Constraints on Disks Models of The Big Blue Bump from UV/Optical/IR Observations

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Abstract. Optical/UV observations provide many constraints on accretion disk models of AGN which aren’t always appreciated by modelers of the X-ray emission (or sometimes even of the optical/UV emission). The spectral behavior at the Ly edge, the polarization, the continuum slopes and breaks, and the variability timescales and phasing all conflict with simple models and strongly constrain the more Baroque ones. Partial-covering absorbers and microlensing data suggest that the radiation is not released simply according to where the potential drop (modified by standard viscous transport) takes place. On the other hand, the orientation-based unified model is in accord with the K-α inclination distributions for the AGN spectral classes, basing the latter on the limited existing data and theoretical understanding.

1. Introduction

This talk considers first the constraints arising from direct observations of Type 1 AGN, including quasars, and in the following section those deriving from the inclination-based Unified Model (described in Antonucci 1993).

2. Constraints from Direct Observations of Type 1 AGN

Here I use a list of diagnostics from a 1986 talk (published as Antonucci 1988) to show some historical development (how little has changed!), also appending more recent information.

The Big Blue Bump optical/UV component, energetically dominant in quasars, was first identified with thermal emission from an accretion disk by Shields (1978). AGN and quasars were subsequently fit to model disks by Malkan, Laor, and many others. These disks were quasistatic and thin, powered by internal viscous dissipation. They radiated locally as blackbodies as assumed by Shakura and Sunyaev (1973); luminosities and spectral turnovers provided diagnostics of accretion rates and black hole masses.

2.1. Lyman Edge

Kolykhalov and Sunyaev (1984) refined the models to include opacity effects, using low-gravity stellar atmosphere models for the spectra of each disk annulus. They predicted enormous Lyman edges in absorption, contrary to observation.

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I was encouraged to pursue this diagnostic by the following quotation from that paper: “A very important feature of our spectra is a considerable decrease of the radiation flux beyond the Lyman continuum limit........ Different variants were calculated to get a smaller Lyman discontinuity, but all attempts failed.”

We designed a study specifically to detect the broadened edges expected from disk atmospheres, and presented the results in Antonucci, Kinney and Ford (1989). No partial, broadened, systemic edges were found in emission or absorption, with noise from the Lyman α forest limiting constraints to 10-20%. Later Koratkar et al. (1992) found a very few candidate edges from IUE data. These await a key test of an atmospheric edge as opposed to one produced by an intervening cold cloud: there must be no accompanying narrow Ly absorption line series with $\sim 10^{17}$ cm$^{-2}$ column density.

Subsequently, Tytler and Davis (1993) and Zheng et al. (1998) produced composites of low-Z quasar spectra with HST, the latter claiming to see a weak feature near the edge position, but the former finding no sign of any discontinuity or slope change. Caution is suggested regarding the Zheng et al. claim. The individual objects in general look very significantly different from the composites (which may be unphysical). Also, errors in Galactic reddening and the necessary neglect of host reddening is a very serious problem at these short wavelengths. For a very clean and high SNR spectrum of a BBB in the edge region, see Appenzeller et al. 1998 ApJ 500 L9: there is no feature, and interestingly, there is a rolloff in $\nu F\nu$ near the Ly α position in the BBB of 3C273, indicating an unexpectedly low temperature for the UV radiation. Cataclysmic variables, which are known to have ADs, generally show Ly and Ba edge features in absorption when optically thick (in outburst), and in emission features when optically thin (in quiescence). The observations are in qualitative agreement with the models. Representative references include Long et al. 1994, Kuigge et al. 1997, and Wagner et al. 1998; this is quite different from the AGN case.

Recent modeling has shown that the edges can be reduced by positing a fast-rotating hole (e.g. Laor 1992), Comptonization (Czerny and Zbyszewska 1991), consideration of metal opacities especially if large turbulence is assumed (Agol et al. 1995; Krolik 1998; Blaes 1998 pc), and probably other effects. A geometrically flat Comptonizing corona would conflict with polarization data (see below). This could be remedied by Faraday-depolarization with an equipartition magnetic field (Agol and Blaes 1995). In that case it would then be necessary to postulate subsequent scattering by material between the disk and the broad line region in order to produce the $\lesssim 1\%$ polarization, parallel to the radio jets, discovered by Stockman et al. (1979).

