THE ORIGIN OF THE INFRARED EMISSION IN RADIO GALAXIES. I. NEW MID- TO FAR-INFRARED AND RADIO OBSERVATIONS OF THE 2 Jy SAMPLE

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ABSTRACT

As part of a large study to investigate the nature of the longer wavelength continuum emission of radio-loud AGNs, we present new mid- to far-infrared (MFIR) and high-frequency radio observations for a complete sample of 2 Jy powerful southern radio galaxies at intermediate redshifts (0.05 < z < 0.7). Utilizing the sensitivity of the Spitzer Space Telescope, we have made deep MIPS observations at wavelengths of 24, 70, and 160 μm, detecting 100% of our sample at 24 μm and 90% at 70 μm. This high detection rate at MFIR wavelengths is unparalleled in samples of intermediate-redshift radio galaxies. Complementing these results, we also present new high-frequency observations (15–24 GHz) from the Australia Telescope Compact Array and the Very Large Array, which are used to investigate the potential contamination of the MFIR continuum by nonthermal synchrotron emission. With the latter observations we detect compact cores in 59% of our complete sample and deduce that nonthermal contamination of the MFIR continuum is significant in a maximum of 30% of our total sample. MFIR fluxes, radio fluxes, and spectral energy distributions for the complete sample are presented here, while in a second paper we will analyze these data and discuss the implications for our understanding of the heating mechanism for the warm/cool dust, star formation in the host galaxies, and the unified schemes for powerful radio sources.

Subject headings: galaxies: active — infrared: galaxies

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1. INTRODUCTION

The mid- to far-infrared (MFIR) is one of the most profitable wavelength ranges for investigating AGNs and associated phenomena. This is primarily because AGN emission suffers less from effects of obscuration at these wavelengths. Moreover, the thermal infrared samples the emission that is absorbed and then reradiated by dust, indirectly sampling the radiative power of the active core and any starburst component that may be present. Therefore, this wavelength range is crucial both for testing the unified schemes for AGNs (e.g., Barthel 1989) and for investigating the link between AGNs and starburst activity as part of the evolution of the host galaxies (Rowan-Robinson 1995; Haas et al. 1998; Archibald et al. 2001).

In terms of testing unified schemes, radio-loud samples of AGNs have the advantage that their extended radio emission is isotropic, allowing samples to be selected free from the orientation bias that affects samples selected at X-ray, optical, and near-infrared wavelengths. However, in order to fully realize the potential of MFIR observations for studies of radio galaxies, it is important to obtain observations of carefully selected samples that attain a high level of completeness in terms of detections. Unfortunately, observing in the MFIR is technically more challenging than at near-infrared wavelengths. Therefore, although IRAS made many significant contributions to our understanding of the MFIR properties of radio-loud AGNs (Neugebauer et al. 1986; Golombek et al. 1988; Knapp et al. 1990; Impey & Gregorini 1993; Heckman et al. 1992, 1994; Hes et al. 1995), it had a relatively low sensitivity, resulting in a typical MFIR detection rate of less than 30%, even for radio galaxies in the local universe (z < 0.3).

Subsequent attempts were made to observe samples of radio galaxies with the Infrared Space Observatory (ISO); Haas et al. 1998, 2004; Polletta et al. 2000; van Bemmel et al. 2000; Meisenheimer et al. 2001). However, meager and sometimes heterogeneous samples and the modest sensitivity of the observatory only allowed for a small improvement on the achievements of IRAS. Studies of samples of radio-loud AGNs with ISO have typical detection rates of no more than 50% in the far-infrared, impeding attempts to understand the MFIR emission.

The launch of Spitzer in 2003 brought an opportunity to make observations with orders of magnitude improved sensitivity at MFIR wavelengths. However, published Spitzer studies of radio-loud AGNs are either based on heterogeneous samples (e.g., Shi et al. 2005) or on samples that are relatively faint and distant, resulting in a low detection rate at 70 μm (e.g., Cleary et al. 2007; Seymour et al. 2007).

A further problem is that many previous MFIR studies of radio-loud AGN samples are selected from the 3C radio catalog, which is hampered by the lack of published high-quality optical spectroscopic observations for many of the objects. In contrast, the southern 2 Jy sample (Tadhunter et al. 1993) is unique in the sense that deep spectra have been published for the whole sample (Tadhunter et al. 1993, 1998, 2002; Wills et al. 2002; Holt et al. 2007). Measured emission-line luminosities for this sample provide information about the intrinsic power of the AGNs (Tadhunter et al. 1998). Moreover, careful modeling of the continuum spectra provides key information about the stellar populations in the host galaxies and, in particular, in the presence of young stellar populations (Tadhunter et al. 2002; Wills et al. 2004). The 2 Jy sample has also been extensively observed at radio wavelengths.
(Morganti et al. 1993, 1997, 1999), allowing links to be made between radio and optical properties and independent estimates of the orientation of the sources to the line of sight. In view of its completeness and the availability of deep spectroscopic and radio data, which makes it well suited to investigating the nature of the MFIR emission and testing the unified schemes, we have undertaken a program of deep imaging with the Multiband Imaging Photometer for Spitzer (MIPS) of the 2 Jy sample.

