THERMAL EMISSION AS A TEST FOR HIDDEN NUCLEI IN NEARBY RADIO GALAXIES

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ABSTRACT

The clear sign of a hidden quasar inside a radio galaxy is the appearance of quasar spectral features in its polarized (scattered) light. However, that observational test requires suitably placed scattering material to act as a mirror, allowing us to see the nuclear light. A rather robust and more general test for a hidden quasar is to look for the predicted high mid-IR luminosity from the nuclear obscuring matter. The nuclear waste heat is detected and well isolated in the nearest narrow-line radio galaxy, Cen A. This confirms other indications that Cen A does contain a modest quasar-like nucleus. However, we show here that M87 does not: at high spatial resolution, the mid-IR nucleus is seen to be very weak and consistent with simple synchrotron emission from the base of the radio jet. This fairly robustly establishes that there are “real” narrow-line radio galaxies, without the putative accretion power and with essentially all the luminosity in kinetic form. Next, we show the intriguing morphology of Cygnus A, where all of the mid-IR emission is consistent with reprocessing by the hidden quasar known to exist from spectropolarimetry and other evidence.

Subject headings: galaxies: active — galaxies: individual (Centaurus A, M87, 3C 273, 3C 405) — infrared: galaxies

1. INTRODUCTION

It is widely believed that the optical/UV continuum of quasars (the “big blue bump”) represents optically thick thermal emission from accretion onto a black hole. Narrow-line radio galaxies do not show such a component directly and were historically thought for that reason to be rotation powered, with large kinetic luminosity in the radio jets but very little accretion or optical radiation. When the unified model came along, identifying at least some narrow-line radio galaxies as hidden quasars, the compelling observational motivation for this radio-galaxy scenario lost some of its force. However, it is far from clear that all narrow-line radio galaxies contain hidden quasar nuclei.

Now that the existence of supermassive black holes in active galactic nuclei (AGNs) seems fairly secure, perhaps the next most fundamental questions are the sources of energy and the nature of the accretion flow in the various classes of objects. Historically (see Begelman, Blandford, & Rees 1984 for an early review), it was thought that the optical/UV continuum (or big blue bump) in quasars (hereafter, by “quasars” we also mean to include broad-line radio galaxies) represents thermal radiation from some sort of cool optically thick accretion flow. Radio galaxies did not show this component and so were posited to be “nonthermal AGNs” with hot radiatively inefficient accretion at a very low rate; in these cases the jet power would derive from the hole rotation rather than release of gravitational potential energy from accretion.

These arguments took a surprising turn when it was realized that many radio galaxies do have the quasar-like nuclei that are invisible from our line of sight. One Fanaroff-Riley II (edge-brightened, very luminous) radio galaxy, 3C 234, was shown in 1982 to have quasar features (broad permitted emission lines and big blue bump) in polarized light (Antonucci 1982, 1984; Antonucci 1993 for a review). Thus 3C 234 does have thermal optical/UV emission, which is visible only via scattering. Many other examples have been shown subsequently (e.g., Hines & Wills 1993; Young et al. 1996). Some invocations of the unified model postulated that this was generally true of the FR II (powerful, edge-brightened) class (e.g., Barthel 1989).

3C 234 has powerful high-ionization narrow lines, consistent with its being a hidden quasar. However, it is still contentious how those FR II galaxies with weak and/or low-ionization narrow emission lines fit in (Singal 1993; Laing 1994; Gopal-Krishna, Kulkarni, & Wiita 1996; Antonucci 2002). The situation is even less clear for the FR I galaxies, almost all of which have undetectable or low-ionization emission lines.

For radio galaxies with no observable high-ionization narrow emission line region present, there is no a priori evidence for the presence of a quasar. These could still have a quasar nucleus, but any narrow-line region would need to be mostly obscured as well. In fact, there is some evidence that the high-ionization narrow emission lines are partially obscured in many 3C radio galaxies (Hes, Barthel, & Fosbury 1993). In NGC 4945 and many other ordinary-looking galaxies, the only present evidence for a hidden AGN is in the hard X-ray (e.g., Madejski et al. 2000).