### 2.2. Polarization

Early models assumed pure scattering atmospheres for AGN accretion disks, which would lead to substantial polarization (mostly 1-10%, depending on inclination) parallel to the disk plane. Instead, $\lesssim 1\%$ polarization is observed, parallel to the radio jets when the latter are observable (Stockman, Angel and Miley 1979, discussed in this context by Antonucci 1988). This polarization is associated with the BBB, not the nonthermal radio core (e.g. see the SEDs in Antonucci, Barvainis and Alloin 1990), and generally arises interior to the
BLR (data of Miller and Goodrich, partially displayed in Antonucci 1988). (By contrast little disk polarization is expected or observed in (dense) CV disks).

Laor et al. (1989) made modeling assumptions leading to very dominant absorption opacity in the rest optical, but considerable Thompson-scattering polarization just below the Lyman edge in frequency. The incorrect direction of polarization was not addressed. I once mentioned to Joe Miller that this and other papers may have predicted the wrong sign of polarization, but that they claimed to get the magnitude right. He replied that “that doesn’t help when you balance your check book.”

More detailed calculations (Agol et al. 1998 and references therein, and Matt et al. 1993), showed that a given contribution of absorption to the opacity produces a disproportionate reduction in polarization, contrary to the assumption of Laor et al. However, most disk models find absorption contributes less to the opacity than those authors did. It is also known that under certain conditions a slight polarization can be produced which is parallel to the disk (and radiojet axis); see e.g. Gnedin and Silantiev 1978. However, this relies on a very steep source function gradient, e.g. at annuli radiating in the exponential tail of the spectrum, and probably isn’t sufficiently general to explain the observations.

As noted above, a favored solution may be complete Faraday depolarization of the disk with a bit of ad hoc downstream scattering parallel to the disk plane (O. Blaes 1998, this meeting). That final scattering, occurring interior to the BLR according to various spectropolarimetry data, would need in essentially every case to lead to 0-1% polarization parallel to the disk axis.

A real surprise is the finding that substantial polarization can appear at \( \lesssim 700\,\AA \) (Impey et al. 1995; Koratkar et al. 1995, 1998). The case of PG1630+377 from the second paper is almost unbelievable, with P rising to \( \sim 20\%\) before the data cut off. We plan to test this result, from the HST FOS spectropolarimeter, with a different instrument. The polarized flux spectrum looks something like a Ly edge in emission, scattered by gas with \( kT \sim 0.1mc^2 \). In fact the object was selected for the “missing” Ly continuum photons (edge seen in absorption), our fond hope being that this indicated a bare accretion disk. I learned at the meeting that A. Beloborodo and collaborators are checking on this possibility. If it works out I’ll feel better about our data set: Eddington once said that he never believed an observation until it was confirmed by theory. More likely (Beloborodo, pc; Blaes and Agol, pc) the steepness of the rise of the polarized flux with frequency, and the exact frequency of its onset, are not fitted correctly at least in axisymmetric models.

2.3. Spectral Turnover for Low and High Luminosity AGN

Active nuclei range over several orders of magnitude in luminosity, so an inverse correlation between luminosity and temperature among the population, as predicted by AD theory, should be easily detectable. (There could in principle be a finely tuned compensating trend in \( L/L_{\text{Edd}} \).) However, Seyferts and quasars generally show similar soft x-ray excesses, indicating no strong differences in temperature if this is the tail of the BBB (e.g. Walter and Fink 1993). Within the rest optical/near-UV, quasars are actually flatter than Seyferts, corresponding to higher rather than lower temperatures.
Some luminous quasars, studied in the context of the $^{4}\text{He}$ Gunn-Peterson effect, have been observed to $\lesssim 300\text{Å}$, and their strength at such short wavelengths certainly contradicts the thin blackbody disk (e.g. Reimers et al. 1989); Comptonization may save the day (Siemiginowska and Dobrzycki 1990), wiping out the Lyman edge in the process. Of course, a plain Comptonizing atmosphere or corona needs a fine-tuned geometrical shape to produce the very low parallel polarization and to avoid major modifications of the disk-like Fe K$-\alpha$ lines. Alternatively the scattering polarization can, in principle, be destroyed by Faraday rotation.