Given that we are interested in the thermal emission and heating mechanism of the warm/cold dust sampled through the MFIR fluxes, possible contamination from nonthermal synchrotron sources could potentially bias our conclusion. Therefore, to complement the MFIR observations, we have also undertaken high-frequency observations at radio wavelengths (15–22 GHz) using the Australia Telescope Compact Array (ATCA) and the Very Large Array (VLA), with the aim of investigating the potential degree of nonthermal contamination.

A preliminary analysis of the results from this program was presented in Tadhunter et al. (2007). Here we present the MFIR and radio core data and discuss the potential nonthermal contamination of the MFIR continuum. A second paper will comprise an in-depth analysis of these data (D. Dicken et al. 2008, in preparation).

2. SAMPLE SELECTION

The sample for this study comprises a complete subsample of all 46 steep-spectrum powerful radio galaxies and quasars with redshifts 0.05 < z < 0.7 and flux densities $S_{27} > 2$ Jy from the sample of Tadhunter et al. (1993). We define the steep-spectrum selection as $\alpha_{27} > 0.5$ ($F_C \propto \nu^{-\alpha}$), which excludes 16 objects within the redshift range. We also include PKS 0347+05, which has since been proved to fulfill the same selection criteria (di Serego Alighieri et al. 1994). The lower redshift limit has been set to ensure that these galaxies are genuinely powerful sources, and the steep-spectrum selection for the quasars rules out objects dominated by emission from the beamed relativistic jet and core components. Overall, the full sample of 46 objects includes a mixture of broad-line radio galaxies/radio-loud quasars (BLRGS/quasars; 35%), narrow-line radio galaxies (NLRGs; 43%), and weak-line radio galaxies (WLRGs; 22%). In terms of radio morphology classification, our complete sample includes 72% FR II sources, 13% FR I sources, and 15% compact steep-spectrum (CSS)/gigahertz peaked-spectrum (GPS) objects.

For comparison purposes we also observed or collected data from the Spitzer and IRAS archives for the flat-spectrum, core-dominated objects 3C 273, PKS 0521–36, and PKS 1549–79. Note that PKS 1549–79 is a particularly interesting source, because it is a rare example of a powerful, flat-spectrum radio source that is classified as a galaxy at optical wavelengths; the nature of this object is discussed in detail in Holt et al. (2006). However, these objects are not part of what we refer to as our complete sample. Our complete sample of 46 objects comprises the 49 objects with Spitzer or IRAS observations presented below, minus the 3 comparison flat-spectrum objects.

3. MFIR OBSERVATIONS AND REDUCTION

3.1. Observations

We have obtained new observations for 43 objects using the Spitzer Space Telescope and, for 37 of these, we have obtained the very first MFIR detections. In addition, we include results from data obtained for five other targets from the Spitzer archive Reserved Observations Catalogue (ROC): PKS 0915–11 (3C 218), PKS 1226+02 (3C 273), PKS 1559+02 (3C 327), PKS 1648+05 (3C 348), and PKS 2221–02 (3C 445). The observations were carried out between 2005 August and 2007 January, and the ROC targets were observed between 2004 March and November.

All targets were observed with MIPS (Rieke et al. 2004) at wavelengths of 24, 70, and 160 µm, apart from five targets that were not observed at 160 µm due to scheduling reasons. Details of the observations are shown in Table 1.

3.2. Reduction

The MIPS instrument on board Spitzer takes short-exposure images in a dither pattern. These are then combined to make a final “mosaicked” image. Rather than use the pipeline-processed data, we have redered the data for all 48 objects in the sample starting from the Basic Calibrated Data (BCD) files to produce final mosaicked images for analysis. The reduction was carried out at the Rochester Institute of Technology and the University of Sheffield using the MOPEX software reduction package (Makovoz et al. 2006) provided by the Spitzer Science Center (SSC). Due to the different nature of the detectors and sensitivities at the three wavelengths observed, the reduction method we selected is different for each. Thus, we discuss the three bands separately below.

3.3. 24 µm Reduction

As the shortest wavelength band, the 24 µm channel of MIPS is also the most sensitive and has the highest spatial resolution (6″ FWHM). Integration times for our targets were in the range 48.2–180.4 s, although over 80% have the longer exposure time (see Table 1).

Minimal processing of the 24 µm SSC pipeline product is required for most general science objectives. However, we reprocessed the data by mosaicking the BCD files using the MOPEX software and adding an additional flat-field and overlap correction. The flat-field script is part of the MOPEX software package. It computes a flat field from the median of all the dithered frames, normalizes this to an average of 1, and divides into all the input BCD files. In contrast, the overlap correction interpolates the input images onto a common grid, and then the cumulative pixel-by-pixel difference between the overlapping areas is minimized. The final mosaic pixel size was set to 2.45″. This was deliberately chosen to match the pipeline post-BCD products for purposes of comparison. Examples of the images can be seen in Figure 1.

