Thermal and Nonthermal Radio Galaxies

ROBERT ANTONUCCI
Department of Physics, University of California, Santa Barbara

Abstract Radio galaxies usually show a subparsec-scale radio core sources, jets, and a pair of giant radio lobes. The optical spectra sometimes show only relatively weak lines of low-ionization ionic species, and no clear nuclear continuum in the optical or UV region of the spectrum. Some show strong high-ionization narrow lines. Finally, a few radio galaxies add broad bases onto the permitted lines. These spectral categories are the same as those for radio-quiet AGN and quasars.

By the 1980s, data from optical polarization and statistics of the radio properties required that many narrow line radio galaxies produce do in fact produce strong optical/UV continuum, hidden from the line of sight by dusty, roughly toroidal gas distributions. *The radio galaxies with hidden quasars are referred to as “thermal.”*

Do all radio galaxies harbor hidden quasars? We now know the answer using arguments based on radio, infrared, optical and X-ray properties. Near the top of the radio luminosity function, for FRII, GPS, and CSS galaxies, the answer is yes. Below the top of the radio luminosity function, many do not. At low radio luminosities, most do not. Instead these *“nonthermal” weakly-accreting galaxies* manifest their energetic output only as kinetic energy in the form of synchrotron jets. These kinetic-energy-only (“nonthermal”) radio galaxies are a subset of those with only weak low-ionization line emission. This applies to all types of radio galaxy, big FR II doubles, as well as the small young GigaHertz-Peaked-Spectrum and Compact Steep Spectrum sources. Only a few FR I sources are of the thermal type.

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1 TERMINOLOGY

1.1 Optical/UV Classes of Radio Sources

This paper concerns primarily radio loud active galactic nuclei (AGN). “Radio loud” is sometimes defined by an absolute radio luminosity cutoff, and sometimes (less usefully) by a ratio of radio to optical luminosity. The nomenclature is multifaceted, complex, and very confusing for a newcomer. We will divide the AGN into two broad classes, which correspond to the two popular and persuasive central-engine models. The presence of an optical/UV continuum of the type called the Big Blue Bump will be called “thermal” because there is a consensus that this is thermal radiation from a copious opaque and probably usually geometrically thin accretion flow. This includes the radio loud quasars, the broad Broad Line Radio Galaxies, and the objects that have similar accretion flows hidden from the line of sight. (Some papers define the Big Blue Bump as the excess over a notional power law extending from the near-IR to the far-UV or X-ray, but that is not the most common usage, or the present usage.) The Big Blue Bump is virtually always accompanied by conspicuous broad permitted emission lines\(^1\) from regions collectively called the Broad Line Region. This combination is called a Type 1 spectrum.

By contrast, a radio loud AGN which lacks visible broad lines, is called a Narrow Line Radio Galaxy (“Type 2” optical spectrum). The narrow-line spectra of all radio types vary enormously from optically weak Low Ionization Galaxies —

\(^1\)Possible exception to this one discussed in the next section.
sometimes loosely called Low Excitation Galaxies — like M87, to very powerful High Ionization Galaxies like Cygnus A. The former are turning out to be almost all “nonthermal” radio galaxies, lacking a powerful Big Blue Bump and Broad Line Region, even a hidden one.\(^2\)

If the Big Blue Bump is directly visible in the total-flux spectrum, the object is called a radio loud quasar,\(^3\) or if low in optical luminosity (e.g. \(M(V) > -23\) for \(H_0 = 50\) km sec\(^{-1}\) Mpc\(^{-1}\), as adopted for the older Veron-Cetty and Veron catalogs), it may be called a Broad Line Radio Galaxy.\(^4\) In fact when it’s clear from context, “quasars” will be taken to include Broad Line Radio Galaxies.

For radio-bright objects at redshifts of larger than a few tenths, the presence of a (directly visible or hidden) optical/UV Big Blue Bump is general — except in those rare objects whose optical/UV spectrum is overwhelmed by beamed synchrotron emission from the bases of favorably oriented relativistic jets (“Blazars”). For objects with a large contribution to the optical/UV continuum by highly variable, highly polarized beamed synchrotron radiation, the general term is Blazars, defined in Stein 1978. Blazars are defined as the union of two classes: 1) objects in which a Big Blue Bump/Broad Line Region is still discernable against a strong synchrotron component (Optically Violently Variable Quasars, also known as Highly Polarized Quasars) with 1960s-1970s technology, and 2) objects with a pure synchrotron continuum in those old spectra, and little or no detectable line emission or absorption (BL Lac Objects). However, it’s been known since the 1970s at least that many historically defined “BL Lacs” show emission lines, both narrow and broad, especially (but not necessarily) when observed in low states. For example, BL Lac itself has weak narrow emission lines, and stellar absorption lines (Miller 1981); now we know that broad lines are often visible as well (Vermeulen et al 1995). In fact it is well known that many highly polarized, violently variable quasars are indistinguishable from BL Lacs when in high states (Miller and French 1978; see also Miller 1981).

None of these, “BL Lac” nor “High Polarization Quasar,” nor “Optically Violently Variable Quasar” is very well defined, and many studies have been damaged by blindly using these historical categories — sometimes just from catalog classifications, or by trying to mimic them with equivalent width cutoffs, which result in classifications changing with time (Antonucci et al 1987, 2002a)! It is also still often incorrectly asserted that the parent population (equivalent objects at

\(^2\)Note that there is only a little evidence yet that the thermal and nonthermal objects are bimodal in any property, and such isn’t necessarily expected theoretically.

\(^3\)Recall that this paper is largely restricted to radio loud AGN.

\(^4\)It is sometimes argued that at these low luminosities, there are some relatively subtle differences with respect to the quasars, e.g., van Bemmel and Barthel 2001, but such a distinction will not be made here.

\(^5\)For redshifts above a few tenths, the first two words of “Narrow Line Radio Galaxy” are often dropped, because the broad line objects are unambiguously called quasars.
more than a few degrees inclination) for “BL Lacs” is FR I double radio sources\(^6\) (the lower-luminosity edge-darkened ones). This is manifestly not the case (see references to maps of diffuse radio emission in Antonucci 2002a, going back for decades). Yet people still write about FR II radio emission in BL Lacs as a “problem” for the unified model. (It is well known that parents of optically-defined “BL Lacs” can be of either FR type, e.g. Kollgaard et al 1992.) This has invalidated studies of cosmological evolution, among other things (e.g., Ostriker and Vietri 1985, 1990.) See Jackson and Wall 1999 for a well-informed and sensible discussion.

Great care is required in classifying AGN, and the price of carelessness is spurious results. For example, historically 3CR382, 3CR390.3 and similar objects were called Broad Line Radio Galaxies (Type 1 optical spectrum), and this is still reasonable. But the same was done for 3CR234, because in fact the broad H-\(\alpha\) line is visible in the total-flux spectrum. This wasn’t an error in its historical context, but we now know that the broad lines and Big Blue Bump are seen only by reflection (Antonucci 1982, 1984; Tran et al 1995; Young et al 1998). Therefore from the point of view of unified schemes, such objects must be included with the Narrow Line Radio Galaxies (Type 2 optical spectrum), just as we keep Seyfert 2s (with hidden Big Blue Bump/Broad Line Region) separate from the Seyfert 1s. It would be great if a multi-dimensional classification scheme could be shown in a drawing, but a confusing “tesseract” would be needed (Blandford 1993). Even a tesseract might oversimplify the true situation.

1.2 AGN with Big Blue Bumps, but said to lack Broad Emission Lines

Note: this section is rather technical, and it may be skipped by the general reader.

Laor and Davis’ (2011) modeling paper has a convenient list of observational papers reporting on very, very few quasars with Big Blue Bumps, yet little or no detectable broad line emission. One limitation of these analyses is that any equivalent width upper limits rely on making an assumption about the broad line width. This is what led Stockton et al (1994) astray in claiming that the radio galaxy Cygus A has no broad emission lines. See Tadhunter et al 1990; Antonucci et al 1994, and Ogle et al 1997 for correction of the Stockton et al claim. However, extremely large line widths are exceptional for quasars, and do not occur in the faint but detectable broad lines in some of these very weak-lined quasars, so the limits on broad line equivalent widths are probably fairly close to the truth.

Laor and Davis (2011) also cite a few papers on a very different kind of AGN. These papers claim (dubiously in my opinion: Antonucci 2002b) that for a few nearby AGN, there is no detectable broad line emission, at an interesting level.

\(^6\)FR I and II radio sources are discussed in Sec. 1.3.
The authors refer to these as “True Type 2 Seyferts,” because broad lines are undetectable in both total flux and polarized flux.

Some problems with these claims: 1) in total flux, the upper limits on broad line equivalent widths depend on assumed line widths in most cases; 2) there are no upper limits given for broad line equivalent widths in polarized flux. Note that such limits must be calculated relative to the BBB component of the continuum only, and this is hardly possible because the spectra in these objects are very much dominated by starlight from the host galaxies; also there is no prediction available for the flux of scattered light from a putative hidden nucleus, detection of which requires well-placed scattering “mirrors.” Also the polarized flux from a large fraction of Type 2 AGN comes from transmission of the optical light starlight in the host galaxy in many cases (Thompson and Martin 1988), so even if upper limits were given on the line equivalent widths in polarized flux for these objects, they would be irrelevant.

2 BROADEST SKETCH

2.1 Where To Find Basic Information

Active Galactic Nuclei (AGN) is a term encompassing a variety of energetic phenomena in galactic centers which are thought to be powered directly or indirectly by accretion of matter onto central supermassive black holes. There are many reviews of this field, including several of book length. Perhaps the most technical and broad book-length review is that of J. Krolik, which was published in 1998. The classic text on spectral analysis of gaseous nebulae and AGN has been updated in 2006 (Osterbrock and Ferland); it’s a wonderful book, but it is biased towards the optical and ultraviolet regions of the spectrum. A new edition (2009) of An Introduction to Radio Astronomy by Burke and Graham-Smith is also noteworthy.

Few theoretical predictions have been borne out in this field, and understanding is still semi-quantitative at best (Alloin et al. 1985; Antonucci 1988, 2002a; Courvoisier and Clavel 1991; Koratkar and Blaes 1999; Blaes 2007). This review will refer to some fairly general theoretical ideas, but it will mainly organize some observational information on radio galaxy central engines that has become clear over recent years. It will not include a general introduction to AGN (see above references), but will address the nature of the central engines in radio galaxies which is a topic tied up as a practical matter with orientation effects on observations. Orientation effects are introduced in the next section, and as needed throughout the text.