Incidentally, the Comptonization (or optically thin thermal source in that model) needs to be very special in order to lead to nearly the same effective $T_{\text{max}}$ for objects over a huge range of luminosity (Walter and Fink 1993). The rather fixed position of the soft excess suggests an atomic process, perhaps broadened emission lines (Czerny and Zycki 1994) or albedo changes (Czerny and Dumont 1998 and earlier references therein).

### 2.4. Variability

Alloin et al. (1985) pointed out that the in-phase rapid variability of the recombination lines (and thus the ionizing continuum) and the optical continuum is inconsistent with the quasistatic viscous models of the day. This type of constraint, from direct multiband monitoring, is known to apply to quasars as well (e.g. Cutri et al. 1985). Recent monitoring campaigns have tightened the limit on any interband lags (e.g. Krolik et al. 1991), showing that in the disk model, the various annuli must communicate at nearly light speed. But the basic problem has been known for a long time. (In CV disks, flares may be rapid but they generally propagate in wavelength and fade over time or reasonable viscous timescales.) Perhaps the x-rays only drive a variable part of the optical/UV; however, the variability amplitude observed in the UV is often of order unity even over just a few years (e.g. Cutri et al. 1985). These observations have lead to a major paradigm shift to a passive disk, heated from above, ostensibly by x-rays. Aside from the fact that such a model may predict large and unseen Lyman emission edges (Sincell and Krolik 1997), they are energetically ruled out for many Seyferts and all quasars because the BBB is far more powerful than the x-ray (e.g. Laor et al. 1997). The only way out for quasars would be to postulate that the x-ray spectra are very different from those of Seyferts, with most of the power in the hard x-rays where the observational limits are poor. The energetics would work for some low luminosity sources, and for some more, though far from all, if the x-rays are beamed downward onto the disk by e.g. Compton scattering. The latter idea is like rearranging the deck chairs to keep the Titanic afloat. It greatly overpredicts the Compton hump in the x-ray spectrum (Malzac et al. 1998).

A separate variability issue, both for viscous disks and externally illuminated ones, is the behavior of optical/UV color and the apparent temperature of the soft x-ray excess as the luminosity of an object varies. As a rule the optical/UV colors get bluer as an object brightens, qualitatively consistent with thermal models. In fact (to paraphrase Jim Ulvestad), all AGN obey this rule, except the ones that don’t. Examples of the latter are Fairall 9 (Clavel et al. 1989; Rodriguez-Pascual et al. 1997; Santos-Lleo et al. 1997) and NGC4593.
(Santos-Lleo et al. 1995). For those which do get bluer, it remains to be shown that they do so in a way that quantitatively matches expectations for optically thick thermal sources!

The “temperature” inferred from the soft x-ray excess is generally very constant as its flux undergoes large variations (e.g. Brandt 1998, this meeting). This is an important puzzle for thermal models whose physical size is set by the region in which the potential drop occurs, and hence which is constant over human time scales. The fixed position of the soft x-ray excess, among objects, and over time for particular objects, suggests atomic emission or reflection to me (as advocated by Czerny and Zycki 1994). Atomic emission may be severely challenged by variability time scales (see the Brandt paper just cited), or observed spectra (modulo some ad hoc Comptonization to hide emission lines), but the idea is worth further analysis.

2.5. Role of the IR Source

Essentially all accretion disk models predict that $F_\nu$ increases with $\nu$. (The few exceptions are cool and produce very few ionizing photons directly, according to Blaes’ talk at this meeting). Almost all quasars show $F_\nu$ decreasing with $\nu$, after cutting out the small blue bump atomic feature. So how do the disk fits work?