The 24 µm fluxes were extracted using aperture photometry in the GAIA package. Aperture corrections were derived from an empirically determined average curve of growth of flux versus aperture diameter derived from observations of bright sources in our sample with $S_{24} > 50$ mJy (PKS 0521–36, PKS 1226+02, PKS 1949+02, PKS 2221–02, and PKS 2314+03). These aperture corrections are broadly consistent with those published by the SSC. For most objects the aperture was set to a standard radius of 15″ corresponding to an aperture correction of 1.08. However, for a few objects an aperture of half this size (7.5″) was used to avoid contamination from the flux of objects close to the source. In the latter cases the applied aperture correction was 1.52.

The standard deviation of six aperture flux measurements of background sky patches, obtained using an identical aperture to that of the object flux measurements, was used to derive the 1σ uncertainties presented in Table 2. These 1σ values represent the fluctuations in the sky background due to photon-counting noise, as well as mosaicking and flat-fielding artifacts. Given that most of the sources are faint relative to the background, these 1σ measurements give a realistic estimate of the 1σ uncertainties in the flux measurement for the fainter sources in the sample. In
addition, there is an estimated ±4% flux calibration uncertainty (Engelbracht et al. 2007), which is likely to dominate for the brightest sources in the sample. Overall, at 24 μm we detect 100% of our sample at the >5 σ level.

3.4. 70 μm Reduction

The 70 μm waveband is less sensitive than the 24 μm band and uses an entirely different Ge:Ga detector technology, which is not as stable as the Si:As detectors used at 24 μm. The spatial resolution of MIPS at 70 μm is 18′′ (FWHM). Integration times for our targets are in the range 37.7–545.3 s, although over 80% have the longer exposure time (see Table 1). The 70 μm data were also reduced with the MOPEX package. In addition to the basic mosaicking process, we used a column-filtering process from the SSC-contributed software pages (IDL program BCD column filter.pro), which calculates the median value for each column and subtracts that from each column for each BCD.
minimal loss of flux from the source. The final mosaic pixel size is 3.9", again chosen to match that of the pipeline mosaic products.

The fluxes at 70 μm were also measured using aperture photometry, with an aperture radius of 24" for the majority of sources. Aperture corrections and 1 σ uncertainties were derived in the same manner as for the 24 μm images. Again, these aperture corrections are broadly consistent with those published by the SSC. In this case the aperture correction factor is 1.33. A smaller aperture of half the size (12") was used for fainter sources to obtain a better signal-to-noise ratio for the detections, with a correction factor of 2.04. There is also an additional ±10% calibration error at 70 μm (Gordon et al. 2007). For undetected sources upper limits were derived using the standard deviation of background measurements to obtain σ. For these sources the values presented in Table 2 are the 3 σ upper limits, of which there are five. Overall, we detect 90% of our sample at 70 μm at the >3 σ level.

3.5. 160 μm Reduction

The longest wavelength MIPS band (160 μm) has the lowest effective sensitivity and utilizes the same detector technology as the 70 μm band. The spatial resolution of MIPS at 160 μm is 40" (FWHM). Integration times for our targets at 160 μm are in the range 41.9–167.8 s, where over 90% have the longer exposure time (see Table 1). In this case we mosaicked the images with the MOPEX software (final image pixel size 7.9") with no additional processing, as none of the available tools appeared to provide any significant improvement to the images.

Aperture photometry proved impossible to use for extracting the 160 μm flux, due to the difficulty in estimating the background accurately. This is because the PSF at 160 μm is on the scale of the image, and there is also the strong possibility of contamination by other sources in the field. Therefore, we used the APEX program in the MOPEX GUI software to extract the fluxes of detected sources using PSF fitting. The standard PSF available with the software was used for this task. Overall, we detect 33% of our sample at 160 μm at the >3 σ level.

The 1 σ errors were derived in a way identical to that of the other two wave bands, and the upper limits were derived in a way identical to that of the 70 μm band. There is also an additional ±20% flux calibration uncertainty, as stated in the MIPS data handbook (available from the SSC Web site). Upper limits were derived using the standard deviation of background measurements to obtain σ. The values presented in Table 2 are the 3 σ upper limits, of which there are 27. Note that a few objects undetected by the APEX software appear to be detected in a visual inspection of the image. Also, overlapping PSFs from nearby objects have prevented the APEX detection of a point source in at least one image. Therefore, we believe that the APEX software underestimates the true detection rate of sources in our sample; in this sense the detection rate is conservative. This conclusion is consistent with the fact that the typical 3 σ detection limit for the 160 μm data is 55 mJy, which is somewhat lower than the lowest measured flux of 84.6 mJy.

3.6. Notes on the MFIR Observations

Due to an error in the acquisition file for the data, PKS 2135–20 was observed twice. This gave us an opportunity to investigate the uncertainty derived from two identical observations of the same source. We found that the fluxes measured for this source in the two data sets were consistent within 10% in all MIPS bands.

6 In the case of 70 and 160 μm, in addition to the photon-counting and instrument-induced fluctuations, there is an additional contribution to the fluctuations in the background from sources close to the detection limit. This is reflected in the 1 σ estimates given in Table 2.

