Galaxy Evolution and Feedback across Different Environments
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Observations of AGN feeding and feedback on Nuclear, Galactic, and Extragalactic Scales

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Abstract. We investigate the processes of active galactic nuclei (AGN) feeding and feedback in the narrow line regions (NLRs) and host galaxies of nearby AGN through spatially resolved spectroscopy with the *Gemini* Near-Infrared Integral Field Spectrograph (NIFS) and the *Hubble Space Telescope's* Space Telescope Imaging Spectrograph (STIS). We examine the connection between nuclear and galactic inflows and outflows by adding long-slit spectra of the host galaxies from Apache Point Observatory. We demonstrate that nearby AGN can be fueled by a variety of mechanisms. We find that the NLR kinematics can often be explained by in situ ionization and radiative acceleration of ambient gas, often in the form of dusty molecular spirals that may be the fueling flow to the AGN.

Keywords. galaxies: active, galaxies: kinematics and dynamics, ISM: jets and outflows

1. Introduction

Recent work summarized by Storchi-Bergmann & Schnorr-Müller (2019) identify several ways to fuel AGN on galactic or extragalactic scales (in addition to chaotic cold accretion onto AGN in the bright center galaxies of rich clusters). 1) Major mergers, where the mass ratio of the two galaxies is $\leqslant 4$, are more likely to occur for luminous quasars at high ($z \geqslant 2$) redshifts. 2) Minor mergers with mass ratios >4, have been identified as fueling mechanisms for a number of local AGN (Martini *et al.* 2013; Fischer *et al.* 2015; Riffel *et al.* 2015; Raimundo *et al.* 2017). 3) Tidal interactions between two galaxies that are not as severe as mergers can result in an exchange of gas from one galaxy to the

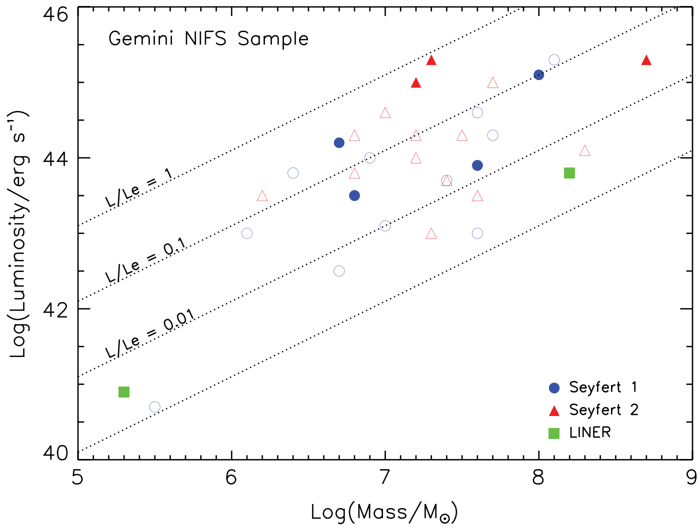

Figure 1. Fundamental properties of the AGN NIFS sample, color- and symbol-coded by AGN type. Existing and planned Z-band observations are given as filled and open symbols, respectively. The new observations will increase the sample by a factor of ∼4, revealing the dependence of outflow and fueling properties on the AGN parameters of black-hole mass, L_{bol}, and L_{bol}/L_{Edd}, as well as other galactic and extragalactic parameters including bulge size, fueling mechanism(s), and environment.

other to fuel the AGN (Davies *et al.* 2017). 4) Secular processes within a galaxy, particularly inflows along a large-scale stellar bar, can drive gas to within a few hundred to a thousand pc of the supermassive black hole (SMBH) (Shlosman *et al.* (1989); Regan *et al.* (1999). Here we present several different examples of these fueling mechanisms and their effects on nuclear (⩽1 kpc) scales.

The fueling of active galactic nuclei (AGN) and subsequent feedback via radiation and gas outflows is thought to play a critical role in the formation of large-scale structure (Scannapieco *et al.* 2004), chemical enrichment of the intergalactic medium (Di Matteo *et al.* 2010), and self-regulation of supermassive black hole (SMBH) and galactic bulge growth (Hopkins *et al.* 2010). Recent progress in understanding the detailed mechanisms of AGN feeding and feedback has come from adaptive optics observations with integral field units such as *Gemini* NIFS to map the kinematics of ionized and molecular gas at ∼0″.1 resolution in nearby AGN. We present examples of outflows based on NIFS and STIS observations and discuss their possible connections to the fueling flow.

2. Sample

Our overall sample consists of 35 nearby ($z < 0.035$) AGN observed in the K-band by NIFS and present in the *Gemini* archives. The K band is important for determining the gravitational potential via the stellar CO bandheads and the kinematics of the warm molecular gas via H_2 lines. We are obtaining matching observations of the [S III] line in the Z band, because it is the brightest ionized gas line in the IR and therefore provides the best opportunity to trace multiple kinematic components of this gas in the NLR.