The general topic of orientation effects (“Unified Models”) is reviewed in detail in Antonucci 1993. The material in that review is almost entirely “still true.” However, it has been updated and elucidated in several more recent (but generally
narrower) reviews (Urry & Padovani 1995; Dopita 1997; Cohen et al. 1999; Wills 1999; Axon 2001; Tadhunter 2008).

In a nutshell, prior to the mid-1980s, it seemed that radio loud quasars (with their powerful thermal optical/UV light) were quite distinct from radio galaxies; the latter are analogous to quasars in general radio properties, but apparently lacked the strong optical/UV electromagnetic luminosity (Big Blue Bump). In a landmark review of bright extragalactic radio sources, Begelman, Blandford and Rees (1984) posited that “The ratio of mass accretion rate to the mass of the hole may determine whether a [radio loud] active galactic nucleus will be primarily a thermal emitter like an optical quasar or a nonthermal object like a radio galaxy.”

Through optical spectropolarimetry and other means, it was subsequently determined that many radio galaxies, especially the most powerful ones, with strong high-ionization narrow emission lines, actually harbor hidden quasars surrounded by opaque dusty tori, so that the observational appearance depends on the inclination of the radio axis to the line of sight. But now we know that for many radio galaxies, any hidden quasar must be very weak.

The radio quiet and radio loud objects with high ionization are virtually all visible (Type 1) or hidden (Type 2) Seyferts or quasars (e.g., Antonucci 2002b). At lower radio luminosities of all radio types, we find mostly LINERs (Low Ionization Nuclear Emission Regions). A recent and comprehensive review of LINERs is that of Ho (2008).

2.2 Nature of Geometrical Unified Models

In the low-redshift universe, there is a near-perfect correspondence between “radio loud” objects — with $L_\nu(1.5 \, \text{GHz})$ loosely extending from perhaps $\sim 10^{28}–10^{36} \, \text{erg sec}^{-1} \, \text{Hz}^{-1}$ — and elliptical hosts. (This paper uses $H_0 = 70 \, \text{km sec}^{-1} \, \text{Mpc}^{-1}$, $\Omega_{\text{matter}} = 0.3$, and $\Omega_{\Lambda} = 0.7$.) For a fiducial $L_\nu \propto \nu^{-1}$ spectrum, for which there is equal power per logarithmic frequency interval — also referred to as “per dex” — the parameter $\nu L_\nu$ gives the power integrated over an interval of 0.30 dex (powers of 10). Thus if one integrates such a spectrum over the “radio region” 30 MHz–300 GHz, the corresponding luminosity is 13.3 times as great; a look at various radio AGN in the NASA Extragalactic Database (http://nedwww.ipac.caltech.edu) shows that the luminosity per dex of the dominant optically thin synchrotron component tends to be lower outside this range, so depending on the application, one may consider this as a crude “radio bolometric correction.” Resulting radio powers can exceed $1 \times 10^{45} \, \text{erg/s}$. Estimates of energy tied up in 100-kpc scale radio lobes are as high as $1 \times 10^{61} \, \text{ergs}$ or more.

A few LINERs have strong broad lines, e.g., Filippenko and Halpern 1984. Many LINERs have very inconspicuous broad Hα components, but it isn’t clear to me that they are strictly analogous to those in low-luminosity Seyferts. For example, we do not know whether they vary rapidly (L. Ho, 2011, private communication).
even using the particle/magnetic field minimum-energy assumption and assuming a lack of a dominant proton contribution. (The minimum-energy assumption posits that energy is apportioned between relativistic electrons and magnetic field in such a way as to minimize lobe energy content for a given synchrotron luminosity.)

Figure 1. A schematic diagram of the current paradigm for radio-loud AGN (not to scale). Surrounding the central black hole is a luminous accretion disk. Broad emission lines are produced in clouds orbiting outside the disk and perhaps by the disk itself. A thick dusty torus (or warped disk) obscures the Broad-Line Region from transverse lines of sight; some continuum and broad-line emission can be scattered into those lines of sight by warm electrons or dust that are outside the observing torus. Narrow emission lines are produced in clouds much farther from the central source. Radio jets, shown here as the diffuse 2-sided jets characteristic of low-luminosity, or FR I-type, radio sources, emanate from the region near the black hole, initially at relativistic speeds. (adapted from Urry & Padovani 1995)

Unified models assert that certain AGN classes differ only in orientation with respect to the line of sight. These models comprise two separate (though interacting) assertions, as illustrated in Fig. 1. The first to be recognized historically is the effect of relativistic beaming (aberration causing anisotropy in the observed frame) in the powerful synchrotron jets which feed particles and magnetic energy into the radio lobes. When seen at low inclinations, beaming amplifies and speeds up “core” (subparsec scale jet, usual synchrotron-self-absorbed) radio flux vari-
ability and (apparent faster-than-light) “superluminal motion.” Thus a special fortuitous orientation of a nearly axisymmetric object leads to a different observational category (Blazars). The same objects, seen at higher inclination, are ordinary radio-loud galaxies and quasars (Blandford et al 1984; Antonucci and Ulvestad 1985; Kollgaard et al 1992, etc.). We can call this the beaming unified model (or more loosely, just the beam model, though that term usually connotes some connection with actual physics).

At low redshift, radio-quiet (but not silent) AGN lie in spiral hosts, and go by the name of Seyfert galaxies. They rarely show detectable motions in their weak radio jets — and when they do show motions, the apparent speed is usually much less than the speed of light. More luminous radio quiet objects are called Radio Quiet Quasars, or historically, Quasistellar Objects (QSOs).

But both radio quiet and many radio loud AGN widely exhibit another kind of orientation unification: many well-studied objects include energetically dominant continuum components in the optical-ultraviolet region, referred to as the Big Blue Bump, and widely attributed to thermal radiation from optical thick accretion flows. (Confirmation of the latter can be found in Kishimoto et al 2004, 2005, 2008.) They are almost always accompanied by broad (5000–10,000 km/s) permitted emission lines. Both these components reside inside optically opaque dusty structures which to zeroth order have the shadowing properties of tori, and these structures are referred to loosely as the “AGN torus.” In some cases we have a direct (low-inclination, polar) view of these compact components (in quasars, Seyfert 1 galaxies, and Broad Line Radio Galaxies). In many other cases (high inclination, equatorial views), we can be sure these two components are present inside the tori using the technique of optical spectropolarimetry, which literally allows us to see the nuclei “from above,” using ambient gas and dust as natural periscopic mirrors.

This wonderful trick of optical spectropolarimetry (e.g. Antonucci 1982, 1983, 1984; Antonucci and Miller 1985) uses the polarization property of scattered light to separate the spectrum of hidden sources from any sources of direct light. The above references show that the Big Blue Bump and the Broad Line Region are present but hidden from direct view. The scattering polarization position angle indicates that the photons emerging from these components can only escape from the hidden nuclei if moving along the radio jet (and lobe) axis, so that the other directions must be blocked by an obscuring torus. This is illustrated in Fig. 2, from Tran 1995, illustrating the total and polarized fluxes, for 3CR234. The polarized photons (scattered light) contribute to both plots of course, but show up with great contrast when plotted alone.
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Figure 2. Total and polarized flux for the Narrow Line Radio Galaxy that showed as the first hidden quasar, 3CR234 (Antonucci 1984; the figure shows the data of Tran et al. 1995.). The polarization angle relative to the radio axis shows that photons can only stream out of the nucleus in the polar directions. The polarized flux (akin to scattered light) spectrum shows the hidden quasar features at good contrast. (In this case, however, the scattered ray is itself reddened.)

If all objects fit in with the above descriptions of orientation unification, we would be left with as few as two independent types of “central engines” on relativistic scales, those for radio quiet and those for radio loud AGN. But we now know that many radio galaxies lack powerful visible or hidden Type 1 engines (Big Blue Bump, Broad Line Region, copious accretion flows). They occur frequently in some regions of parameter space (as delineated for example by redshift and radio flux or luminosity), and not in others. The purpose of this review is to gather the multiwavelength evidence for the last two statements, and emphasize the dependence of the distribution of central engine types on parameter space, which is the key to avoiding many errors and much confusion and even discord. We will see that a great deal of self-consistent information is available on the occurrence of the two types of radio galaxy/quasar central engines.

2.3 Types of Powerful Radio Source; Scope for Unification by Orientation

Within the radio loud AGN arena, several types are also distinguished based not on central engine properties but on extended radio morphology. Unfortunately, they do not correspond very closely to the optical categories!

The most luminous giant ($\ell \gtrsim 100$ kpc) double radio sources are designated FR II (“Classical Double”), for Fanaroff and Riley (1974); those authors noted that a whole suite of properties change together fairly suddenly over a critical radio

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8This refers to regions where the jet velocity is almost the speed of light, $c$, and also the gravitational potential energy per unit mass is of order $c^2$. 
luminosity (referring to the roughly isotropic diffuse emission). Sources above \( \sim 2 \times 10^{32} \) erg/sec/Hz at 1.5GHz show edge-brightening and hot spots, where the radio jets impinge on an external medium, and shocks partially convert bulk kinetic energy to particle and field energy. They also tend to have strong side-to-side asymmetry (generally attributed to relativistic beaming) of the jets over scales from the relativistic region up to tens of kpc. The lower luminosity giant (also \( \ell > \sim 100 \) kpc) objects (FR I galaxies) also have strong side-to-side jet asymmetry, but only on 1–1000pc scales in most cases. An important refinement to the FR classification scheme is that the dependence of the exact radio luminosity cutoff depends on the optical luminosity of the host galaxy (Owen and Ledlow 1994, but see Best 2009, Fig. 4a).

The “FR” types of radio galaxy generally have sizes of 25–1000kpc, but large populations of smaller sources exist, and they can still be very powerful. (The small sizes mean that their lobe energy content is very much lower, however.) They are denoted in an inconsistent way, according to their means of discovery. Optically thin, steep-spectrum radio sources which were historically unresolved on arcminute scales, were (and are) called Compact Steep Spectrum (CSS) sources to distinguish them from opaque beamed synchrotron cores; their spectra peak at \( \sim 100\)MHz, and they are generally defined to be in the size range 1kpc–15 or 25kpc. Sometimes they are crudely defined to be sources smaller than typical host galaxies. Sources whose extent is less than \( \sim 1\)kpc, with even more compact substructure, are often dominated by synchrotron components which are self-absorbed up to \( \sim \)GHz frequencies\(^9\), and are called Gigahertz-Peaked-Spectrum sources (GPS). (Even tinier sources are being sought by selecting for self-absorption peaks at even higher frequencies.) These classes are reviewed by O’Dea (1998). Since that paper was written, much evidence has accumulated from VLBI proper motions that the sources are small because they are very young (\( \sim 1000–100,000 \) years\(^{10}\)). In at least some cases it is known from faint extended emission that these very young ages refer only to a recent phase of activity however. Statistically, only a very small fraction of small and very short-lived sources can grow to be huge bright long-lived sources.