The answer is that they generally rely on extrapolating an “IR power law” under the optical, subtracting it off, and fitting the difference. Only trouble is, it is now almost universally agreed that the IR component is thermal emission from dust grains (blazars excepted). Many good arguments lead to this conclusion, including e.g. low frequency cutoff slopes, concomitant CO emission, very low polarization and variability, the unified model and obvious thermal emission in Type 2s, and most crucially here, the universal inflection at $\sim 1\mu$ in the rest frames and the near IR reverberation mapping (see e.g. Barvainis 1992 for details and references). Dust emission cuts off sharply at $\sim 1\mu$ because of sublimation. (This is a good example of a universal frequency for a spectral feature indicating an atomic process.) Thus it is illegitimate to subtract an “IR power law” from the optical data. This point is also relevant for interpretation of microlensing surface brightness constraints as described below.

2.6. Opaque Partial Covering by Associated Absorbers

Quasars have a well-studied subclass of narrow absorption lines among the so-called “associated absorbers,” generally (but not always) with nearly the systemic redshift. These absorbers are “macroscopic,” arising on scales orders of magnitudes larger than an accretion disk. Yet some show unambiguous evidence for opaque partial covering, that is, various doublet ratios show saturation, so that $\tau \gg 1$; at the same time they are partial rather than black, typically absorbing only $\sim 50\%$ of the continuum. Thus they are thought to be opaque but to cover only part of the continuum sources. It is very doubtful that the light under the absorption lines can be attributed to photons scattering around the clouds. This does happen in some BAL quasars and the scattered photons are highly polarized. The very low continuum polarizations of ordinary quasars, together with the moderate line depth, proves generally that the residual photons which get through at the wavelengths of the absorptions lines also have low
polarization. The macroscopic cloud would have to be well centered on the AD in all cases, with light scattering around it symmetrically, to exhibit such a low polarization.

The implications for the AD model don’t seem to be widely appreciated. A macroscopic absorber would need to have an atmosphere or edge (i.e. a region of intermediate optical depth) small compared with the continuum source size, and cleanly cutting the continuum source in two! This is impossibly unlikely for a large foreground cloud if all the radiation comes from $\sim R_g$ scales. The near constancy with time of the absorption lines could also require that the cloud have virtually no transverse velocity.

Less crazy, and interesting from the point of view of the nature of the absorbers, is an array of tiny ($\sim R_g$) clouds with sharp edges in a stationary state (as remarked by J. Krolik). Here it might still be challenging to ensure that a negligible fraction of their cross-sections have intermediate optical depths. This is necessary to preserve the saturated line ratios.

This is one of several arguments that a significant part of the power may escape the zone where the potential drop occurs without being converted into radiation. The case of SS433 certainly shows that nature doesn’t abhor this situation.

2.7. Microlensing Constraints

This is an argument that a considerable fraction of the light of some quasars must originate on a scale too small for an AD. The argument is that the rapid microlensing of the Huchra lens (aka Einstein Cross), Q2237+0305, sets a lower limit to the surface brightness greater than that of even a blackbody of the same color temperature (Rauch and Blandford 1991). Thus the thermodynamic emissivity of the disk model must be $\gtrsim 10^5$. The models apportioned luminosity with radius in such a way as to reproduce the spectrum, thus implicitly including energy transport (and thermalization) before radiation in a generic way.

One can relax the assumption that the model must fit the spectrum, and then successfully fit the variations at the observed wavelength (Jaroszynski, Wambgamss and Pacynski 1992). I think the basic effect is that the disk temperature can be higher than the observed color temperature. The Rauch and Blandford paper was also criticized by e.g. Czerny et al. (1994) who were able to fit the flux monitoring as well as the spectral data. Their disk had extra red flux from some somewhat ad hoc irradiation. This reduced the disk flux, and more importantly, increases the color temperature and hence surface brightness. Their disk also benefited slightly, through boundary conditions, from allowing $L/L_{Edd} = 0.5$ for a thin disk rather than 0.3 as in Rauch and Blandford. Finally, Czerny et al. implicitly allowed the fastest observed flux variation to be atypically rapid (though not very rare), unlike Rauch and Blandford.

