Slicing the Torus: Obscuring Structures in Quasars

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Abstract. Quasars and Active Galactic Nuclei (AGNs) are often obscured by dust and gas. It is normally assumed that the obscuration occurs in an oblate "obscuring torus", that begins at the radius at which the most refractive dust can remain solid. The most famous form of this torus is a donut-shaped region of molecular gas with a large scale-height. While this model is elegant and accounts for many phenomena at once, it does not hold up to detailed tests. Instead the obscuration in AGNs must occur on a wide range of scales and be due to a minimum of three physically distinct absorbers. Slicing the "torus" into these three regions will allow interesting physics of the AGN to be extracted.

1. The Quasar Standard Model
There is a "standard model" for quasars, which was put in place within a decade of the discovery of quasars [1], i.e. by 1973. This standard model consists of three elements: (1) a supermassive (10^6-10^9 M_☉) black hole (SMBH, [2]), surrounded by (2) an accretion disk [3], with (3) a relativistic jet [4, 5] emerging perpendicular to the disk and originating at just a few Schwarzschild radii away from the black hole. The elements of this model successfully account for, in turn: (1) the total power output of the quasar, from the gravitational energy released by infall to near the event horizon of the black hole; (2) the maximum temperature of 50,000 K - 100,000 K of the ultraviolet (UV) continuum that dominates the luminosity, from the thermalization of the gravitational energy release in the accretion disk; and (3) the phenomenology of apparent superluminal motion, rapid variability and polarization of the radio emission in those quasars where a jet is pointing almost directly at us (the blazars). This is a pretty good list of successes, and they have held up well against decades of tests.

However, unlike the predictive power of the contemporaneous particle physics standard model [6], the quasar standard model predicts little of the rich phenomenology of quasars: (a) the various 'types' of active galaxies [7, 8]; (b) the maximally hot dust found in quasars, but not in starburst galaxies [9, 10, 11], (c) the strong X-ray emission [12, 13], and (d) all of the many atomic emission and absorption features seen in the spectra of quasars [14], not even the broad (~1% c) emission lines that led to their initial recognition as exceptional objects [15].

As a response to several of these gaps, a fourth element of the standard model has been commonly accepted since about 1985: a flattened, but large scale-height, obscuring torus.

2. The Obscuring Donut Torus
A flattened obscuring torus coaligned with the accretion disk is an appealingly simple addition to the standard model. It is able to explain both the variety of types of AGNs, the existence of maximally hot dust, and the bi-conical morphology often shown by the narrow emission lines.

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of AGNs. This paradigm is known as the Unified Scheme [16, 17, 18, 19, 20]. The Unified Scheme posits obscuration by an optically and geometrically thick "torus", lying between the inner, broad \((\sim 10^4 \text{ km s}^{-1})\), and outer \((\sim 10^5 \text{ km s}^{-1})\), narrow, line emitting regions.

The torus is almost universally taken to be a large scale-height \((H/R \sim 1)\), cold structure, rich in molecular gas and dust, that is co-planar with the accretion disk [18]. As such it resembles a donut with a hole in the center, notably in the famous illustration in Urry & Padovani [20]. This specific form of non-spherical obscuring region has been called the "donut torus" [21]. The "strong" form of the Unified Scheme asserts that our orientation relative to the one jet/disk/torus axis explains all of the variety of AGN types.

The strong Unified Scheme cannot be 100% correct as, e.g., the incidence of X-ray obscuration is clearly more common at low luminosities [22, 23, 24, 25], requiring some modification [26]. Nonetheless this scheme does explain [16, 27]: (1) the distinction between type 1 (with broad emission lines) and type 2 (no broad emission lines) AGNs, due to optical dust obscuration between the two emission regions; (2) the presence of heavy X-ray obscuration in type 2 AGNs, due mainly to gas; (3) the biconical geometry of the outer narrow line region, due to geometric collimation of the continuum; (4) the finding of polarized broad lines in otherwise purely narrow-lined type 2 AGNs [27, 28, 29], due to scattering off warm electrons above the torus; and (5) the relative space densities of type 1 and type 2 AGNs. All these achievements apply equally to radio-loud AGNs [17], and can be successfully extended to connect the luminosity functions of blazars and radio galaxies [30].

