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OBSERVATIONS FROM 1 TO 20 MICRONS OF LOW-LUMINOSITY ACTIVE GALAXIES

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ABSTRACT

We present and discuss 1–20 μm photometry of Liners (low-ionization nuclear emission-line regions), star burst nuclei, and high-excitation (mostly Seyfert 2) nuclei. Liners have strong, flattish 10–20 μm excesses but are dominated by a stellar population through 1–5 μm. By contrast, most type 2 Seyfert galaxies and all starburst nuclei have flux distributions that are flat through 1–5 μm, and steeply rising through 10–20 μm. The 1–5 μm flux distributions of type 2 Seyfert galaxies and starburst nuclei can be explained by mixtures of stellar emission, recombination radiation, and hot dust, although a nonthermal component is likely in a few objects. One Liner, NGC 3079, was found to be extended at 10 μm. We present a map which shows the 10 μm and optical maxima to differ by 6″.
Subject headings: galaxies: nuclei — galaxies: Seyfert — infrared: sources

I. INTRODUCTION

This paper presents an IR study of low-level (i.e., non-Seyfert 1) activity in the nuclei of spiral galaxies. Currently it is not clear which phenomena really are due to exotic processes and which may be explainable in purely stellar terms. IR photometry should be a powerful diagnostic for these weak "active" galactic nuclei (especially longward of 2 μm, where stellar contamination will be small) and may distinguish between thermal dust emission and nonthermal activity. Our approach has been to make *JHKLMNQ* observations of three classes of such low-level "active" nuclei and to compare the results to empirical templates representing the components we believe to be present in galactic nuclei.

a) *Classes of Low-Level Activity*

Three main classes have emerged: (i) type 2 Seyfert galaxies, by which we understand objects with high excitation but narrow (compared to type 1 Seyfert) optical emission lines. Examples in this group have come from a variety of sources. (ii) Starburst nuclei comprise the second class. There are actually two groups of objects, discovered in different ways, which may or may not be the same class. First, pioneering IR studies found many non-Seyfert galaxies with large IR luminosities (see review by Rieke and Lebofsky 1979). Careful studies of a few nearby cases have provided detailed explanations in terms of a recent burst of star formation: e.g., M82 (Rieke *et al.* 1980); NGC 253 (Becklin, Fomalont, and Neugebauer 1973; Glass 1973; Rieke and Low 1975); NGC 5253 (Moorwood and Glass 1982). The second, much more numerous group, are blue objects, mostly from the Markarian lists, with strong, narrow, low-excitation optical emission lines (Huchra 1977; Weedman *et al.* 1981; Balzano 1983). This paper considers the IR properties of this second group. (iii) Liners comprise the third class. Heckman (1980), Keel (1983), and Stauffer (1983) have presented evidence from spectroscopic surveys to suggest that very low level activity is common in spiral galaxy nuclei. Galaxies christened "Liners" by Heckman show low-excitation emission lines different from those found in either Seyfert galaxies or H II regions. Heckman (1980) originally suggested that the unusual line ratios result from shock ionization, but recent calculations demonstrate that the main features can be replicated by power-law photoionization models with a small ionization parameter (Pequignot 1981; Ferland and Netzer 1983) or a largely obscured ionizing source (Halpern and Steiner 1983). This hints that Liners may in some sense be "microquasars." The well-known Liner NGC 1052 was previously studied in the IR by Rieke, Lebofsky, and Kemp (1982) and Becklin, Tokunaga, and Wynn-Williams (1982). Both found a large excess at 10 μm. Rieke *et al.* (1982) attributed it to a nonthermal process, whereas Becklin *et al.* (1982) explained it as hot dust reemission.

Classification of individual galaxies is frequently ambiguous (see notes on individual galaxies attached to Table 2), and, of course, more than one kind of "activity" may coexist in the same object. In particular, we will argue that "type 2 Seyferts" are not a well-defined class.

b) *Empirical Templates*

We may expect three possible components to be present in galactic nuclei: normal stars, normal H II regions, and emission

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from processes associated with a nonthermal source, i.e., a Seyfert nucleus. IR flux density distributions of "pure" examples of these are shown in Figure 1*d*.

i) *Emission from a Normal Stellar Population*

In a companion paper (Willner *et al.* 1984) we present data on spiral galaxy nuclei selected for having *no* signs of optical activity. The near IR colors follow $J-H=0.75$, $H-K=K-L=0.25$, within ± 0.05. The results on *JHK* colors agree well with large aperture studies of elliptical galaxies and spiral galaxy nuclei (Persson, Frogel, and Aaronson 1979; Aaronson 1977; Griersmith, Hyland, and Jones 1982). The overall colors resemble those of an ensemble of M giants, suggesting a very old stellar population.

ii) *Emission from a Type 1 Seyfert Nucleus*

From a further companion paper (Ward *et al.* 1985) and earlier 1–10 μm studies by Rieke (1978), we know that the flux distributions of the more powerful type 1 Seyfert galaxies generally follow a power law of slope $\alpha \approx 1$–1.5 (in the sense $F_\nu = K\nu^{-\alpha}$) throughout 1–20 μm.