The relevant properties of classes will be discussed in turn, generally starting with the radio data and proceeding upwards in frequency. We will discover that some FR II radio galaxies at \( z \lesssim 0.5–1.0 \) lack powerful hidden quasars. These objects may \(^{11}\) have hidden Type 1 nuclei, but they are constrained to be much weaker than those of the “matched” visible quasars, and thus they are not “unified” (identified) with them via orientation with respect to the line of sight.

\(^9\)It is proposed by Begelman (1999) that the weak fluxes at low frequencies result from free-free rather than inverse synchrotron absorption. Encouraging follow-up work can be found in Stawarz et al 2008 and Ostorero et al 2010.

\(^{10}\)This material was reviewed recently by Giroletti 2008.

\(^{11}\)In radio flux and redshift.
At low redshifts ($z < \sim 0.5$) it is probable that only a minority of FR II radio galaxies in the 3CR catalog host hidden quasars.

Next we will tackle the less powerful (FR I) giant radio galaxies, which are by selection nearby in almost all cases. The 3CR catalog flux cutoff of 10 Jy at 178MHz (Laing, Riley and Longair 1983) corresponds to the FR I vs. II radio luminosity separation at $z \sim 0.2$. Most (but by no means all) of these objects have nuclear spectral energy distributions dominated by synchrotron radiation, with no evidence for visible or hidden “Type 1” central engines.

Finally the small, young GPS and CSS sources will be discussed. Very recent information from the ISO and Spitzer infrared satellites has greatly increased our knowledge of “shadowing unification” at various radio luminosities.

A major caveat of this paper, and of this field, is that most of the information derives from the brightest radio sources, especially those in the 3CR catalog, so no implication is made for unexplored regions of parameter space! Another major caveat is that while we discuss thermal vs. nonthermal galaxies, relatively little evidence is presented that any parameter is bimodal, so that there could be a continuum of properties.

### 2.4 The Infrared Calorimeter

Radiation absorbed by the dusty torus is largely reradiated as infrared, and many studies have concluded that in reasonably luminous AGN (so that the IR is not dominated by a normal host galaxy), at least the near- and mid-infrared reradiation ($\approx 1–40$ microns) is dominated by reprocessed nuclear optical/UV/X-ray light. In specific populations, the entire IR seems to be radiated by the torus, because the colors are warm throughout, and there is evidence for only weak star formation (e.g. PAHs) or synchrotron radiation (e.g., strong radio-mm emission). Thus the infrared reradiation of nuclear light can potentially be used as a calorimetric indicator for the luminosity of any hidden AGN.

There are at least two ambiguities in using this infrared emission as an AGN calorimeter. The first is that some of the nuclear radiation may not reach the torus, either because of the intrinsic latitude-dependence expected for many models of the Big Blue Bump (e.g. Netzer 1985), or preferentially planar Broad Line Region absorption (Maiolino et al 2001c; Gaskell et al 2007). Both of these effects add noise to the dust reradiation calorimeter, and tend to make hidden quasars look dimmer than visible quasars in the infrared for a given opening angle. Nevertheless most studies show infrared luminosity about as expected, from detailed

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12 As a reminder, unification of broad line and narrow line AGN by orientation of a toroidal nuclear obscurer is here called “shadowing unification.” Ascription of superluminal motion and other relativistic effects in subpopulations to orientation is called “beaming unification.”

13 Recall that thermal vs. non-thermal refers not to the radio emission itself, but to the presence of an energetically dominant optical/UV source thought to arise from an accretion disk.
studies of individual objects (Carleton et al 1984; Storchi-Bergmann et al 1992) and for populations of Type 1 and Type 2 objects within isotropically selected samples (Keel et al 1994). Carleton et al (1984, see Fig. 3) shows how the infrared calorimeter works, based on the first spectropolarimetric hidden AGN, 3CR234.

![Figure 3. 3CR234 continuum observations plus model fits. The ordinate is linear in $\nu L_\nu$, and the area under any portion of a curve is proportional to the luminosity in that portion of the spectrum. The hidden optical/UV component (Big Blue Bump) has been reprocessed into the infrared in this hidden quasar.]

Also, although the covering factor deduced from dividing infrared re-emission by Big Blue Bump luminosities are therefore lower limits, they tend to be high ($\sim 0.1–1$) so that they can’t be too far off.

Another concern with the infrared calorimeter is the expected anisotropy of the thermal dust emission due to the large dust column densities (Pier and Krolik 1992, 1993). Many Type 2 AGN have X-ray columns of $\gtrsim 1 \times 10^{24} \text{ cm}^{-2}$; absorption of mid-IR lines, molecular maps, and the great difference in the average X-ray columns between Type 1 and Type 2 AGN suggest that a commensurate dust extinction is present. (See Maiolino et al 2001a,b,c for arguments which affect this line of reasoning quantitatively but not qualitatively.)

There is a limit on the anisotropy of the ratio $[\text{O III}] \lambda 5007/F_\nu(60\mu)$ in Seyferts from Fig. 3 of Keel et al 1994. The figure shows that in their well-selected sample (60$\mu$ flux with a mild $25\mu$–60$\mu$ warmth criterion), Type 1 and Type 2 objects

\[14\text{Although Maiolino et al 2007 didn’t actually integrate over the SED and should therefore be viewed with much caution, it is interesting that they actually find some covering factors nominally greater than one for low-moderate luminosity objects. This was predicted qualitatively by Gaskell et al (2004), who argued that a preponderance of large grains leads to less apparent absorption (spectral curvature) in the optical/UV region than otherwise, and thus one may fall into the trap of inferring very low extinction. The inner torus is expected to lack small grains, most robustly perhaps on the grounds that the torus sublimation radius must be larger for small grains according to radiative equilibrium. The lack of small grains at the sublimation radius is supported by the data of Suganuma et al 2006: see discussion in Kishimoto et al 2007.}\]
have indistinguishable distributions of $L(60\mu)$, $L[5007]$, and of course their ratio. The $\lambda5007$ line is produced outside the torus in most objects like these: it doesn’t appear in polarized flux along with the broad emission lines and Big Blue Bump. Thus it’s not significantly hidden inside the torus, is likely quite isotropic in this parameter space, and is nearly isotropically selected\textsuperscript{15}, fairly powerful Seyferts.

Torus models do predict that the optical depths will be small in the far-infrared in general. For AGN-dominated infrared SEDs, that means there is an elegant and detailed method of deriving the degree and wavelength-dependence of the dust emission anisotropy. For isotropically selected samples, we can divide composite or representative Type 1 SEDs by those for Type 2, tying them together at $60\mu$.

In order to make the infrared calorimeter accurate, we need to account for the common anisotropy of the near- and mid-thermal dust emission. There is general agreement on near isotropy past $\sim 30\mu$, as was first predicted by Pier and Krolik (1992, 1993). The main basis for their prediction of anisotropy at shorter wavelengths was that many Seyfert 2’s are Compton-thick, including NGC1068 — which is completely opaque and for which $N(H) \gtrsim 10^{25}$ according to the X-ray spectrum (e.g., Pounds and Vaughan 2006). In Galactic dusty gas this corresponds to $A(V) \sim 1000$. (See e.g., Maiolino et al 2001a,b for a quantitative correction, which however doesn’t greatly affect the discussion of gas vs. dust columns below.) As an aside, I do think that dust-free atomic gas can contribute to the X-ray absorption in some cases (e.g., Risaliti et al 2011; Antonucci et al 2004), but the X-ray columns of Type 2 AGN are on average $\gtrsim 100 \times$ those of Type 1, so most of the column is connected with the Type 2 classification. Also in some cases, the dust column can be constrained to be similar to the very high X-ray columns. For example, Lutz et al (2000) used the lack of Pf-$\alpha$ at $7.46\mu$ to show that $A(V) > 50$ in NGC 1068.

Recall that one could pick spectral Type 1 (broad-line) radio loud quasars and radio galaxies by some fairly isotropic AGN-related luminosity (e.g., lobe-power), and divide the two spectra to produce a spectrum of diminution from anisotropy. We were able to do this for the $z > 1$ 3CR (Fig. 4) because all of the radio galaxies seem to host hidden quasars, but only out to $\sim 15\mu$ in the rest frame. \textit{The correction for anisotropy is around a factor of 10 in the near-IR, 1.5–2 on both sides of the silicate feature, and about three in the silicate feature}, but varies significantly from object to object. As expected, it flattens out at $\sim 1$ at long wavelengths.

Recall that torus shape was inferred from the high\textsuperscript{16} typical polarization of the

\textsuperscript{15}Isotropic selection means selection on an isotropic AGN property, which avoids powerful biases in comparisons between classes. It is essential in order to produce intelligible results.

\textsuperscript{16}A common error is to use the percent polarization of the continuum (after correcting for bulge or elliptical starlight) as the scattering polarization: that is usually contaminated by hot stars, and only the broad lines themselves can be used to find, or more often place a lower limit on, the percent polarization of the scattered nuclear light (Antonucci 2002b).
reflected light in hidden-Broad Line Region objects, which is generally perpendicular to the radio axis, meaning that photons can only escape the nucleus to scatter into the line of sight if they leave the nucleus in the polar directions.

The obscuring dusty tori invoked in the shadowing aspect of the unified model are active, not just passive, components. Modulo factors of order unity for geometry and dust cloud albedo, the tori will reprocess almost all of the incident Big Blue Bump/Broad Line Region luminosity into the infrared. Thus the ratio of re-emitted infrared emission to Big Blue Bump (and often considerable absorbed X-ray) emission tells us the approximate covering factor of the dusty gas which is idealized as a torus shape.

The covering fraction should agree with the fraction of Type 2 (hidden) nuclei in a sample which is selected by any isotropic AGN property. What are the results of this comparison? I’m crudely leaving out intermediate types, and the substantial minority of Seyfert 2s whose Type 1 nuclei are hidden by dust in the host galaxy plane (Keel 1980; Lawrence and Elvis 1982) rather than by a nuclear torus. Keel et al (1994) found 80 far-IR selected Seyfert 1s and 141 Seyfert 2s (plus some H II galaxies that they weeded out). So one expects a dust covering factor of ~ two-thirds in this parameter space. While the paper describes dust and gas covering factors as “broadly consistent” with the model, it would still be very valuable at this point to take advantage of this sample and actually measure covering factor for the Type 1s based on existing spectral energy distributions.