This is a long list of accomplishments, and there can be no doubt that flattened obscuring regions are important in AGNs. However, the elegant reduction of these effects to a single region cannot be sustained for both theoretical and observational reasons.

2.1. Problems with the Donut Torus

There are four theoretical challenges to the donut torus picture of AGN obscuration. While none of them is individually inescapable, together they are a significant challenge. They are:

(i) **The large, \(H/R \sim 1\), scale height in cold material:** Clearly a cold \((\sim 100 \text{ K})\) medium does not have thermal velocities of greater than the \(\sim 1000 \text{ km s}^{-1}\) of the narrow emission lines, as would be required to reach \(H/R \sim 1\) interior to the region emitting those lines. (This assumes that the lines have widths comparable to virial or Keplerian values.) The alternative is that the material is highly clumped and has many clouds on highly inclined orbits. A clumpy torus explains the observed AGN spectral energy distributions (SEDs) better than a continuous medium [31]. A clumpy torus is observationally supported by the emission seen outside of the bicone in NGC 4151, both in optical emission lines (the "rogue clouds" of [32]) and soft X-rays [33]. However these clouds must then collide with one another and collapse on some unclear, but probably short, timescale. A non-static, though possibly steady-state, model is needed (e.g. [34, 35]).

(ii) **The energy and photon deficit problem for the broad emission line region:** Netzer (1987) noted that the observed UV continuum could not be extrapolated in a simple, accretion disk like, way (e.g. [36]) and still provide sufficient photons to ionize the gas producing the broad emission lines. More recent inferred continuum shapes suggest even fewer photons in the extreme UV [37, 38]. Nor does the continuum provide sufficient energy input to power the broad emission lines [39]. Netzer’s solution was to locate the broad emission line region directly above the accretion disk. In this way the broad emission line gas sees a more powerful continuum than an observer at a random angle. This explanation works as, above the disk, neither the geometrical cosine \(\theta\) nor limb darkening [40] diminish the continuum. However, if the torus is co-planar with the disk, and covers the direct view of the disk over 80% of side-on viewing directions, then we can only see the broad emission...
lines almost perpendicular to the disk, so we also see the same continuum as that gas. The continuum may not be a simple extrapolation of an $\alpha$-disk spectrum, but could have a second, short-wavelength, peak, e.g. due to blurred Lyman-$\beta$ and HeII emitted by dense clouds at small radii Lawrence [41], which may solve these problems.

(iii) The impedance of feedback: As is now well known, the mass of the stellar bulge and the mass of the SMBH in a galaxy are closely tied together (see, e.g. [42]). Assuming that the two masses are causally linked (but see [43]), some feedback mechanism must keep the two growing in synchrony. There are three ways the power output of a quasar can interact with the host galaxy interstellar medium (ISM): (1) radiation; (2) broad slow winds; (3) narrow relativistic jets. While relativistic jets from their central galaxies are clearly important in clusters of galaxies [44], this mechanism is unlikely to be important in either less massive systems with lower density ISMs, or in the 10 times more numerous radio-quiet quasars. However, both radiation and slow winds will be inhibited by the presence of an exterior donut torus that blocks 80% of the sky as seen from the inner nucleus. This large covering factor increases the efficiency needed to deposit the $\sim 5\%$ of the total radiative quasar power needed to unbind the host galaxy ISM [45, 46] to $\sim 25\%$ of the escaping radiation. More efficient scenarios have been proposed however [47].