iii) *Emission from a Giant Star-forming Complex*

A variety of IR flux distributions are observed in many interesting sites connected with star formation in our own Galaxy. This corresponds to a diversity of phenomena and conditions: dust heated to various temperatures, thermal gaseous emission, masers, widely varying degrees of extinction, and so on. There is a tendency to study small highlights, and we do not know the typical integrated spectrum from a very large star-forming area (on a scale of hundreds of parsecs, as opposed to individual H II regions on a scale of parsecs). Even the giant H II regions of the LMC have too large an angular scale. The proper template for starburst nuclei should be the integrated emission from giant H II complexes *in the spiral arms* of nearby galaxies. (It is essential that there should be no suspicion of a "hidden" Seyfert nucleus). The only available data are on NGC 5461, an H II complex in M101 (Blitz *et al.* 1981); their data are reproduced in Figure 1*d*. The overall shape is clear and distinctive—flattish *JHK*, steep *NQ* ($\alpha \approx 3$). This suggests that the integrated emission is dominated by extensive "dilute" parts between the dense sites studied in the Galaxy.

II. OBSERVATIONS AND DATA REDUCTION

Observations were performed in 1982 May, 1982 October, 1983 February, and 1983 August with the UKIRT, the NASA IRTF, and the CTIO 4 m telescope, as part of a larger general program of IR observations of active galaxies (see Ward *et al.* 1985; Elvis *et al.* 1984; Willner *et al.* 1984). Apertures from 5″ to 12″ were used, with chopper throws in the range 20″–30″. A detailed journal of observations with instrumental parameters is presented in Table 1. The aperture was placed on the optical center of the galaxy, which was unambiguous, except in the case of NGC 3079. This galaxy was found to be extended at 10 μm, and is discussed in detail in the notes to Table 2.

Measurements were calibrated and corrected for air mass by observations of standard stars (Elias *et al.* 1982; Forrest 1974) and converted to monochromatic flux densities using the Caltech calibration (Wilson *et al.* 1972). The results are shown in Table 2. Statistical errors, where 0.03 or greater, are noted with the magnitudes. Total (statistical and experimental) errors are noted with the derived monochromatic flux densities.

There is a further, systematic uncertainty in flux densities, arising from the fact that the spectral distributions of many of the objects studied are very different from those of the standard stars. This can also be seen as an uncertainty in the effective wavelength of broad-band measurements. The effect is worst in the very broad *N* and *Q* bands. Since we do not know the flux distribution within a band, a correction cannot be calculated, but numerical experiments show that effects of up to 30% may occur at *N* and *Q*. It should be emphasized that this is a serious worry for precise comparison with theory, but not so serious for empirical comparison of classes of objects. It has been the custom of earlier workers to ignore color effects, so our results are directly comparable with theirs.

III. RESULTS

Twenty-one galaxies were measured. All galaxies have *JHKL* detections and over half were measured at *M*. Ten galaxies were *detected* at *N*, and seven at *Q*. In addition, four galaxies (NGC 1614, 7714, 7582, and 7552) had *Q*, *N*, or both measurements available in the literature. The data are plotted in Figure 1, in the form log of the flux density versus log of the frequency, along with other relevant published measurements. The plots are grouped as "starburst," "high excitation," or "Liner," according to the optical spectroscopy referenced in Table 2. The classification of some of the galaxies discussed here is controversial, as discussed in the notes to Table 2. For this reason we use the term "high excitation" rather than "Seyfert 2."

Detailed discussion of some individual sources is presented

TABLE 1

OBSERVING LOG

Dates	Telescope	Detector	Aperture(s)/Chop	Filters
1982 May 25/26, 27/28	UKIRT	Ga:Ge bolometer (Big Bertha)	8″/20″	*NQ*
1982 Oct 13/14, 14/15, 15/16	UKIRT	InSb photometer (UKT 6)	8″ and 5″/20″	*JHKLM*
1983 Feb 4/5, 5/6	IRTF	Ga:Ge bolometer (BOLO 1)	6″/30″	*NQ*
1983 Feb 6/7	IRTF	In Sb photometer (RC2)	6″/30″	*JHKLM*
1983 Aug 25/26	CTIO 4 m	In Sb photometer (DEV A)	5″, 7″, 12″/30″	*JHKL*

NOTE.—Filter Wavelengths were as follows (in microns):

