Tracing the feeding and feedback of active galaxies

Thematic Areas:
- □ Planetary Systems
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Abstract:

Supermassive black holes in active galaxies accrete mass from their surroundings, and inject energy as well as mass to the galactic medium through outflows. Strong accretion signatures onto the active nucleus are evident at sub-pc scales. Their host galaxies show the presence of outflowing and inflowing material from hundreds to tens of parsecs. The interface between the active nuclei and their host galaxies is a region of a few pc in size with a gas and dust flow cycle, a so-called torus. The torus and accretion disk fuel accretion and launch outflows, which fundamentally connect the black holes to their host galaxies. Under this scheme, the torus is dynamically connected to galaxy evolution. However, many key questions remain: What is the origin and evolution of the torus? What is the structure of the torus during its existence? What is the feeding and feedback role of the torus? The lack of observational capabilities that can resolve the torus hinders a full understanding of the feeding material building up the mass of the central black holes in galaxies. New capabilities that resolve this interface will present empirical constraints that will be used to physically guide the theories of galaxy evolution.
The physical interface between active nuclei and their host galaxies

The relation between the masses of host galaxies and their central supermassive black holes (BHs) (e.g., Gebhardt et al. 2000) implies an evolutionary connection. However, the physical process by which this occurs is uncertain. The buildup of a central BH may occur over $10^7 – 10^9$ yr (e.g., Marconi et al. 2004), with active spurts of accretion over $10^6 – 10^8$ yr (Netzer 2015). Hydrodynamical simulations suggest that early BH growth is limited by stellar feedback, which expels gas from the galactic nuclei (Anglés-Alcázar et al. 2018). However, the immediate surroundings of active galactic nuclei (AGN) hide the direct signatures of this activity—which proceeds through an accretion disk—along certain lines of sight. This obscuring material, the so-called torus, is also important as the physical interface between the central engine and host galaxy. The torus is the immediate source of fuel for both accretion and outflow.

For a few decades, the best picture of the material between the active nucleus and the host galaxy has been a static structure that reprocesses the emission from the central engine. In its most simplistic geometrical form, this interface is an obscuring toroidal distribution of dusty and molecular matter. Some of the evidences for this structure are the lack of broad emission lines in some hidden AGN (Tran et al. 2003), the emergence of broad lines in polarized light in hidden AGN (Antonucci & Miller 1985), and the detection of discrete X-ray obscuration events (Markowitz et al. 2014). Infrared (IR) and X-ray observations suggest that the dust distribution is clumpy (Ramos Almeida et al. 2009, Markowitz et al. 2014), producing an emission morphology within the central 10 pc that varies with wavelength (Ramos Almeida & Ricci 2017, Lopez-Rodriguez et al. 2018a).

Figure 1: The morphology of the dust emission in the central 10 pc of NGC 1068 varies as a function of wavelength and shows more extended structures connecting with the galaxy. The IR dust emission arises from a compact pc-scale structure dominated by hot dust and a larger polar emission by thin dust (Left; López-Gonzaga et al. 2014). The cold dust is mainly concentrated in the equatorial plane, which represents the bulk of dust distribution in the torus (Middle; García-Burillo et al. 2016). The broadband cold reflected X-ray emission of NGC 1068 can be explained by multiple reflectors with three different column densities (Right; Bauer et al. 2015). The highest $N_H$ component is the dominant contribution to the Compton hump.

The absorbed and reprocessed X-ray radiation is produced in a compact source within several gravitational radii of the central engine (Zoghbi et al. 2012). X-ray surveys have shown that the cold component with the highest column density ($N_H \geq 10^{24}$ cm$^{-2}$) covers $\sim$20–30% of the AGN (e.g., Burlon et al. 2011, Ricci et al. 2015). Some of the most surprising results come from ALMA, which resolved the obscuring structure of NGC 1068, an AGN with a fully obscured core. These observations indicate that the torus of NGC 1068 is a rotating, turbulent, compact and inhomogeneous structure of $\sim$ 10 pc ($\sim$ 0.16″) in diameter (García-Burillo et al. 2016, Imanishi et al. 2016,
2018) with possible outflows (Gallimore et al. 2016). However, in general, IR interferometric observations show that most of the MIR emission of Seyfert galaxies arises from a polar elongated structure (Honig et al. 2012, 2013). Our current understanding has formed using sub-mm observations with ALMA, IR single-dish observations with 8–10 m class telescopes, IR interferometric observations with the Very Large Telescope Interferometer (VLTI), and X-rays (Figure 1). These studies, with the exception of ALMA, are based on the integrated signature of the spatially unresolved emission across the electromagnetic spectrum. Because of the small physical scale (≤10 pc) of this structure, we cannot currently characterize the torus in detail.