Figure 4 (from Hönig et al. 2011) shows the quotient SED for $z > 1$ individual quasars and the radio galaxy composite, which however only covers up to 15 microns in the rest frame. Again this plot purports to give us directly the anisotropy as a function of wavelength.

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17 There is at least one obscured quasar with a thin obscuring disk — the radio-loud, mini-MgII BAL OII287 (Goodrich and Miller 1988; Rudy and Schmidt 1988; Ulvestad and Antonucci 1988; Antonucci, Kinney, and Hurt 1993); however, even that one seems to have an upturn longward of 1µ at least according to the NED figures.

18 Buchanan et al (2006) does this type of division for a 12µ (better than optical, but not ideal) selected sample of Seyfert galaxies. As expected, their anisotropy curve flattens at long wavelengths, but oddly not at a value of unity.
Figure 4. The infrared SEDs of \( z > 1 \) 3CR quasars and the matched radio galaxy composite, from Hönig et al (2011). Since these radio galaxies are all edge-on quasars, this quotient spectrum measures the orientation dependence at each wavelength.

3 CLASSICAL DOUBLE, OR FR II RADIO SOURCES

3.1 Spectropolarimetry of Radio Galaxies and the Discovery of Hidden Quasars

Hidden quasars inside radio galaxies are discussed in Antonucci 1993, Wills 1999, and Tadhunter 2008. I’ll describe many relevant observations here, moving from the radio and then on up in frequency to the X-ray. First though I will introduce some background optical information, and will return to that waveband in Section 2.5.

It was noticed in the early 1980s that for some Narrow Line Radio Galaxies and Seyfert 2 galaxies, a small measured optical polarization could often be intrinsically large (\( \gtrsim 10\% \)) after starlight subtraction, and that the electric vector position angle was generally perpendicular to the radio structure axis (Antonucci 1982, 1983, 2002; Miller and Antonucci 1983; McLean et al 1983; Draper et al 1993 etc). Furthermore, the polarized light spectrum (similar to the scattered light spectrum in spectral features) revealed the features of Type 1 AGN, with the first case being the powerful hidden quasar in the radio galaxy 3CR234 shown in Fig. 2 (Antonucci 1982, 1984; Tran et al 1995; Young et al 1998). As noted
earlier, this means that the galaxies contain hidden quasars, and that their photons can reach us by exiting the nuclei along the (radio) structural axes and then scattering into the line of sight. The Tran et al 1995 polarized flux spectrum is shown in Fig. 2.

Since then many other radio galaxies, in general those with strong high-ionization lines like 3CR234, have shown hidden quasars in polarized light. These papers include most of them: Tran et al 1995, 1998; Cohen et al 1999; Young et al 1996; Dey et al 1996; Cimatti et al. 1996, 1997; Ogle et al 1997 on Cygnus A (see also Antonucci et al 1994); Cohen et al 1999; Hurt et al 1999; Kishimoto et al 2001; Vernet et al 2001; Tadhunter et al 2002; Solorzano-Inarea et al 2004; Tadhunter 2005.

Many Seyfert 2s were subsequently shown to have hidden Type 1 nuclei by this method (Antonucci and Miller 1985; many references are given in Tran 2003), but radio loud cases were fewer, at least partially because they are more distant and fainter.

While there is no question that 3CR234 hosts a powerful hidden quasar, it has some properties which make it somewhat special as a radio galaxy: the luminous high-ionization narrow lines, and the powerful infrared dust source (see Fig. 3; also Young et al 1998). Most of the other radio galaxies shown to host hidden quasars in this way share these properties (Cohen et al 1999). Both properties are rare in FR I radio galaxies, and at low and moderate redshift, many FR IIIs differ from this pattern as well (e.g., Hine and Longair 1979; Table 2 of Cohen and Osterbrock 1981 on optical spectra; Ogle et al 2006, Dicken et al 2009 on infrared observations). Many of these have low-ionization, low luminosity emission lines (Miley and Osterbrock 1979). (All of my reference lists are undoubtedly incomplete!)

Radio galaxies with \( z > \sim 1 \) usually have resolved optical light, and much of the light is scattered from hidden quasars (Chambers et al 1987; McCarthy et al 1987; Dunlop and Peacock 1993; Cimatti et al 1993). Spectacular exceptions include 4C41.17 (Dey et al 1997) and 6C 1908+722 (Dey 1999); they show optical light extended along the radio axes, but it is mostly unpolarized starlight. However, these \( z \sim 4 \) objects are observed at higher rest-frame frequencies than explored in other objects.

### 3.2 Puzzling statistics on the radio properties of FR II radio galaxies and quasars

There are a few historical papers which are interesting and illustrative of the reasoning that led to much progress on unification. Peter Barthel worked mostly on VLBI observations of superluminal sources in the 1980s, noting that the beam model explained many properties such as superluminal motions and jet sidedness qualitatively, but he was (according to the title of a rumination for a confer-
ence) “feeling uncomfortable” because one had to assume that a large fraction
of these sources in various samples have jet axes fortuitously close to the line
of sight.\footnote{When selecting by high-frequency radio flux, one preferentially
selects objects whose jet axes point in our general direction because of beaming,
but this effect can’t explain the apparent preference for this orientation quantitatively.}
Barthel later wrote a famous paper (Barthel 1989) entitled “Are all quasars
beamed?” suggesting that those quasars whose axes lie near the sky
plane somehow fall out of quasar samples, and (inspired by the spectropolarimetry)
might be classified as radio galaxies. Note though that he did not entitle
his paper “Do all radio galaxies contain hidden quasars?” The answer to that
question would be no, but the answer to the question he posed is still basically
yes.

The general idea of beaming to explain superluminal motions and one-sided
jets was accepted by most doubters as a result of two key discovery papers
reporting on the so-called lobe depolarization asymmetry. There is a very strong
tendency for one radio lobe in double-lobed radio quasars to be depolarized at
low frequencies by Faraday rotation within the observing beam on the side of the
single-jet sources which \textit{lacks} the jet (Laing 1988; Garrington et al 1988). Most
people accepted that the depolarized lobe must be the more distant one, located
behind a large-scale depolarizing magnetoionic medium; thus the polarized lobe is
on the near side, so that the jet is also on the near side, as expected for beaming.
(A demur can be found in Pedelty et al 1989.)

The selection criteria in Laing 1988 and in Garrington et al 1988 favored low-inclination
sources; nevertheless it is amusing that the former paper has this
disclaimer: “The sources observed here must then be oriented within about 45
degrees of the line of sight…to generate sufficient asymmetry in path length…”
to fit the depolarization data. Their referees must not have been particularly
curious people not to ask for elaboration. We now know that many of the high-inclination
sources were masquerading as FR II radio galaxies.

Barthel (1989) focused on the 3CR sources in the redshift interval \(0.5 < z < 1.0,\)
in order to avoid low-luminosity, especially FR I radio galaxies, which he did
not propose to identify with quasars, noting that “radio loud quasars invariably\footnote{“Almost invariably” would have been more accurate, e.g., quasar 1028+313 in Gower and
Hutchings 1984}
have (lobe) luminosities in excess of the Fanaroff and Riley division.” He also
pointed out that the 3CR radio galaxies above \(z = 0.5\) have strong emission
lines like quasars.\footnote{Today we would say that the large majority of them have strong emission lines.}
He notes further that, based on early fragmentary data, only
a subset of FR II radio galaxies are strong IR dust emitters. Finally, Barthel
crucially adds this claim later in the paper: “…including the \(0.3 < z < 0.5\)
and/or the \(1.0 < z < 1.5\) redshift range does not alter [his conclusions] markedly.”

I was particularly moved a few years later by a paper by Singal (1993), entitled
“Evidence against the Unified Scheme for Powerful Radio Galaxies and Quasars.” I reproduce two of his figures here (the present Fig. 5 and 6). His histograms of number densities and cumulative linear size distributions are similar to Barthel’s for $z > 0.5$, but he includes low-redshift FR II sources in a new $z < 0.5$ bin, where “all hell breaks loose.” The median projected linear size in quasars relative to radio galaxies no longer shows a satisfying reduction expected for foreshortening, and the number density of FR II radio galaxies becomes much higher than those of quasars.

![Figure 5. Redshift distribution of 131 radio galaxies and quasars in the 3CR sample, taken from Singal 1993. Crucially, the hashed “Broad Line Radio Galaxies” must be mentally moved to the lower plot for the purposes of this paper. Note the large ratio of the number of radio galaxies to that of quasars at low redshift.](image1)

![Figure 6. Cumulative distributions of projected linear sizes of radio galaxies (continuous curve) and quasars (dashed curve) in several redshift bins. Crosses mark the median values, and arrows are for a test used by the author, but not referred to here (Singal 1993). The foreshortening expected in the shadowing Unified Model is not seen at low redshift.](image2)

Singal suggested that this spoiled the Unified Scheme, but a clever alternative was suggested by Gopal-Krishna et al (1996). They showed that subject to two assumptions justified or at least motivated by independent observations, Singal’s histograms could all be easily understood in the beam model. One hypothesis was that the torus opening is set by the initial radio power of a source; the other was that the luminosity of a growing giant double radio source decreases over time in a certain way. Without going through all the reasoning, it turns out in
this case that in the lowest redshift bin, one is preferentially comparing older quasars to younger radio galaxies, canceling (to the modest accuracy attainable) the expected size difference between the two types of radio source.

There is another possible explanation for Singal’s histograms: there is a population of FR II radio galaxies, concentrated at low redshift, which simply lacks hidden quasars.

3.3 The infrared calorimeter for visible and hidden FR II radio sources

Distinguishing these two hypotheses motivated my group and others to pursue observations of radio galaxies in the thermal infrared, where the infrared calorimeter (radiation reprocessed as infrared) must show us the putative hidden quasars, independently of orientation. Remember that the spectropolarimetric test for hidden AGN requires a somewhat fortuitous geometry, where a gas and dust cloud must have sufficient optical depth and covering factor to reflect detectable light, and it must have a view of both the hidden quasar and the observer on Earth. Thus it is an incomplete method for finding hidden AGN.

David Whysong and I started imaging 3CR radio galaxies and quasars from Singal’s list at Keck Observatory in the 1990s, but equipment problems, terrible weather, and refractory referees delayed our project until ISO and even Spitzer were making big radio galaxy surveys, albeit at low angular resolution. The power and elegance of the infrared calorimeter is shown best however in the composite of high-resolution (≈ 0.3″) images reproduced from Whysong’s (2005) thesis, and shown here as Fig. 7.