J	*H*	*K*	*L*	*M*	*N*	*Q*
1.2	1.65	2.2	3.5	4.8	10.0	20.0

TABLE 2

DATA

Coordinate Type	Common Names	Z	J (mag) F_J (mJy)	H (mag) F_H (mJy)	K (mag) F_K (mJy)	L (mag) F_L (mJy)	M (mag) F_M (mJy)	N (mag) F_N (mJy)	Q (mag) F_Q (mJy)	Date Telescope	Aperture	Optical Reference X-Ray Reference Other IR Reference
0039+40 .... High excitation	5C 3.100[g]	0.0711	13.52 5.9 ± 0.2	12.76 ± 0.03 7.7 ± 0.3	12.08 ± 0.03 9.1 ± 0.5	11.19 ± 0.14 9.4 ± 1.5				1982 Oct UKIRT	8″	1 2 ...
0124+19 .... High excitation	Mrk 359[h]	0.0169	12.51 15.1 ± 0.9	11.74 19.7 ± 0.6	11.20 20.5 ± 0.6	10.07 ± 0.05 26.3 ± 1.5				1982 Oct UKIRT	8″	3 ...
			12.94 ± 0.03 10.1 ± 0.9	12.06 14.7 ± 0.4	11.51 15.4 ± 0.5	10.33 ± 0.06 20.7 ± 1.8	9.24 ± 0.14 30.8 ± 7.5			1982 Oct UKIRT	5″	...
0431−09 .... Starburst	NGC 1614 II Zw 15	0.0155	11.57 35.8 ± 1.4	10.73 50.0 ± 2.0	10.21 51.1 ± 2.0	9.08 65.3 ± 2.6				1982 Oct UKIRT	8″	4, 5 ...
	Mrk 617					9.21 58.0 ± 3.1	8.77 ± 0.07 47.5 ± 10.1				5″	6, 7
0549−07 .... Liner	NGC 2110[a]	0.0076	11.74 30.6 ± 1.8	10.77 48.2 ± 3.4	10.29 47.5 ± 2.8	9.43 47.5 ± 2.8	8.94 ± 0.15 40.6 ± 10.2	5.70 ± 0.11 198 ± 22	3.12 ± 0.10 562 ± 79	1983 Feb IRTF	6″	8, 9 10, 11 12, 13, 14, 15
0918+51 .... Liner	NGC 2841	0.0023	10.23 123 ± 5	9.48 158 ± 5	9.21 128 ± 5	8.88 78.6 ± 63				1982 Oct UKIRT	8″	16 17
								[8.57] 14.1 ± 6.8		1983 Feb IRTF	6″	18, 19
0958+56 .... Liner	NGC 3079[b]	0.0040	11.85 27.7 ± 1.7	10.52 60.7 ± 4.2	9.77 76.6 ± 4.6	9.16 60.7 ± 3.6	9.41 ± 0.24 26.3 ± 8.2	5.46 ± 0.05 247 ± 26	3.55 ± 0.13 378 ± 60	1983 Feb IRTF	6″	20 2 ...
1225+13 .... Liner	NGC 4438	0.0006	10.97 62.2 ± 3.7	10.08 91.0 ± 6.4	9.77 76.6 ± 4.6	9.53 43.2 ± 2.6		7.68 ± 0.24 32.0 ± 7.9	[5.04] 95.8 ± 102	1983 Feb IRTF	6″	20 21 22
1235+12 .... Liner	NC 4579 M58	0.0058	10.84 70.1 ± 4.2	10.08 91.0 ± 6.4	9.79 75.2 ± 4.5	9.41 48.2 ± 8.7	9.51 ± 0.3 24.0 ± 2.9	6.88 ± 0.13 66.8 ± 8.9	[5.62] 56.2 ± 90.7	1983 Feb IRTF	6″	20 17 22
1254+22 .... Liner	NGC 4826[c] M64	0.0013	10.22 124 ± 7	9.37 175 ± 12	9.05 148 ± 9	8.94 74.3 ± 4.5	9.22 ± 0.21 31.4 ± 6.9	6.39 ± 0.11 105 ± 12	4.11 ± 0.25 226 ± 62	1983 Feb IRTF	6″	16 17 18, 23, 19, 7
1311+37 .... Liner	NGC 5033[d]	0.0025	11.17 51.7 ± 3.1	10.36 70.3 ± 4.9	10.06 58.7 ± 3.5	9.89 31.0 ± 1.9	[10.24] 12.0 ± 10.0	7.64 ± 0.35 33.2 ± 12.6	[6.43] 26.6 ± 59.8	1983 Feb IRTF	6″	9 10, 24, 2
									[3.90] 274 ± 158		8″	13
1342+56 .... High excitation	Mrk 273[g]	0.038						6.47 ± 0.11 97.5 ± 12.0	2.64 ± 0.06 874 ± 99	1983 Feb IRTF	6″	1, 25 26 27
1439+54 .... High Excitation	I Zw 92 Mrk 477	0.0374	14.01 3.78 ± 0.23	13.35 4.48 ± 0.31	12.89 4.33 ± 0.26	11.84 ± 0.06 5.14 ± 0.44	... 0 ± 8.8	6.95 ± 0.15 62.6 ± 9.8	3.37 ± 0.12 446 ± 68	1983 Feb IRTF	6″	28, 29 26 30, 31
1524+42 .... High Excitation	NGC 5929	0.009	12.65 13.2 ± 0.8	11.88 17.3 ± 1.2	11.61 14.1 ± 0.8	11.46 ± 0.07 7.30 ± 0.7		[8.27] 18.6 ± 20.4	[5.42] 67.5 ± 35.0	1983 Feb IRTF	6″ ...	32 ...