7 See http://ssc.spitzer.caltech.edu/mips/dh/.
the far-infrared fluxes, it was necessary to extrapolate the flux measurements. However, in order to make the comparison for fluxes of the two observations. The fluxes presented in Table 2 for PKS 2135

| PKS Name  | Other Name | $z$  | $S_{60}$ (mJy) | $S_{50}$ (mJy) | $S_{60}$ (mJy) |
|-----------|------------|-----|----------------|----------------|----------------|
| 0023–26   | 3C 015     | 0.220 | 26.3 | 3.1 | 83.6 | 16.7 |
| 0034–01   | 3C 017     | 0.188 | 17.9 | 2.1 | <43.1 | 14.4 |
| 0035–02   | 3C 18      | 0.346 | 23.6 | 4.8 | 97.2 | 9.1 |
| 0038+09   | 3C 459     | 0.116 | 9.7  | 0.2 | <11.8 | 3.9 |
| 0039–44   | 3C 32      | 0.400 | 32.2 | 4.8 | <37.8 | 12.6 |
| 0043–42   | 3C 403     | 0.258 | 20.2 | 1.8 | <46.4 | 15.5 |
| 0105–16   | 3C 62      | 0.147 | 37.1 | 2.9 | <51.1 | 17.0 |
| 0117–15   | OD 159     | 0.200 | 23.6 | 2.5 | <22.5 | 7.5 |
| 0123–13   | 3C 38      | 0.059 | 30.8 | 4.3 | <52.2 | 17.4 |
| 0235–19   | OD 159     | 0.339 | 7.9  | 0.3 | <31.3 | 10.4 |
| 0252–71   | 3C 273     | 0.089 | 11.2 | 1.9 | <36.4 | 12.1 |
| 0347+05   | 3C 273     | 0.057 | 23.6 | 5.2 | <24.3 | 8.1 |
| 0349–27   | 3C 273     | 0.055 | 204.1 | 6.0 | 950.1 | 13.3 |
| 0404+03   | 3C 459     | 0.051 | 24.7 | 1.3 | 131.0 | 11.2 |
| 0409–75   | 3C 459     | 0.054 | 1.3  | 0.2 | <10.8 | 3.6 |
| 0442–28   | 3C 459     | 0.050 | 19.4 | 0.3 | <37.4 | 12.5 |
| 0521–36   | 3C 459     | 0.055 | 489.7 | 1.3 | 308.7 | 7.1 |
| 0620–52   | 3C 18      | 0.050 | 115.3 | 4.8 | 164.4 | 7.3 |
| 0625–53   | OH 342     | 0.058 | 232.1 | 0.3 | <52.3 | 17.4 |
| 0806–10   | 3C 195     | 0.054 | 204.1 | 0.3 | <52.3 | 17.4 |
| 0859–25   | 3C 227     | 0.055 | 13.8 | 2.8 | <23.2 | 7.7 |
| 0915–11   | Hydra A    | 0.050 | 16.4 | 3.0 | <46.3 | 15.4 |
| 0945+07   | 3C 273     | 0.055 | 14.9 | 3.9 | 402.1 | 11.9 |
| 1136–13   | 3C 273     | 0.054 | 184.9 | 3.9 | 308.7 | 7.1 |
| 1151–34   | 3C 273     | 0.055 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1226+02   | 3C 273     | 0.055 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1306–09   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1355–41   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1547–79   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1559+02   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1602+01   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1648+05   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1733–56   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1814–63   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1839–48   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1932–46   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1938–63   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1949–02   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 1954–55   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2135–14   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2135–20   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2211–17   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2221–02   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2250–41   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2314+03   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |
| 2356–61   | 3C 273     | 0.054 | 19.4 | 3.5 | <44.1 | 14.7 |

Notes.—All images reduced were from the BCD files, SSC pipeline version 14.4.0. Fluxes presented for 2135–20 are the mean fluxes of two identical observations; see § 3.6.

The fluxes presented in Table 2 for PKS 2135–20 are the mean fluxes of the two observations. It has also been possible to compare some of our flux values obtained using Spitzer with those based on IRAS observations. Taking into account BLRG/quasar objects that are potentially variable, we directly compared the IRAS 25 μm and Spitzer 24 μm flux measurements. However, in order to make the comparison for the far-infrared fluxes, it was necessary to extrapolate the IRAS 60 μm fluxes to the Spitzer 70 μm band using the IRAS 25–60 μm spectral index. We find that the Spitzer and IRAS fluxes agree to within better than 20% at 24 μm and 30% at 70 μm. It is also worth noting that our Spitzer-measured flux values for sources in common agree with the published Spitzer fluxes in Shi et al. (2005) to within a few percent.

4. RADIO OBSERVATIONS AND REDUCTION

4.1. Sample

The radio sample is identical to that discussed in § 2. The objects were divided between ATCA and the VLA according to the

Table 2: Spitzer Data Results
To resolve the core in these compact objects, declination of the source (cutoff $\delta \approx -25^\circ$). Four objects—PKS 0023–26, PKS 0349–27, PKS 0442–28, and PKS 0859–25—were observed with both ATCA and the VLA.