To summarize, many FR II radio galaxies fall into the apparently weak, low-ionization emission line category. Most of the FR I radio galaxies do as well. These spectra have been described as “optically dull.” Quite recently, Chiaberge, Capetti, & Celotti (1999, 2000) have shown that among these optically dull sources of both FR types, a majority show unresolved optical sources in Hubble Space Telescope (HST) images, and of course more might do so with better imaging data. Note that their result seems surprising at first: one might have guessed that those with stronger high-ionization spectra would have the unresolved sources, but the opposite is true.

Chiaberge et al. argue that those with detectable unresolved optical sources cannot in general have thick obscuring tori. The reason is, if the point sources are truly nuclear, then we can see
to the very center in most of these objects. These radio galaxies are effectively selected by an isotropic emission property—the radio lobe flux—so the source orientations should have an isotropic distribution. That is, the radio axes should be randomly oriented with respect to our line of sight. Since we can see unresolved optical sources in most optically dull objects, most lines of sight to their nuclei must be unobscured in general. Recall that in the Chiaberge et al. picture, the HST unresolved optical sources are the bases of the synchrotron jets that emit in the radio. As they point out, one caveat must be given with their line of argument. It is possible that obscuring tori exist below the HST resolution and hide the nucleus and the very innermost region of the conical jet. For example, their unresolved optical sources may really be jet emission on ~1 pc scales, and optical big blue bump sources are much smaller. A torus might be large enough to obscure the latter while still allowing the parsec-scale jet emission to be seen over the top.

In the Chiaberge et al. scenario the unresolved optical sources represent synchrotron emission from the bases of the jets. In support of this idea, those authors show that the optical fluxes correlate roughly with the core radio fluxes at 6 cm. It should be easy to check this: the relationship should tighten up substantially using millimeter fluxes instead of those at 6 cm.

It is very important to remember that many narrow-line radio galaxies do have strong high-ionization emission lines and, in some cases, definitive spectropolarimetric evidence of a hidden thermal nucleus. In general, such objects have no detectable unresolved optical source. They behave instead like Seyfert 2 nuclei, which show just spatially resolved scattered light and the extended narrow-line region directly. Low-redshift examples can be found in Hurt et al. (1999) and Cohen et al. (1999). At high z there are many examples, of which Cimatti et al. (1996), Dey et al. (1996), and Vernet et al. (2001) show typical cases.

Our goal is to determine robustly which, if any, radio galaxies lack a hidden thermal (optical/UV continuum) nucleus. This is crucial for AGN theory since it would prove the existence of an accretion mode different from that in quasars. In particular, current wisdom would posit a very low accretion rate and a very low radiative efficiency, that is, some variant of the advection-dominated accretion flow (ADAF), for those radio galaxies. Then by default the enormous kinetic luminosity of the radio jets would be attributed to black hole rotational energy.

How can we tell whether or not a hidden nucleus is present? One method is via the hard X-rays. Many hidden AGNs that are not Compton-thick have been discovered with X-ray observations. Some references to penetrating X-rays in optically dull objects represent synchrotron emission from the bases of the synchrotron jets that emit in the radio. As they point out, one caveat must be given with their line of argument. It is possible that obscuring tori exist below the HST resolution and hide the nucleus and the very innermost region of the conical jet. For example, their unresolved optical sources may really be jet emission on ~1 pc scales, and optical big blue bump sources are much smaller. A torus might be large enough to obscure the latter while still allowing the parsec-scale jet emission to be seen over the top.

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Our approach here is to look instead for reradiation of the absorbed light from any hidden quasar-like nucleus by the dusty obscuring matter (torus). Modulo factors of order unity, the various models of the obscuring tori predict that the “waste heat” from the obscuring matter will emerge in the mid-IR and that this emission is roughly isotropic in all but the highest inclination cases. The various torus models predict that this is true to within a factor of a few.