TABLE 2—*Continued*

Coordinate Type	Common Names	Z	J (mag) F_J (mJy)	H (mag) F_H (mJy)	K (mag) F_K (mJy)	L (mag) F_L (mJy)	M (mag) F_M (mJy)	N (mag) F_N (mJy)	Q (mag) F_Q (mJy)	Date Telescope	Aperture	Optical Reference X-Ray Reference Other IR Reference
1524+42	NGC 5930	0.0096	12.26	11.36	10.94	10.43	[11.20]	5.84 ± 0.08	2.53 ± 0.09	1983 Feb	6″	33
Starburst			19.0 ± 1.1	28.0 ± 2.0	26.1 ± 1.6	18.8 ± 1.1	5.1 ± 3.4	174 ± 16	967 ± 122	IRTF		...
								5.80 ± 0.24	2.53 ± 0.14	1982 May	8″	...
								181 ± 48	967 ± 162	UKIRT		
1907+51	NGC 6764[e]	0.0082	12.65	11.82	11.44	10.63				1982 Oct	8″	1
Starburst			13.2 ± 0.8	18.3 ± 0.6	16.5 ± 0.5	15.7 ± 0.5				UKIRT		26
					11.66	10.91	9.93 ± 0.24				5″	27
					13.4 ± 0.4	12.1 ± 0.7	16.3 ± 5.1					
								6.44 ± 0.21	3.01 ± 0.15	1982 May	8″	
								100 ± 23	621 ± 110	UKIRT		
2158−321	NGC 7172[i]	0.0086	11.72	10.58	9.72	8.17				1982 Oct	8″	34
High excitation			31.2 ± 1.2	57.4 ± 1.7	80.2 ± 3.2	151 ± 6				UKIRT		24, 35
										(14/15)		
							7.30 ± 0.04				5″	34
							184 ± 38					
						8.37				1982 Oct	8″	
						126 ± 4				UKIRT		
						8.39				(15/16)		
						123 ± 7						
2205+32	NGC 7217	0.0041	11.01	10.25	9.99	9.77 ± 0.04				1982 Oct	8″	36
Liner			60.0 ± 2.4	77.8 ± 3.1	62.6 ± 2.5	34.6 ± 2.0				UKIRT		...
												...
2313−43	NGC 7552[f]	0.005	10.46	9.70	9.12	8.19 ± 0.03				1983 Aug	12″.4	37
Starburst			99.5 ± 4.0	129 ± 5	139 ± 6	148 ± 7				CTIO		38
			10.68	9.94	9.62	8.82					7″.1	18, 39, 40
			81.3 ± 3.3	104 ± 4	88.0 ± 3.5	83.0 ± 3.3						
			11.22 ± 0.04	10.46 ± 0.03	9.96	9.24 ± 0.04					5″	
			49.4 ± 3.6	64.2 ± 4.3	64.3 ± 3.9	56.4 ± 4.1						
2316−43	NGC 7582	0.0053	11.31	10.27	9.49	8.23				1983 Aug	7″.1	37
High excitation			45.5 ± 1.8	76.4 ± 3.1	99.2 ± 4.0	143 ± 6				CTIO		38, 24, 35
												18, 12, 13, 15
												39, 40
2333+02	NGC 7714	0.0099	11.97	11.29	10.94	10.15 ± 0.05				1982 Oct	8″	41
Starburst	Mrk 538		248 ± 1.5	29.9 ± 0.9	26.1 ± 0.8	24.4 ± 1.6				UKIRT		42
			12.24	11.56	11.23	10.27 ± 0.05					5″	43, 7, 15
			19.3 ± 1.5	23.3 ± 0.7	20.0 ± 0.6	21.8 ± 1.5						
2336−13	NGC 7723		12.19	11.42	11.15	10.87 ± 0.12				1982 Oct	8″	36
Starburst			20.2 ± 0.8	26.5 ± 1.1	21.5 ± 0.9	12.6 ± 2.9				UKIRT		...
												...

in notes to Table 2 (see also Fig. 2). General results can be seen first by direct comparison of the flux density distributions with the empirical templates (Fig. 1*d*) and second by use of two simple diagnostic diagrams. The starburst nuclei are similar to NGC 5461—flat *JHKL*, steep *NQ*—although a substantial stellar component is often present. The Liners have purely stellar colors through *JHKL* and have *NQ* excesses which are relatively flat and similar in slope to type 1 Seyfert galaxies Whether or not this necessarily implies a weak nonthermal component is discussed in § IV. The high-excitation galaxies show a variety of shapes, including some which are similar to NGC 5461, and some which suggest a strong nonthermal component.

Figure 3 is a two-color (*JHK*) diagram. Mixing curves are shown between "normal" galaxy colors and the expected colors of (*a*) recombination radiation, (*b*) a power law of slope 1.5 (typical of type 1 Seyferts), and (*c*) a blackbody with $T = 1100$ K (very hot dust). The recombination line separates well from the other two, which are similar. In the *HKL* diagram these mixing curves are all roughly parallel. Figure 3 includes measurements of type 2 Seyfert galaxies from Rieke (1978) and starburst nuclei from Balzano and Weedman (1981) (those with $J-K \geq 1.15$). We also plot data for several nearby galaxies classified as starbursts on the basis of their infrared properties.

In the mid-infrared we have sufficient data to compare the $N-Q$ colors of the different classes of active galaxies for the first time. Figure 4 shows the F_Q/F_N ratios of our sample galaxies. We have added NGC 5461, some large aperture measurements of M82, NGC 253, and NGC 6946, and the one previously measured Liner, NGC 1052. Additional axes indicate effective power-law slopes and blackbody color temperatures. A complication cautions against the simple interpretation of this color as a temperature. Spectroscopy in the 8–13 μm window frequently reveals a deep silicate absorption (Lebofsky and Rieke 1979; Frogel, Elias, and Phillips 1982; Phillips, Aitken, and Roche 1984). This can depress a broad-band *N* measurement by up to 30%, leading to a reduction in apparent temperature of ~20–30 K.