3. Indirect Constraints Based on Unified Models

3.1. Expected Orientation of ADs of Type 1 Objects

Spectropolarimetric and other evidence indicates that the nuclear featureless continuum sources in broad line regions are surrounded by $\gtrsim$pc-scale opaque
dusty tori oriented perpendicular to the nuclear radio axes. If the ADs on much smaller scales are oriented similarly, than we observe them generally at inclinations \( \lesssim 45^\circ \). Thus we needn’t be embarrassed if a sample of such disks are all at relatively small inclinations, when using diagnostics such as the Fe K\( \alpha \) line profiles.

### 3.2. Orientation of ADs in Type 2 Objects

It is well known that the nuclear jets and tori are not preferentially oriented along the host spiral galaxies’ axes and planes (Ulvestad and Wilson 1984; Schmitt et al. 1997). Thus if torus orientation were the sole determinant of spectral classification; the ratio of the numbers of the two types would be independent of host orientation. That is not the case however, with Seyfert 1’s showing a particular aversion to edge-on hosts (Keel 1980). Thus, if tori are ubiquitous, some objects with face-on tori are still classified as type 2, because dust in the host galaxy plane obscures the nuclear featureless continuum and broad line region (Lawrence and Elvis 1982).

A sample of Seyfert 2’s, while probably primarily objects with highly inclined tori (and by inference, ADs), will have significant contamination by objects with face-on tori. For certain studies these are imposters which can spoil a sample; they generally have smaller x-ray columns than “true” Seyfert 2’s. (They also would not be expected to show ionization cones.) Turner et al. (1998) concluded, based on K\( \alpha \) profiles of Compton-thin Seyfert 2’s, that they have face-on ADs just like the 1s. They may have been mislead in part by neglecting this fact. Their four “Seyfert 2” objects with K\( \alpha \) lines seen directly, the keys to their conclusion, include NGC526A. It is really a Seyfert 1 (e.g. see the spectrum of Storchi-Bergmann et al. 1996) in a nearly edge-on host. I believe another problem with the conclusion of Turner et al. is that there is no suitable (e.g. infrared-loud) numerically sufficient parent population for the combined Seyferts if the latter are all at \( \lesssim 30^\circ \) inclinations as claimed. See also Weaver and Reynolds (1998), who find much higher inclinations than Turner et al. for the Seyfert 2 sample, using the same data.

Why do we need to invoke tori at all for the “imposter” Seyfert 2s, or for that matter for all of the Seyfert 1s? I think the most direct answer is that the universal near-IR excesses (and the reverberation studies of those components) in Seyferts and quasars indicate substantial nuclear covering factors of hot dust.

Another paper has appeared recently which claims to find evidence restricting the generality of the Seyfert 1/2 unification, in this case based on an HST imaging survey (Malkan, Gorjian and Tam 1998). This result, and the little critique that comprises the rest of this subsection, relate to ADs only indirectly, so may be skipped by the reader.

When testing a unification hypothesis, it’s best to select the samples by a property thought to be isotropic; second best is to match by such a property after the fact. Neither was done in this paper; the targets were just taken from the Veron-Cetty and Veron catalog of all known objects. Thus the results can be suggestive at best. The claims to be unbiased are unconvincing: the radio and [O III] \( \text{fluxes} \) are claimed to be statistically indistinguishable in their sample. Aside from the fact that luminosities would appear more relevant, statistical significance of a difference in their sample is not the criterion for determining
a bias - especially since the ultimate conclusions are based on several-sigma differences at best, which could be made insignificant by correction of even a small bias. Similarly the claim that the 12µ-selected sample (which is too small in itself to be statistically significant) behaves similarly, does NOT “avoid the usual biases” as claimed, since in the unified models, the hot dust emission is highly anisotropic. See e.g. Pier and Krolik (1993) ApJ 418, 673, but the anisotropy is pretty much guaranteed in any model since the columns are generally so high that the dust is very opaque at that wavelength. (The mere fact that hidden AGN have different infrared SEDs shows the IR is anisotropic.)

