressing InfraRed Integral field Spectrograph (OSIRIS) (Larkin *et al.* 2006) and the LGS AO system on the Keck II telescope to obtain spatially resolved spectroscopy for SDSS J091646.03+283526.7, SDSS J110851.04+065901.4, and SDSS J095207.62+255257.2 (respectively shortened to J0916+2835, J1108+0659, and J0952+2552 for the rest of the paper). The 0.100″/spatial pixel (spaxel) plate scale was used to maximize throughput.

We used a modified† version of the OSIRIS Data Reduction Pipeline (ODRP) v2.3‡ to process our images. Instead of using the standard mosaicking tools provided in the ODRP, we determined relative offsets between the images by fitting two-dimensional Lorentzian profiles to the main galaxy in each frame, and then input the relative offsets directly into the mosaicking module of the ODRP¶. Finally, we extracted and combined spectra from the five spatial pixels with the highest signal-to-noise ratio (S/N) of both the main galaxy, the companion galaxy, and any interesting local features, as shown in Figures 1 and 2 for J1108+0659 and

Figure 2. Keck OSIRIS data for the galaxy and AGN J0916+2835, its outflow, and its companion. *Left:* OSIRIS *K*-band continuum image of the galaxy (bottom) and its fainter companion (top). *Right:* Extracted spectra: top black box shows the quiescent companion galaxy, bottom blue box shows the AGN, middle red box shows the outflow. Multiple lines are observed in the AGN at the SDSS redshift of 0.142. In a continuum-less region 1.2 kpc West of the AGN (middle red box), we observe a second Paα peak at +450 km s^{-1}, consistent with the SDSS [O III] λ5008 velocity difference of 425 km s^{-1}. This ionized gas emission without stellar continuum is well explained by an outflow. The companion galaxy (top, black box) contains no significant emission lines (ignoring one cosmic ray). It is either a quiescent galaxy or a foreground or background object.

J0916+2835, respectively. Additionally, an OSIRIS image can be created by summing up the flux over all of the wavelengths (Figure 1, middle-left panel, and Figure 2, left panel).
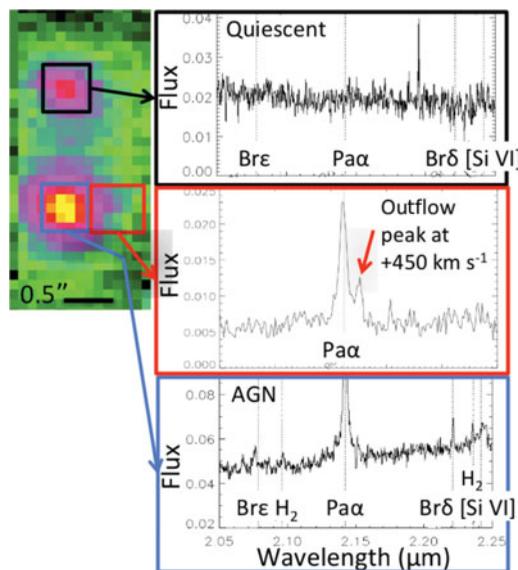
3. Discussion

For the in-depth discussion of J1108+0659 and J0916+2835, please see the captions of Figures 1 and 2, respectively. For an in-depth discussion of J0952+2552, please see

† Correcting for a ~ 6Å shift of the previous wavelength calibration Wright 2011.
‡ http://irlab.astro.ucla.edu/osiris/pipeline.html
¶ See http://irlab.astro.ucla.edu/osiriswiki/dokuphp?id=mosaic_with_a_list_of_offsets for a detailed explanation.

McGurk *et al.* (2011). In J1108+0659, both the main galaxy and the companion galaxy show [Fe II] $\lambda1.2570\mu$m and Paβ emission lines, although the lines lack signal-to-noise to conclude their precise wavelength centers and velocity differences. Independent of the spectral resolution, our high spatial resolution allows us to independently determine that the main galaxy contains the AGN detected by the SDSS at the redshift of 0.182 while the emission lines from the companion galaxy are at the same redshift and appear to be due to star-formation. In J0916+2835, multiple emission lines confirm that there is an AGN at the SDSS redshift of 0.142. However, the companion galaxy contains no significant emission lines, and is either a quiescent galaxy or a foreground or background object. Excitingly, in a continuumless region 1.2 kpc West of the AGN, we observe a second Paα at $+450$ km s^{-1} with respect to the central AGN, consistent with the SDSS [O III] $\lambda5008$ velocity difference of 425 km s^{-1}. Ionized gas emission without stellar continuum is well-explained by the presence of an outflow; a second, less likely possibility is the presence of a supermassive black hole retaining its accretion disk and narrow line region, without any nearby stars to supply continuum light.

These results and more will be discussed in McGurk *et al.* (in prep.).

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