As we will see, some FR II radio sources do lack quasars, even hidden quasars, and they should form a roughly isotropic distribution. So an easy study would be to look at the strengths of their depolarizations. Another easy armchair ApJ Lett would be to re-create the Singal plots, but leaving out the nonthermal galaxies (no hidden quasars), which should be fairly isotropic and whose removal should make the $z < 0.5$ bin look more like the other bins.
3.4 Infrared properties of FR II quasars and radio galaxies from the 3CR catalog

Many groups have been seduced by the seeming simplicity and robustness of the infrared calorimeter. A rather complete review of early (pre-Spitzer) observations is given in the Introduction to Cleary et al 2007, reporting on Spitzer observations of 3CR objects with $0.5 < z < 1.4$. Other recent papers include Meisenheimer et al 2001; Siebenmorgen et al 2004; and Whysong and Antonucci 2004, including some $0.3''$-resolution Keck data at $11.7\mu$.

Meisenheimer et al (2001) observed 20 3CR objects with ISO, finding the results compatible with hidden quasars, except possibly for some at the low luminosity/redshift end. Relatedly, Siebenmorgen et al (2004) found 68 detected 3CR objects in the ISO archive, finding that, “In most 3CR objects, the mid- and far-IR flux cannot arise from stars nor from the radio core because an extrapolation of either component to the infrared fails by orders of magnitude.”

Shi et al (2005) used Spitzer photometry to study a sample of 3CR radio galaxies and steep-spectrum quasars with good Hubble Space Telescope (HST) images, and with “a preference for $z < 0.4$”. The data are consistent with the assertion that most radio galaxies have hidden quasars. Furthermore, there is evidence for nonzero optical depths at $24\mu$. Importantly, the entire infrared dust
spectrum is generally inferred to be AGN powered, even at 70µ.

Spectroscopy in the optical and the infrared can deliver more specific information. Sometimes the optical narrow line spectrum indicates a lower ionization or luminosity than is actually present, and thus one could conclude that a hidden quasar is not present. Again infrared photometry and spectroscopy are more complete. Haas et al (2005) wrote a key paper which must be kept in mind whenever narrow line spectra are discussed. I hope more work is done along these lines. Haas et al (2005) found that in a set of seven radio galaxies and seven quasars from the 3CR catalog, the radio galaxies observed in the optical have on average less luminous high ionization lines than the quasars, but that in the relatively transparent mid-IR region, for this small sample of FR IIs at least, this is not the case. Haas et al find that “the luminosity ratio [OIII]5007Å / [OIV]25.9µ of most galaxies is lower by a factor of 10 than that of the quasars”

Similarly, di Serego Alighieri et al (1997) showed that for some powerful radio galaxies at least, [O III]5007Å shows up to some degree in polarized flux, indicating some [O III]5007Å is probably hidden by the torus in some cases; but note that it’s not always easy to interpret the small polarizations of [O III]5007.

Another important consideration is that at least part of the obscuration of the Narrow Line Region in radio galaxies is due to the modest-optical-depth kpc-scale dust lanes as seen so dramatically in Cyg A and Cen A. See discussion in Antonucci and Barvainis 1990. Ignoring this information in testing and exploiting the Unified Model will produce erroneous results. Absorption by cold foreground dust is manifest as very deep mid-IR absorption features.

Now let’s go back to the figures from Singal et al 1993, here Fig. 5 and 6. We noted that at low redshift, a large fraction of 3CR FR II radio galaxies are smaller than expected for high inclination quasars. This could be interpreted as evidence that there are many intrinsically small radio galaxies which lack powerful hidden quasars. By powerful, I mean hidden quasars roughly matched in reradiated Big Blue Bump luminosity with radio galaxies of the same lobe flux and redshift. (Some allowance needs to be made for mid-IR anisotropy.) Alternatively, recall that Gopal-Krishna et al (1996) cleverly noted that two externally motivated assumptions would cause a universally applicable unified model (hidden quasars in all radio galaxies) to lead to data matching the observations; one has to assume that radio sources tend to fade over time, and that the opening angle of the torus increases with the original radio power. Our group was fortunate to receive time for Spitzer IRS surveys of several types of radio-loud AGN, including 3CR FR II radio galaxies and quasars (Ogle et al 2006, 2007). The 2006 paper was the first from a big Spitzer IRS-spectrograph survey.

These infrared data show in fact that many of the 3CR FR II radio galaxies,

\footnote{Note that this large anisotropy or at least absorption of [O III]λ5007 differs markedly from the situation in the Seyfert sample discussed in Sec. 1.4.}
especially those at $z \lesssim 0.5$ (below the redshift considered in Barthel 1989), have only weak and cool dust emission. Again if many of these objects have AGN hidden by dust, then the average dust covering factor would need to be reasonably large, so that the dust calorimeter should work at least statistically. Most 3CR FR II radio galaxies with $0.5 < z < 1.0$ do have strong, quasar-like mid-IR emission. This is qualitatively in accord with both Barthel’s and Singal’s figures (which suggests a dearth of hidden AGN in FR IIs only at $z < 0.5$). Also we now know from Spitzer that essentially all the $z \gtrsim 1$ radio galaxies in the 3CR can be unified with quasars by orientation (Ogle et al 2006; Haas et al 2008; Leipski et al 2010; de Breuck et al 2010, which covers (non-3CR) galaxies up to $z = 5.2$). Compare Fig. 8, showing mid infrared luminosity vs. $z$, with Figs. 5 and 6 (from Singal 1993).²⁴

Figure 8. The ordinate shows the rest-frame 15 shows the luminosity $\nu L_\nu$, normalized to the rest-frame 178 MHz luminosity, also referring to $\nu L_\nu$. Plotting this normalized infrared luminosity allows us to compare objects of fixed power in the nearly isotropic diffuse radio emission. Thus, there are no selection biases with respect to orientation and so the objects in various categories are directly comparable. Stars represent quasars and filled circles refer to the putative hidden quasars, with $L(\text{MIR}) \sim L(\text{MIR})$ for visible quasars. Empty circles lack visible or hidden quasars, and their presence at low $z$ can explain the present Figs. 5–7. (see text).

Now let’s see how the accretion luminosities, taking account of the IR data, compare with $L_{\text{Edd}}$ (Fig. 9). Among these radio galaxy black holes, the ones considered to be hidden quasars (for which probably $M_{BH} \sim 10^9 M_\odot$) radiate at $\sim 0.1\%$ of Eddington in dust reradiation only, and the others are below that value. (Figure 9 is a preliminary version of this plot, with some subjective elements, kindly supplied by P. Ogle 2010.) Although this cut isn’t always accepted by nature, it’s interestingly close to the value expected for the shift from ADAF to

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²⁴One can also see this effect to some extent in the closely related top parts of Fig. 8 of Cleary et al 2007.
thermal optically thick Big Blue Bump ($\dot{m}_{\text{crit}} = 1.3\alpha^2$ which produces $L \sim 0.13\%$ of $L_{\text{Edd}}$, for 10% efficiency in $\alpha = 0.1$ models: Esin et al 1997).

If one were to display the apparent optical luminosities in Eddington terms, there would be no change in narrow line ionization (see $H$ and $L$ symbols) at this expected location in $L/L_{\text{Edd}}$ of the accretion mode change. But using the infrared luminosities\footnote{Marchesini et al (2004) present a proxy for this test which could be made without IR data. Using line emission to estimate bolometric luminosities for radio galaxies, they found a probable gap in $L/L_{\text{Edd}}$ at $\sim 0.01$.} seems to confirm theory spectacularly, if approximately. It is also very clear that both the ionization level and (more surprisingly) the FR type are tightly correlated with accretion mode, as deduced by many authors over the years, and cited in context in this paper.

When a galaxy lacks an observable Big Blue Bump, even when using the IR reradiation to find it, we can of course only put an upper limit on the flux of that component. According to theory, objects with $L/L_{\text{Edd}} \lesssim 0.01$ aren’t expected to produce optically thick accretion disks (Big Blue Bumps), so perhaps few weak ones are missed (Begelman, Blandford and Rees 1984). However, the theory isn’t yet robust enough to be used in this way with certainty.
There are several fiducial luminosity comparisons that we can make to our infrared upper limits in the radio galaxies: we can compare them to those of matched broad line objects to constrain the universality of the unified model. More important physically, we can compare it to the jet power. The latter is hard to get, and other than for the nearby and powerful object M87, the infrared limits are too high to be of interest in comparing to jet power. But for M87, any hidden quasar must produce much less radiative than kinetic luminosity (Whysong and Antonucci 2004; Owen et al 2000; Perlman et al 2001).

I end this section with some general caveats on unified models and accretion modes for FR II radio sources. 1) We’re discussing the highest-luminosity radio sources at each redshift, and in the case of the complete geometrical unification at $z > 1$, we’re only talking about some of the most luminous radio sources in the universe. 2) The statistical significance of the Singal figures makes them robust, but it isn’t sufficient for any further investigation by subdivision. 3) At least at the highest redshifts, we know that there is a major contribution to the projected linear sizes of radio sources besides foreshortening. It was shown by Best et al 2000 and subsequent papers that the $z \sim 1$ 3CR radio galaxies’ projected linear sizes in the extended gas correlates strongly with ionization level, the smaller ones tending to have shock spectra. Aside from adding noise to the radio size tests, this doesn’t affect the discussion too much, though of course it’s important from a physical point of view. Note also that that correlation is shown in Best et al 2000 for the radio galaxies alone, where orientation is relatively unimportant, so the claim would have to be softened if made for the entire high-$z$ 3CR sample.

### 3.5 Nonthermal optical “compact cores”

Several authors have commented on the optical point sources seen even in some Narrow Line Radio Galaxies which lack a visible Type 1 spectrum. This is different behavior than that in Seyfert 2s, few of which have point sources or variability — their mirrors are extended and spatially resolved by the Hubble Space Telescope in nearby cases, e.g., Capetti et al 1995a,b; Kishimoto 1999, 2002a,b.

It’s artificial to separate the FR Is from the FR IIs in this context, because the entire radio galaxy population empirically separates itself in a different way: the large majority of 3CR FR Is (these are nearby, $z \lesssim 0.2$), and many low ($z < 0.5$) and some intermediate ($0.5 < z < 1.0$) redshift 3CR sources have optical nuclei which are consistent with emission from the unresolved bases of the radio jets. References are given below.