IV. DISCUSSION

a) Liners

In six out of eight cases, we have a clearly detected 10 μm excess. Three detections at 20 μm and two useful upper limits

NOTES TO TABLE 2

[a] *NGC 2110*.—The brightness throughout *JHKL* has decreased since the 1979 measurements of Ward *et al.* (1982) through a similar aperture. The near-IR emission thus originates within a region 1 pc across. It is not necessarily nonthermal emission, but may be due to hot dust heated by a central source. Using our template stellar distribution (Fig. 1*d*) we can subtract a stellar contribution consistent with the *JHKL* colors, and conclude that curvature through *NQ* to *M* is required at at least the 3 σ level. Thus, the *NQ* emission is almost certainly thermal in origin. NGC 2110 is a variable hard X-ray source of luminosity L(2–10 keV) $\approx 10^{43}$ ergs s^{-1} (Bradt *et al.* 1978; McHardy *et al.* 1981). It also has faint wide wings on Hα (Shuder 1980). These properties are characteristic of type 1 Seyfert galaxies.

[b] *NGC 3079*.—We found this galaxy to be considerably extended at 10 μm. A crude map is presented in Fig. 2 (measurements were not made with the intention of mapping the source, but of locating the peak of emission). Time permitted only a single 20 μm measurement. The 10 μm peak position is $09^h58^m35^s.3 + 55°55'17''$ (1950.0). This is very close to the VLA radio peak (Condon *et al.* 1982): $09^h48^m35^s.01 + 55°55'15''.5$. The optically brightest point lies 5″ south (Dressel and Condon 1976; our measurements): $09^h58^m35^s.4 + 55°55'11''$. It seems likely that the infrared-radio peak is the true nucleus of NGC 3079 and that the optical bright spot is merely a region of anomalously low extinction. The FWHM of the Condon *et al.* map is ~2″ (200 pc) after deconvolving the 2″ beam size. Our measured 10 μm distribution has FWHM ~8″ along the galaxy major axis. The measured beam profile was 75%, 4″.1; 50%, 5″.3; 25%, 6″.2. This implies a 10 μm source FWHM of ~5″–6″, considerably larger than the radio source. The *JHKLM* measurements were taken the next night, offsetting to the measured 10 μm peak from a nearby star. For this reason, there may be an offset between *JHKLM* and *NQ* data. This could mean that the apparent curvature required for the *NQ* component to join the *JHKLM* component is not real. However, even a 3″ error, which would be larger than expected, would cause a shift of at most a factor 3. The *JHKLM* colors are much redder than expected from a normal old stellar population; however, NGC 3079 is edge-on—the colors are consistent with $A_v \approx 4$ (see Fig. 3).

[c] *NGC 4826*.—Again, curvature through *NQ* to *M* seems to be required. Aftering subtracting a stellar contribution at *M*, the effect is significant at at least the 3 σ level.

[d] *NGC 5033*.—This is another link case between type 1 Seyfert galaxies and Liners, with faint wide wings on Hα (Shuder 1980) and hard X-ray emission (Marshall *et al.* 1979). However, the X-ray luminosity is only 6×10^{41} ergs s^{-1}, and we have detected nothing unusual except a weak 10 μm excess at 2.6 σ.

STARBURST NUCLEI

[e] *NGC 6764*.—This object was originally classified Seyfert 2 (e.g., Koski 1978). On the diagrams of Baldwin, Phillips, and Terlevich (1981), it falls into the area of H II regions. Halpern and Steiner (1983) claim it has Liner-like qualities. However, it has clear Wolf-Rayet emission features (Osterbrock and Cohen 1982), direct evidence of the presence of the hottest, most massive stars. The IR spectrum is typical of the starburst galaxies.

[f] *NGC 7552*.—Comparing data through 12″ (Frogel, Elias, and Phillips 1982) and 4″.5 (Phillips, Aitken, and Roche 1984) apertures, we see that the 10 μm source must have uniform surface brightness over a region 2 kpc across, requiring a distributed heating source. Our *JHKL* colors through 5″, 7″, and 12″ apertures become somewhat redder progressing outward, possibly indicating that a uniform surface brightness component comprising recombination, hot dust emission, or both, is mixed with a normal stellar component which decreases radially in surface brightness.

HIGH-EXCITATION NUCLEI

[g] *Mrk 273 and 5C 3.100*.—These objects are described by Halpern and Steiner (1983) as transition cases between type 2 Seyfert galaxies and Liners. 5C 3.100, in particular, has a considerable soft X-ray flux, L(1.5–4.5 keV) $\approx 10^{43}$ ergs s^{-1} (Halpern and Steiner 1983). The narrow-line galaxy 5C 3.100 (Börngen, Bronkalla, and Dantcourt 1970; Koski 1978; Grandi and Osterbrock 1978) should not be confused with the very nearby type 1 Seyfert IV ZW 29 = ZW 0039.5 + 4003 (Zwicky *et al.* 1969; Grandi and Osterbrock 1978).

