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1–20 MICRON INFRARED PHOTOMETRY OF 3CR RADIO GALAXIES

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ABSTRACT

We have observed seven emission-line radio galaxies in the wavelength range 1–20 μm. The three broad emission-line radio galaxies (BLRGs; 3C 109, 3C 234, and 3C 445) showed strong infrared fluxes beyond 3.5 μm and one, 3C 234, was even detected at 20 μm. Their infrared slopes are steep ($\alpha \sim -2$) and similar to their optical slopes, implying that most of their energy probably emerges in the far-infrared. Comparison with earlier data indicates that two of the BLRGs are variable at *JHK* without a change of slope. The simplest explanation would be that the optical to infrared observed continuum is "nonthermal." This assumption then requires an extra source of ionizing photons in the ultraviolet to account for the optical emission lines. Alternatively the optical continuum could be heavily reddened, as would be suggested by the steep Balmer decrements in these galaxies. The infrared continuum would then be thermal. This assumption requires a fortunate coincidence between reddening and dust reemission to mimic a power law.

By contrast the narrow emission-line radio galaxies (NLRGs; 3C 98, 3C 198, 3C 223, and 3C 293) showed no strong excess at 10 μm and only normal elliptical galaxy colors at *JHK* and *L*. Simple predictions based on type 2 Seyfert galaxies give predictions in the range of our 3 σ upper limits, suggesting but not proving that strong infrared excesses are absent. However, observations 5–10 times more sensitive are needed to make a conclusive statement. The NLRG 3C 293 has a $(K-L) = -0.09$. This is too blue to be explained by any normal stellar population.

Subject headings: galaxies: photometry — infrared: sources — radiation mechanisms — radio sources: galaxies

I. INTRODUCTION

Emission-line radio galaxies and Seyfert galaxies show similar properties in their optical spectra and their X-ray emission (Osterbrock 1978; Fabbiano *et al.* 1984). Although the radio galaxies show a correlation between nuclear radio flux and X-ray emission (Fabbiano *et al.* 1984), the presence or absence of radio emission has not seemed to be of fundamental importance to the optical/X-ray nucleus.

Seyfert galaxies have well-defined infrared properties: Broad-line (type 1) Seyfert galaxies typically have an approximate power law extending at least to ~ 20 μm with a slope $\alpha \approx -1$ to -1.5, where $F_\nu \propto \nu^{+\alpha}$ (Ward *et al.* 1984; Rieke 1978). Narrow-line (type 2) Seyferts typically have steep, $\alpha \approx -2$ to -3, mid-IR excesses and flat near-IR excesses, which probably consist of thermal radiation from dust and gas (Lawrence *et al.* 1984; Rieke 1978). Broad- and narrow-lined radio galaxies might be expected to behave similarly. However, almost no observations of radio galaxies have been published beyond the *K* band. The "Far Infrared Supplement" (Gezari, Schmitz, and Mead 1982) lists *no* observations of 3C radio galaxies between 5 μm and 1000 μm except for five very bright and famous galaxies (3C 84 = NGC 1275, 3C 120, 3C 390.3, 3C 274 = M87, and 3C 405 = Cyg A). Nor are radio galaxies discussed in the recent review of infrared spectroscopy by Smith (1983).

The reason for this neglect has been that these galaxies are relatively distant and faint. Infrared detectors and telescopes have now improved to the point where observations from 3.5 to 20 μm are feasible. We report in this paper some exploratory observations in this wavelength range for both broad and narrow emission-line 3CR radio galaxies.

Since these galaxies were expected to be faint at 10 μm it seemed best to choose those that had evidence for the presence of large amounts of dust. The three BLRGs chosen are unusual in that they all have steep optical continua ($\alpha \lesssim -2$) with only small contributions from starlight (Yee and Oke 1978). They also have large Balmer decrements with Hα/H$\beta \sim 10$ (Yee and Oke 1978; Osterbrock, Koski, and Phillips 1976). These values are too large to be explained purely in terms of radiative transfer effects (Kwan and Krolik 1981). Strong reddening ($A_v \gtrsim 1$) by dust surrounding at least the broad-line region in the three galaxies is the most plausible explanation for these two features of their spectra. In this case strong dust reradiation would be expected in the infrared and is seen in optically similar Seyfert galaxies (Lawrence *et al.* 1984). They were thus the most promising candidates for a first investigation of BLRGs in the 3.5–20 μm region.

