OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Radio-AGN as star formation regulators: ionized gas kinematics along the radio jet

P.I.: Marios Karouzos (SNU; *mkarouzos@gmail.com*; +821050556638)

CoI(s): Hyun-Jin Bae⋆ (Yonsei University), Kooksub Jo⋆ (SNU), Aeree Chung (Yonsei University), Evangelia Tremou (Yonsei University), Taehyun Jung (Korean Astronomy and Space Science Institute), Jong-Hak Woo (SNU)

Abstract of Scientific Justification

In the last decade a suite of scaling relations have emerged that seem to link the properties of supermassive black holes and their host galaxies. Active galactic nuclei (AGN) have been suggested as a way to establish such a link, through regulation of star formation in their host galaxies. This regulation could be achieved through deposition of the AGN energy into its surroundings through direct photo-ionization of star-forming regions, expulsion of gas through outflows, or a combination of both. The observational evidence of this AGN feedback, however, still remain scarce. We propose to acquire long-slit spectroscopy along the kpc-scale jets of a sample of type 2 radio-luminous AGN that exhibit strong ionized gas outflows in their spatially integrated SDSS spectra. These rare objects, selected from a large sample of 34,000 type 2 AGN (at z$<$ 0.2), present ***a unique opportunity to study the connection between radio jets and gas outflows in the local universe***. We aim to answer whether there is any spatial and energetic connection between extended radio jets and ionized gas outflows. Due to the wide range of [OIII] luminosities covered by the proposed targets, we will also contrast ionized gas kinematics in the Seyfert and QSO AGN regime and thus contextualize the radio jet/ionized gas outflows comparison within the more general proposed frame of radio- and QSO-mode AGN feedback.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/9	Red Echelle			2	grey	Feb–Apr	Feb–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	9204	07:58:28.1	+37:47:12	z=0.04089, m_r=12.98, p=A
2	18240	10:20:53.7	+48:31:24	z=0.05314, m_r=15.07, p=A
3	10372	08:36:37.8	+44:01:10	z=0.05539, m_r=15.20, p=A
4	3858	09:35:52	+61:21:12	z=0.0392, m_r=14.08, p=A
5	44911	10:40:30	+29:57:58	z=0.0909, m_r=15.66, p=A
6	55152	13:03:47	+19:16:17	z=0.0635, m_r=13.75, p=A
7	58273	08:45:22	+11:25:55	z=0.0662, m_r=14.69, p=A
8	27842	11:40:28	+12:03:08	z=0.0811, m_r=14.84, p=A
9	4659	14:49:22	+63:16:14	z=0.0414, m_r=13.52, p=A
10	13284	13:41:34.8	+53:44:44	z=0.14109, m_r=16.67, p=B
11	13250	10:31:43.5	+52:25:35	z=0.16638, m_r=17.34, p=B
12	5782	11:42:58.7	+01:54:22	z=0.13264, m_r=17.64, p=B
13	44612	13:52:18	+31:26:47	z=0.0449, m_r=14.12, p=B
14	41659	08:06:01.5	+19:06:15	z=0.09816, m_r=15.6, p=B
15	40507	13:34:25.2	+38:17:59	z=0.06253, m_r=16.01, p=B
16	53935	11:45:05.0	+19:36:23	z=0.02172, m_r=12.47, p=B

Approval for Instrument Use from PI: ____________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Kooksup Jo	Jong-Hak Woo		no	no

Scientific Justification

Scientific Rationale: The last decade has seen huge leaps in our understanding of how galaxies and the supermassive black holes (SMBH) at their centers evolve. While large-scale cosmological simulations (such as the Millennium Simulation, Springel et al. 2005) showed how galaxies grow through cosmic time, it soon became apparent that some star formation regulation is needed in order to reconcile the observed mass function of galaxies in the local universe with the one derived from these numerical simulations (e.g., Croton et al. 2006, Sijacki et al. 2007). On a parallel front, a suite of observed scaling relations between galaxies and their hosted SMBHs (e.g., Kormendy & Ho 2013, Woo et al. 2013) gave rise to the coevolution paradigm, advocating that these two components, through some form of self-regulation, grow in tandem.