The earliest torus models, those of Pier & Krolik (1992), produce small anisotropy (a factor of ~2) for Compton depths of 0.1 in both the vertical and radial directions. This value for the Compton depth is typical for Seyfert 2 galaxies based on X-ray spectra; there is little information for radio galaxies. Many Seyfert 2 galaxies have Compton depths of ~1 based on their X-ray spectra, and thus potentially greater anisotropies. However, the dust-to-gas ratio seems to be smaller than the canonical value used in the models (e.g., Maiolino et al. 2001). The Pier & Krolik models have the most anisotropic mid-IR emission, and later models are more encouraging (Granato, Danese, & Franceschini 1997; Efstathiou & Rowan-Robinson 1995; a related model in Königl & Kartje 1994 should also be consulted; Cen A is discussed specifically in Alexander et al. 1999).

These papers all model the torus with a unit filling factor. However, a clumpy distribution of torus dust seems to be required theoretically to avoid collapse of the torus on a few times the dynamical timescale (Krolik & Begelman 1988). This is emphatically confirmed by molecular line observations (e.g., Tacconi et al. 1994). This can also affect the anisotropy, according to the models of Nenkova, Ivezic, & Elvis (2002), but the results are qualitatively similar.

Given the theoretical uncertainties, it may be better to take a cue from observations and use Seyfert galaxies as a proxy for the very poorly observed radio galaxies. In all models, the 60 µm emission is much more isotropic than the 12 µm emission. To first order we can assume that the 60 µm emission is isotropic and determine the anisotropy at 12 µm by the observed ratios of 12 µm/60 µm emission. If we believe that type 1 and 2 Seyfert galaxies are similar except for orientation, a difference between the two classes in this ratio can be ascribed only to anisotropy of the 12 µm emission. There are caveats such as host-galaxy contamination and aperture effects; however, both Seyfert types show very warm dust, which is lacking in non-AGN sources (e.g., Edelson & Malkan 1986). Also, the warm dust emission correlates well with the strengths of high-ionization lines (e.g., Garcia & Espinosa 2001 and references therein).

We have selected our radio galaxy/quasar sample by a nearly isotropic property (lobe radio emission) because this avoids orientation selection effects. For Seyfert galaxies the best samples in the literature in this regard are probably the CfA Seyferts, selected mainly by host-galaxy properties (Garcia & Espinosa 2001), and the 60 µm-selected Seyferts (Keel et al. 1994; Schmitt et al. 2001). The former reference states that the warm dust dominating at 12 µm is 0.4 dex greater in Seyfert 1s relative to Seyfert 2s, when normalized to the radio emission.

The Schmitt group (of which Antonucci is a member) studying the 60 µm-selected Seyfert galaxies has not yet published a value for the 12 µm/60 µm ratio difference between the Seyfert types. However, the mean values are 0.231 ± 0.018 for Seyfert 1s and 0.181 ± 0.017 for Seyfert 2s (H. Schmitt 2003, private communication). This leads to an estimate that the anisotropy is ~30% for both Seyfert and radio galaxies.

Why might the anisotropy diagnosed observationally be so much more moderate than that from torus models? Crucial information comes from actual imaging of nearby Seyfert galaxies in the mid-IR. The best available data are for NGC 1068 (Bock et al. 2000). It is very clear that the 12 µm emission is extended along the radio axis and not the torus plane. This shows that some of the attenuation of mid-IR emission from the warm innermost parts of the tori is made up by dust that is directly exposed to the optical/UV and directly seen from Earth. Thus, the empirical result from comparing visible and hidden type 1 nuclei that the mid-IR emission is modest can be understood.

