1. Introduction

My topic was to be Thermal Emission as a Test for Hidden AGN in Radio Galaxies, work in collaboration with, and in fact largely carried out by UCSB graduate student Dave Whysong. As I will explain, we are attempting to determine which FRII radio galaxies in the 3C catalog are likely to have hidden quasars by the consequent reradiation of energy by warm dust. The answer is far from all, and the dependence on optical spectrum, radio size, etc is essential for the Unified Model, and for black hole accretion mechanisms and demographic studies. Since our data set is insufficiently complete, I will emphasize instead some nearby individual objects of interest. These latter are discussed in astro-ph/0207385, a manuscript submitted to ApJ.

Four partially baked (about half actually) results together must suffice for one fully baked one. Therefore I’ve added some information on a recent discovery by Makoto Kishimoto, Omer Blaes and myself, which reveals the spectral shape of the Big Blue Bump for the first time in the important region of the Balmer edge. Next I show some results on the quasar reddening curve, which are startling, and very important, or else wrong. The authors there are Martin Gaskell, Rene Goosmann, David Whysong, and myself. Finally I preview some adaptive optics work from Keck on Cygnus A and NGC6240, courtesy of collab-
2. Thermal Emission as a Test for Hidden Quasars in Radio Galaxy Nuclei

Supermassive black holes, or something that behaves a lot like them, lie at the heart of radio galaxies, quasars, and other AGN. However, they manifest themselves in a (formerly) bewildering variety of ways. In particular, quasars are powerful optical/UV emitters, and this emission is thought to arise somehow in matter radiating as it approaches the hole's horizon. As far as I know this "Big Blue Bump" relatively quiescent and low polarization continuum component is always accompanied by commensurate broad emission lines. Powerful radio galaxies and radio quasars also have jets and lobes. It’s been known or suspected for 20 years that the most powerful radio galaxies actually contain quasars hidden from our direct view, hidden by something that acts like a geometrically thick torus oriented perpendicular to the radio jets.

My strong impression is that this is almost universally true at the very top end of the radio galaxy luminosity function, where giant bipolar reflection nebulae are seen whose polarized spectra show the quasar-like broad emission lines. Figures 1 and 2 in Singal 1993 (compare Barthel 1989) show that the $Z > 0.5$ radio galaxies in the culled 3C catalog bear the expected relationship to the quasars in space density and projected linear size of the radio sources for this simple picture. (The “culled” catalog is pretty cleanly those with enough isotropic flux to satisfy the minimum catalog flux requirement.) At low Z (which may simply mean lower luminosity) the simplest and most charitable thing that can be said is that perhaps there are many radio galaxies of a new type present, which do not have hidden quasars, and which spoil the statistical relationships of the quasars to the radio galaxies. This speculation was made by many of us early on.

However a paper appeared soon after Singal’s which taught me that I have no critical faculty; that all the statistics are just as expected if more powerful nuclei tend to have larger torus opening angles, and if in addition radio sources tend to fade over time (Gopal-Krishna et al 1996). In Singal’s low redshift/luminosity bin our eyes are then comparing old quasars to younger radio galaxies. Clearly this idea can’t be tested against the idea of a new population of small “true” radio galaxies by reason alone. Spectropolarimetry affords a robust detection of a hidden quasar in favorable cases, but if the opening angle is small or zero, or if insufficient scattering material is visible, it simply returns a false negative answer. But if the initial Big Blue Bump radiation is even roughly isotropic, and if the reradiation by the torus is even roughly isotropic (there are good arguments for both of these), then the “waste heat” from the hidden nucleus must appear as thermal emission from warm dust. Experience and theory show that the mid-IR provides the best combination of isotropy and contrast relative to any cooler dust heated by a starburst component.
Our initial results on special targets were presented in a conference in 2000, and made public in Mar 2001 as astro-ph/0103048 (Antonucci 2002); Whysong and Antonucci 2001 (astro-ph/0106381, June 2001); and Whysong and Antonucci 2002 (astro-ph/0207385, sub to ApJ). I'm specific here because of some puzzling subsequent statements by other authors. Perlman et al (2001) discussed our result showing the lack of an energetically significant hidden Big Blue Bump in M87, refined it slightly, and then with Gemini Observatory issued a press release strongly suggesting it was theirs.\(^1\) Radomski et al (2002) use our Cygnus A photometry in their paper, but publish and analyze their image without reference to our similar image and brief analysis in the paper of ours which they cite.