[h] *Mrk 359*.—The flux distribution through a 5″ aperture is steeper than that through an 8″ aperture. The classification of this galaxy has been particularly unstable! Compare Davidson and Kinman (1978; Seyfert 2), Feldman *et al.* (1981; Seyfert 1), and Balzano and Weedman (1981; starburst).

[i] *NGC 7172*.—Variable by 0.3 mag at *K* in three months (Sharples *et al.* 1984). Our data are consistent with the brighter (1980 Sep) Sharples *et al.* data. Sharples *et al.* also present detailed arguments for the case that NGC 7172 is an obscured Seyfert galaxy. The peak *K* signal lies 2″–3″ north of the optically brightest point (Sharples *et al.* 1984). We set on the optical peak.

REFERENCES.—(1) Koski 1978. (2) Halpern and Steiner 1983. (3) Davidson and Kinman 1978. (4) Feldman *et al.* 1982. (5) Aitken, Roche, and Phillips 1981. (6) Lebofsky and Rieke 1979. (7) Rieke and Low 1972. (8) McClintock *et al.* 1979. (9) Shuder 1980. (10) Marshall *et al.* 1979. (11) Hayes, Culhane, and Bell-Burnell 1980. (12) Glass 1981. (13) McAlary *et al.* 1983. (14) Ward *et al.* 1982. (15) Phillips, Aitken, and Roche 1984. (16) Heckman, Balick, and Crane 1980. (17) Long and van Speybroeck 1984. (18) Glass 1976. (19) Rieke and Lebofsky 1978. (20) Stauffer 1983. (21) Forman *et al.* 1979. (22) Scoville *et al.* 1984. (23) Balzano and Weedman 1981. (24) McHardy *et al.* 1981. (25) Yee 1980. (26) Kriss, Canizares, and Ricker 1980. (27) Rieke 1978. (28) O'Connell and Kingham 1978. (29) Shuder and Osterbrock 1981. (30) Rudy, Le Van, and Rodriguez-Espinosa 1982. (31) Allen 1976. (32) Huchra, Wyatt, and Davis 1983. (33) Huchra, private communication. (34) Sharples *et al.* 1984. (35) Picinotti *et al.* 1982. (36) Keel 1983. (37) Ward *et al.* 1980. (38) Charles and Phillips 1982. (39) Frogel, Elias, and Phillips 1982. (40) Glass, Moorwood, and Eichendorf 1982. (41) French 1980. (42) Weedman *et al.* 1981. (43) Kleinmann and Low 1970.

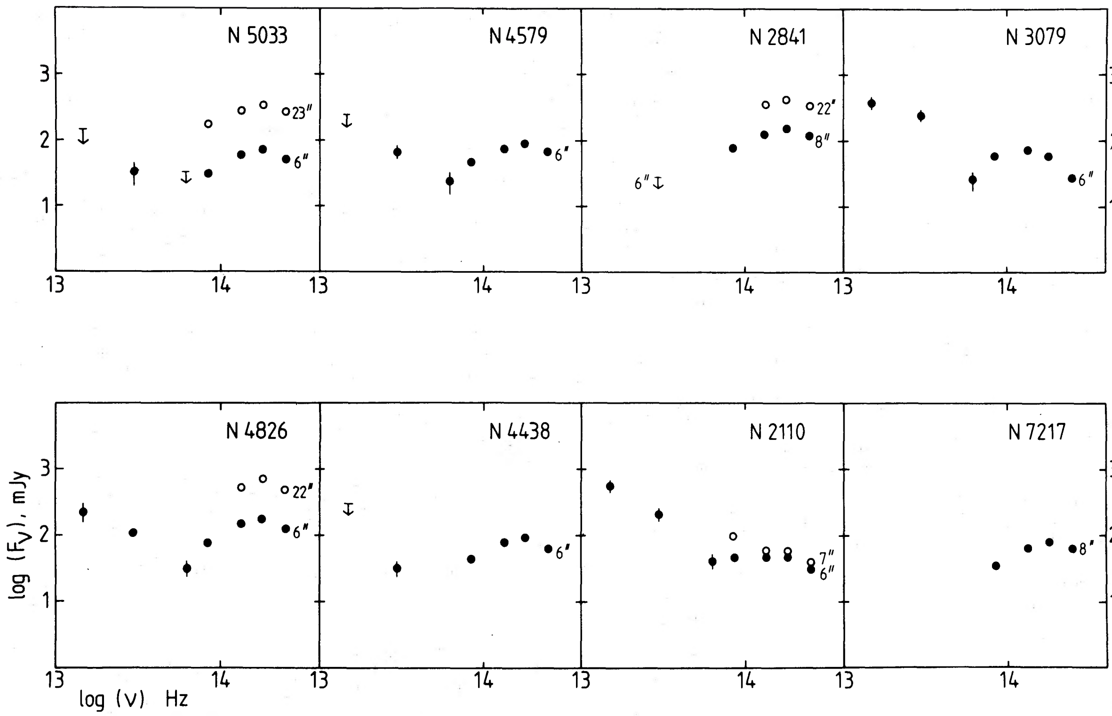

FIG. 1*a*.—Flux density distributions of Liners. Our own observations are plotted as solid circles or stars; those of others workers are open circles (see references in Table 2). Error bars are indicated where larger than the size of the symbol. Aperture sizes refer to all measurements plotted using the same symbol.