The claim is also made by Malkan et al. that the Seyfert 1s in the sample favor later Hubble types, and that this may mean some Seyfert BLRs are obscured by material in the host plane rather than the nuclear torus. As explained above, this has been known for at least 20 years. See for example the discussion in Antonucci 1993, Section 2.2. Malkan et al. go on to say that nuclear dust lanes are more likely to occur in Seyfert 2s than in 1s. The difference is marginal statistically and becomes insignificant when the samples are matched more closely in redshift, a key requirement for comparing small scale structures. In fact it might be harder to see such structures in Seyfert 1s even at the same redshift since over half have saturated nuclei. Their test of this effect seems to indicate that they “missed only one sixth of [the dust lanes]” due to simulated saturated point sources - but the effect would still seemingly be enough to reduce the statistical significance of the result substantially. Similarly, limiting the data to the 1s without detected point sources substantially reduces the size of the effect, and renders it insignificant statistically.

The Malkan et al. paper has other puzzling statements, such as that the outer part of the torus is “not expected to be much more than one or two orders of magnitude larger [than the inner radius],” with no basis given. However, the most bothersome error in the paper is the statement that Seyfert 2 continuum polarizations are low, only “up to 15%”, so that the obscuring matter is geometrically thin in most cases. However, the polarization papers have explained many times that the BLR polarization is generally very high, with 16% in NGC1068 being arguably the minimum observed. In most cases we just get an upper limit to BLR total flux , and thus just a lower limit to P. The normal Seyfert 1 seen in polarized flux is thus polarized at a high level in general, with a second continuum contribution (sometimes referred to as “FC2”) diluting the continuum polarization. It is now known that much of the dilution is from hot stars (e.g. Heckman et al. 1997; Gonzalez-Delgado et al. 1998).

3.3. Beamed X-rays in Radio Loud AGN

Wozniak et al. (1998) review the x-ray spectral properties of broad line radio galaxies, explaining that the contrast of the Kα and Compton hump features are lower than in Seyfert 1s. Dilution by a beamed core component could in principle be the cause.

In my opinion the unification by orientation of blazars with normal radio doubles is most robustly inferred from a direct argument based on associated
diffuse radio emissions (Antonucci and Ulvestad 1985). The excess x-ray flux of radio loud AGN relative to the radio quiet ones or to most lobe-dominant ones closely tracks the beamed radio core flux (e.g. Kembhavi 1993; Baker et al. 1995) so that in the Unified Model the radio core flux can be used to predict the level of the beamed x-rays. This provides another handle on possible dilution of the K$\alpha$ equivalent width and Compton hump contrast.

3.4. D. Nonthermal AGN?

Finally tests of the unified model indicate a possible class of radio galaxy without significant “thermal” luminosity from accretion. The argument goes like this. At the highest radio lobe luminosities, e.g. the distant 3C sources, the numbers of FR II radio galaxies and radio quasars are comparable, and there is evidence that the projected linear sizes of the latter are substantially smaller, in accord with the expected foreshortening (Barthel 1989). However, at lower luminosities (e.g. the nearby 3C sources), the FR II radio galaxies greatly outnumber the quasars (e.g. Lawrence 1991; Kapahi 1990) and many have small projected linear sizes compared with quasars (e.g. Singal 1993). (I think that the Molonglo survey data may be consistent with this general description also, e.g. Kapahi et al. 1995.)

Many FR II radio galaxies have been shown directly to harbor hidden quasars with spectropolarimetry. However, the radio galaxies with small projected linear sizes, mostly “optically dull” (Laing 1994), might simply lack them. Perhaps that would mean they are “nonthermal AGN,” e.g. powered by rotation, via the Blandford and Znajack (1977) mechanism. Alternatively, FR II radio galaxies may still have hidden quasars. With the additional supposition that torus opening angles increase with luminosity, and that the individual object radio luminosities evolve in a reasonable way, Gopal-Krishna et al. (1996) have shown that all the observed behavior described above is actually as expected; see also Punsly (1996) in which detailed modeling leads to a similar conclusion. I am trying to observe them in the mid-IR to look for the waste heat from the putative hidden quasars, and ISO may also have something to say about this. A serious x-ray survey on these (probably) faint objects would be very valuable.

4. Conclusion

The arguments given are not airtight. Perhaps I will write a paper attacking this one, using an assumed name. Nevertheless, they should be considered by those who would invoke accretion disks for the Big Blue Bump in AGN: many AD advocates have been notorious for failing to address counter arguments to the model.

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