Active galactic nuclei (AGN) and their enormous energy output have been argued to be key players in this self-regulation. The process of star formation regulation or suppression through mechanisms related to the AGN (coined as AGN feedback), has been suggested as the answer to both problems stated above. AGN feedback is generally argued to manifest itself in two distinct modes (e.g., Kormendy & Ho 2013). The QSO-mode feedback is attributed to high Eddington ratio AGN (QSO), mainly at intermediate to high redshifts, whose effects are driven by deposition of energy in the inter-stellar medium (ISM) through the AGN radiative pressure. On the other hand, radio-mode feedback is associated with radio-AGN, mainly at low redshifts, and relies on the deposition of mechanical energy from a radio jet. In particular, simulations by Croton et al. (2006) showed that radio-mode feedback could regulate gas cooling and hence halt the growth of the galaxy. Several observational studies have shown this mechanical energy deposition in action (e.g., McNamara et al. 2005). Furthermore, in some cases radio jets have been associated with ionized and molecular gas outflows (e.g., Nesvadba et al. 2011, Morganti et al. 2013), which would offer an alternative, if not complimentary, way of halting star formation through the depletion of a galaxy's gas reservoirs. **Despite the theoretical predictions, the observational signatures of feedback "in action" have been rather scarce.** This has led to a still ongoing debate concerning the viability of AGN feedback in general, and radio-mode feedback in particular, as growth regulators.

Ionized gas outflows may be observationally the most straightforward way to investigate whether and to what degree AGN can affect the ISM of their host galaxy. The velocity of [OIII] λ5007 emission line is of particular interest for probing such outflows (e.g., Zamanov et al. 2002, Komossa et al. 2008). The spatially-integrated [OIII] lines of Seyfert galaxies and QSOs have been observed to be shifted with respect to low-ionization lines (e.g., Boroson 2005), which is presumably due to the combined effect of outflows and dust extinction (Crenshaw et al. 2010). Furthermore, the line profile of [OIII] is often seen to be asymmetric with a broad wing component, indicating the presence of high velocity gas. Spatially resolved measurements of the NLR can therefore provide a better understanding of the nature of AGN-driven outflows and their impact on the ISM. Assuming the knowledge of the radio jet kinematics and morphology, the resolved NLR ionized gas kinematics can probe potential spatial and energetic links between these two components.

Bae & Woo (2014) recently performed a census of ionized gas outflows using a large sample of 23,000 type 2 AGN out to z$\sim$0.1, by investigating the velocity offset of the [OIII] line with respect to the stellar absorption line based systematic velocity (see Fig. 1 left). By analyzing the spatially-integrated SDSS spectra, they concluded that $\sim$ 47% of type 2 AGN show line-of-sigh offsets in [OIII] ($>$ 20 km s^{-1}). They also revealed a strong contrast of the [OIII] velocity dispersion (2nd moment) between AGN and star-forming galaxies. While star-forming galaxies gave relatively narrow [OIII] ($\sim$ 50 km s^{-1}), AGN show a broad range of [OIII] line widths (50–500 km s^{-1}). This indicates dramatically different kinematics of the ionized gas, presumably due to outflows (Fig. 1 left). Perhaps most intriguingly, while for the total sample they found a $\sim$ 10% radio detection rate (at a 1.4 GHz flux density limit of 1 mJy from the FIRST radio survey), this rate quadruples to $\sim$ 40% for those AGN with large [OIII] offset velocities. This suggests an implicit connection between the ionized gas outflows and radio jets. *This is one of the first large-scale, statistical studies of its kind that has revealed this link between radio emission and ionized gas outflows.*

Moreover, Karouzos et al. (2014b) showed that for a sample of low to intermediate redshift radio-luminous AGN, strong radio jets lead to a suppression of star formation in their host galaxies, without however totally quenching it. Whether this is a result of ionized gas outflows launched and driven by the radio jet is still unclear. **The SDSS sample of AGN with detected gas outflows and radio counterparts is a unique testbed to investigate this putative link in the local universe.** The proximity of these sources makes them ideal targets for follow-up spatially resolved studies (e.g., along the radio jet) to investigate in detail the nature of their gas outflows, the connection of the ionized gas outflows to the radio emission (e.g., radio jet-driven or shock-driven radio emission, see a recent discussion by Zakamska & Greene 2014), revealing the potential impact of radio jets and the ionized gas outflows on the ongoing star formation in their host galaxies, and ultimately for understanding the role of outflows as one of the potential AGN feedback mechanisms.

