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Quasar structure and cosmological feedback

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Abstract. Feedback from quasars and AGNs is being invoked frequently in several cosmological settings. Currently, order of magnitude, or more, uncertainties in the structure of both the wind and the 'obscuring torus' make predictions highly uncertain. To make testable models of this 'cosmological feedback' it is essential to understand the detailed structure of AGNs sufficiently well to predict their properties for the whole quasar population, at all redshifts. Progress in both areas is rapid, and I describe the near-term prospects for reducing these uncertainties for 'slow' (non-relativistic) AGN winds and the obscuring torus.

Key words. Quasars – Cosmology

1. Introduction

Feedback is the key to an interesting Universe. In particular, feedback from quasars and their less luminous cousins, Active Galactic Nuclei (AGNs), has been newly recognized as a potentially crucial input to multiple areas of galaxy formation (§2). However, so far, arguments using AGN feedback have been forced to make simple assumptions: that all SMBHs accrete at the Eddington limit while active and that 10% the accreted mass is successfully ejected.

To become a testable science, "cosmological feedback" from AGNs must use the details of the structure of quasar nuclei, both on a small scale, where the winds most likely arise, and on a larger scale, at the 'obscuring torus' of Unification Models (Urry & Padovani 1995).

2. Cosmological Feedback

There are six areas where AGNs are being called upon to provide cosmological feedback:

1. Co-evolution of SMBHs and their Host Galaxies. Some form of feedback is required by the $M_{BH} - \sigma_{BULGE}$ relation (Ferrarese & Merritt 2000) (Gebhardt et al. 2000) so that the central black hole does not grow at a rate independent of the surrounding dark matter halo (Silk & Rees 1998).

2. Prevention of Star Formation in Mergers. The deep HST GEMS survey (Bell et al. 2006) does not find the predicted blue branch of young stars in the ($g-i$ vs. M_V) plane among the most massive ($M > 2 \times 10^{10} M_{\odot}$) galaxies, implying that star formation is prevented during the mergers that form these galaxies ('dry mergers'). Can AGN remove the cold ISM from these galaxies?

3. Limiting the Upper Mass of Galaxies ΛCDM models produce too many high mass galaxies, contrary to observations. Reduced cooling and feedback from supernovae are insufficient to prevent galaxy growth (Thoul & Weinberg 1995). Heating by AGN radio sources is a promising alternative (Croton et al. 2005).

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3. Inhibition of cooling flows is demonstrated by *XMM-Newton* spectra and *Chandra* imaging of the hot intracluster medium of rich clusters of galaxies which show that their dense cores are not cooling, and so not inflowing onto the central galaxy, contrary to hydrostatic equilibrium model predictions (Kaastra et al. 2001). Instead something is providing an extra heat source; very likely relativistic jets (§ 3.2).

4. Enrichment of the intergalactic medium. Both the cool Lyman-α forest (Pettini 2004), and the hotter 'Warm-Hot Intergalactic Medium' that produces the 'X-ray forest' (Fang et al. 2002) seen in *Chandra* grating spectra (Nicastro et al. 2005) are far from having a primordial composition, but are instead enriched with heavy elements. Supernova driven 'superwinds' from starburst galaxies and AGN winds can both escape their galaxies: which dominates in IGM enrichment?

5. Dust at high redshift is seen in z~6 quasars Omont et al. (2001). Dust is important to catalyze efficient star formation by shielding gas from UV heating and by enhancing cooling (Hirashita & Ferrara 2002). But dust at z~6 is hard to make (Edmunds & Eales 1998), and cannot be created in AGB-star winds (the process that dominates in the Milky Way), as these stars take ~1 Gyr to evolve. Supernovae may create dust, but the rate is unknown, so the origin of high z dust is open. Cool clumps in AGN winds may be an effective alternative site.

3. Pathways for AGN Feedback

Quasars and AGN have three pathways by which they can provide feedback:

1. Radiation: The defining characteristic of an AGN is the huge radiative output, which can be comparable to that of an L^* galaxy. This radiation carries energy and momentum that can affect the quasar's environment. Radiation can enrich the IGM indirectly by *heating, ionizing and accelerating the ISM from the quasar host galaxy*, which inhibits star formation in the host. But radiation is easily absorbed by dusty nuclear material.