II. OBSERVATIONS AND ANALYSIS

The observations were made using the NASA Infrared Telescope Facility (IRTF) on 1983 February 5–7 and the UK Infrared Telescope on 1982 October 13–14, both on Mauna Kea, Hawaii. Standard *JHKLMN* and *Q* filters were used. At IRTF the "CT1" bolometer was used for *N* and *Q* and the

TABLE 1

INFRARED FLUXES FOR 3C RADIO GALAXIES

Object Name and Classification: Coordinate	Common Classification	z	Band[a]: 1.25 μm: J	1.65 μm: H	2.2 μm: K	3.5 μm: L	4.8 μm: M	10.2 μm: N	20 μm: Q
0356+102	3C 98	0.0306	13.46	12.59	12.24	11.80	...	>7.2	...
	NLRG		6.3 ± 0.4	9.0 ± 0.6	7.9 ± 0.5	5.5 ± 0.7	...	15.3 ± 15.6	...
0410+110	3C 109	0.3056	15.20	14.27	13.17	11.51	...	6.96	>3.4
	BLRG		1.3 ± 0.1	1.9 ± 0.1	3.3 ± 0.2	7.0 ± 0.8	...	62.1 ± 9.0	17.6 ± 136.0
0802+243	3C 192	0.0599	[14.64]	[13.51]	[12.50]	...	...	>8.7	...
	NLRG		[2.1]	[3.9]	[6.2]	...	...	2.7 ± 7.1	...
0936+361	3C 223	0.1368	[15.15]	[14.38]	[13.82]	...	...	>7.2	...
	NLRG		[1.3]	[1.8]	[1.9]	...	...	8.0 ± 16.3	...
0958+290	3C 234	0.1848	15.42	14.28	12.97	10.88	9.29	6.72	3.96
	BLRG		1.0 ± 0.1	1.9 ± 0.1	4.0 ± 0.3	12.4 ± 1.1	29.4 ± 7.5	77.4 ± 7.0	259.0 ± 30.0
1350+316	3C 293	0.0452	13.82	12.95	12.57	12.66	...	>7.2	>4.3
	NLRG		4.5 ± 0.3	6.5 ± 0.5	5.8 ± 0.4	2.4 ± 0.2	...	7.90 ± 11.0	8.0 ± 61.0
2216+027	3C 445	0.0568	13.63	12.68	11.44	9.51	8.62	...	...
	BLRG		5.4 ± 0.2	8.3 ± 0.3	16.5 ± 0.6	44.0 ± 3.5	55.0 ± 6.0	...	...

NOTES.—Upper limits for magnitudes are 3 σ. All observations used IRTF with a 6″ aperture *except* for those of 3C 445 which used UKIRT with a 8″ aperture for *JHKL* and 5″ for *M*. Observations in brackets are from Lilly and Longair (1982) at UKIRT with a 10″.8 aperture.

[a] Entries in each column are mag (*upper*) and mJy ± error (*lower*).

"RC1" InSb detector for the near-infrared bands. A 6″ aperture and an E-W chopper throw of 30″ were used. Integration times at N were about 20–30 minutes. At UKIRT an E-W chop of 20″ was used with an 8″ aperture at *JHKL* and a 5″ aperture at M. Magnitudes were derived from comparisons with standard stars (Forrest 1974; Elias *et al.* 1982) and converted to flux densities using the Caltech calibration (Wilson *et al.* 1972). Table 1 lists the results of our observations for the seven galaxies studied. The uncertainties given for the flux densities are statistical only. Possible systematic errors include shifts in effective wavelength between the standard stars and the galaxies, guiding errors, possible flux in the reference beam, and system responsivity changes during the night. These are likely to be less than 10% at and beyond 5 μm and less than 5% at the shorter wavelengths.