In general there are no spectra available of these optical point sources, and certainly no spectropolarimetry. However, the red-region HST point source luminosities and fluxes correlate fairly well with the 5GHz (usually flat spectrum) radio cores, which are indeed the bases of jets as shown by VLBI maps. It’s important that the correlation shows up in a flux-flux plot as well as in a luminosity-
Chiaberge and collaborators have worked carefully and doggedly on these sources, and FR IIIs are described primarily in Chiaberge et al. 2000, 2002a,b. The entire data set and analysis is consistent with (but preceded!) the inferences from the infrared. Chiaberge et al argue that the radio galaxies that fall on the well-populated (putative) synchrotron line in the optical/core-radio plane are likely to be nonthermal AGN. The group of radio galaxies with larger optical flux than expected for synchrotron radiation then host a visible Big Blue Bump/Broad Line Region.

These authors further suppose that any opaque tori would be larger than the optical point sources, in which case they would block the optical light; therefore there are no tori in most such cases. Although M87 is an FR I (or hybrid) source, it’s worth mentioning in this section that its HST point source is indeed small, because it varies on timescales of months.

Detailed study of 100 low luminosity 3CR radio galaxies with HST at 1.6 µ is quite consistent with the prior conclusions of the Chiaberge et al group. In particular the low ionization galaxies of both FR types show “central compact cores” which are probably nonthermal in nature (Baldi et al. 2010).

Powerful supporting evidence by the same group comes in the form of a spectroscopic survey of z < 0.3 galaxies (Buttiglione et al. 2010). As had been noted by e.g., Hine and Longair (1979), FR II radio galaxies can be naturally divided into low and high ionization objects. But Buttiglione et al. (2010) go a big step further and assert that their emission-line “excitation index” is bimodal (their Fig. 4)! The first and only other claim of a related bimodality of which I am aware is that of Marchesini et al. (2004), who cite such a feature in the distribution of \( L/L_{\text{Edd}} \) at a value of \( \sim 0.01 \). It’s worth keeping that value in mind.

Just as for the infrared data, the demographic conclusion from these optical

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26 In luminosity-luminosity plots of AGN (radio loudness vs. optical power is an example of an exception), you will almost always see a correlation because more powerful objects tend to have more of everything. When I retire I’ll make a plot of the number of bookstores vs. the number of bars in US cities and towns — I predict at least an “astronomical-quality” correlation, which does not mean however that readers like to drink. Flux-flux plots have their own peculiarities, but they are different peculiarities than in luminosity-luminosity. Two other very common statistical errors that drive me crazy are: 1. in plots of the form A vs. A/B (or B/A), which are very common, the correlation slope, which may be intrinsically zero, will be strongly biased towards a positive (negative) value — it is not a discovery when this happens, if the ordinate range due to errors and population dispersions isn’t much smaller than the range of the “correlation.” People actually publish plots like this all the time, then go as far as analyzing these spurious slopes and trying to extract physics from them. 2. Survival statistics are often used to deal with upper limits, but most astronomical data sets violate the key requirement for this method: that the limits have the same distribution as the detections. In astronomy, we tend to have the exact opposite case: that the upper limits are usually concentrated towards the bottom of the distribution of detections!

27 However, this in itself is still no proof that it’s smaller than any possible torus.
studies is that the fraction of 3CR FR II radio galaxies with visible or hidden quasars is relatively small at low redshift, increasing up to at least $z \sim 0.6$ (see also Varano et al 2004, and for a slightly different opinion, Dicken et al 2010).

Finally, it’s been found that as a group, “radio loud” galaxies and quasars (in this case with a flux cutoff or 3.5mJy at 1.5GHz — which is extremely low compared with the 3CRs) are clustered differently, with the quasars favoring richer environments (Donoso et al 2010). This result is consistent with the views expressed here because objects with $L_\nu$ (1.5GHz) \( \gtrsim \) 10^{33} erg/sec/Hz (essentially the range of 3CR radio galaxies and quasars) do cluster more like quasars, according to that paper. Nevertheless it strongly suggests that the shadowing unification doesn’t apply at lower radio luminosities.\(^{28}\)

3.6 X-rays

Hidden radio quasars are characterized by large ($\sim 10^{22} – 10^{25}$ cm$^{-2}$ or more) cold absorbing columns, like the Seyfert 2s and radio-quiet quasar 2s. The Low Ionization Galaxies generally don’t show large columns,\(^ {29}\) and this suggests that they lack tori and Broad Line Regions, although it’s always possible that the jet continuum emission extends beyond a torus (Hardcastle et al 2009). See their Fig. 16 and their table 7 for the columns for Low Ionization Galaxies and other classes of AGN. These authors argue persuasively that one can separate X-ray components from hidden quasars and from jet emission, modeling the X-ray spectra with high-column and zero-column components, respectively (see Figure 10).

\(^{28}\) Another easy but worthwhile “armchair ApJ Letter” could be written to test whether restriction of the Donoso et al (2010) radio galaxies to those of high radio luminosity would cause their clustering properties to match those of the quasars.

\(^{29}\) One exception is found in Ramos Almeida, et al 2011. For a radio-quiet exception, see Filippenko 1984.
Figure 10. The vertical axis shows the X-ray luminosity for the ‘accretion-related’ (absorbed) component as a function of 178-MHz total radio luminosity for the $z < 1.0$ 3CRR sample. Regression is for detected Narrow Line Radio Galaxies only. Black open circles indicate Low-Ionization Narrow Line Radio Galaxies, red filled circles High-Ionization Narrow Line Radio Galaxies, green open stars Broad Line Radio Galaxies and blue filled stars quasars. Clearly the Low Ionization objects have little or no thermal emission. (Adapted from Hardcastle et al 2009)

Thus with reasonable SNR in the X-ray spectrum, one can say which spectral component likely dominates that ostensibly derived from jet synchrotron emission and those directly related to a copious accretion flow — and often one dominates completely. Examples of each type are shown in the FR II galaxies in Rinn et al 2005; Kraft et al 2007; Trussoni et al 2007; and Evans et al 2010. The X-ray spectroscopic survey of high-z 3CR objects of Wilkes et al 2009, like the infrared study of Leipski et al 2010, is extremely supportive of complete unification of 3CR radio galaxies and quasars at $z > \sim 1$.

The putative accretion-disk K-α lines in the thermal radio galaxies and quasars seem to be weaker and narrower than in Seyferts, a fact often attributed to an inner edge of an optically thick flat accretion disk at a greater radius than that at which the disks in radio quiets terminate (e.g. Ogle et al 2005; Sambruna et al 2009; Tazaki et al 2010). The accretion disks are often taken to have inner edges at the Innermost Stable Circular Orbit, but this is controversial (e.g. Agol and Krolik 2000). If the innermost part of the opaque thin disk is missing, the efficiency of the standard disk is reduced, and also the thermal spectrum is cooler, so one would expect (but doesn’t see) corresponding changes in the spectral line ratios and luminosities (Ogle et al 2005). Also in a recent

\footnote{An interesting possibility is that a large ISCO results from disk counter-rotation (Garofalo 2010).}

\footnote{Optically thick, geometrical thin disks with the alpha viscosity prescription, e.g., Pringle 1981.}
study by Molina et al (2008) on a sample selected at 20–40 keV, for their six “definite” Broad Line Radio Galaxies, “we only find marginal evidence for weaker reprocessing features in our objects compared to their radio quiet counterparts.” More commentary on this can be found in Kaburaki et al 2010.

4 FR I RADIO GALAXIES

4.1 Radio Properties

These lower-luminosity ($\lesssim 2 \times 10^{32} \text{ erg/s Hz}^{-1}$ at 1.5GHz) big radio doubles generally have fairly symmetric twin jets on $> 1$ kpc scale, and the lobes are edge-darkened with no terminal hotspots. Much of the VLBI data on FR Is (and much of it on low-luminosity FR IIs) come from the group behind these references: Giovannini et al 2001, 2005; T. Venturi, pc, 2010. The data, though somewhat sparse on speeds especially, are consistent with the assertion that FR I jets start out relativistic, with the FR Is being a little slower than the low-luminosity FR IIs. The fraction of sources studied in the isotropically selected 2005 sample which are visibly two-sided on VLBI maps is $\sim 30\%$, vs. 5–10\% in earlier core-flux-selected samples. Somewhat of an update was provided by Liuzzo et al (2009), with single-epoch data on low-frequency selected FR Is, with aggregate results consistent with a single unified (beam) model.

The overall statistics on the depolarization asymmetry, another powerful constraint on the inclination distribution, show that the effect is weaker than for quasars, and probably consistent with an isotropic distribution, though data are scarce. For example, Morganti et al (1997) looked at this for an FR I sample and found that the depolarization asymmetry is usually weak. Garrington et al (1996) had come to a similar conclusion, noting however that strongly one-sided jet sources have strong depolarization asymmetry. Capetti et al (1995c) found a strong depolarization asymmetry in 2 out of 3 intermediate radio luminosity (between FR I and FR II) radio galaxies. I think that more depolarization work should be done, not just for the AGN field but for understanding galaxy and cluster hot gas atmospheres, where the depolarization presumably takes place.

4.2 Infrared

Finally I’m getting to a topic that is a little bit controversial. It’s not very controversial in that everyone seems to agree that most FR Is have predominantly nonthermal radio/infrared/optical and X-ray nuclei, e.g. M’uller et al 2004. But it is important not to overgeneralize, and assert a direct connection between FR I morphology and a nonthermal engine. I listed a few exceptions in Antonucci

\[32\] It is easy to imagine that the few exceptions can be attributed to the grossly different timescales on which the core ($\sim 1$ yr) and the lobes ($\sim 10^8$ yr) are created. On the other hand, the host-dependence of the luminosity cutoff, strongly suggests environmental factors also play
2002a,b, going back to the first FR I quasar, reported in 1984 by Gower and Hutchings. (I don’t know why the more common FR I Broad Line Radio Galaxies don’t impress people equally, but some extra cachet seems to attach to those of quasar optical/UV luminosity.)

Recently there have been several papers modeling individual FR I nuclei as purely nonthermal, which I think have been contradicted by subsequent Spitzer spectra. For example, consider NGC6251, analyzed by Chiaberge et al (2003), for which the spectral index over most of the infrared is inferred to be $\sim -0.6$. Leipski et al (2009) shows that the mid-IR spectrum exceeds their predictions, and shows strong dust emission features. Our conclusion from the SED is that there is hot dust with at least as much flux as that due to synchrotron radiation. The aperture was $\sim 4''$ but that may not matter much because dust emitting at a few microns must be near a somewhat powerful optical/UV source, i.e., the nucleus. It’d be easy to check from the ground. Thus the substantial near- and mid-IR dust emission may signal a hidden thermal optical/UV also. See however Gliozzi et al 2008, who shows that the X-rays are likely to be dominated by the jet in NGC6251. I think a problem with most published decomposition of radio galaxy infrared spectra is that they require slopes flatter than those of Blazars, opposite to the beaming prediction.