We observed 23 objects (with $\delta < -25^\circ$) from our sample with ATCA. For one object (PKS 0023–26) the quality of the ATCA data turned out to be quite low; we have therefore excluded it from our ATCA list and use only the VLA data.

The sources were observed using the 6 km configuration, the longest available for this radio telescope. These observations were carried out between 2006 July 19 and 23 in perfect weather conditions. The total run comprised a continuous 100 hr of observations.

Data were taken simultaneously at 17.9 and 24.1 GHz. These high frequencies allowed us to achieve a relatively high resolution. Each source was observed for a period ranging from 30 to 60 minutes (depending on scheduling constraints) in scans of 10 minutes spread over a period of 12 hr in order to obtain a good enough $uv$ coverage. In each scan we swapped between the two frequencies. Furthermore, for each frequency we actually took data simultaneously at 17.47 and 18.50 GHz in the first observation and at 23.62 and 24.64 GHz in the second, with a bandwidth of 128 MHz for each of these frequencies. These separate frequencies allowed us to (radially) improve the $uv$ coverage. The flux calibrator, PKS 1934–64, flux level at 12 mm = 1.03 Jy, was observed a few times during the whole run. In addition, a nearby phase calibrator was observed for 5 minutes before every scan on a source. A reference pointing observation was also carried out before every source.

The ATCA data were calibrated using the MIRIAD software package (Sault et al. 1995). The final images were obtained using the multifrequency synthesis option and adding together the two nearby frequencies (17.47 and 18.50 GHz; 23.62 and 24.64 GHz) to increase the sensitivity and improve the $uv$ coverage. Typically, two cycles of self-calibration were needed to obtain the final images. In these images we have used uniform weighting to achieve the highest possible resolution.

Table 3 summarizes the results of the ATCA observations, including beam size and noise for each object and frequency. We have detected radio cores in 14 of the 22 sources (63%; PKS 0023–26 is excluded from the ATCA list as discussed above). In a few cases, in particular those for which the core was not detected, we have combined both frequencies (17 and 24 GHz) in order to improve the sensitivity (PKS 0043–42, PKS 0859–25, and PKS 1547–79). Upper limits to the flux and power of the undetected cores were estimated using $3 \sigma$ of the noise level. A few objects are known to be CSS (PKS 0252–71, PKS 1151–34, PKS 1814–63, and PKS 1934–63). These sources are already part of the list of ATCA calibrators, and indeed, the resolution of our observation is not good enough to pinpoint a possible core. We have used these objects as a check on our measured flux level (they agree very well with the data from the calibration archive, and they show no indication of variability). For these sources, core fluxes or upper limits have been measured from VLBI maps in Tzioumis et al. (2002; see Table 4).

Finally, in a number of objects (PKS 0039–44, PKS 0043–42, PKS 0409–75, PKS 0442–28, PKS 0859–25, PKS 1355–41, PKS 1547–79, PKS 1932–46, and PKS 2250–41) we also detected radio emission from other regions of the radio galaxy and, in particular, from the hot spots. Two examples of this are shown in Figure 2. These maps illustrate the fact that at the high radio frequency and resolution of the observations, the maps are dominated by the compact cores, hot spots, and knot features along the jets, and the diffuse lobe emission is resolved out.
TABLE 4

| PKS Name | $S_{\text{core}}$ (mJy) | Frequency (GHz) |
|----------|------------------------|----------------|
| 0023−26  | <20                    | 2.3            |
| 0252−71  | <40                    | 2.3            |
| 1151−34  | <20                    | 8.3            |
| 1306−09  | <28.5                  | 2.3            |
| 1814−63  | 87                     | 2.3            |
| 2135−20  | <11.5                  | 5              |

Notes.—VLBI core fluxes and upper limits for compact objects in the sample from Tzioumis et al. (2002).

a Possible detection at the 15 $\sigma$ level.

4.3. VLA Observations

We observed 27 objects with the VLA at frequencies of 14.9 and 22.4 GHz. The observations were carried out between 2006 August 4 and September 2-3 in the B configuration. Due to servicing, 10 out of 27 dishes were not operating during the observation period. For one object (PKS 0442−28) the quality of the VLA data turned out to be quite low due to the declination of the source; therefore, we have excluded it from our VLA list and use only the ATCA data.

Each source was observed for about 15 minutes per frequency, separated into three scans of 5 minutes each. In addition, a reference pointing observation was carried out before every source. The observations at the two frequencies were interleaved to provide better $uv$ coverage. As flux calibrators we used PKS 0713+438 for the $U$ band (14.4−14.9 GHz) and PKS 1331+305 (3C 286) for the $K$ band (22.1−26.0 GHz). These calibrators were observed a few times during the run. Data splitting and opacity corrections were done in AIPS, while the rest of the data reduction was done using the MIRIAD software package. Images of the separate frequencies were obtained for each source, and combined images were also made in order to attempt to detect these objects with faint cores, to no avail. Table 5 summarizes the results of the VLA observations.