This proposal: We have expanded the parent sample of Bae & Woo (2014) by pushing the redshift limit of our study to z$<$ 0.2. We have thus a parent sample of $\sim$34,000 type 2 AGN out to z=0.2, for which we have fully characterized their optical SDSS spectra and derived their [OIII] and Hα velocity offsets and velocity dispersions. We cross-matched our parent sample with the FIRST survey (Becker et al. 1995) at a 1.4 GHz flux density limit of 1 mJy and have carefully identified radio-luminous type 2 AGN with extended jet emission in the available radio images (at resolutions of $\gtrsim$1 arc sec). Furthermore, we require our targets to show clear signatures of ionized gas outflows, fulfilling one of the following: (1) a [OIII] velocity offset above 100 km s^{-1} or (2) an [OIII] velocity dispersion above 150 km s^{-1} and an [OIII] to stellar velocity dispersion ratio above 1.2 (see Fig. 1 left). The latter criterion ensures that there is an additional kinematic component in [OIII] that cannot be attributed to the host galaxy but instead is potentially due to an ionized gas outflow. Based on these criteria, we carefully select a sample of 16 most radio luminous type 2 AGN with known ionized gas outflows from their spatially integrated SDSS spectra and extended radio jet structure, for which we propose to perform long-slit spectroscopy.

The selected sample is complete in terms of its radio luminosity ($>\sim$ 10^{40} erg s^{-1}), [OIII] luminosity ($>\sim$ 10^{37} erg s^{-1}, see Fig. 1 right), and [OIII] kinematics ($\sigma_{\rm [OIII]}$ $>$ 150 km s^{-1}). *The unique selection of this sample provides us with an exciting opportunity to conduct a detailed study of AGN ionized gas outflows and their connection to radio jets.* The proposed observations will provide us with spatially-resolved measurements over several kpc scales along the extended jet direction, enabling us to examine the ionized gas kinematics in relation to the radio jet and to look for evidence of ongoing feedback from the radio jet on the ISM along its wake. Of importance is the fact that the proposed sample uniquely covers a wide range of [OIII] luminosities (10^{39}–10^{43} erg s^{-1}), essentially probing both the Seyfert and QSO luminosity range. As a result, we will be equipped to make a first-order comparison between the two modes of AGN feedback, radio- and QSO-mode. In particular, given the low Eddington ratios (and hence radiative power) of the lowest [OIII] luminosity objects, a detection of ionized gas outflows along the radio jet will be direct evidence for these outflows being driven by the mechanical power of the radio jet itself.

The proposed observations will enable us to attack the following open questions:

• **Is there a link between radio jets and ionized gas outflows?** Given our unique target selection and observational setup (Fig. 2), we will look for the signature of ionized gas outflows along the radio jet and thus investigate the connection between these two components. If the radio jet is indeed responsible for launching these outflows, then we expect a stronger kinematic signature along the jet, compared to the spatially integrated SDSS spectra. A non-detection gives an equally interesting result as it places an upper limit on the impact of the radio jet on the surrounding ISM.

• **What is the dominant driver of AGN feedback?** After characterizing both the ionized gas and radio outflows (luminosities and spatial properties), we will calculate the radiative and mechanical energy deposited in the ISM from the nucleus and the radio jet, respectively. Coupled with the [OIII] kinematics, our knowledge of the host galaxy properties, and some physically motivated assumptions, we will be able to calculate the energy budget of each of our targets and thus investigate the energy balance between the different feedback components as a function of [OIII] luminosity. This will allow us to explore differences or even possible links between the QSO- and radio-mode feedback.

References: Springel, et al., 2005, Nature, 435, 629S • Croton, et al., 2006, MNRAS, 365, 11 • Sijacki, et al., 2007, MNRAS, 380, 877S • Kormendy & Ho, 2013, ARAA, 51, 511 • Woo, et al., 2013, ApJ, 772, 49 • McNamara, et al., 2005, Nature, 433, 45 • Nesvadba, et al., 2011, MNRAS, 415, 2359 • Morganti, et al., 2013, Science, 341, 1082M • Zamanov, et al., 2002, ApJ, 576L, 9Z • Komossa, et al., 2008, ApJ, 680, 926K • Boroson, 2005, AJ, 130, 381B • Crenshaw, et al., 2010, ApJ, 708, 419C • Bae & Woo, 2014, ApJ, in press • Karouzos, et al., 2014b, ApJ, 784, 37K • Zakamska & Greene, 2014, MNRAS, 442, 784 • Mauch & Sadler, 2007, MNRAS, 375, 931M • Sadler, et al., 2007, MNRAS, 381, 211S