The classifications of the sources as broad-line radio galaxy (BLRG) and narrow-line radio galaxy (NLRG) are taken from Grandi and Osterbrock (1978) except for 3C 293 which comes from van Breugel *et al.* (1984). The three BLRG are also

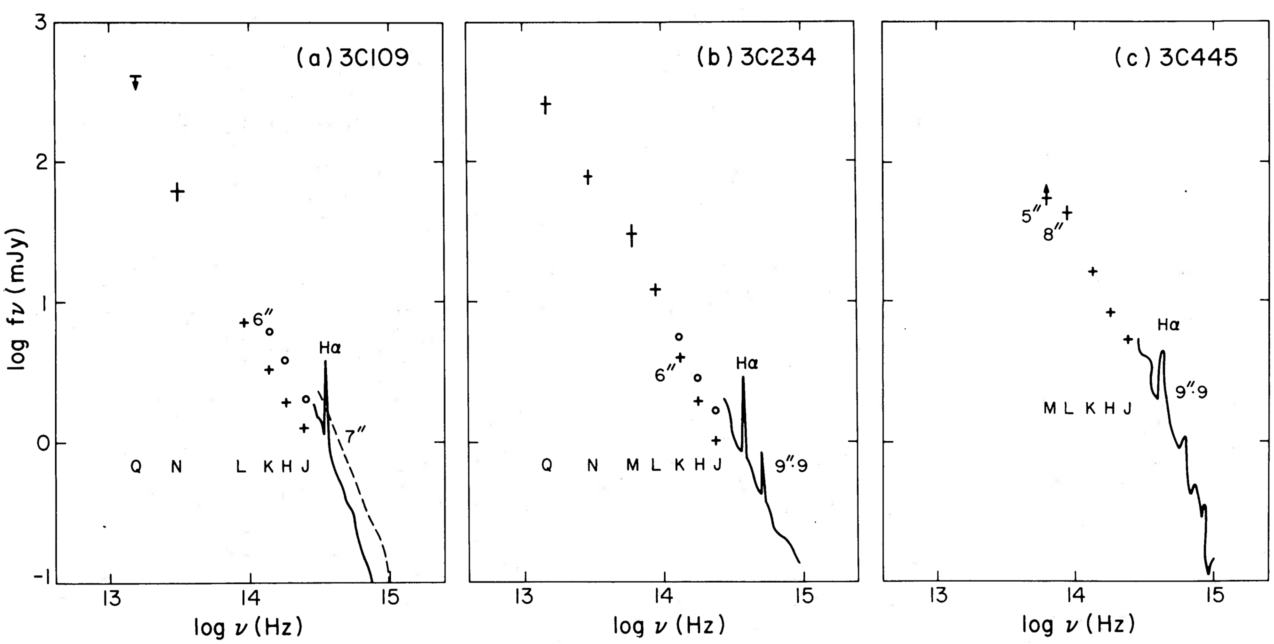

FIG. 1.—Infrared-optical flux distributions for the three BLRGs: (*a*) 3C 109; (*b*) 3C 234; (*c*) 3C 445. The crosses are the infrared data reported in this paper. The solid line is a smoothed version of Yee and Oke's (1978) continuum data. The strongest emission lines are shown, and Hα is marked. The aperture sizes used for each wavelength range are indicated. The dashed line in Fig. 1*a* shows the effect of dereddening 3C 109 by $E(B-V) = 0.25$, the galactic reddening value (Burstein and Heiles 1982).