A Spitzer IRS spectrum for BL Lac is shown in Fig. 2 of Leipski et al 2009: the slope is $\sim -0.8$ between 5 and 30$\mu$, considerably steeper than the synchrotron slopes in most published nonthermal models for radio galaxies. What’s more, Impey et al (1988) find that “The spectra of Blazars steepen continuously between $10^9$–$10^{15}$ Hz… the [frequency] at which the energy distribution turns down in $\sim 2 \times 10^{11}$ Hz with a very narrow range of spectral indices. Half of the Blazars with less than $10^{11}$ L$_\odot$ show evidence for thermal infrared components…” to which I’d add: which should be much more conspicuous and thus more widespread in the high-inclination objects (radio galaxies). Moreover, “The average Blazar spectrum is flat ($\alpha \sim 0$) at $10^9$ Hz and steepens continuously to $\alpha \sim -1.5$ at $10^{15}$ Hz. Table 4 shows that the infrared slopes from $3 \times 10^{12}$ Hz (100$\mu$) to $3 \times 10^{14}$ Hz (1$\mu$) are all steeper than 1.” For the SEDs of FR I synchrotron components, with lots of infrared Spitzer data, and both with and without dust bumps, see Leipski et al 2009: in our models, which feature relatively low synchrotron contributions throughout the infrared, the slopes are steeper than those found by other investigators and thus more reasonable in my opinion.

There are at least two ways around this objection to the required flatness of the synchrotron components in some of the published infrared decompositions. First, the emission from high-inclination may be dominated by a slow-moving component which is for some reason intrinsically flatter, and not directly related

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a role (Owen and Ledlow 1994).

33 This is the first object with good evidence of a narrow line flux variation: Antonucci 1984, Fig. 1.
to the strong beamed component (e.g. Chiaberge et al 2000). Also, the Blazar samples aren’t necessarily matched to the lobe-dominated radio galaxy samples and this could conceivably make a difference. They do however include many objects with FR I diffuse radio power.

Van Bemmel et al (2004) account for most of the nonstellar radiation from 3CR270 (=NGC4261) with a nonthermal model, but find some evidence for a weak thermal component. Our Spitzer data show a big dust bump, which covers 3µ–100µ, and dominates the infrared energetically, at least as observed in the 4” Spitzer aperture. Please see Fig. 9 of Leipski et al 2009 for our spectral decomposition, and the location of the synchrotron component. The Big Blue Bump is extremely well correlated with the Broad Line Region in AGN, and I consider the possible detection of broad polarized H-α in this object by Barth et al (1999) well worth following up. Again skipping ahead to the X-ray, Zezas et al (2005) conclude that 3CR270 is a heavily absorbed nucleus, $N_H \sim 8 \times 10^{22}$ cm$^{-2}$, far higher than most FR Is (see Figure 10 here; also Balmaverde et al 2006). Synchrotron is thought by Zezas et al (2005) to contribute only $\sim 10\%$ of the X-ray flux.

The detailed discussion of Cen A in Whysong and Antonucci 2004 still represents our views on this controversial and somewhat complicated case. We think it contains a hidden Big Blue Bump/Broad Line Region. Optical polarization imaging is relevant for this FR I radio galaxy. Capetti et al (2007) have measured the percent polarization of the HST nuclear sources at $\sim 6060\AA$ in several FR I galaxies. Restricting to those with PA errors $\leq 10^\circ$ (the error functions have strong tails, unlike the Gaussian function), the seven remaining objects are a few percent polarized at random-looking angles. Cen A has a similarly puzzling optical (R/I band) polarization, influenced greatly by a foreground dust lane (Schreier et al 1996).

In the near-IR K band however, one can sometimes see through kpc-scale dust lanes of modest optical depth to the nuclear occultation/reflection region (Antonucci and Barvainis 1990; Whysong and Antonucci 2004; see also Bailey et al 1986). Packham et al (1996) report on both the near-IR polarization and the millimeter polarization (which turns out to be crucial): the polarization of the nucleus after various corrections is given as an impressive 17% (“in the near-IR”), and exactly perpendicular to the inner radio axis. This is expected for hidden thermal AGN rather than for Blazars. (Refined values can be found in Capetti et al 2000.) Packham et al remark that the millimeter polarization, given simply as “zero,” is “not...consistent...with that of BL Lacs.” As noted, we believe that near-IR observations often see through the dust lanes, enabling us to see this very high polarization exactly perpendicular to the radio jet, as we demonstrated with the radio galaxy 2C223.1 (Antonucci and Barvainis 1990; we used a 1-channel polarimeter [!] but our measurement was accurately confirmed with a modern
The mere fact that the PA is constant in time for each near-IR observation of Cen A is unlike BL Lacs (or compact synchrotron sources in general), as is the perpendicular relation to the radio jet. We also think that the spatially resolved azimuthal off nuclear near-IR polarization (Capetti et al 2000) is most consistent with scattering from a normal Type 1 nucleus.

For Cen A, we mention the X-ray spectrum here (Markowitz et al 2007). The superb Suzaku spectrum shows a column above $10^{23}$ cm$^{-2}$ for two separate components, and many narrow fluorescent lines, including Fe K-$\alpha$, like a Seyfert 2.

Going back to the mid-IR data on FR Is and FR IIs generally, an imaging survey of nearby objects at 12$\mu$m by van der Wolk et al (2010) revealed results which are generally understandable and consistent with other arguments: the broad line objects, all FR IIs, were easily detected at 7 mJy sensitivity (they quote 10$\sigma$!), as well as most of the High-Ionization Narrow Line Objects (also FR IIs). The low-excitation galaxies of both types were not detected.

Spitzer is much more sensitive than any ground-based instrument. The current state of the mid-IR art survey of FR Is from the IRS spectrograph is described in Leipski et al 2009. Here’s where there is a little more controversy. We observed 25 FR I radio galaxies, and carefully removed the star formation contributions as well as possible using the PAH features, and also removed old stellar populations using the Rayleigh-Jeans tail of the starlight, and using the AGB star features at longer wavelengths. We reached the following conclusions for the 15 putative pure-synchrotron sources described in Chiaberge et al 1999. Of the 15 sources with “optical compact cores” from the Chiaberge group and others (see the “Optical” section below), we see four with the infrared dominated by contributions from the host galaxies. In another four of the galaxies with optical point sources (but probably no exposed Big Blue Bump/Broad Line Region), warm dust emission dominates, and is probably at least in part due to hidden nuclei, contrary to the conclusions from the optical papers. In seven cases, synchrotron radiation dominates the mid-IR. The comparison to the Chaberge et al core decompositions cannot be considered definitive however because of the larger Spitzer aperture.

4.3 Optical

Some information about the optical point sources was used above to provide context for the IR fluxes, but we must note here that these cores (Zirbel and Baum 1995, 2003; Verdoes Kleijn et al 2002; Chiaberge et al 1999, 2000) have been used to argue for synchrotron optical emission and no powerful hidden AGN or tori in most FR I radio galaxies; Baldi et al 2010 is closely related. Zirbel and Baum (1998, 2003) find that the low-luminosity radio galaxies with detected central compact optical cores are the ones with visible (single or highly one-sided) jets, and thus probably low inclinations. This is compatible with the jet idea for
the optical cases.

There has also been a series of papers by the Chiaberge, Capetti group (Capetti et al 2005) on emission lines from low-luminosity radio galaxies. These papers report that the putative synchrotron continuum is sufficient to produce the observed emission lines, if the covering factors average about 0.3. They estimate the ionizing continuum from that in the UV with power laws.

Another ambiguity is that the UV continuum can be very steep, and the reddening corrections may be very large and uncertain (Chiaberge et al 2002a). Also the observed “UV excess” in at least a few low luminosity radio galaxies is due to starlight, according to Wills et al 2004. In that case too the ionizing radiation can’t be quantified easily.

Capetti et al (2005) also made a factor of 5 correction downward to estimate the H-\(\alpha\) emission line flux from the measured flux of the blend with the \([N\, II]\) doublet. The factor of 5 seems too high to me, and comes not from typical AGN behavior, but from a UGC sample of ordinary LINERs. Also, there was apparently no starlight subtraction before this factor was determined from spectroscopy (Noel-Storr et al 2003). (The effect of this can be estimated from formulae in Keel 1983.) Finally, they detected in most cases probable broad bases to the H-\(\alpha\) line, but not the forbidden lines. These lines are said to be “compatible with the broad lines seen in LINERs” by Ho et al (1997). Any Big Blue Bump accompanying these lines would probably be undetectable, at least with present data, so this is consistent with (but not proof of) the presence of a Big Blue Bump, albeit of low luminosity. Ho (1999,2009) has argued however that for his LINERs with weak broad H-\(\alpha\), the central engines are radiatively inefficient. My overall conclusion regarding the central compact optical cores is that they are indeed mostly synchrotron sources, but I don’t share the same degree of confidence as the various authors.

Let us now return briefly to the question of broad emission lines in FR I galaxies, concentrating on AGN that can be observed with good contrast relative to the host galaxies. The most familiar object of this type is 3C120, with a fast superluminal VLBI source. Several others (Antonucci 2002a gives a brief compilation) are also highly core dominated, including BL Lac itself, in which the broad lines need to compete with the beamed radiation in order to be detected. This suggests that a Broad Line Region is sometimes visible in an FR I radio galaxy, when seen at low inclination. Falcke et al (1995) wrote a clever paper on this “missing FR I quasar population.”

4.4 X-rays

This section will be brief because the results of many excellent studies are simple and consistent, within the noise and the limited number of sources analyzed, and the selection biases specific to each. Refer again to the present Fig. 10 (Hardcastle
et al 2009) for strong evidence of very weak (ostensibly) accretion-related power. Low-Ionization Galaxies, including both FR types. Other papers are generally very supportive of (and in some ways anticipated) Hardcastle et al 2009.

Some recent surveys with lots of FR I results: Donato et al 2004; Balmaverde et al 2006; Rinn et al 2005; Evans et al 2006; and Hardcastle et al 2006. Overall, the great majority of X-ray spectra of FR I radio galaxies suggest nonthermal emission. This finds strong independent support in that most of these objects (the current Fig. 10) differ from Cen A, and do not show the high absorption columns typical of hidden AGN.

5 SMALL SOURCES: COMPACT STEEP SPECTRUM AND GIGAHERTZ-PEAK SPECTRUM

The radio properties of these young sources are described briefly in Section 1, the Introduction. The classic complete review is O’Dea 1998, while a shorter but recent review is Fanti 2009.