2. OBSERVATIONS

2.1. 3C 405 (Cygnus A)

In Figure 1 we present a diffraction-limited mid-IR image of the nuclear source in 3C 405 (Cyg A), obtained with the Long
Wavelength Spectrometer (LWS) instrument at the Keck I telescope. All data were taken with the 11.7 μm filter, which has a ~1 μm bandpass from 11.2 to 12.2 μm.

The nucleus of 3C 405 was imaged at 11.7 μm with Keck I/LWS on 1999 September 30. The chop/nod throw was set to 10″ in order to allow imaging of larger scale extended structure; this places the chop beam off the chip, which has a 10″ field. We do not report on structures larger than the 10″ chop distance. The images were dithered in a five-position box pattern, 2″ to a side, with 53.1 s on-source for the positive image per dither position. The entire five-position exposure was repeated three times, for a total on-source time of 796.6 s.

Data were processed by subtracting all background chop/nod frames, shifting each dithered image to the correct position, and co-adding all dithered images. The standard star was 61 Ari, with a flux scale of 0.0730 mJy/(ADU s⁻¹) and a FWHM of 0.27″. Morphology is extended, with structure to the east and southeast of the nucleus (Fig. 1). Because of the extended nature of the source, we present the photometry as a function of radius in Table 1. The ~10% errors are due to uncertainty in the flux calibration. For comparison, the IRAS (large aperture) data for Cygnus A are listed in Table 2.

2. M87

Here a new high-resolution Keck I image is also crucial. We obtained this data for M87 on 2000 January 18. The observation was made in chop/nod mode using a small 3″ aperture; we adopt a value of 13 mJy. A synthetic aperture of 0.96 was used, but the source is unresolved so the flux is insensitive to the aperture. Again we note that the large-aperture fluxes (Table 3) are much higher (Moshir et al. 1990).

2.3. Cen A

The high-resolution mid-IR data on Cen A also come from the Keck I telescope. Data were obtained on our behalf by R. Campbell on 2002 June 28. Three filters were used: the 11.7 μm filter with a 1 μm bandpass, a wider “SiC” filter centered at 11.7 μm but with a 2.4 μm bandwidth, and the 17.75 μm filter with a ~1 μm bandwidth. The standard star was σ Sco, a multiple star that was partially resolved so that it was necessary to increase the synthetic aperture to 2.24″ in order to include all components. No photometric data are available for σ Sco at wavelengths longer than M, so we extrapolated to longer wavelengths using the Rayleigh-Jeans approximation. The flux scale was 0.0841 mJy/(ADU s⁻¹) at 11.7 μm and 0.329 mJy/(ADU s⁻¹) at 17.75 μm.

The Cen A images show only an unresolved source in all filters. Photometric calibration results are \( F(11.7 \mu m) = 1.6 \pm 0.2 \) Jy, \( F(\text{SiC}) = 1.8 \pm 0.2 \) Jy with \( \approx 0.3 \) FWHM resolution, and \( F(17.75 \mu m) = 2.3 \pm 0.2 \) Jy with \( \approx 0.5 \) FWHM resolution. The errors are dominated by uncertainties in the flux calibration.

Since Cen A is so close, there are published data for relatively small physical apertures. A small physical aperture is key, because for both Cen A and M87, the large-aperture (e.g., \( \text{IRAS, ISO} \)) fluxes are much larger than that from the nucleus. But the much higher resolution Keck data isolate a nuclear point source with size ≤5.6 pc at 11.7 μm and ≤8.5 pc at 17.75 μm given a distance of 3.5 Mpc (Hui et al. 1993). We assume that this is mostly dust emission heated by the nucleus.