Radiation pressure may be particularly important in a proposed evolutionary phase when the quasar may blow away a layer of shrouding material surrounding the SMBH at early epochs (Sanders et al. 1988).

2. Relativistic Jets: Tightly collimated jets with relativistic bulk velocities (Γ ~10) commonly emanate from the central galaxy in rich clusters of galaxies. *Chandra* X-ray images of the hot intracluster medium show holes into which the radio structures fit like jigsaw pieces (McNamara et al. 2005). There is clearly a close interaction between the relativistic plasma and the X-ray hot plasma in these clusters. Even a tightly collimated jet will spread heat throughout the intracluster medium and so *prevent a cooling flow* (Ruszkowski et al. 2004), so *setting an upper bound to galaxy, and black hole, masses*. Only the most powerful jets, though, escape their clusters to *enrich the IGM*.

However, relativistic jets are not common among AGNs: only about 10% of AGNs are radio loud, either because radio jet formation is a transient phase of black hole activity, or because only a few black holes are ever able to form a jet. In either case the total amount of energy and momentum available from radio jets is reduced by this factor, so that they may have difficulty solving other feedback problems, especially in less massive systems.

It is possible that the majority of SMBHs, which - at any one time - are quiescent rather than active, have 'dark' (i.e. non-radiative) jets that carry substantial mass, energy and momentum - explaining why they do not radiate anywhere near to the Bondi rate (Soria et al. 2006).

3. Slow (non-relativistic) Winds: Moderate velocity (~1000 - 2000 km s^{-1}) outflows are seen in absorption ~50% of AGNs and quasars, and so form weakly collimated, wide angle winds. They are seen through the blueshifted narrow absorption lines (NALs) they imprint on the UV continuum, and the 'Warm Absorber' (WA) features on the X-ray continuum. Less common (~15%) are the ~10 times faster, but still non-relativistic, outflows seen in the 'Broad Absorption Line', BAL, quasars (Crenshaw et al. 2003). Being nearly universal in AGNs, these slow winds could create *co-evolution*. BALs, at least, escape their hosts and *enrich the IGM*.

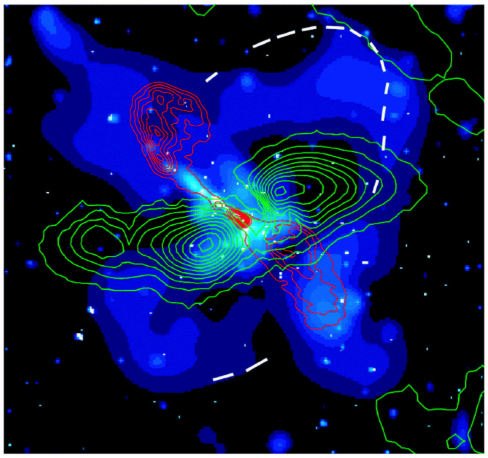

Fig. 1. *Chandra* image of Cen A/NGC 5128 (blue) overlaid with HI (green) and radio continuum (red) contours (Karovska et al. 2002). An annulus of hot gas emission is evident perpendicular to the radio jet. This may be the result of an impulsive event $\sim 10^7$yr ago, at the time of the galaxies' merger.

Moreover, conditions in quasar winds at large radii, assuming that the cooler ($\sim 10^4$K), denser (10^{10}-10^{11}cm^{-3}), broad emission line (BEL) gas is part of the wind, will match those in AGB-star winds, and so dust should form copiously in AGN winds (Elvis et al. 2002), especially as high z quasars have super-solar abundances (Hamann & Ferland 2002).

3.1. *Impulsive Events during Mergers*

An unexplored variant on the usually assumed continuous application of these mechanisms over an AGN lifetime is an impulsive event associated with a merger. Such an event could include all three mechanisms. One object - the nearest radio-loud AGN: Cen A/NGC 5128 - gives us reason to consider this option.

Cen A (fig.1) shows an elliptical 8 kpc radius annulus of hot (kT$\sim 10^6$ K) gas aligned with the radio jet axis (Karovska et al. 2002). This alignment seems to require a driving input from the nuclear region. The thermal energy in this 'smoke ring' is substantial, $\sim 10^{55}$ erg, with a gas mass of $\sim 10^6$ M$_\odot$. Projecting backwards at the thermal velocity, the ring would have been ejected $\sim 10^7$ yr ago, about the time of the evident merger in NGC 5128. Unfortunately such a feature is visible, for now, only in Cen A, because Cen A lies just 3 Mpc away.