Overall, from the VLA observations we detected cores in 58% of the sources (15 cores detected in the 26 sources successfully observed). Again, in seven of the VLA objects (PKS 0117−15, PKS 0347−05, PKS 0859−25, PKS 0915−11, PKS 1136+07, PKS 1602−01, and PKS 2314−03) we also detected radio emission from extended regions of the radio galaxy and, in particular, from the hot spots.

4.4. Notes on the Radio Observations

We chose a high-resolution array configuration in order to try to detect the high-frequency radio cores. Because of this, the resolution of the images resolves out the extended structure of the sources. Therefore, it would be impossible to provide accurate measurements for the total emission from our sources with these observations at 15−22 GHz.

Also, in the final column of the ATCA and VLA data tables we present estimates of the orientation-sensitive $R$-parameter defined as $S_{\text{core}}/(S_{\text{tot}} - S_{\text{core}})$. In order to determine this we use estimates of the total radio flux measured at 5 GHz $S_{\text{tot}}$ taken from Morganti et al. (1993), and the core measurement is taken from the lower of the two observed frequency core detections of either the ATCA (18 GHz) or VLA (15 GHz) observations. Here we assume that the flat-spectrum core flux remains constant between 5 GHz and the higher frequencies. The analysis of these data will be addressed in the detailed discussion paper to follow.

5. NONTHERMAL CONTAMINATION

MFIR emission can potentially have a thermal and/or nonthermal origin in radio-loud AGNs: thermal emission from re-radiation of AGN light by dust and nonthermal synchrotron radiation. Therefore, in order to investigate the MFIR dust emission we need to be aware of the potential contamination by nonthermal sources. There are two important components to consider when investigating the nonthermal contamination in a sample of steep-spectrum radio-loud AGNs.

1. Total steep-spectrum emission.—Steep-spectrum components such as lobes and hot spots could be potential nonthermal contaminants of the MFIR emission. Despite the fact that these components fall in flux toward higher frequencies, they could still potentially dominate the flux of an object at MFIR wavelengths. However, the proportion of this nonthermal contamination also depends on how much of the steep-spectrum emission region lies within the MFIR instrument beam (in this case the Spitzer beam). The degree of contamination by steep-spectrum components for most of the nearby extended sources in our sample will be insignificant because they have a high proportion of their synchrotron-emitting lobes/hot spots far outside the beam. The contamination is likely to be most important for compact objects such as CSS and GPS objects and for extended FR II sources at high redshift that appear small because of their large distances. At the average redshift ($z = 0.244$) of our complete sample, objects with diameters <80 kpc would fit entirely within the 18" Spitzer beam at 70 $\mu$m.

2. Flat-spectrum core/jet components.—Flat-spectrum core/jet components can also be a potential nonthermal contaminant of the MFIR emission. We can detect strong nonthermal jet emission at optical wavelengths in some objects (e.g., 3C 273), so it is reasonable to assume that this emission may contribute to the
observed flux at MFIR wavelengths. Quasars and BLRGS are known to have strong nonthermal beamed-core components (Morganti et al. 1997), where the strength of this contamination is dependent on the orientation of the object to the line of sight.

Identifying the nonthermal contribution to the MFIR is not a trivial task, because the spectral shape of radio-loud AGNs is often poorly sampled in key areas such as the submillimeter and far-infrared. Although some flat-spectrum quasars and BL Lac/blazar objects are clearly dominated by their nonthermal components at submillimeter and infrared wavelengths, our steep-spectrum selected sample has been chosen to avoid such objects, in order to investigate the thermal emission from dust. Despite this, the contribution from nonthermal emission from objects with relatively strong radio cores and from steep-spectrum lobe/hot-spot components in the Spitzer beam remains a possibility and should be carefully investigated.

5.1. Spectral Energy Distributions

In Figures 3–8 we present spectral energy distributions (SEDs) for the entire sample described in § 2. The data plotted include the results of the Spitzer, ATCA, and VLA observations presented in this paper, along with IRAS and ISO photometry total flux measurements and other total flux data taken from the NASA/IPAC Extragalactic Database (NED). Additional core radio data are taken from Morganti et al. (1993, 1997, 1999).

Total flux observations from ATCA of a large proportion of the sample have been made at 18.5 and 22 GHz (Ricci et al. 2006), which would complement our core measurements well. Unfortunately, the atmospheric phase stability during the latter observations was poor, which may have contributed to the fact that, when plotted in the SEDs, many of the values seemed unphysical compared to the other data sets. Thus, these results are not included in our SED plots.

The solid line in each plot represents a single power-law fit to the total radio flux data of the objects between 10^9 and 10^11 Hz. A few objects have an additional dashed line fitted to the data between 10^9 and 10^11 Hz, when good data above 10^10 Hz are available. Unfortunately, this is a relatively undersampled region in our data set, and we can fit this extra line to only six of the objects in our sample. In the following analysis this second fitted line, which better accounts for any high-frequency steepening/flattening of the SED, is used in preference to the first solid line fit, where applicable.