2 Instrument reference is available at http://www2.keck.hawaii.edu/inst/lws/lws.html.
3 A table of photometric standards is available at http://www2.keck.hawaii.edu/inst/lws/IRTF_Standards.html.

| Table 1: LWS Photometry Results for Cygnus A |
|---------------------------------------------|
| Aperture Diameter (arcsec) | Flux (mJy) |
|---------------------------|-----------|
| 0.64                       | 44 ± 4    |
| 0.96                       | 71 ± 7    |
| 1.28                       | 93 ± 9    |
| 1.60                       | 111 ± 11  |
| 1.92                       | 122 ± 12  |
| 2.56                       | 139 ± 14  |
| 3.20                       | 152 ± 15  |

4 Gemini mid-IR images were published and analyzed by Perlman et al. (2001). Their measurements and conclusions were similar to ours. Since their images were very deep, they were also able to detect extended jet emission.
This is consistent with the 10–20 μm nuclear spectrum taken by ISOCAM CVF in a ~4″ aperture (Mirabel et al. 1999, see their Fig. 2). In fact, our 11.7 μm flux is in good agreement with that of the spectrum, suggesting that it is in fact the nuclear spectrum. That the high-ionization emission features seen in the ISOCAM spectrum are present only in the (admittedly 4″ aperture) nuclear spectrum and not in the surrounding star formation regions suggests the presence of a hidden ionizing continuum.

For comparison, the published, larger aperture mid-IR fluxes are much higher. The Cen A central region flux has been measured in the mid-IR by Grasden & Joyce (1976). Their 3″ aperture has the same flux as the 5″ aperture, so there is a compact source surrounded by a region of little or no flux. The 3.5″ aperture corresponds to 50 pc, and the enclosed flux is given as ~2.6 Jy at 11 μm and 4.3 Jy at 12.6 μm. The IRAS 12.6 μm flux measurement is even higher at 13.3 Jy.

3. DISCUSSION

3.1. Cygnus A

This is a very powerful FR II radio galaxy at a redshift of 0.056. It has strong high-ionization narrow lines, suggestive of a hidden AGN. A broad Mg II2800 emission line is detectable in total flux (Antonucci, Hurt, & Kinney 1994). That line may or may not be highly polarized and thus scattered from a hidden nucleus. Several detailed papers report spectroscopic and spectropolarimetric data (Goodrich & Miller 1989; Tadhunter, Metz, & Robinson 1994; Shaw & Tadhunter 1994; Vestergaard & Barthel 1998; Stockton, Ridgway, & Lilly 1994; see also Tadhunter et al. 2000 and Thornton, Stockton, & Ridgway 1999; there are several others), culminating in Ogle et al. (1997), which shows an extremely broad Hα line in polarized flux. It is virtually invisible in total flux because its great width makes it hard to distinguish from continuum emission.

An unresolved nuclear source in the near-IR was noted by Djorgovski et al. (1991), and they consider hot dust emission for this excess over the extrapolation from the optical light.

A powerful hidden nucleus should manifest a mid-IR dust luminosity much larger than the observed optical luminosity. However, for this object and M87 (and virtually all others!) the only IR data available were taken with very large beam sizes. We (and Radomski et al. 2002) isolate the core much better with the ~0.7″ (~1.1 kpc) resolution provided by the Keck I telescope and find a nuclear flux of ~60 mJy. An uncertainty here derives from the extended emission, but flux as a function of aperture size does flatten out for apertures larger than the seeing disk, so the 0″6 measurement should be approximately correct (see Table 1). However, we cannot be sure from this observation alone that the emission is on parsec scales. Since the emission is powerful and at the relatively short wavelength of 11.7 μm, it is very likely that this comes from nuclear dust rather than a starburst.

If the intrinsic spectral energy distribution (SED) is similar to those of radio-loud Palomar-Green (PG) quasars (Sanders et al. 1989), the 11.7 μm value implies a bolometric luminosity of 16.5Ld (11.7 μm) ~ 1.5 x 10^45 ergs s⁻¹. A very similar value for the Lbol/Ld conversion can be obtained from the Elvis et al. (1994) composites.⁵

It is entirely possible that the extended emission is thermal dust even at radii up to 1 kpc. The temperature of nuclear dust can be estimated according to Barvainis (1987). Adopting a Hubble constant of 75 km s⁻¹ Mpc, the Ld luminosity at 11.7 μm is 9.2 x 10^43 ergs s⁻¹. An optical luminosity of ~10^45 ergs s⁻¹ produces a dust temperature of ~120 K at a 500 pc radius. A similar calculation of the dust temperature was done by Radomski et al. (2002), yielding a slightly higher result (150 K) because of a higher estimate of the optical luminosity. Single-photon heating could also raise the color temperature above that for dust in thermal equilibrium. This can affect the argument that the mid-IR dust emission a few tenths of an arcsecond from the nucleus is actually heated by nuclear light.