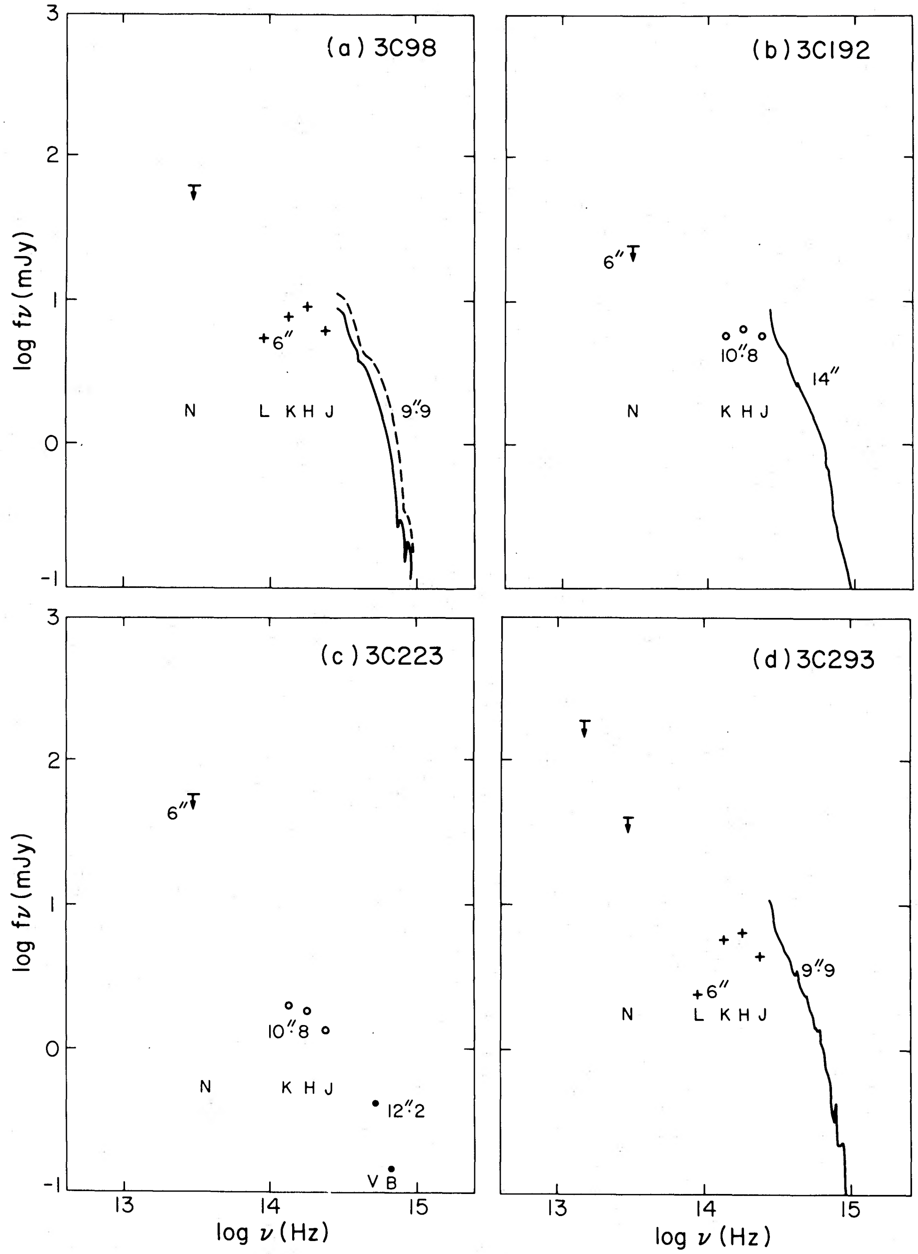

FIG. 2.—Infrared-optical flux distributions for the four NLRGs: (*a*) 3C 98; (*b*) 3C 192; (*c*) 3C 223; (*d*) 3C 293. Symbols are as in Fig. 1 with these differences: in Fig. 2*a*, the dashed line shows the 3C 98 spectrum dereddened by $E(B-V) = 0.15$, the galactic reddening value (Burstein and Heiles 1982); in Figs. 2*b* and 2*c* the open circles are the data of Lilly and Longair (1982); in Fig. 2*c* the filled circles are the data of Sandage (1972).

classified as N galaxies (Sandage 1972). Figures 1 and 2 show the infrared to optical energy distributions of the BLRGs and NLRGs, respectively. The solid lines show the multichannel photometer data of Yee and Oke (1978). Only the BLRG (or, equivalently, the N galaxies) were detected at long wavelengths. 3C 109 and 3C 234 were detected at 10 μm. 3C 234 was also detected at 5 μm and 20 μm. The third broad-line galaxy, 3C 445, was detected at 5 μm.

a) *The Three Broad-Line Radio Galaxies* (*BLRGs*)