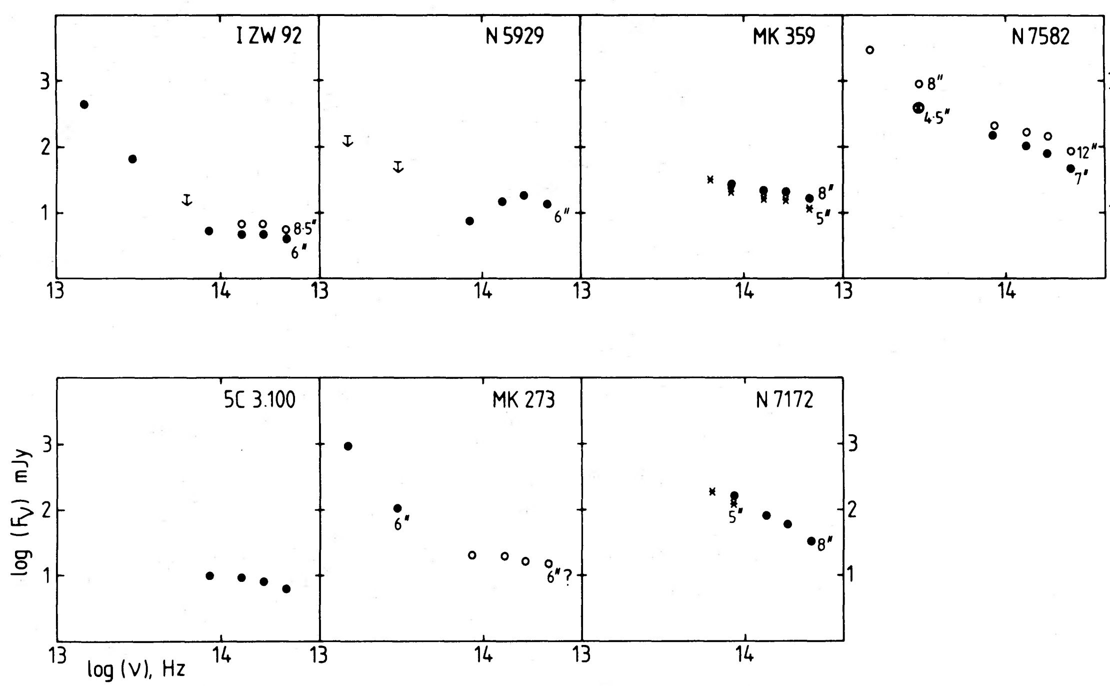

FIG. 1*b*.—Flux density distributions of high-excitation nuclei

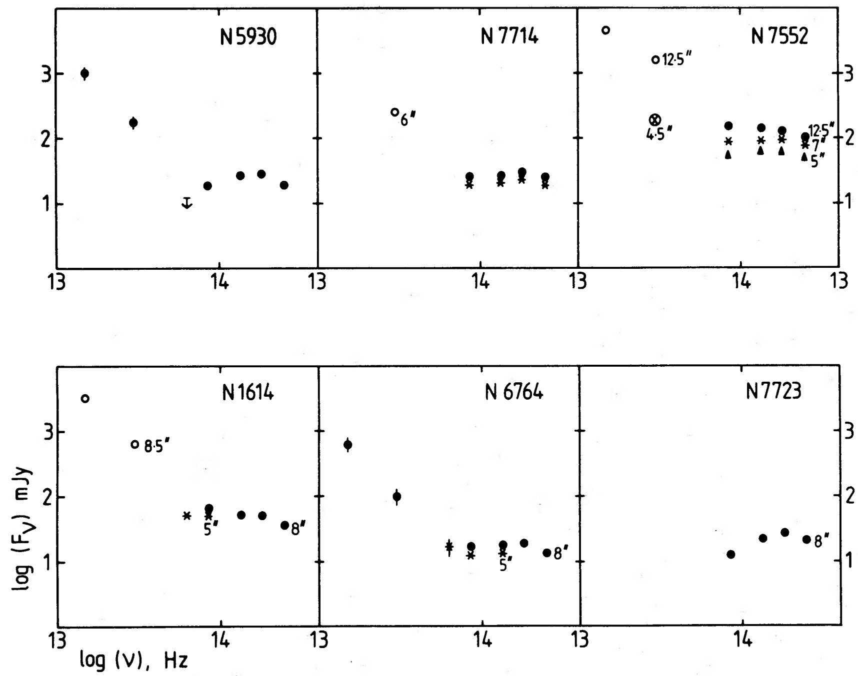

FIG. 1*c*.—Flux density distributions of starburst nuclei

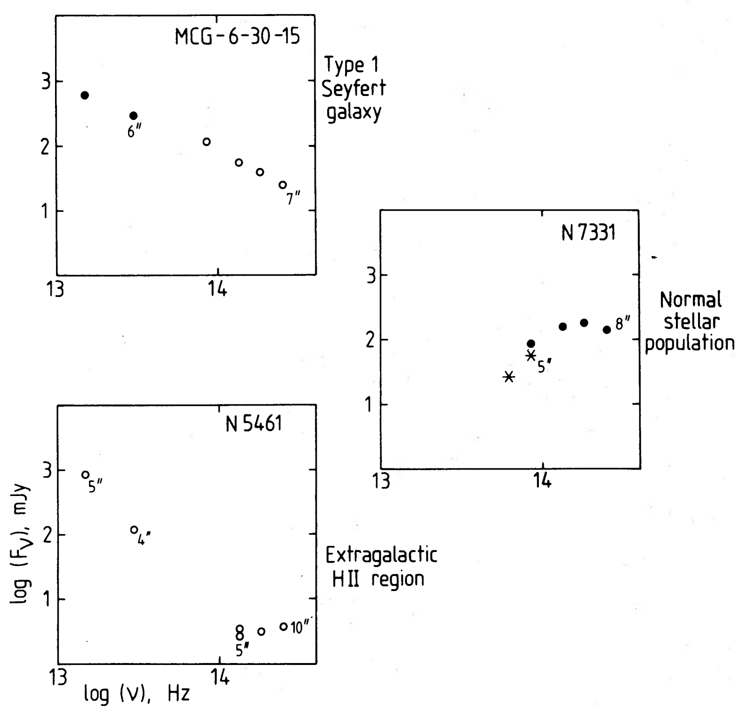

FIG. 1*d*.—"Template" flux density distributions. Data come from companion papers (Willner *et al.* 1984; Ward *et al.* 1985); also from Ward *et al.* (1982) (MCG 6-30-15) and Blitz *et al.* (1981) (NGC 5461).

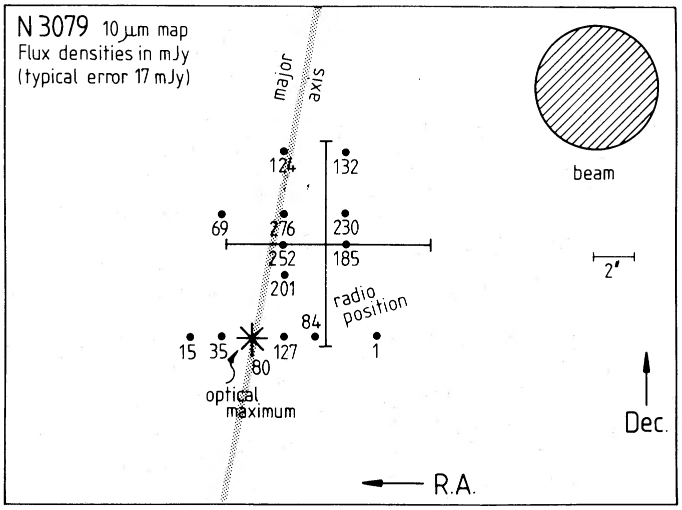

FIG. 2.—10 μm map of NGC 3079. Positions are relative to the optical maximum, so that the marked error for the radio position actually reflects the error in the absolute optical position. The beam size shown is at 25% of peak response.

show that the slope of the 10–20 μm excess is similar to that seen in type 1 Seyfert galaxies and is shallower than that seen in NGC 5461 (see Fig. 4). In at least three cases, however, the excess does not continue as a power law