The IRAS (large aperture; see Table 2) dust spectrum is quite cool, suggesting a large starburst contribution. Extended emission is seen in our image at 11.7 μm. The core cannot be exactly separated from the extensions (see Table 1), but we can estimate around 60 mJy for the nuclear dust. Figure 1 shows the Cyg A 11.7 μm image. The nuclear luminosity Ld at 11.7 μm is 10 times higher than that at 0.5 μm. The latter wavelength needs two roughly canceling corrections: subtraction of optical light from the host galaxy, and dereddening (Ogle et al. 1997). The starburst contribution to the nuclear 11.7 μm emission is expected to be small, but this should be checked with a spectral slope measurement.

The conclusion is simple and expected from prior evidence: Cyg A has a moderately powerful hidden nucleus. As noted above, the estimated bolometric luminosity is 1.5 x 10^45 ergs s⁻¹. For comparison the jet power is estimated several different ways (Carilli & Barthel 1996; Sikora 2001; Punsly 2001). The values are rough, but generally lie in the ~10^45 ergs s⁻¹ range. This is consistent with the finding that jet power and optical/UV luminosity are often comparable in double radio quasars (e.g., Falcke, Malkan, & Biermann 1995).

Thus, this is a moderate-luminosity broad-line radio galaxy with a very high luminosity radio source. It has in fact been inferred already that Cygnus A is an overachiever in the radio (Carilli & Barthel 1996; Barthel & Arnaud 1996). This is well explained qualitatively by the fact that it is the only known nearby FR II radio source in a rich X-ray-emitting cluster; the confining pressure greatly diminishes adiabatic expansion losses.

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⁵ The SED from Elvis et al. (1994) has a lower Lbol/Ld(B) than that from Sanders et al. (1989), but the mid-IR/B ratio is also different. The corrections approximately cancel.
3.2. M87

This radio galaxy is on the FR I-II borderline, both in morphology and in radio power (Owen, Eilek, & Kassim 2000). It is one of the majority of FR I radio galaxies with an unresolved optical/UV source (Chiaberge et al. 1999, 2000). This unresolved optical source is tentatively ascribed to synchrotron radiation associated with the radio core (see Ford & Tsvetanov 1999, as well as the Chiaberge et al. papers). However it is not known whether this light is highly polarized or whether broad emission lines are strong in either total or polarized optical/UV flux.

Our small ~0\textquoteleft\textquoteleft\textquoteleft\textquoteleft3 FWHM beam isolates the innermost ~25 pc in M87. The enclosed 11.7 \(\mu\)m flux in a 0\textquoteleft\textquoteleft\textquoteleft\textquoteleft6 synthetic aperture is 13 mJy; this aperture matches that used for Cen A in physical size. The flux measured in this way is much lower than the large-aperture measurements in the literature. Published large-aperture data leave plenty of room for waste heat from a hidden AGN, but our data do not (Fig. 2). The mid-IR luminosity \(\nu L_{\nu}\) is only of order that in the optical rather than much greater, as for the hidden-AGN sources. In fact, much or all of the mid-IR flux could simply be synchrotron radiation associated with the innermost part of the jet, so the measured flux is an upper limit to the dust luminosity. Note that this outcome for M87 is just what Chiaberge et al. implicitly predicted.