5.2. Lobe/Hot-Spot Synchrotron Contamination

By using the fitted power laws to extrapolate the total synchrotron radio emission through to the MFIR, it is possible to gain an indication of whether a contribution to the MFIR flux is possible from the nonbeamed synchrotron-emitting lobes and hot spots. However, Spitzer’s beam size of 6′, 18′, and 40′ at 24, 70, and 160 μm, respectively, means that for many targets in our sample most of the extended steep-spectrum emission lies well outside the beam. In Table 6 we address this issue, presenting a truth table from a visual analysis of the SEDs, where we have used the 70 μm flux as a reference point for the analysis.
Fig. 3.—SEDs of objects in our sample. Upper limits are represented by arrows. The solid line is fitted to the data points from $10^9$ to $10^{10}$ Hz, and the dashed line is fitted to the data points from $10^9$ to $10^{11}$ Hz. The VLA data for CSS object PKS 0023–26 are the total flux measurement and an upper limit on the core (open circle; Tzioumis et al. 2002). [See the electronic edition of the Journal for a color version of this figure.]
Fig. 4.—SEDs of objects in our sample. The ATCA data in the SEDs of CSS object PKS 0252–71 are the total flux measurement and an upper limit on the core (open circle; Tzioumis et al. 2002). [See the electronic edition of the Journal for a color version of this figure.]
Fig. 5.—SEDs of objects in our sample. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 6.—SEDs of objects in our sample. PKS 1226+02 (3C 273) clearly demonstrates its flat-spectrum dominant characteristics from the fitted power law. Note the variability in the MFIR flux density of 3C 273, where there is approximately a decade between the observations of IRAS, ISO, and Spitzer. This object is clearly in low synchrotron emission phase; see § 5.5. The ATCA and VLA data in the SEDs of CSS objects PKS 1151–34 and PKS 1306–09 are the total flux measurement and an upper limit on the cores (open circles; Tzioumis et al. 2002). [See the electronic edition of the Journal for a color version of this figure.]
Fig. 7.—SEDs of objects in our sample. The ATCA and VLA core measurement in PKS 1648+05 are from Gizani & Leahy (2003). PKS 1938–15 was not observed in our high radio frequency program. The ATCA data in the SED of CSS object PKS 1814–63 are the total flux measurement and a possible detection of the core at a 15σ level (open circle; Tzioumis et al. 2002). We have included PKS 1938–15 as a candidate for steep-spectrum nonthermal contamination, despite the extrapolation falling below 70 µm. We believe that a jet component may be contributing to the upturn in the high-frequency radio region’s SED. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 8.—SEDs of objects in our sample. The VLA data in the SED of CSS object PKS 2135 – 20 are the total flux measurement and an upper limit on the core (open circle; Tzioumis et al. 2002). [See the electronic edition of the Journal for a color version of this figure.]
For an object to be considered as a candidate for possible steep-spectrum synchrotron contamination, a source was required to fulfill two criteria. First, the power-law extrapolation of the total (steep-spectrum-dominated) radio lobe/hot-spot flux was required to fall close to or above the 70 \(\mu\text{m}\) flux. Second, a substantial fraction of the total radio emission at 5 GHz (>30%, as determined from visual inspection of radio maps) was required to fall within the Spitzer beam at 70 \(\mu\text{m}\). A check mark in column (5) in Table 6 indicates that an object fulfills both of these criteria. We find that only 7 objects out of our complete sample of 46 fulfill both these criteria, indicating that these objects have the potential for contamination by their extended synchrotron components that fall within the Spitzer beam. We emphasize that this is a conservative estimate, given that the steep-spectrum synchrotron component is likely to fall quicker than the fitted power law at higher frequencies due to spectral aging of the electron population. Evidence for such spectral steepening can be seen in the SEDs of PKS 0105−16, PKS 0625−35, and PKS 1549−79 (see Figs. 3, 5, and 6). Indeed, other authors (e.g., Shi et al. 2005; Cleary et al. 2007) fit a parabola to the steep-spectrum components in order to take this high-frequency steepening into consideration. Therefore, our power-law extrapolation is likely to provide an overestimate of the rate of steep-spectrum contamination at MFIR wavelengths in our sample. We believe that more detailed parabolic or multiple power-law fits to the total radio flux spectra are unwarranted given the lack of submillimeter data for most of the objects.

5.3. Core/Jet Synchrotron Contamination

The thermal dust contribution to the MFIR observed flux can be identified by extrapolating the total radio flux data to higher frequencies and interpreting everything above that extrapolation as the thermal bump (e.g., Hughes et al. 1997; see § 5.2). However, this does not take into account any contribution one might have from a flatter spectrum core/jet component. Using our high-frequency radio core observations and additional data from the literature, we have plotted the radio core fluxes and upper limits on the SEDs of most objects, in order to investigate their possible contribution to the MFIR flux. Again, using the 70 \(\mu\text{m}\) flux point as a reference and assuming the core spectral shape to be flat, we deem nonthermal contamination to be possible for those objects whose high-frequency radio core/jet fluxes lie level with or above the 70 \(\mu\text{m}\) flux.