Very briefly our conclusions on the nearby objects are 1) M87 shows a point source of 13 mJy at 11.7 microns, consistent with synchrotron emission from the radio core. Any reradiated thermal mid-infrared emission is several orders of magnitude weaker than the kinetic power. Arguably this is the first near-proof of the existence of a “nonthermal AGN,” i.e. an AGN with a negligible fraction of its total power output as optical/UV emission. Cygnus A on the other hand has a fairly powerful and extended infrared source, as expected for this object in which a hidden quasar has been detected via spectropolarimetry (Ogle et al 1997).

We found that Cen A has a point source at wavelengths 11.7 and 17.7 microns for which the slope and spectrum is suggestive of thermal reradiation from a hidden Big Blue Bump. In this case there is supportive but not definitive polarimetric evidence for a hidden low-luminosity quasar (Marconi et al 2000). Also our point source flux at 0.3” resolution flux matches that measured by ISO in a 4” aperture; the ISO spectrum, which thus is also a spectrum of our point source, has strong dust absorption features, and pretty convincing dust emission features as well (Mirabel et al 1999). Comparing M87 to Cen A, a key conclusion is that some FR I radio galaxies have the hidden Big Blue Bump and some do not!\(^2\)

### 3. All Quasars are Blue

I have undergone a religious conversion regarding quasar reddening. With the zeal of a convert, I believe that most quasars are reddened in the optical, and absorbed but not reddened in the UV. Despite my zeal, I still have some doubts, but they can be addressed robustly in the near future.

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\(^1\)The Perlman et al. data have somewhat lower spatial resolution but much better surface brightness sensitivity to off nuclear emission when compared with ours. The authors argue that the latter gives them better limits on nuclear reradiated emission, but at these luminosity levels the reradiated mid-IR would be spatially unresolved.

\(^2\)A pet peeve of mine is the constant refrain in the literature stating that BL Lacs are beamed FR1 radio sources; as has been known for a decade or two, depending on how you count it, this is not true of the ones which have FR2 diffuse radio emission. Similarly I read now that FRIs are generically nonthermal (no hidden Big Blue Bump). This is in fact true for all of them except the ones that are thermal and do have a visible or hidden BBB.
As usual there are many prescient papers on this subject\(^3\), but I'll again feature just a few landmarks from my personal reading odyssey. J Baker and colleagues wrote a series of papers a few years back on the radio and optical properties of the Molonglo radio survey quasars, a sample selected at low frequencies and with very good completeness and follow-up of the optical identifications. Most relevant here are Baker and Hunstead 1995, Baker 1997, and Baker et al 1999.

For the 13 objects with broad line Balmer decrements available, the quasars showed a good correlation between that parameter and the optical slope (Baker 1997, Fig 16). The authors interpreted this indicative of reddening. The consequences were profound and perhaps not widely appreciated. Such a general effect should have major implications for modeling of the Big Blue Bump, the energetically dominant continuum component. In particular, it implies that almost all these radio loud quasars are intrinsically quite blue in the optical, and theorists should feel no obligation to model the steeper ones. On the other hand, it means that observed trends in optical slope, e.g. correlations with luminosity, can not be interpreted with confidence as effects of changing luminosity or Eddington ratio.

The impact is equally profound for quasar and black hole demographic studies: such studies universally assume that broad line object luminosities are just about what we observe them to be. If the optical slopes generally have a non-negligible signature of reddening, then even with the reddening law we discuss below, Most of the optical/UV luminosity is absorbed by dust. Thus both their luminosities and the luminosities of the hidden ones must be revised upward substantially.

I suggested in Antonucci 2002 (most easily accessed as astro-ph/0103048) that the optical slopes could not in fact be so influenced by reddening without seeing the sharp characteristic curvature of foreground reddening at the short wavelength end of the published spectra\(^4\). I thought using the single line pair broad H-alpha/broad H-beta was risky, and that that particular pair might be influenced by ionization parameter effect. After discussing this in detail with Martin Gaskell and Rene Goosman, those workers showed me that all broad line ratios agree with the reddening notion, and that it’s possible to derive nearly identical continuum and emission line reddening curves using all six well measured emission lines. Physically, this simply means that the small grains are efficiently destroyed; there are many independent arguments for that. Our “universal” (radio loud) quasar reddening curve is shown in Fig 1 of Gaskell et al 2002.

The beauty of all this is that absorption of this magnitude can be readily recognized by the concommitant infrared luminosity, which almost necessarily accompanies it. We are gathering data on this now.

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\(^3\)Early examples include Osterbrock, Koski and Phillips 1976 for radio galaxies’ broad line regions and continua, and de Zotti and Gaskell 1985 for dust in the host galaxy planes of Seyferts. Some especially telling later work on radio galaxies includes Hill, Goodrich and dePoy 1996 and Hines et al 1999, but again these comprise a small fraction of the literature.