Figure 2: The 1-13 μm dust emission of the torus of NGC 1068 can be resolved using 30-m class telescopes. The first row shows the pupil images of the JWST (6m), Keck (10m), GMT (25m), and TMT (30m) left to right. From the second row, the first column shows, at several wavelengths, the 2D brightness map of a CLUMPY torus model of NGC 1068 with ‘infinite’ resolution. The remaining panels show the synthetic observations with each telescope (columns) at each wavelength (rows).

In the next decade, we will resolve the physical interface between the AGN and host galaxy. To obtain useful constraints on the putative torus, it is important to improve the spatial resolution and sensitivity of observational studies. Then, we can measure torus sizes, covering factors, inclinations, optical depths and masses at high spatial resolution. For example, using the radiative transfer model CLUMPY (Nenkova et al. 2008a,b) and assuming the torus parameters inferred from the IR spectral energy distribution (SED) by Lopez-Rodriguez et al. (2018a), the torus emission in the 1 – 13 μm wavelength range of NGC 1068 is resolvable using 30-m class telescopes (Figure 2). Specifically, the torus is very compact, ≤ 2 pc, at near-IR (NIR) wavelengths while it is more extended, ≤ 10 pc, in the mid-IR (MIR). At NIR, the hot dust (1000 – 1500 K) is located at the inner edge of the torus where it is directly irradiated by the central engine. In the MIR, the emitting dust is located further away and/or in the shadowed regions of the dusty clumps, which makes the torus appear more extended. While the James Webb Space Telescope (JWST) will have sensitive
NIR and MIR instruments that will resolve the gas out to hundreds of pc, the origin of the torus may be traced to the smaller-scale torus interface. Recently, observations using IR interferometry and 10-m class telescopes of the central \(\sim 40\) pc of Circinus have been explained by the contribution of an equatorial disk and a hyperboloid/conical wind model (Stalevski et al. 2017, 2019). This unique study uses the current state-of-the-art facilities and can only be performed in a handful of objects. The next generation of 30-m telescopes and the already on-going theoretical modeling will explain the physical connection between the AGN and the host galaxy in a statistically significant sample of AGN. Assuming a 15 mas angular resolution at 2.2 \(\mu m\), and 68 mas at 10 \(\mu m\) for a 30-m telescope, and using the above typical torus sizes of 2 pc at 2.2 \(\mu m\) and 20 pc at 10 \(\mu m\), the potential AGN which have resolvable tori (torus size at least twice the angular resolution at a given wavelength) need to be at a distance \(\leq 50\) Mpc. Several tens of AGN located within 50 Mpc could be resolved with the next generation of 30-m class telescopes, which will allow for a comprehensive physical account of the torus.

**Towards a dynamical AGN torus**

*In the last ten years, we learned that AGN inject mass to the galactic medium through outflows observed on scales from tens to a few hundred pc.* Mapping the distribution and kinematics of high excitation lines in both the NIR and MIR (e.g. 1.08 \(\mu m\) He I, 1.64 \(\mu m\) [Fe II], 1.96 \(\mu m\) [Si VI], 2.17 \(\mu m\) Br\(\gamma\) in the NIR, and 7.65 \(\mu m\) [Ne VI], 12.81\(\mu m\) [Ne II] in the MIR) has verified that the NIR high excitation lines trace an outflow. The typical full-width-at-half-maximum (FWHM) is estimated to be 25 pc, and further modeling places tight constraints on the outflow speeds and mass loss rates out to scales of a few hundred parsecs (Müller Sánchez et al. 2011). Line emission from molecular hydrogen (rovibrational lines in the NIR, e.g. 2.12 \(\mu m\) H\(_2\) 1-0 S(1), and rotational S(2) to S(13) H\(_2\) lines in the 3-13 \(\mu m\) range) has primarily revealed the morphology, mass, and kinematics of the molecular gas in the galaxy disk as well as traced the inflowing and outflowing material down to scales near the torus (Figure 3).