All three BLRGs show continuous and steeply rising spectra from 0.3 μm to at least 5 μm. Single power-law fits to our infrared data give slopes $\alpha = -1.9 \pm 0.2$ for 3C 109, -2.0 ± 0.1 for 3C 234, and -2.3 ± 0.2 for 3C 445. A single power-law fit to 3C 234 is not good and inspection of the data (Fig. 1*b*) suggests a slight flattening of the slope from 5 μm to 20 μm. A simple fit to two power laws gives $\alpha = -1.6 \pm 0.2$ for $\lambda \geq 5$ μm and $\alpha = -2.4 \pm 0.1$ for $1.2 < \lambda < 3.5$ μm. These 1.25–10 μm slopes are similar to the slopes observed in the optical band (0.3–1.0 μm) for 3C 234 and 3C 445 by Yee and Oke (1978). They find $\alpha = -2.0$ for 3C 234, $\alpha = -2.4$ for 3C 445, and $\alpha = -3.0$ for 3C 109 with uncertainties of ± 0.1.

The steeper observed optical slope of $\alpha = -3.0$ for 3C 109 is at least partially due to reddening since the Galactic reddening towards 3C 109 is substantial. Burstein and Heiles (1982) give $0.24 < E(B-V) < 0.27$ ($N_H \approx 2 \times 10^{21}$ cm^{-2}; Jenkins and Savage 1974 and Seaton 1979). Figure 1*a* shows the effect of removing $E(B-V) = 0.25$ of reddening from 3C 109 (*dashed line*). The dereddened optical slope is -2.4. For 3C 234 and 3C 445 the reddening from our Galaxy is negligible [($E(B-V) < 0.06$; Burstein and Heiles 1982]. Additional intrinsic reddening may be present in all three galaxies.

b) *The Four Narrow-Line Radio Galaxies* (*NLRGs*)

None of the four NLRGs (3CR 98, 192, 223, 293) was detected at 10 μm or 20 μm although their near-infrared flux densities are similar to those of the BLRGs, and the integration times used were similar. Figure 2 shows our measurements and those of Sandage (1972), Yee and Oke (1978), and Lilly and Longair (1982). Galactic reddening is negligible for these galaxies except for 3C 98 which has an $E(B-V) = 0.15$ (Burstein and Heiles 1982). Figure 2*a* shows the effect of removing this reddening (dashed line).

III. DISCUSSION

a) *The Broad-Line Radio Galaxies*

i) *Intrinsically Steep Nonthermal Continuum?*

The similarity of the slopes of the infrared and optical energy distributions of 3C 109, 3C 234, and 3C 445 suggests a single mechanism for producing both forms of radiation. 3C 109 and 3C 234 are the only two in the study of Yee and Oke (1978) that showed no evidence for stellar absorption features. They set limits of 30% and 25% galaxy contribution to the light at V for 3C 109 and 3C 234, respectively. Miller (1981) found <20% galaxy fraction in 3C 109 and detected a 30% galaxy fraction in 3C 234. The steep optical continua of these galaxies are most probably predominantly nonthermal. These two galaxies and 3C 445 (which has a detection of 30% galaxy light at V; Yee and Oke 1978) are also the only ones in the Yee and Oke (1978) sample with steep optical continua. That our 1.2–10 μm photometry continues these same slopes for another decade in frequency suggests that the infrared is simply a continuation of this non-thermal power law.

At 1 μm the photometry of Yee and Oke (1978) lies about a factor of 2 above our J band measurement for both 3C 109 and 3C 234. Other measurements made on the same nights (Ward *et al.* 1984; Lawrence *et al.* 1984) showed good agreement with previous workers. Although Yee and Oke used a larger aperture than we did, these two galaxies are sufficiently distant that almost all the galaxy light will be included in our aperture. (Six arcseconds corresponds to about 40 kpc diameter in 3C 109 and about 30 kpc in 3C 234 for $H_0 = 50$.) The difference is probably due to variability of the "nonthermal" continuum in each galaxy over the intervening 10 years. Comparison with the JHK photometry of Lilly and Longair (1982; Fig. 2, *filled circles*) for the same two galaxies also shows evidence for variability in the same sense. Lilly and Longair used a 10″8 aperture and observed in 1980 and 1981. The time scale of variability at JHK is thus at least as short as 2–3 years for a factor of ~ 50%. The variations seem to be roughly the same in each band. These points tend to support the possibility that a single steep "nonthermal" continuum is being seen in these galaxies.