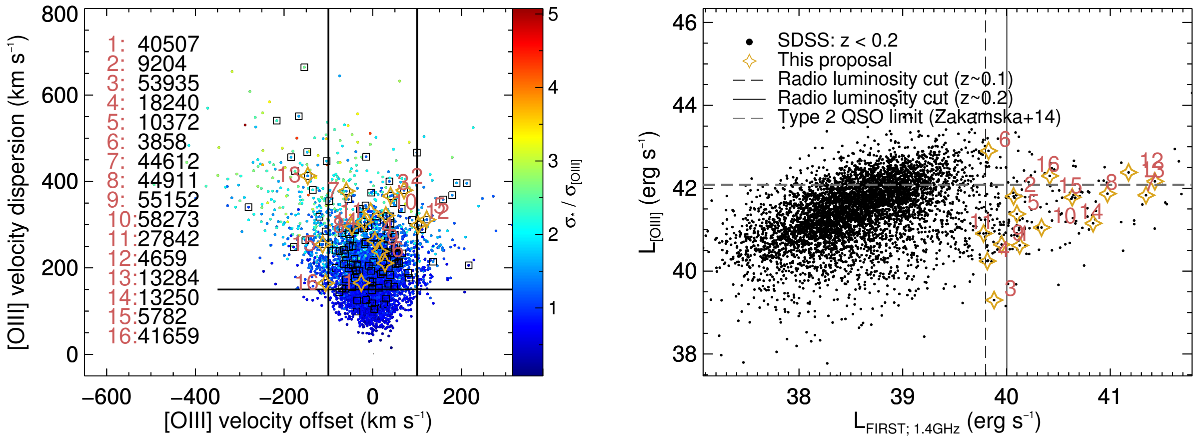

Figure 1: Left: [OIII] velocity dispersion versus [OIII] velocity offset for the radio-detected sources in our parent sample of $\sim 34,000$ SDSS type 2 AGN. The color coding shows the stellar to [OIII] velocity dispersion ratio. Values higher than 1 imply the presence of an additional kinematic component in the profile of the [OIII] line, potentially due to an outflow. Squares denote sources classified as radio-luminous. Stars denote the targets for this proposal. Right: [OIII] luminosity versus radio luminosity at 1.4 GHz, in logarithmic scale, for all radio-detected sources (black circles) and the targets for this proposal (golden stars). We also denote our radio luminosity limits for the z$<$ 0.1 (dashed vertical line) and $0.1 <$ z < 0.2 (solid line) samples, based on the local radio luminosity function (Mauch & Sadler 2007) and the expected radio luminosity function evolution with redshift (Sadler et al. 2007). Finally, the dashed horizontal line shows the type 2 QSO luminosity cut employed in Zakamska et al. (2014).

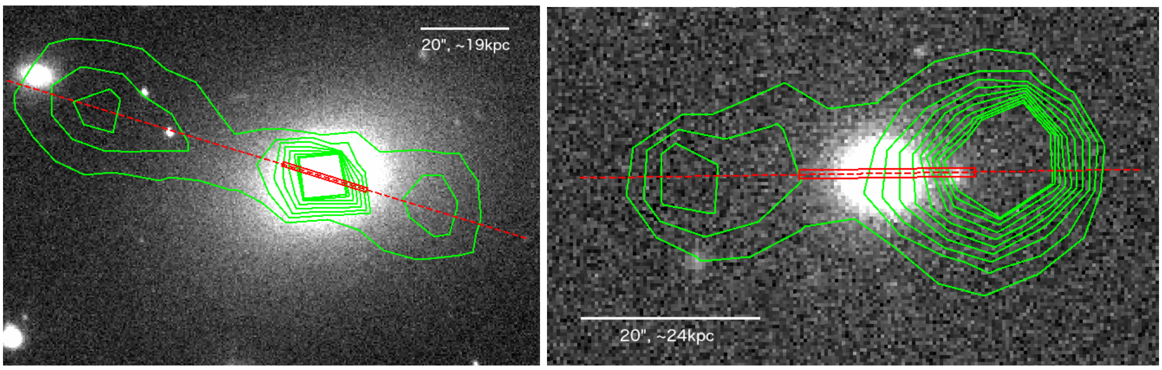

Figure 2: Two examples of our observational setup. SDSS *r*-band images of sources 9204 and 40507. Overlaid are radio 1.4 GHz flux density contours from the FIRST survey. The red dashed lines define the jet axis, along which our main long slits will be placed. The slits, of width 1 arcsec and length 20 arcsec, are shown with red boxes and they cover the length of the host galaxy along the radio jet. At the redshift of these sources, we will probe linear scales of ~ 20 and ~ 10 kpc, respectively, along the jet propagation direction.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