Figure 1 shows the fundamental properties of these AGN, which span a wide range in properties including black-hole mass (3.4 dex), bolometric luminosity (L_{bol}, 4.6 dex), and Eddington ratio (L_{bol}/L_{Edd}, 2.8 dex). The AGN host galaxies also span a wide

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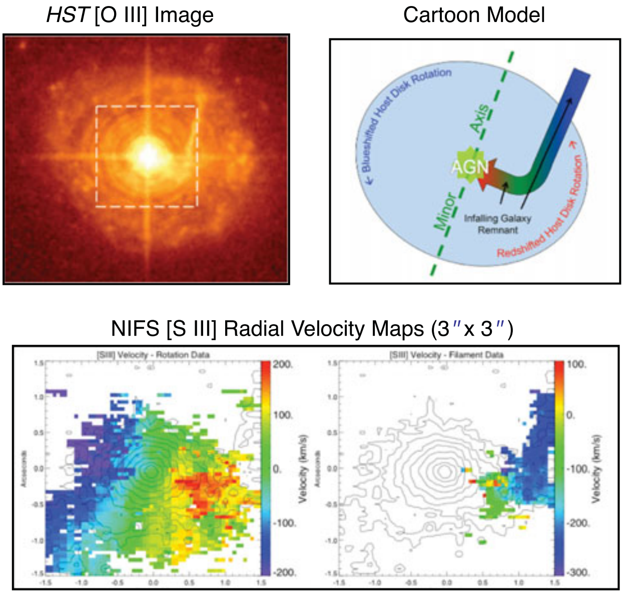

Figure 2. Kinematics of Mrk 509 from Fischer *et al.* (2015). **Top left:** *HST* [O III] image showing "check mark" feature that also appears in the optical continuum. The dashed-lined box show the 3″ × 3″ NIFS field of view. **Bottom:** Radial velocity maps of [S III] showing rotation (left) and a mostly blueshifted component associated with the check mark. **Top Right:** Our interpretation that this feature is due to tidal disruption of a satellite galaxy that is now fueling the host galaxy of Mrk 509 and its AGN.

range in galactic and extragalactic parameters including bulge size, fueling mechanism(s), and environment. We have obtained Z-band observations of 9 of these AGN to date, and our results from some of these are detailed below.

3. AGN feeding

An example of fueling an AGN through a minor merger is given in Figure 2, where we see a "check mark" in ionized gas and continuum emission from *HST* images of the bright Seyfert 1 Mrk 509. NIFS radial velocity maps of [S III] emission show that the kinematics of the ionized gas in the inner ∼1 kpc is dominated by rotation and blueshifted emission from the check mark. We claim this feature is the result of a minor merger, which has torn a galaxy that about the size of the Small Magellanic Cloud apart and is now fueling the central host galaxy and AGN (Fischer *et al.* 2015).

An example of AGN fueling by a tidal interaction is shown in Figure 3. A tidal tail of H I gas extends from the gas-rich galaxy UGC 3422 to Mrk 3 (UGC 3426), an S0 galaxy containing a Seyfert 2 nucleus, and beyond. This fueling results in a large-scale gas/dust disk offset from the stellar major axis in position angle by ∼100° and in the direction of the tidal stream, which we confirmed with *APO* long-slit spectra showing its rotation curve (Gnilka *et al.* 2020). NIFS observations of the central 800 pc × 800pc region in Mrk 3 shows a nuclear stellar disk aligned with the large-scale disk, and a counter-rotating ionized and warm molecular gas disk. This finding is consistent with claims that AGN in S0 galaxies are fueled by external sources (Hicks *et al.* 2013; Davies *et al.* 2014; Raimundo *et al.* 2017).

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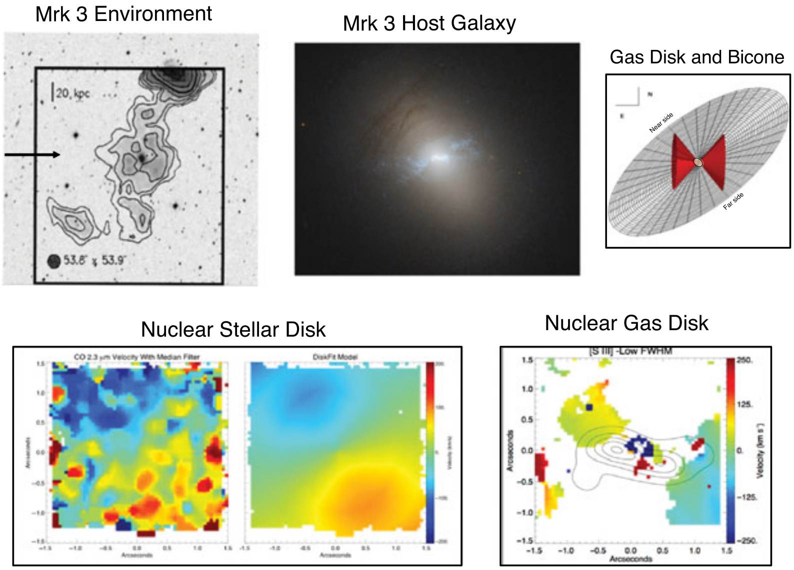