There are problems with this simple interpretation. The $\alpha \sim -2$ continuum, when continued shortward into the UV, does not provide sufficient ionizing flux for the emission lines. For all three galaxies the extrapolated continuum fails by a factor of at least 10 to achieve this. For 3C 234 a further comparison is possible. Penston and Fosbury (1978) have used the He II λ4686/Hβ ratio to measure the 912–228 Å slope of the ionizing continuum. Grandi and Osterbrock (1978) have measured this ratio for the *narrow* lines in 3C 234 and find a value of 0.22. (Contamination of He II λ4686 by Fe II multiplets (Kwan and Krolik 1981) is not important in this galaxy and would only lead to a flatter implied slope if it did occur.) This ratio implies a slope of -1.6 (Penston and Fosbury 1978). The observed 0.3–20 μm continuum slope of -2.0 would give He II λ4686/Hβ = 0.13, much smaller than observed. To retain the intrinsically steep infrared-optical slope in these galaxies, some new source of ionizing photons needs to be invoked, such as the UV excess as seen in quasars (Malkan and Sargent 1982) but shifted to higher frequencies.

The slope of the continuum spectrum in the ionizing UV and soft X-ray region is also critical to the existence of a two-phase instability which could give rise to the dense broad-line region clouds (Krolik, McKee, and Tarter 1981). In particular models due to Guilbert, Fabian, and McCray (1983), two-phase solutions do not exist for slopes steeper than $\alpha = -2$. Our observed slopes all slightly exceed this critical value. If we are seeing the true continuum slope then, since broad lines are seen in each galaxy, we have an apparent contradiction.

ii) *Dust plus Reddening?*

There may be an entirely different explanation. Infrared radiation from thermal emission by dust together with strong optical reddening could also explain our results. This viewpoint has the advantage of not needing any extra source of ionizing ultraviolet photons since the observed optical continuum, when dereddened, is sufficient to produce the observed emission lines. The steep Balmer decrements in all three galaxies (Yee and Oke 1978; Osterbrock, Koski, and Phillips 1976) are already suggestive of strong reddening. It is also hard to explain the large Paα/Hα flux ratio in 3C 445 (Rudy and Tokunaga 1982) other than through strong reddening. Carleton *et al.* (1984) find the same for the Paα/Hα ratio in 3C 234. A similar situation may exist in 3C 109 (Kollatschny and Fricke 1981).

The difficulty with this explanation is the continuity of slope observed from 0.3 μm to 20 μm. For this to be the result of adding a reddened power law of slope ~ -1 to emission by dust at a range of temperatures would seem to require an unlikely coincidence. However, models involving dust distribution around, and heated by, a central source produce power-law energy distributions in a fairly natural way (Rees *et al.* 1969; Panagia 1974). The JHK variability we have noted above implies that the nonthermal continuum dominates out to 2 μm. Carleton *et al.* (1984) will examine this possibility in detail for the case of 3C 234. A search for 3.3 μm and 10 μm dust features should provide a direct indication of the presence or absence of dust.

Another consequence of steep continuum slopes in these broad-line radio galaxies is that most of the energy emerges from these galaxies in the far infrared (unless they have flat γ-ray spectra). Delineation of their 20 μm to 1 mm continua is thus important and feasible. We note in particular that in 3C 234 the flux density at 20 μm exceeds that at 5 GHz (Preuss and Fosbury 1983).

b) The Narrow-Line Radio Galaxies

We find that, after K-corrections are made (Persson, Frogel, and Aaronson 1979), all these galaxies have JHK flux distributions typical of E and S0 galaxies (Frogel *et al.* 1978). (Note that the K-correction for 3C 223 is particularly large.) No survey of $(K-L)$ colors for normal ellipticals currently exists. Our $(K-L)$ measurements are discussed below. Our $JHKL$ photometry for 3C 98 and 3C 293 lies below the Yee and Oke (1978) optical data by about a factor of 2 in both cases. In contrast to the BLRGs, these galaxies are sufficiently nearby that the change in aperture between the two sets of measurements will include different amounts of galaxy, so that no variability is implied.