Unless the nuclear dust is too obscured to emit in the mid-IR, this rules out a powerful hidden nucleus. The observed 11.7 \(\mu\)m flux corresponds to \(\nu L_{\nu} = 1.0 \times 10^{41}\) ergs s\(^{-1}\), for a distance of 15 Mpc. Suppose the mid-IR core is in fact all dust emission. For the SED for the PG quasar composite of Sanders et al. (1989), a bolometric luminosity of \(\sim 1.6 \times 10^{42}\) ergs s\(^{-1}\) is expected. For comparison, a lower source to the jet kinetic luminosity in M87 is \(\sim 5 \times 10^{44}\) ergs s\(^{-1}\) (Owen et al. 2000), so the jet is by far the dominant channel for energy release. If correct, this suggests that M87 is the true “misaligned BL Lac object.”

Published ADAF models (Reynolds et al. 1996) predict very low IR-optical-UV luminosities compared with those in the radio and X-ray. Our 11.7 \(\mu\)m point is about equal to the optical value, which does not fit the ADAF model, but certainly our 11.7 \(\mu\)m point may be partially or completely jet emission. Also, the Reynolds et al. figure apparently uses 3C 273 as a thermal quasar-like template, but that object definitely has a large jet contribution in the radio and infrared (Robson et al. 1993).

3.3. Cen A

Figure 3 shows the SED for Cen A, combining all the \(\sim 1\arcsec\) measurements. For AGNs that show the quasar-like optical nucleus in scattered light only, the mid-IR emission is typically 2 orders of magnitude greater than the (scattered) optical light. For Cen A the situation is similar, but with a slight modification (Bailey et al. 1986; Hough et al. 1987; Antonucci & Barvainis 1990; Alexander et al. 1999): the ratio is inflated by absorption of the parsec-scale scattered optical light by the kiloparsec dust lane famous from photographs.

At 2 \(\mu\)m, a highly polarized point source indicates detection of a \(\sim\)parsec-scale reflection region. The near-IR reflected light from parsec scales penetrates the kiloparsec-scale dust lane, which has only moderate optical depth. This situation was deduced for 3C 323.1 and Cen A by Antonucci & Barvainis (1990). The parsec-scale dust screen can be consistently identified with the cold absorber seen in the X-ray spectrum, which has a column density of \(\sim 3 \times 10^{23}\) cm\(^{-2}\). Additional centrosymmetric optical and near-IR scattered light on \(\sim 10\) pc scales has been mapped and discussed by Capetti et al. (2000) and Marconi et al. (2000); clearly, this is not expected in the synchrotron jet hypothesis for the polarized near-IR light. Furthermore, the bright near-IR peak is highly polarized, with an electric vector position angle that is perpendicular to the radio jet axis. Empirically, this is normal for all reflected light objects but would be an unusually fortuitous situation for synchrotron jets.

The case of Cen A shows that even radio galaxies with weak or low-ionization lines (the “optically dull” ones) can have hidden type 1 nuclei. Others can be found in, e.g., Ekers & Simkin (1983) and Sambruna et al. (2000).

To show the level of the reflected light in the nuclear region, we have plotted the value at 2 \(\mu\)m rather than that in the optical (which is highly absorbed). The K-band nuclear flux with starlight subtracted (Marconi et al. 2000) is \(F(K) \sim 38\) mJy, and \(\nu L_{\nu} \sim 7 \times 10^{40}\) ergs s\(^{-1}\) for a distance of 3.5 Mpc. The SED in Figure 3 shows that the mid-IR luminosity of the
nucleus is much larger than the optical/near-IR value, as expected. This is consistent with all other reflected-light objects.

The mid-IR flux of \( \sim 1.6 \) Jy at 11.7 \( \mu \)m corresponds to \( \nu L_{\nu} \sim 6 \times 10^{41} \) ergs s\(^{-1}\). Assuming a normal quasar SED (e.g., Sanders et al. 1989; Barvainis 1990), this translates to a bolometric luminosity of \( 1 \times 10^{43} \) ergs s\(^{-1}\) for the hidden AGN.