(iv) The wide range of obscuring X-ray column density: The donut torus was invoked to explain AGNs such as NGC 1068, in which the direct central radiation was completely blocked by a Compton thick obscurer ($\tau_{\text{Compton}}=1$ corresponds to $N_H=2\times10^{24}\text{cm}^{-2}$). However, there are many intermediate type AGNs, with a wide range of lower X-ray column densities, and optical reddening values. Values of $N_H$ from $\sim10^{21}\text{cm}^{-2}$ to $>10^{25}\text{cm}^{-2}$ are often observed. This is roughly the difference between a thin sheet of paper and a brick, so that a single physical cause is not required, and may be hard to produce. Usually, in the donut torus scheme, these intermediate column densities are attributed to viewing the donut torus at a grazing angle [48]. In the case of NGC 4151 this may be correct [32]. However, these intermediate column densities are rather common [49]. The extended "atmosphere" of the donut torus must then cover $\sim 35\%$ of the sky seen from the inner nucleus, which is a substantial change to the picture. A clumpy wind can produce the observed $N_H$ distribution [31].

One recurring observational problem is that the broad line widths seem to be dominated by orbital rotation [50, 51, 52]. That requires that most broad emission line regions are seen at a large angle to the rotation axis, but the donut torus would prevent this.

These problems can be eased if one or more of the assumptions of the strong Unified Scheme are relaxed: if the ratio of type 2:type 1 AGNs is smaller than had been thought, if the torus is not co-planar, if the X-ray and optical (or equivalently the gas and dust) obscurers are not tightly connected, or if the obscuring region can be sliced into several layers. I will discuss this last possibility next.

### 3. Slicing the Torus

In the years since the donut torus was proposed there has been much detailed observational work on each of the features that the scheme was invented to explain. One consequence is accumulating evidence that obscuration in AGNs occurs on both smaller and larger scales than that of the hot dust limited radius of the donut torus alone. Here I slice the obscuration into three scales (Figure 1).

#### 3.1. Smaller Scale Obscuration

Large amplitude changes in absorbing X-ray column density have been seen on briefer and briefer time intervals. There are now numerous examples of large changes ($\Delta N_H >10^{23-24}\text{cm}^{-2}$) in a few
Figure 1. Scales of obscuration in quasars and AGNs. The horizontal scale is in log(Rs).

days or hours (e.g. [53, 54]). The most dramatic example is NGC 1365, in which the X-ray source underwent a total eclipse by a Compton-thick cloud within two days, and emerged within another two days [55]. For any velocity comparable to the Keplerian velocity for the eclipsing clouds, these events all imply that they lie at about the same distance as the broad emission line gas (r < 10^{3-4} R_s) and have comparably high densities (n_e > 10^9-10^{10} cm^{-3}). The obvious conclusion is that the eclipsers are discrete clouds of broad emission line gas. Further investigations seem to be revealing unexpected features in these clouds with surprising implications [56, 57].

For our purpose here, these eclipses show that obscuration, at least by gas, occurs well within the dust sublimation radius. The observed low dust-to-gas ratios, from comparisons of optical reddening with X-ray absorption [58, 59], may be explained by a mix of inner, dust-free, and outer, dusty, absorbers [60].

As the UV continuum source has ~10 times the radius and so ~100 times the area of the X-ray continuum, it is less likely that similar large amplitude eclipses could be seen at UV wavelengths, which makes it hard to tell if the clouds are dusty, as suggested by Czerny & Hryniewicz [61]. (In principle transiting exoplanet techniques could look for these partial eclipses.)

3.2. Larger Scale Obscuration

Since 1980 there have been many papers demonstrating a clear connection between the obscuration of the AGN and the inclination angle of the host galaxy [62, 16, 63, 64, 65, 66, 67, 68]. Evidently there is some obscuring region dominated by the host galaxy dynamics, and so outside the SMBH sphere of influence, though the radial scale of this obscurer is uncertain. Moreover, as the radio jets of these galaxies lie at random angles to the host galaxy disk plane, within a very wide cone [69, 70], the obscurer, the jet and the accretion disk cannot all share the same axis.

Hubble imaging of type 1 and type 2 hosts also clearly shows that there are many more dust lanes crossing the nuclei of type 2 AGNs than of type 1s on a several 100 pc scale [22]. This obscuration lies beyond the region producing the infrared emission from these AGNs. As these type 2 hosts are of later morphological type than the type 1s, they undermine the strong Unified Scheme.