4. Structure Influences Feedback

Here I will first concentrate on slow, non-relativistic, winds, since radiation and jet inputs have been long known, while the prevalence and strength of slow AGN winds is only now becoming clear as a potential source of cosmological feedback. Also, progress here has been rapid. Then I will discuss how our ideas of the 'obscuring torus' are developing away from the canonical 'donut', and how these changes affect feedback.

4.1. *Slow Wind Structure*

The mass loss rate in AGN winds, $\dot{M}_W$, is uncertain by six orders of magnitude. This is because $\dot{M}_W$ depends on the assumed distance of the wind from the ionizing continuum source, R. For a conical wind, with radial velocity v_r, and column density N_H (Krongold et al. 2006):

$$\dot{M}_W = 0.8\pi m_p N_H v_r R f(\delta, \phi) \qquad (1)$$

[$f(\delta, \phi)$ is a factor that depends on the orientation of the disk and the wind to our line of sight and, for reasonable angles, is of order unity.]

The distance R is uncertain by more than a factor 10^6 ($\sim$ 10 kpc to $\sim$ 0.001 pc). The proposed sites are: (a) the Narrow Emission Line Region (NELR) (Kinkhabwala et al. 2002) (b) the inner edge of the 'obscuring torus' (§4.2) (Krolik & Kriss 1995), and (c) the accretion disk itself (Murray et al. 1995; Elvis 2000). Large radii pose a serious paradox for AGN winds: they require $\dot{M}_W \sim 10$ - 1000 $\dot{M}_{acc}$, implying short-lived winds (Netzer et al. 2003): a result at odds with the high frequency of outflows in AGN.

Discriminating between these widely different scales requires breaking the intrinsic degeneracy of the gas density, n_e, and distance from the ionizing continuum source, R, in the equation that relates the two observables: the

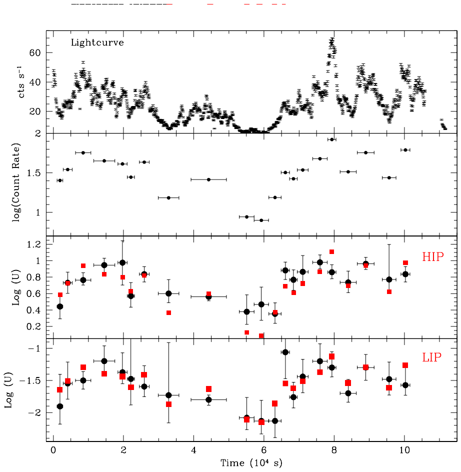

Fig. 2. NGC 4051 *XMM* flux and U_X light curves for the two dominant WA components: the 'HIP' (High Ionization Component) and 'LIP' (Low Ionization Component) (Krongold et al. 2006). The red squares show the predicted ionization parameter, U_X, for ionization equilibrium.

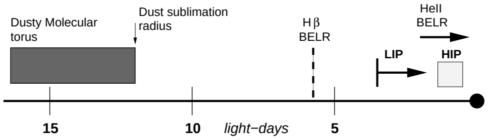

Fig. 3. A map of the inner regions of the AGN NGC 4051. The map is only 1-dimensional but is to scale, and shows the location of the WA [high- ('HIP') and low-ionization ('LIP') components] in NGC 4051 compared to the location of the high- (HeII) and low-ionization (Hβ) broad emission line regions, and to the innermost location of a dusty torus (Krongold et al. 2006).

luminosity of ionizing photons Q_x, and the average ionization parameter of the gas

$$U_X = Q_x/(4\pi c R^2 n_e) \qquad (2)$$

Time dependent photoionization (Nicastro et al. 1999) provides the answer: lower density gas recombines more slowly, so the lag between a continuum change and the response of the WA U_X can determine n_e. Given the definition of U_X, R follows, breaking the degeneracy.