Yee and Oke (1978) find no UV excess in these two galaxies, and they do see strong stellar absorption features. At V any nonstellar component is at most a few percent of the total emission. This is consistent with our JHK colors.

Measurements at 3.5 μm of elliptical galaxies are rare. Johnson (1966) found a mean $(K-L)$ color of 0.44, but the measurements were very uncertain and included only five galaxies. M. Rieke (1983, private communication) has recently measured numerous elliptical galaxies and finds slightly bluer average colors with a dispersion $\gtrsim 0.1$ mag. The $(K-L)$ color of 3C 98 seems consistent with these values and with the assumption that the radiation arises from late-type stars. 3C 293, on the other hand, is substantially bluer, having the $(K-L)$ color of an O star (Johnson 1966). Our single measurement might be in error, but M. Rieke (1983, private communication) found similar colors for NGC 3379 and NGC 4278. Presumably these galaxies have an additional source of radiation in the 2.2 μm band. The $(H-K)$ and $(J-H)$ colors of 3C 293 suggest that the extra radiation source also contributes at 1.65 μm, but not at 1.25 μm. These conclusions are, however, very uncertain because of the small sample size. The $(J-H)$ colors of 3C 98 and 3C 293 are the same in spite of the differences at 3.5 μm. Spectroscopic information might help determine the presence and nature of any excess radiation source.

The NLRG energy distributions appear very different from those of Seyfert 2 galaxies since they show no strong 3.5 μm or 10 μm excess even though the two types of objects have similar optical and X-ray properties. The galaxy 3C 98 does show a slight excess of $(K-L)$ compared to normal spiral nuclei (Willner *et al.* 1984) and elliptical galaxies (M. Rieke 1983, private communication). We should note that the NLRGs are more distant than the type 2 Seyfert galaxies available for comparison and so a larger fraction of the galaxy is included in the aperture. Are our 10 μm upper limits consistent with the presence of a type 2 Seyfert nucleus? We have tried predicting the 10 μm flux density from other quantities uncontaminated by the stellar population, e.g., X-ray and emission-line flux densities. The predictions are in the same range as our upper limits, but have a large uncertainty. Observations only a few times more sensitive should give a clear answer to this question.

IV. CONCLUSIONS

Our three examples of broad emission-line galaxies have steep ($\alpha \approx -2$) continua extending from ≥ 5 μm into the optical U band. In 3C 109 and 3C 234 we find variability at JHK. The BLRG continua are significantly steeper than the $\alpha \approx -(1-1.5)$ of type 1 Seyfert galaxies. This steep continuum cannot be the dominant cause of ionization since it would give insufficient Lyman continuum photons by a factor of ≥ 10, and, for 3C 234, a He II $\lambda 4686/\mathrm{H}\beta$ ratio of about one-half the observed value.

Two different explanations are possible: (*a*) Emission from a single, steep-spectrum, nonthermal source from 0.3 μm to 20 μm (requiring an additional source of ionizing photons); (*b*) a normal, but highly reddened, nonthermal optical continuum combined with thermal reradiation from dust to mimic a single steep power law. This would be consistent with the steep Balmer decrements seen in these galaxies. Although this possibility requires a coincidence to produce a single spectral index from 1 μm to 10 μm, it does have the advantage of providing sufficient ionizing flux in the unreddened continuum to power the emission lines. The observed JHK variability shows that the continuum, even if highly reddened, probably dominates out to 2 μm.

The narrow-line galaxies show no deviations from normal elliptical $JHKL$ colors. The galaxy 3C 293 has a very blue $K-L$, which is difficult to reconcile with any normal stellar population. This property has been found in some other ellipticals that are not radio galaxies. No strong excesses are seen in NLRGs at 3.5 μm or 10 μm, unlike type 2 Seyfert galaxies, although dilution effects could explain this.

Our preliminary investigation needs to be followed up with 3.5–20 μm observations of a large and unbiased sample of radio galaxies. In particular, broad-line radio galaxies with flatter optical slopes should be observed, where a dust excess would be unexpected. Observations of narrow-line radio galaxies a few times more sensitive are needed to put tight limits on their dust emission.

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