Although the above results support the unification model (Antonucci 1993) of AGN, we now have a new paradigm. The torus is the central structure in a gas flow cycle (Krolik & Begelman 1988) in which gas is brought in from the host galaxy disk (inflow) and then driven out radiatively by an AGN wind (e.g., the Wada (2012) fountain model; Figure 4-a, Schartmann et al. 2011, Dorodnitsyn, Bisnovatyi-Kogan & Kallman 2011, Hopkins et al. 2012, Ricci et al. 2017) and/or magnetic disk-wind (i.e. Blanford & Payne 1982, Emmering et al. 1992, Konigl & Kartje 1994, Elitzur & Shlosman 2006, Figure 4-b). These views are both supported by the presence of inflows and outflows in nearby Seyferts (e.g., Garcia-Burillo et al. 2005; Barbosa et al. 2009; Muller-Sanchez et al. 2011; Davies et al. 2014), large reservoirs of molecular gas in their circumnuclear disks (typical sizes \(\sim 100\) pc, see Hicks et al. 2013; Izumi et al. 2016), and magnetic fields at scales of few pc (i.e. Lopez-Rodriguez et al 2015, 2018a,c). However, since the torus is only detected as a point-like source, these studies are based on integrated emission of the whole structure. The lack of observational capabilities that can resolve the torus hinders a full understanding of the feeding material building up the mass of the central black holes in galaxies. These resolve observations will present empirical constraints that can then be used to physically guide the theories of galaxy evolution.

*In the coming decade, we will demonstrate more directly the active role of the torus in galaxy evolution.* To understand the dynamics of the torus, it is crucial to achieve spectral and angular
Figure 3: The H$_2$ 2.12 µm emission in Seyfert 1 galaxy NGC 5643 shows evidence of molecular hydrogen in disk rotation, as well as inflow and outflow (Davies et al. 2014). Upper row from left to right: H$_2$ flux distribution, HST V-H dust structure, Br$\gamma$ 2.16 µm emission and velocity. Lower row from left to right: ALMA CO (2-1) velocity (Alonso-Herrero et al. 2018), H$_2$ 2.12 µm velocity, non-circular velocity, and velocity dispersion. The inflow seen in both H$_2$ 2.12 µm and CO (2-1) is coincident with the spiral dust lanes indicated by the reddened (dark) regions of the dust structure map and outlined by the orange lines. The outflow indicated by the redshifted and high velocity dispersion H$_2$ 2.12 µm emission in the northeast is coincident with the blue (white) region of the dust structure map and the Br$\gamma$ emission and velocity. It is indicated by the pink lines at the border of the outflow region. The warm molecular gas traced by H$_2$ 2.12 µm traces the cold gas measured by CO (2-1).

resolutions that allow characterizing the dynamics of the gas over a range of temperatures. 1 – 13 µm spectroscopic observations will facilitate connecting the gas flow cycle on scales of a few pc to the inflows and outflows on larger scales. For example, 2.12 µm H$_2$ emission will be detected throughout the central few pc and therefore provide the ability to trace the inflow of gas observed on larger scales from the host galaxy down to the torus (Hicks et al. 2009). A key advantage of the MIR H$_2$ lines is that they trace the molecular gas at the temperatures ($\sim$ 100 K, Izumi et al. 2016) typical of the nuclear disks of AGN rather than the T $\sim$ 1500 K gas traced by the vibrationally excited NIR H$_2$ lines (Rigopoulou et al. 2002; U et al. 2019). By measuring the inflowing and outflowing gas down to the torus scales and across a range of gas and dust temperatures, we will show the effect on host galaxy evolution. Thus, dependencies of these key processes on fundamental AGN and host galaxy properties can be established reliably, advancing current work (e.g. Davies et al. 2014, 2015, 2017, U et al. 2019). Moreover, facilities such as the ngVLA will be able to characterize the content and the dynamics of the gas at comparable resolution in the central few pc, which will allow us to quantify the effect of winds on BH growth (Anglés-Alcázar et al. 2018) and explore jet-ISM feedback from the multi-phase perspective (Nyland et al. 2018).