We have recently applied this method to the WA in the narrow line Seyfert 1 galaxy (NLSy1) NGC 4051, determining all the main physical and geometrical properties of this WA (Krongold et al. 2006). The key to success is the broad nature of the 0.6-0.9 keV Fe-M shell UTA and the 0.9-2 keV Fe-L shell and OVIII line complexes, which put strong constraints on the U_X of the two main WA components with XMM-EPIC data. The high resolution/low signal-to-noise RGS spectrum provides confirmation and sets the starting parameters, and both high- and low-ionization (HIP, LIP) components follow the rapid variations of the ionizing continuum (fig.2). Hence the WA gas must be dense, and located at small radii, $R \sim few 1000$ R$_S$, i.e. accretion disk sizes. Because the BEL region (BELR) sizes in NGC 4051 are also well known from reverberation mapping (Peterson et al. 2000) we can draw a first map of the nucleus on a well-determined physical scale (fig.3).

This result rules out a wind origin in a dusty obscuring torus, or any larger region. Moreover, the derived wind radius is inside the Hβ emission line region, and is consistent with the high ionization HeII emission line region size, long suspected to have an outflowing component (Gaskell 1982). Several features of the NGC4051 wind: the disk origin, high density, narrow thickness ($\Delta R/R(HIP) \sim 0.1-0.2$), and pressure balance between HIP and LIP (Krongold et al. 2006) are also features of my 'funnel-wind' model for quasar structure (Elvis 2000), which suggests that something along these lines will turn out to be the correct picture. If so, then we have a tightly constrained geometry and kinematics which will admit of few explanations. We must then be close to a physical understanding of AGN winds.

The implied mass outflow rate from the NGC 4051 wind is just 2−5 % of $\dot{M}_{acc}$, solving the $\dot{M}_W >> \dot{M}_{acc}$ paradox. Yet, if this mass outflow rate is representative of all quasars, powerful quasars still deploy large amounts of material and energy into their environment.

However, NGC 4051 is a pathological AGN: with a small black hole mass [(2×10^6 M$_\odot$, (Peterson et al. 2000)], and the unusual characteristics of NLSy1s (esp.

rapidly variable X-rays with a steep spectrum, and narrow broad emission lines, 'BELs' -and so a distant BEL region, in R_S). To extrapolate from NGC 4051 to all quasars at all redshifts is risky. We need examples spanning the range of SMBH masses and AGN luminosities.

The AGN winds seen as NALs are moving primarily transverse to our line of sight (Arav et al. 2000; Mathur et al. 1995). Moreover if these outflows are launched at ~1000 R_S, as we find for NGC 4051 ((Krongold et al. 2006), then the observed line-of-sight velocities are well below escape velocity, so subsequent acceleration to BAL-like velocities is required if the matter is not simply to fall back. The typical kinetic power in the slow wind is then increased by a factor of order 100. We need to understand the driving physics of the wind to know this factor.

4.2. Obscuring Torus Structure

The longstanding picture of a dusty obscuring torus has served well, but is now being reassessed as new observations come in. I emphasize that the basic insight of Unification Models is unchanged: angle dependent obscuration clearly produces the two types of AGN (Lawrence & Elvis 1982; deZotti & Gaskell 1985) in most cases [but see Nicastro et al. (2003)]. This was demonstrated convincingly by the finding of 'hidden' BELs characteristic of 'type-1 AGN', in the polarized spectrum in many otherwise narrow-lined 'type-2 AGN' (Antonucci & Miller 1985). The issue is what this torus consists of.

The obscuring torus also explains the observed 4:1 ratio of type-2:type-1 AGNs, if the obscuring 'torus' covers 80% of the AGN sky. Feedback to larger scales will thus reduced by a factor 5 from estimates based simply on SMBH mass density. The third feature explained by an obscuring torus is the 'ionization cone' structure found on kiloparsec scales in several AGNs (Tadhunter & Tsvetanov 1989). The torus can collimate the radiation to about the correct angle. Some 'ionization' cones though seem to be hollow expanding shells - matter-bounded, not radiation-bounded (Crenshaw & Kraemer 2000) - showing large scale outflows at work.

The canonical picture of the obscuring torus (Krolik & Begelman 1988) is a 'donut'(Urry & Padovani 1995): a Compton thick ($N_H > 10^{24} cm^{-2}$), dusty molecular ring, of large scale-height (h/r~0.7), with an inner radius set by the dust sublimation radius, R_{sub}, to be on ~parsec scales (Barvainis 1987):

$$R_{sub} = 1.3 L_{46}(UV)^{0.5} T(1500\ K)^{-2.8} pc, \qquad (3)$$

where $L_{46}(UV)$ is the ultraviolet continuum luminosity of the AGN in units of 10^{46}erg s^{-1}.