Figure 3. Fueling of the AGN Mrk 3 on different scales. **Upper Left:** Contour map of H I 21 cm emission from Noordermeer *et al.* (2005) superimposed on a DSS red image, showing a tidal tail of H I gas extending from UGC 3422 (100 kpc to the NW) to Mrk 3 and beyond. **Upper Middle:** Composite $50'' \times 50''$ (13.5 kpc × 13.5 kpc) *HST* image of Mrk 3 showing the orientation of the host galaxy (red), dust lanes (dark), and the ionized gas in the NLR (white) and ENLR (blue). **Upper Right:** Geometric model of the NLR bicone and large-scale gas/dust disk in Mrk 3, offset in position angle by 100° from the stellar major axis (Crenshaw *et al.* 2010). **Lower Left:** Radial velocity map from NIFS $3'' \times 3''$ (800 pc × 800 pc) observation of the stellar CO bandheads smoothed with a 5×5 pixel median filter and the resulting Diskfit rotation model. **Lower Right:** NIFS radial velocity map of the low width (FWHM $\leqslant 250$ km s^{-1}) ionized gas, showing counter-rotation with respect to the stellar nuclear and galactic disks.

4. AGN feedback

An intimate connection between feeding and feedback is demonstrated in Figure 4, which shows NIFS radial velocity maps of the stellar, warm molecular, and ionized gas in the central ∼1 kpc of Mrk 573. Nuclear dust/gas spirals thought to represent the fueling flows to the AGN are illuminated when they enter its bicone of ionizing radiation (Fischer *et al.* 2017). NIFS K-band observations of H_2 show that the inner dust spirals coincide with warm molecular gas that is rotating with the disk until it enters the bicone within a few hundred parsecs of the AGN where it is driven outward. NIFS Z-band observations of [S III] show that this gas is then ionized and radiatively driven to a distance of only ∼600 pc, whereas AGN-ionized gas at greater distances is rotating with the galactic disk out to ∼4 kpc according to our *APO* long-slit spectra. Mrk 3 shows a similar pattern of ionization and acceleration of ambient gas from the nuclear spirals (Gnilka *et al.* 2020).

We have measured spatially-resolved mass and kinetic energy outflow rates based on *HST* [O III] images, STIS long-slit spectra, and photoionization models (Crenshaw *et al.* 2015; Revalski *et al.* 2018a,b, 2021). In general we find that the mass outflow rates peak at values of $3-12$ $M_{\odot}$ and that the peaks and extents of the outflows appear to scale with luminosity. However, the outflow extents at these Seyfert luminosities are in the range $100-800$ pc, which are significantly less than the effective bulge radii of their host galaxies. Thus, we are extending our studies to quasars at higher redshifts (Fischer *et al.* 2018; A.L. Trindade Falcao, in preparation) to determine if there is a transition luminosity at which the NLR outflows can clear their bulges.

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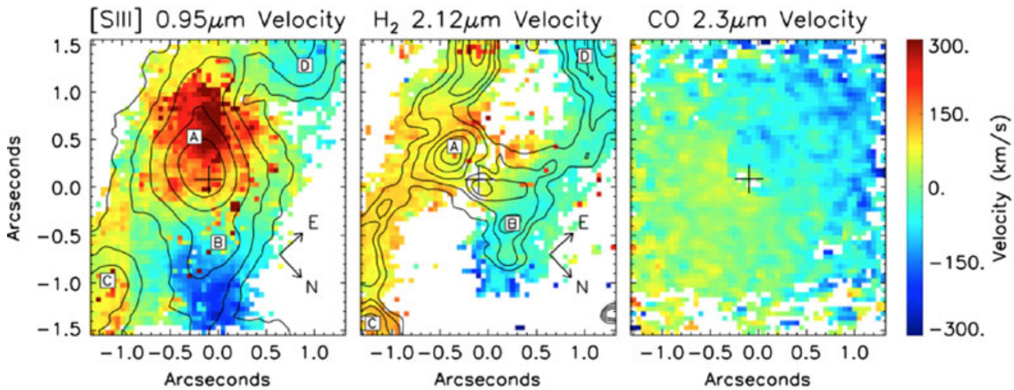

Figure 4. Radial velocity centroid maps from NIFS observations of Mrk 573 (Fischer *et al.* 2017). **Right:** Inner disk rotation from the stellar CO band heads. **Middle:** Arcs of warm H_2 gas that line up with the *HST* dust spirals match the rotation curve at points C and D. As the gas enters the ionizing bicone (roughly vertical in the figure), it is accelerated outward (points A and B) and starts to become ionized. **Left:** [S III] emission shows the full extent of the ionized gas outflows (extending past A and B), whereas the ionized gas at larger distances (beginning at C and D) is primarily in rotation.

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