In addition to previous models, a magneto-hydrodynamical (MHD) (i.e. Blanford & Payne 1982, Emmering et al. 1992, Konigl & Kartje 1994, Elitzur & Shlosman 2006, Figure 4-b) outflow wind can lift the plasma from the mid-plane of the accretion disk to form a geometrically thick distribution of dusty clouds surrounding the central engine. The potential influence of the magnetic
Figure 4: **a)** Cartoon representing an edge-on view of the nuclear regions of the radiation-driven fountain model (Izumi et al. 2018). The traditional torus is the $300 – 1500$ K dust component, the extended dust emission and outflows along the polar direction are part of the fountain flow, and the nuclear star formation (SF) is traced by the molecular gas in the circumnuclear disk (CND) as an extension of the dusty torus. **b)** Hydromagnetic outflow wind model (Emmering et al. 1992) of AGN. Close to the black hole, the accretion disk is ionized and becomes molecular at larger distances. Dense molecular clouds are lifted and accelerated away from the accretion disk moving along the magnetic field. The torus is that region of an outflow wind where the clouds are optically thick and dusty.

Field on the outflowing material and accreting activity can be investigated using its IR polarization signature. Dust grains can be aligned by the presence of magnetic fields, described by theories of radiative torques (RATs, Lazarian & Hoang 2007) and also by intense radiation fields or outflowing media. As radiation propagates through these aligned dust grains, preferential extinction of radiation along one plane leads to a measurable polarization in the transmission/emission of this radiation, a term called dichroic absorption (at NIR)/emission (at MIR). The short axis of the dust grains aligns parallel to the local magnetic field lines, and the observed position angle (PA) of the polarization traces the direction of the magnetic field. Recent studies using IR polarimetry found a coherent magnetic field in the inner wall ($\sim 1$ pc) of the torus of radio-loud (i.e. IC5063 and Cygnus A; Lopez-Rodriguez et al. 2013, 2018c), and radio-quiet (NGC 1068, Lopez-Rodriguez et al. 2015) AGN. These results suggest that the magnetic fields can play an important role in the origin, kinematics, and evolution of the torus. As higher angular resolution and better sensitivity become available, polarimetric techniques are more efficient. To characterize the origin and dynamics of the torus, it is crucial to provide IR polarimetric capabilities.

As the interface between active nuclei and their host galaxies, AGN tori are dynamically connected to galaxy evolution. Completing a quantitative picture of the dust and gas flow cycle is therefore critical in establishing the mechanisms that drive the co-evolution of the central supermassive black holes and their host galaxies.
References


Lopez-Rodriguez, E., Packham, C., Young, S., Elitzur, M., Levenson, N. A., Mason, R. E., Ramos Almeida, C.,
Lopez-Rodriguez, E., Packham, C., Jones, T. J., Nikutta, R., Mcmaster, L., Mason, R. E., Elvis, M., Shenoy, D.,
Lopez-Rodriguez, E., Alonso-Herrero, A., Diaz-Santos, T., Gonzalez-Martin, O., Ichikawa, K., Levenson, N. A.,
Martinez-Paredes, M., Nikutta, R., Packham, C., Perlman, E., Ramos Almeida, C., Rodriguez-Espinosa, J. M., Tele-
Lopez-Rodriguez, E., Fuller, L., Alonso-Herrero, A., Efstathiou, A., Ichikawa, K., Levenson, N. A.; Packham, C.,
Ricci, C., Trakhtenbrot, B., Koss, M. J., Ueda, Y., Schawinski, K., Oh, K., Lamperti, I., Mushotzky, R., Treister, E.,