Note again that this criterion is conservative in the sense that the SEDs of flat-spectrum core radio components may not remain flat up to MFIR wavelengths as we have assumed. Indeed, the three flat-spectrum, core-dominated objects in our sample (3C 273, PKS 0521−36, and PKS 1549−79) all show significant declines between the radio and the submillimeter MFIR. In the case of 3C 273 this decline is 2 orders of magnitude between the radio and MFIR.

We have also investigated the alternative of fitting a power law to the core radio data and extrapolating this through to infrared frequencies. Unfortunately, due to the small number of core data points and relatively narrow wavelength range, there is a relatively large uncertainty in the extrapolations of the core data to the MFIR. Future observations in the submillimeter region for the complete sample will allow us to constrain the possible contribution of the flat-spectrum core/jet components to the MFIR more accurately.

In column (6) of Table 6 we present the results, finding that 11 out of 46 objects in our complete sample have a possibility of contamination of their MFIR emission from flat-spectrum core/jet components.

5.4. Level of Potential Nonthermal Contamination

Overall, we have found that 15% of our complete sample has potential contamination from the steep-spectrum components (lobes/hot spots), and 24% has potential contamination from a core/jet component. Out of the 46 objects in our complete sample, a maximum of 30% has the possibility of significant nonthermal contamination of their thermal MFIR emission from either steep-spectrum components or a core/jet component. However, as discussed above (§§ 5.2 and 5.3), these are likely to be conservative estimates, because the strength of both the flat core and
steep-spectrum components conceivably declines toward MFIR wavelengths faster than our simple analysis assumes.

We stress to the reader that we have deliberately chosen a conservative approach to estimating the nonthermal contamination in this study. The results we present here are therefore likely to represent an upper limit to the true degree of nonthermal contamination in our sample.

5.5. Variability

The two core-dominated objects 3C 273 and PKS 0521−36, observed by Spitzer, were included in our observations and this study for comparative purposes, because of the large amount of previous data available. It is possible to identify their nonthermal core/jet component contribution at MFIR wavelengths if a relatively short timescale flux variation is observed, since the synchrotron-beamed component is thought to originate from a very compact region.

The MFIR emission from 3C 273 has been noted to be variable, decreasing between IRAS (1983) and ISO (1995−1998) observations in a way that is consistent with monitoring at other wavelengths (Meisenheimer et al. 2001). We can report that 3C 273 has declined further still in MFIR emission since these previous observations, by a similar factor of 2 between the IRAS and ISO data (see Fig. 6). Because of the timescale of this variation, it is most likely due to a change in core synchrotron emission, since the cool extended dust is unlikely to vary on the current observing timescales of decades. This implies that claimed ISO detections of thermal emission from dust underlying the powerful nonthermal emission in 3C 273 are unlikely to have been correct. The far-infrared emission now lies well below that of the supposed thermal bump. Our data provide no evidence for the detection of the thermal component in the MFIR SED of 3C 273. The MFIR emission of the BL Lac object PKS 0521−36 is also known to be dominated by its nonthermal component; however, we do not see such strong evidence for variability.

5.6. Comparison with Previous Studies

Previous MFIR investigations have considered the relative contributions of thermal and nonthermal emission in radio galaxies and quasars (Hes et al. 1995; van Bemmel et al. 1998; Polletta et al. 2000; Shi et al. 2005; Cleary et al. 2007). Studies such as those by Polletta et al. (2000), Shi et al. (2005), and Cleary et al. (2007) fit radio to MFIR SEDs using various synchrotron and thermal infrared emission components. Our findings agree with the main conclusions from these studies that the proportion of objects with nonthermal contamination of the MFIR by synchrotron-emitting components is small for an unbiased sample of radio-loud AGNs.

In the context of unified schemes, we can also investigate the optical classifications of those objects we believe have a possibility of core nonthermal contamination of the MFIR thermal emission. Out of the 11 objects with possible nonthermal contamination from the cores, 6 are classified as WLRGs and 5 as BLRGs/quasars. A large proportion of BLRGs/quasars with nonthermal contamination is what we might expect if these objects have a beamed component oriented close to the line of sight. Overall, our results are consistent with unified schemes that require a beamed component for the BLRG/quasar objects (e.g., Barthel 1989).

For the WLRGs, some of which are FR I galaxies, significant nonthermal contamination is consistent with the relatively stronger cores detected in FR I sources in general, as well as the detection of nonthermal cores in such sources at optical/infrared wavelengths (Chiaberge et al. 1999; Capetti et al. 2007).

6. SUMMARY

We have presented new MFIR and high-frequency radio core data for a complete sample of powerful southern radio galaxies. We detect objects down to 0.5 mJy at 24 μm, 8.4 mJy at 70 μm, and 83.6 mJy at 160 μm, obtaining a uniquely high detection rate at 24 and 70 μm.

In addition, we have presented new high-frequency radio core flux measurements, detecting radio cores for 59% of our complete sample. With these data we have made a conservative estimate of the nonthermal contribution to the MFIR continuum. Careful analysis of the SEDs for our entire sample reveals that nonthermal contamination of the MFIR is possible for a maximum of 30% of the sources in our sample.

An in-depth analysis of these data will be presented in a second paper (D. Dicken et al. 2008, in preparation).

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