A different argument against the donut torus, coming from properties on similarly large scales
of up to \(\sim 1\) kpc, is based on the bi-conical regions marked out by the narrow emission lines. A series of papers using Hubble STIS long slit spectroscopy \([71, 72]\) has found that these bi-cones are not made up of pre-existing ISM illuminated by the AGN, as in the donut torus model, but by outflowing hollow cones with wide opening angles. Hence the bi-cone shapes are often not formed by a collimated incident radiation pattern, but are matter-bounded, i.e. limited by the shape of the wind coming from the nucleus. Moreover, the wide angles derived for the wind bi-cones (\(\sim 50^\circ\) \([73]\)) imply that any torus covers a more limited solid angle than in the donut torus model. (These bi-cones also show feedback in action, \([74]\)).

Larger scale obscuration may be due to matter streaming toward the accretion disk, as observed in \(H_2\) emission \([75, 76]\), and predicted in some galaxy merger models \([77]\). Improved imaging in molecular lines in the mm- and sub-mm bands, primarily of CO, have begun to image obscuring structures at the \(\sim 100\) pc radius scale. In the prototypical type 2 AGN, NGC 1068 (for which the donut torus was largely originally created \([27]\)), a Compton thick warped disk with an inner radius of \(\sim 70\) pc curls up to just cross our line of sight to the nucleus \([78]\). This molecular disk appears to be disconnected from any smaller structure stretching down to the dust sublimation radius. ALMA will revolutionize this field.

### 3.3. Hot Dust Scale Obscuration

Nonetheless, a substantial fraction of the AGN nuclear power is absorbed and re-radiated by hot dust in most AGNs \([79, 80]\). The peak of the AGN dust emission lies in the 10 \(\mu m\) to 20 \(\mu m\) range, implying temperatures of order 200 K, and reaches shortward to \(\sim 1\) \(\mu m\), implying \(T \sim 1800\) K, comparable to the maximum dust sublimation temperature. For the simple black body case \([24]\) this region spans a factor of \(\sim 1000\) in radius, with most of the emitting area, and presumably most of the mass, at the larger radii.

Indeed, direct mid-IR imaging at 12\(\mu m\) with VLT \([81, 77, 81]\), shows that the mid-IR emission becomes tightly correlated with the AGN continuum only within \(\sim 600 R_{sub}\), comparable with the expected scale. More extended 12\(\mu m\) emission dilutes the correlation and so presumably arises from star formation.

The dust emitting radius \(R_{dust}(T)\) can be expressed in terms of the Eddington ratio of the accretion rate onto the black hole \(L/0.1L_{Edd} = \lambda_{0.1}\), and the Schwarzschild radius \((R_g)\):

\[
R_{dust}(T) = 1.5 \times 10^6 \lambda_{0.1} T_{44}^{0.5} T_{2000K}^{-2.8} R_g
\]

Radii of about \(10^6R_g\) apply to the 200 K dust, while the hottest dust, at \(T \sim 1800\) K, has \(R(\text{hot}) \sim 3000 R_g\).

It is instructive to compare these dust emitting radii with size of the SMBH sphere of influence, \(R_{BHinfl} = G M_{BH}/\sigma^2\) \([42]\), so that \(R_{BHinfl} = 10^6\sigma_{200} R_g\). The main AGN dust emission thus spans the region in which the host galaxy potential takes over from the black hole potential (Figure 1). We might expect interesting things to happen as this boundary is crossed. A stable \(H/R \sim 1\) torus is unlikely to be continuous across this region.

The most discussed alternative to explain this dust emission is a dusty wind off the accretion disk. The wind may be driven by magneto-centrifugal forces \([83, 84, 21]\), by external irradiation of the disk making it unbound \([35]\), or by star formation in the gravitationally unstable part of the disk \([85]\). A steady state accretion model \([34]\) can also sustain a large scale height torus, but only at locally super-Eddington accretion rates.