The longstanding problem with this picture is how to support a large scale height in a cold structure. Thermal support is clearly out, while invoking a mist of orbiting clouds will lead to flattening through cloud-cloud collisions on an uncertain, but probably short, timescale. A dynamic picture with continuous accretion onto the torus from the host galaxy has more success (Vollmer et al. 2004), but seems to require $\dot{M}_{torus} > \dot{M}_{Edd}$, which implies mass loss.

A more subtle difficulty with the 'donut' comes from the AGN 'photon deficit' problem. It is a longstanding puzzle that the BELs from AGNs emit more power than is present in the ionizing continuum (Netzer 1985) and, a related puzzle, require more ionizing photons than are present by factors of 4 – 25 (Binette et al. 1993). Variability and dust extinction have been suggested to explain this deficit but do not work well. It seems that a major piece of the EUV continuum seen by the BELR is missing from the observed spectrum. How can the BEL gas see a much stronger continuum than we do? If the BELR lies above the disk [where the BELR would have to be part of the wind (Elvis 2000)], then the BELR sees the full UV radiation field from the disk, while a typical observer ($i = 60°$) sees the continuum reduced by geometric and limb darkening factors (Netzer 1985). This may work, but a disk-aligned 'donut' would prevent us seeing the BELR sufficiently edge-on to provide a large enough effect.

The 'donut' picture is further complicated when AGN winds are considered. The rapid acceleration expected from UV line driving argues that BALs will be essentially equatorial

(Murray et al. 1995). Certainly, BALs must be at least partially radiatively accelerated as, e.g., at least ~ 25% of the UV radiation emitted by the BAL quasar PG 1254+047 is absorbed by a gas with $N_H \sim 10^{23}$ cm^{-2} (Hamann 1998). So, if $L(UV)$ is even 10% of the Eddington luminosity, the momentum in the wind is of the order of that absorbed from the UV (Risaliti & Elvis 2006). BAL winds cannot then lie in objects with co-aligned obscuring tori and accretion disks, contrary to the usual assumption.

There are only a few ways out of these 'donut' related problems:

1. the wind may be polar or bi-conical and so rise above the torus;
2. the accretion disk and the torus may not be aligned;
3. the torus may be the host ISM;
4. the torus may be the wind.

There is evidence that all four wind escape mechanisms occur:

1. Bi-conical winds: are indicated by transverse motions and sub-escape velocities (see §4.1);

2. Disk-torus misalignment: If a radio jet axis shows us the accretion disk orientation, and optical continuum polarization position angle (PA) shows us the torus orientation, then early evidence for their alignment (Antonucci 1983) seems to be supplanted by later, larger, samples (Thompson & Martin 1988). Mis-alignment offers a solution to the photon deficit problem.

3. Host galaxy obscuration: Edge-on host galaxies have a deficit of type 1 AGNs (Keel 1980; Kirhakos & Steiner 1990) indicating obscuration related to the host Lawrence & Elvis (1982). Moreover the optical polarization PA is aligned with the host galaxy disk major axis (Thompson & Martin 1988), and obscuring kiloparsec scale dust has been directly imaged in type 2 AGNs (Malkan et al. 1998). Even for the archetype 'hidden type 1' AGN - NGC 1068 - CO imaging shows that it is a warped disk on a ~100 pc scale that blocks our view of the nucleus (Schinnerer et al. 2000). Variable X-ray obscuration is seen on a timescale of a few years, suggesting similarly distant obscurers (Risaliti et al. 2002).

4. Wind obscuration: Large variations of the X-ray obscuring column density within one day have now been seen in three heavily obscured AGNs ($N_H \sim 10^{22}$-10^{23}cm^{-2}) (Elvis et al. 2004; Risaliti et al. 2005; Puccetti et al. 2006). Such rapid changes can only be accomplished, for material moving at Keplerian velocities, if the matter lies close in, at about the BELR radius. This must be well within the proposed torus, as the torus must hide the BELs, and would be too hot for dust to survive at BELR radii.