Recall that few can grow into large bright sources, because they are nearly as common as the big ones (as selected in the centimeter region), but have very short kinematic and synchrotron-aging lifetimes. Recall also that many of the tiny kinematic ages probably measure just the age of the current stage of activity, which may repeat many times. It’s also possible that their birthrate is extremely high, but that most fade out before they grow.

The experts generally seem to agree that the radio-galaxy/quasar unification holds fairly generally, for the well-studied very radio luminous population. That is, the radio galaxies are in the thermal class. At more modest luminosities, there is less information, and some hints from the infrared that this may not be the case. If so they behave similarly to the giant doubles.

5.1 Radio Properties

Saikia et al (2001) provide several good arguments for small ages and unification by geometry. On the former, kinematic and synchrotron losses ages are small and generally consistent. On the latter, the authors note that the quasars are more core-dominant in the radio, and they have more asymmetric morphologies consistent with oppositely directed twin jets. Several optical and radio papers present evidence for absorption by molecules and HI, preferentially for the galaxies and thus near the plane according to the Unified Model, e.g., Baker et al 2002; Gupta and Saikia 2006; and Fanti 2009.

5.2 Infrared

Astronomers studied this class of radio source in the infrared with IRAS (Heckman et al 1994) and with ISO (e.g., Fanti et al 2000). These radio emitters show
generally high (quasar-like) power in the aggregate. The ISO mission was able to make many individual detections, but the Fanti et al 2000 paper did not make a comparison of their observed galaxies with GPS/CSS quasars.

In the Spitzer era, Willett et al (2010) presented data for eight relatively radio-faint “compact symmetric objects,” which heavily overlap the GPS class. Only one was a broad-line object (OQ 208); one was a BL Lac Object. Their Fig. 8 shows a plot of the Si strength vs. equivalent width of the 6.2μ PAH feature, demonstrating that hidden AGN (marked by moderate Si absorption and fairly weak PAHs) probably dominate the mid-IR emission of the galaxies in all cases. The quasar has Si slightly in emission, also as expected for the unified model. However, if considered bolometrically, the AGN luminosities are low (except for the quasar) and PAH features indicate that star formation may contribute significant luminosity. Ionization levels are low. The authors favor Bondi accretion or black-hole spin energy for most of the galaxies, not a thermal Big Blue Bump, so in our parlance they would fall into the non-thermal class.

Our larger Spitzer survey, Ogle et al 2010, contains 13 quasars and 11 radio galaxies from the 3CR catalog. It contains objects of substantially higher redshift (0.4–1.0) and luminosity (10^{34}–10^{35} erg s^{-1} Hz^{-1} at 1.5 GHz and 5 GHz), as compared with the Willett et al 2010 sample.

The radio luminosities of our sample sound much higher than most FR IIs, where the FR I/II cutoff is \(\sim 2 \times 10^{32}\) erg sec^{-1} Hz^{-1} at 1.5 GHz, but the CSS and especially the GPS sources are much weaker relative to the big doubles at low frequency. Also note that this and their small sizes indicate that they contain much less energy in particles and fields overall.

It is not so easy to get a complete isotropic sample of GPS sources because they don’t have dominant isotropic lobe emission. Possibly one could select by an emission line, preferably in the infrared, after radio classification. We took the GPS sources from Stanghellini et al 1998, a complete GHz-selected sample but likely with beaming effects favoring low inclination. This might not be too bad since we are mainly comparing quasars and radio galaxies, with the latter still at larger inclinations by hypothesis (shadowing Unified Model); however they may not be at the same level on the luminosity function. For the CSS sources, we could find a roughly isotropic sample in the 3CR, and we took them from Fanti et al 1995.

We find that the GPS/CSS galaxies in our sample are all powerful thermal dust emitters, with \(\nu L_\nu(15\mu) \sim 5–500 \times 10^{43}\) erg s^{-1}. The Si features behave somewhat erratically vs. optical type, although most follow the pattern of emission for quasars and absorption for galaxies. This can be accommodated by clumpy torus models, but since it’s specific to the small objects, it might also be from the effects of colder foreground off-nuclear dust. The interpretation of the galaxies as

\[34\]This refers to the overall SED, and not the infrared emission specifically.
hidden quasars is greatly strengthened by the [Ne V] and [Ne VI] lines detected in all of the quasars and many of the galaxies. We detect no PAH or H$_2$ features.

In summary, the infrared evidence favors a (nearly?) ubiquitous shadowing unified model for the most radio-luminous small sources. Remember, however, these are the highest-luminosity members of the class, and it’s likely that at lower luminosities, some radio galaxies lack the hidden uasars, based on Willett et al 2010.

5.3 Optical

Bright GPS and CSS radio sources tend to have strong line emission. All three 3CR CSS sources studied by Labiano et al (2005), two radio galaxies and one quasar, show [O III]$_{\lambda 5007}$/ narrow H$_\beta > 10$, so they have high ionization. There is evidence for shocks also in these nice HST spectra.

There is a wealth of information in de Vries et al 1999 and Axon et al 2000 on HST imaging of CSS radio galaxies. These groups imaged in the H$\alpha$ or [O III]$_{\lambda 5007}$ line in tens of objects. Only the broad line objects have point continuum sources, in accord with the Unified Model. Thus there are almost no known “bare synchrotron” sources as described above for FR I and FR II galaxies. This is not really a demonstrated difference however since until very recently, only the most luminous GPS/CSS sources have been studied in detail. In fact, very recently Kunert-Bajraszewska and Labiano (2010) have reported on line emission on fainter small radio sources, finding that many have Low Ionization Galaxies spectra, just like for the giant doubles.

Both de Vries et al (1999) and Axon et al (2000) also found that the line emission lies preferentially parallel to the radio axes, and Axon et al add that photon counting arguments require a hidden radiation source. Those alone are powerful arguments for unification with quasars.

5.4 X-rays

There are several papers on X-rays from small radio sources. Guainazzi et al (2006) reported on a small sample of GPS galaxies at redshifts between 0.2 and 1. All four with adequate SNR have large column densities, “consistent with that measured in High-Excitation FR II galaxies,” strongly indicating hidden quasars. The radio luminosities are around $10^{34-35}$ erg s$^{-1}$ Hz$^{-1}$ at 1.5GHz, near the

\[35\text{An exception is PKS 0116+082, from Cohen et al 1997. This really anomalous object has high and variable polarization like a Blazar and good limits on broad H$\alpha$/[O III]$_{\lambda 5007}$, yet very strong narrow emission lines. There is actually a possible broad H$\alpha$ line in polarized flux, which is however unexpected in a Blazar. This object is not analogous to the much lower luminosity HST optical point sources studied by Zirbel and Baum, and Chiaberge et al, and discussed in the previous two sections. One point in common though is at least a few percent optical polarization (Capetti et al 2007).}\]
spectral peaks. The 2–10 keV X-ray de-absorbed luminosities are $10^{44}$–$10^{45}$ erg s$^{-1}$. (The authors give their $H_0 = 70$, but no other cosmological parameters, so this is approximate.) Since that band covers only 0.7 dex in frequency, the X-ray luminosity alone is $\gtrsim 1 \times 10^{45}$ erg s$^{-1}$, and the bolometric luminosity is likely to be at least a few times higher. There is one exception, which is convincingly argued to be Compton-thick and so opaque in the X-ray. Consistent results were reported by Siemiginowska et al (2008).

This group expanded their survey of GPS galaxies (Tengstrand et al 2009; neither study included quasars) and confirms and extends these results, again concentrating on the most radio-luminous objects.

6 Summary

First a hearty congratulations to all the theorists who predicted that accretion would become inefficient below $L \sim 0.01L_{\text{Edd}}$. Apparently the initial argument to this effect is that of Rees et al 1982. Parts of the theory were anticipated by Shapiro et al 1976 and Ichimaru 1977. More recently, Esin et al 1997 quotes 0.4 $\alpha^2 L_{\text{Edd}}$ as the cutoff luminosity in the $\alpha$ prescription, which they find fits well with black hole binary state changes.

The first radio galaxy discovered and interferometrically mapped was Cygnus A, which has a whopping apparent brightness of 8700 Jansky at 178MHz. At low frequencies, you can actually point the VLA 90 degrees away from Cygnus A and map it in a sidelobe! (F. Owen, pc 2010.) Also interesting: considering the volume enclosed by the Cyg A distance and the very strong cosmological evolution of FR II radio sources, folklore says only one universe in 10,000 should be so lucky as to have such a prize!

The first map of Cygnus A is very impressive for the time, and the map is very charming (Fig. 11 here, from Jennison and Das Gupta 1953). There is no question that it has a hidden quasar of moderate luminosity (Antonucci et al 1994; Ogle et al 1997; infrared fluxes from NED). See Barthel and Arnaud 1996 to find out how such a modest quasar can be so incredibly powerful in the radio.
Thermal and Nonthermal Radio Galaxies

Figure 11. Approximate intensity distribution of the extra-terrestrial radio source in Cygnus. (Jennison & Das Gupta 1953). This very early interferometric observation first revealed the double-lobed nature of most radio galaxies.

We know now that some powerful radio galaxies, and many weaker ones, lack detectable visible or hidden thermal AGN. It is however very important to remember that in all but a couple of contentious cases, Type 2 radio quiet quasars have hidden AGN, until you get to the LINER (very low luminosity) regime, which then shows ADAF behavior according to most investigators (Elitzur and Shlossman 2006; Chiaberge et al 2000; Ho 2009; many others), along with weak broad wings to Hα in many cases.

The time has come to stop proving this! We have all together quite settled the question. It’s worthwhile exploring more parameter space, e.g., weaker radio/IR/optical/X-ray sources, and to follow up on individual interesting cases, but the overall pattern is clear now for all types of bright radio source.

So what should we do instead? The result of all this work is that we can now hold many things constant while we vary just one thing, the tremendous thermal emission (Big Blue Bump). The two types must differ drastically in their structure on relativistic scales. We are limited by our imaginations in how to take advantage of this situation. My group is trying to determine how the thermal/nonthermal states correlate with VLBI properties, i.e. jet launching, collimation, and proper motion, to the extent that’s possible with current VLBI angular resolution, all while holding the large-scale structure constant as far as we can discern. Another obvious observation, which really requires next-generation X-ray telescopes to do well, is to compare the reflection signatures of the two types. The putative accretion disk K-α fluorescence line isn’t expected to be so broad or strong if there is no opaque accretion disk at small radii. Next, AGN feedback in galaxy evolution might be mediated by radiation pressure on dust in many cases, or else by PdV work or particles from jets and lobes, or other mechanisms. Here we can keep everything the same (?) as far as the latter
go, but turn off the radiation. Does it make a difference? These new data might actually help with the physics of AGN and of galaxies, and not just the astronomy of AGN. Enjoy!

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