\(^4\)It’s common for intermixed stars and gas to show optical reddening without an exponential UV cutoff, but it’s quite novel for the case of a point source and foreground absorption.
4. Se Raser la Barbe

A completely frustrating aspect of the quasar spectrum is that the underlying continuum with its diagnostic features is very heavily contaminated by overlying atomic emission from the broad emission line region. There is a way to get rid of it however! At least a few quasars have a small wavelength-independent polarization in the bits which are thought to be uncontaminated by atomic emission. At the same time, these objects have undetectably low polarization of the broad emission lines. Because of the latter feature, a plot of polarized flux acts to shave off all the atomic emission as one can shave off a beard with a razor blade. Note that the cause of the polarization needn’t be known; I think of it as the stinky stuff they add to natural gas to make it noticeable. It’s worth noting however that the polarization angle is parallel to the radio structure axis, suggestive of light both generated and scattered within a thin disk; it is not consistent with light scattered in a photosphere above a glowing thin disk (Stockman, Angel and Miley 1979).

Of particular interest is the Balmer edge region. Kolykhalov and Sunyaev (1984) on the theoretical side, and our group on the observational side (Antonucci, Kinney and Ford 1989), started a cottage industry trying to use the Ly edge feature (or lack of it) to diagnose the Big Blue Bump emission mechanism. However, in a thermal model such as a thin accretion disk, the Ly edge region can be substantially affected by relativistic broadening and shifting effects; it’s also sensitive to the non-LTE conditions thought to prevail in the innermost regions; and it depends on the physics in a region subject to various classical instabilities. All these problems are much mitigated for the case of the Ba edge. It hasn’t been possible to study the Big Blue Bump Balmer edge region observationally however, because of an enormous relatively localized atomic feature called the Small Blue Bump. But we can shave that off with the polarized flux method.

Several quasars are known to have continuum polarization, but little or no polarization in their broad emission lines and Small Blue Bump features (data of Miller and Goodrich in Antonucci 1988; Antonucci et al 1996; Schmidt and Smith 2000). Using the Keck and VLT observatories we can now get more detailed data and our fearless leader M. Kishimoto (these proceedings) shows that the quasar Ton 202 has an unpolarized Small Blue Bump. More importantly, the data reveal that the underlying Big Blue Bump continuum component has a break at the exact same wavelength that the Small Blue Bump arises, namely around 4000Å in the rest frame! This probably means that the former is thermal and optically thick.

A consequence is that the Small Blue Bump, which is already quite problematically huge to explain with the usual Balmer line + Fe II interpretation, is even huger since it lies in a region deficient in underlying continuum flux. This last conclusion would be affected though if the deficit in polarized flux derives from localized diminished percent polarization in the Big Bump rather than diminished flux. Theoretical discussions of the wavelength-dependence of accretion disk polarization can be found in for example Laor, Netzer and Piran 1990, with the state of the art being Agol, Blaes and Ionescu-Zanetti 1998.

Note that the data do not indicate any particular physics for the Big Bump however; at this point we can only say they probably indicate an origin in
optically thick thermal matter. Of course this new information does not negate the many really damning arguments against the Shakura-Sunyaev disk and some of its simple variants (e.g. Antonucci 1999).

5. V Better than Hubble? Keck Adaptive Optics Observations of Cygnus A and NGC6240

This section refers to work by Claire Max - the captain of this enterprise, G Canalizo, D Whysong, B Macintosh, and myself, and by Claire with other collaborators (see author lists).

Is a big ground-based telescope sharper for imaging and spectroscopy than the Hubble? The answer is of course yes if the same wavelength (and A.O.) is used; however, the dynamic range and the field size are both lower. Fig 1 shows the core region of Cygnus A imaged at 2 microns by HST and by Keck, using a fortuitously placed natural guide star. Clearly the Keck data are at considerably higher resolution as well as taken with good sampling, yet our restoration is still necessarily very conservative relative to the diffraction limit. There is a published Abstract on this: Max et al 2001; and much more and sharper data are in hand!

To my biased eye, this and some published images (for example Jackson et al 1998, Tadhunter et al 1999, Fosbury et al 1999) look like you can reach right out and touch Cygnus, and in particular it looks like various parts of the Humunculus nebula associated with eta Carinae. Our data also include high-resolution spectra, but I am truly running out of space, so I’ll just close with a mention of the spectrum of NGC6240.

This is another prototypical object by which the good gods have placed a natural guide star. NGC6240 is a prototype ULIRG double galaxy with powerful AGN and starburst activity. Lacking room to show the images and slit spectra, I’ll just have to note that they show the \( H_2 \) thermal line, and also Fe II characteristic of Liners in exquisite detail. A little more information is available in Max et al 2000 and Bogdanovic et al 2001; a paper is in preparation.

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