High sensitivity, good spatial and spectral resolution, and excellent wavelength coverage, make the MMT telescope and the Red Channel Cross Dispersed Echellette Spectrograph mode an ideal setup to measure spatially resolved flux and kinematics of emission lines. We will use the 7-13 orders of the grating, at a central wavelength of $\sim 5250\mathring{A}$. At the mean redshift of our targets, this positions the [OIII] emission line around the central wavelength. With a spectral range of 4300-8900Å, we will be measure all the important AGN emission lines, including the [OIII], Hβ, Hα, and NII lines. The spectral resolution of the echellette mode yields a ~ 90 km s^{-1} and is adequate to spectrally resolve narrow and broad components of the AGN emission lines.

Using the systemic velocity of these systems from their SDSS spectra, we will calculate velocity offsets for [OIII] and the Balmer emission lines. Together with the line dispersion, these quantities will allow us to fully characterize the ionized gas kinematics along the jet. In particular, we aim to extract spectra from spatial bins along the length of the slit of 1 to 2 arcsec size. We will thus establish how the kinematics of [OIII] and Hα behave as a function of distance from the core and along the radio jet. The full wavelength coverage will be used to (i) calculate emission line flux ratios to quantify the radiative influence of the AGN as a function of distance along the radio jet, (ii) constrain the nuclear and host galaxy dust opacity, which should strongly affect the observational footprint of the ionized gas outflows, and (iii) allow the study of ionized gas outflows at larger distances from AGN, due to the lower ionization potential of Hα.

To obtain spatially resolved measurements of emission lines out to $\sim$ several kpc scales, we need to have S/N$\sim$10-15 in the continuum. While easily obtained for the central part of the galaxy, longer exposure is required for the outer part due to the much lower emission line flux and stellar surface brightness. We use the spatially integrated spectral fluxes, S/N, and exposure times from SDSS to estimate the MMT exposure times needed to reach the desired S/N out to a distance of $\sim 1.5\, r_{\rm eff}$ from the core. We assume an exponential decline of the flux density from the core, using the relevant quantities from the SDSS *r*-band images. Based on the above and on our previous experiences with long-slit spectroscopy with Subaru, Gemini, and other large-aperture telescopes, we estimate on source integration time of 0.6 hrs for the brightest targets and $\sim$1.2 hr for fainter sources ($m_r > 15.5$), for obtaining high S/N spectra. Including the overhead per object, we request 2 nights of MMT Red Channel Cross Dispersed Echellette Spectrograph time for this project. We have assigned priority tiers to our targets. Fainter and/or smaller angular size objects have lower priority. In case of adverse weather conditions, we will focus on priority A targets (see Target table), allowing longer exposure times for our best targets.

We selected a sample of 16 most luminous radio AGNs, for which we can determine the direction of ionized gas outflows based on the jet morphology at kpc scales from the FIRST survey imaging (assuming that ionized gas outflow and radio jet have the same direction). All 16 objects show extended jet emission ($\gtrsim$1 arcsec) and thus we are able to accurately calculate the position angle of the jet, along which the the long-slits will be placed (see examples in Fig. 2). The position angle of the radio jet on the plane of the sky is either defined by the line connecting the core of the radio source and the furthermost radio jet component (for core-jet radio morphologies), or by the line connecting the radio lobes (for double-jetted radio morphologies).

This pilot study is part of the Optical Radio Galactic Gas Outflows Survey (ORGGOS) project, which aims to study galactic outflows in the different phases of the ISM and their connection to AGN. The ORGGOS project is a collaborative effort between the Seoul National University, Yonsei University, and the Korean Astronomy and Space Science Institute (KASI). In the near future we plan to expand this program to a larger sample of sources. We are currently in the process of analyzing archival radio interferometric data in order to reveal the potential extended jet structure from the rest of our radio-luminous sources with strong ionized gas outflows. For the sources without archival radio data, a Karl Jansky VLA proposal will be submitted in the coming semester. The high quality spectra from MMT will allow us to showcase the merits of these observations, investigate the link between the radio jet and ionized gas outflows, and be the precursor to a, for the first time, large-scale study of these two outflow components in AGN.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*