The nature of the mid-IR emission is important. The SED has been fitted to a synchrotron self-Compton model (Chiaberge, Capetti, & Celotti 2001), which would lead to a classification for Cen A as a misaligned BL Lac object. However, the fit was to the mid-IR continuum slope instead of the different ISO bands because the latter were heavily affected by absorption and emission features (M. Chiaberge 2001, private communication). Small-aperture mid-IR spectra show polycyclic aromatic hydrocarbon and Si features (Mirabel et al. 1999), and the SED in \(<4''\) apertures is consistent with predominantly dust rather than synchrotron (Alexander et al. 1999; note also that the ISOCAM CVF flux from the Mirabel et al. 1999 spectrum is consistent with our 11.7 \( \mu \)m measurement, suggesting that the spectrum is representative of our smaller aperture). The spectrum also shows “[Ne iii] and [Ne v] emission lines detected in the nuclear region only. The [Ne v] high-excitation line which is predominantly powered by hard AGN radiation fields (Genzel et al. 1998) is only present in the nuclear region of Cen A” (Mirabel et al. 1999). These features indicate that most of the mid-IR flux is thermal emission, as expected for the torus model.

**4. RELATION TO OTHER RADIO GALAXIES AND CONCLUSION**

Radio lobe emission is fairly isotropic, so it is easy to make lists of double radio sources that are nearly unbiased with respect to orientation. The visibility of unresolved optical sources in most of the optically dull (weak or low-ionization emission line) galaxies show that there are no \( \geq \)parsec-scale tori present that are able to obscure the unresolved optical sources in those cases (Chiaberge et al. 1999, 2000). Whatever the nature of the M87 unresolved optical source, we know it is no larger than light-months in size, since the flux was observed to change by a factor of 2 in just \( \sim 2.5\) months (Tsvetanov et al. 1998). The same would apply to the other optically dull nuclei if they vary as M87 does. This would strengthen the Chiaberge et al. argument that we have unobscured sight lines nearly all the way to the central engines.

Since the M87 optical/UV flux is quite variable, jet synchrotron emission is a possibility. By correlating the radio synchrotron core fluxes and the optical point source fluxes in FR I radio galaxies generally, Chiaberge et al. (1999) infer that the latter are in fact likely to be beamed synchrotron sources. Crucial tests of the nature of the unresolved optical sources can be made with spectroscopy and polarimetry. We hope to do this with adaptive optics, excluding most of the starlight that dominates in arcsecond apertures.

However, a large minority of low-ionization FR I and FR II radio galaxies show no point source and are similar in this way to AGNs with hidden nuclei. In fact, the closest FR I, Cen A, does have a big molecular torus (see Fig. 2 of Rydbeck et al. 1993!) and substantial evidence for a hidden nucleus as well (see references cited earlier). Rydbeck reports that the “high-velocity ring” in their Figure 2 has mass \( \sim 6 \times 10^6 \) M\(_{\odot}\), over \( \sim 70\) to \( \sim 120\) pc, which gives a dust column similar to the moderate observed \( K\)-band attenuation. As a working hypothesis, we might suppose that the same is true for all those without detectable optical pointlike nuclei. (Of course, sensitivity of the optical/UV observations also must be considered.)

Thus, the FR I family is heterogeneous: some contain hidden optical/UV nuclei and some do not. It has been difficult to find FR I objects with strong evidence of hidden AGNs, but in fact at least a few are known to be quasar-like from direct spectroscopy (3C 120 is well known; see also Lara et al. 1999 and Sarazin et al. 1999). Therefore, the nonthermal model does not apply to all optically dull or low-ionization radio galaxies or to all FR I galaxies. The FR class has no apparent direct relation to the mode of energy production, consistent with much recent evidence that FR I galaxies behave very much like FR II galaxies at VLBI scales. We will understand this better after the completion of our mid-IR program.

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