This small-scale obscurer could be the wind, if the wind can be blown off the accretion disk from radii where the disk temperature has never risen above ~1500 K, so that the material retains the dust-to-gas ratio of the host galaxy ISM; a mix of this outer material with more central hotter gas could explain the low dust-to-gas ratios typically encountered in AGNs (Maccacaro et al. 1982; Maiolino et al. 2001). Hydromagnetic models can reproduce the observed distribution of N_H (Kartje 1995; Kartje et al. 1999).

Clearly obscuration does take place on both a host galaxy ISM scale and a quasi-BELR, slow wind, scale in many AGNs. A dusty disk wind is toroidal and allows a large scale height obscuring region. As the structure is a steady state flow, not a static structure, the torus support problem disappears.

For cosmological feedback, the wind-as-torus picture still blocks 80% of the radiation from affecting the host galaxy, but the mass, energy and momentum of the wind all escape cleanly. When the main obscuring matter is located in the host galaxy, then the torus is the very target ISM material that the AGN is supposed to heat, ionize and remove, so all the radiative energy is also available. Both a biconical wind and a misaligned disk and torus allow the wind to escape, often to the IGM.

This is still an emerging picture, but shows promise. Without knowing the details though, we will not be able to discriminate which is the important element for feedback in particular circumstances, nor the total mass, energy and momentum input to the ISM and IGM.

5. Wind Physics

There are three ways to accelerate a wind:

1. Thermal gas pressure: acts isotropically and has $v_{max} = v(sound)$ ~100 km s^{-1} for T~10^7K. Thermal pressure occurs naturally at inner edge of obscuring torus where temperatures of 10^6-10^7K are reached (Krolik & Kriss 1995). But even slow winds have $v_r \sim 10\ v(sound)$ and need to be driven by gas at ~10^9K. Moreover, isotropic acceleration naturally and produces 100% covering factors (Balsara & Krolik 1993), yet half of all AGNs show no WAs or NALs. One clever way to heat gas is via cosmic rays. The decay of relativistic neutrons to protons a few parsecs from the nucleus can heat gas locally, without causing heating closer in (Begelman et al. 1991).

2. Radiation pressure: acts radially and has $v_{max} = 2 \times v(critical point) \sim 2 \times v(Kepler, launch)$ ~10^4 km s^{-1}. The radiation force has an 'Effective Eddington Limit' depending on the dominant mechanism: electron scattering (weak) (King & Pounds 2003); UV line driving (which can be suppressed by strong X-rays overionizing gas) (Murray & Chiang 1995); and dust absorption (which is only effective beyond the dust sublimation radius) (Binette 1998). UV line driving is the most discussed mechanism (Murray et al. 1995; Proga 2000; Leighly 2004; Risaliti & Elvis 2006).

3. Magneto-Centrifugal: models accelerate plasma along field lines 'like beads on a wire', and has $v_{max} = c$. These winds remove angular momentum from the disk, which enhances accretion (Blandford & Payne 1982; Kartje et al. 1999). A magneto-centrifugal base to a wind could provide the shielding gas for UV line driving further out (Everett 2005).

Radiation and magneto-centrifugal are the two most promising mechanisms.

Whichever mechanisms dominate in quasars, the wind must ultimately be a function of the basic AGN parameters: the SMBH mass and the accretion rates, both at the continuum emitting region (which drives luminosity), and at the wind launching radius (which could limit the wind mass supply).

The successful wind model will also have to explain the observed regularities in quasar properties: the Baldwin effect (Baldwin 1977) - the luminosity dependence of the BEL equivalent width - and 'Eigenvector 1' - a clustering of emission line and X-ray properties that seems to be a function of $\dot{M}_{acc}$ (Marziani et al. 2001).

6. Conclusions

I have discussed why the details of the inner structure of quasars makes for orders of magnitude differences in the strength of the cosmological feedback from AGNs. The form of that feedback: energy, momentum or mass, also depends on the details of the wind driving mechanisms and obscuration.

Because slow, non-relativistic, winds are now thought to produce most of the atomic emission and absorption features in AGN spectra a huge range of possible tests of wind models has now opened up. With adaptive optics poised to give diffraction limited near-infrared on large telescopes, the dusty tori in AGN will be imaged down to parsec scales, while smaller scale obscuration, possibly from a wind, will be studied via X-ray and optical variability.

When we understand AGN winds we will not only have solved a major part of AGN astrophysics, but have a strong basis for extrapolating wind properties to all SMBHs at all redshifts. And then we will be able to put AGN cosmological feedback on a firm basis.

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