A warped disk \([79]\) can have a large covering factor without needing a large scale height, and so is an alternative to a planar torus. This form has gained new relevance as the means by which a black hole is fed and spun up has been investigated in more detail. Individual accretion events with random angular momentum vectors will naturally produce a low spin black hole \([86]\). Lawrence & Elvis \([24]\) point out that a warped disk will result, and will produce a type 1\(^1\)

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\(^1\) Following \([82]\), for \(\tau = 3\), and a typical dust grain size \(a = 0.05\mu m\). Here \(L_{44}\) is the AGN UV continuum luminosity in units of \(10^{44}\) erg s\(^{-1}\), and \(T_{2000K}\) is the dust temperature in units of 200 K.
or type 2 appearance depending on orientation, similar to that from a donut torus, but with observable differences. Small angle warps are seen in some AGN megamasers on parsec scales [87], and are implied in the Galactic Center [88].

A simple warped disk, with no rotation of the line of nodes, and random accretion directions, predicts a 1:1 type 2:type 1 ratio [24]. These authors then show that this ratio is consistent with observations, if LINERS are excluded, for AGN samples selected by reasonably isotropic indicators (radio, [OIII], mid-IR fluxes). The exception is samples selected in X-rays, which show a higher fraction of X-ray obscured objects. This suggests an extra, dust-free, absorber of X-rays, probably at smaller radii. These absorbers could be the broad emission line clouds noted above (§3.1).

A 1:1 ratio, though, also eases several of the objections to the donut torus. The resulting wider opening angles ease the photon and energy budget deficits, allow wide angle biconical winds to escape, and so greater feedback, and require a more physically reasonable smaller scale height torus. The solution is still open.

Another prediction of the warped disk model is that the radio jets and the bi-cones will not generally be aligned. Several anecdotal examples suggest that this is the case [24], but a general survey is needed. The canonical Hubble snapshot survey [70] needs to be repeated to greater depth, perhaps with AO on 8-meter class telescopes. Infrared interferometers are now beginning to resolve this region as well as, or better than, Hubble [89, 90, 91], so we may be able to see warped AGN dust disks directly in a few years. Eventually, imaging reverberation mapping will let us image the broad line region motions too, in all three spatial and velocity components [92].

4. Conclusions
A complete physical model for quasars is developing, but has some way to go: The atomic emission and absorption features all have promising explanations in terms of winds or failed winds subject to radiation pressure [57]. Although a great deal is know about the behavior of the X-ray source, physically it is normally ascribed to a "hot corona" which is not understood. I anticipate that accurate measurements of the temperature of the X-ray emission by NuSTAR [93] will begin to unpick this knot.

The origin of the AGN powered hot dust and of the various types of AGN is becoming more refined, but also, perhaps, more interesting and tractable. The view of AGN obscuration as being due to a single donut torus does not capture the complexity now realized to exist within AGNs. While acknowledging that the illustration from Urry & Padovani is graphic and immediate, I would urge that it should not be our default picture, as this form tends to become imprinted, and is then hard to get beyond.

In the emerging, more complex, picture - as in the donut torus model - the various types of AGNs continue to be explained by obscuration. However, at least three separate obscuring regions must exist in quasars and AGNs: (1) an inner, probably dust-free, region producing rapid X-ray eclipses, most likely due to broad emission line clouds; (2) an intermediate scale dusty region that reprocesses much of the AGN luminosity into thermal dust emission, including the hottest dust. This region spans the boundary between the black hole- and host-dominated gravitational potentials, and is perhaps in the form of a warped disk; (3) outer regions on 0.1-1 kpc scales, connected to the host disk and/or dust lanes.

By separating out the effects of these different obscurers we are starting to learn much more about the inner structure of AGNs, and their feeding on sub-kiloparsec scales.

Acknowledgments
The author would like to the thank his many collaborators in this area over the years, especially Andy Lawrence and Guido Risaliti, Bozena Czerny, and Gordon Richards, and is grateful to the scientific organizing committee for the opportunity to present this work at AHAR 2011.
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