to shorter wavelengths. When a stellar contribution is subtracted at 5 μm (see notes to Table 2) from the measured flux for NGC 2110, NGC 3079, and NGC 4826, a downturn in the power law is required at $\geq 3\ \sigma$. This strongly suggests a thermal origin for the mid-infrared emission. The NQ color temperature is higher than for starbursts; however, the absence of 5 μm emission suggests a lack of very hot dust. We can conclude that the dust temperature distribution is narrower than that of the typical starburst, and thus the method of heating or dust distribution must be different.

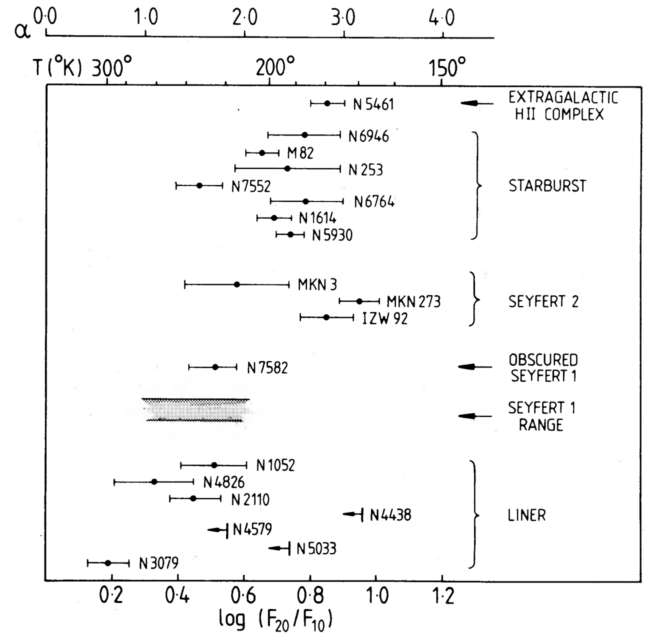

FIG. 4.—20/10 μm flux density ratios for various classes of object. Corresponding color temperatures and spectral slopes are indicated. Data are from this paper, except NGC 1052 (Rieke, Lebofsky and Kemp 1982), Mrk 3 (Neugebauer 1978), NGC 253 (Rieke and Low 1975), M82 and NGC 6946 (Rieke and Low 1972); NGC 5461 (Blitz *et al.* 1981).

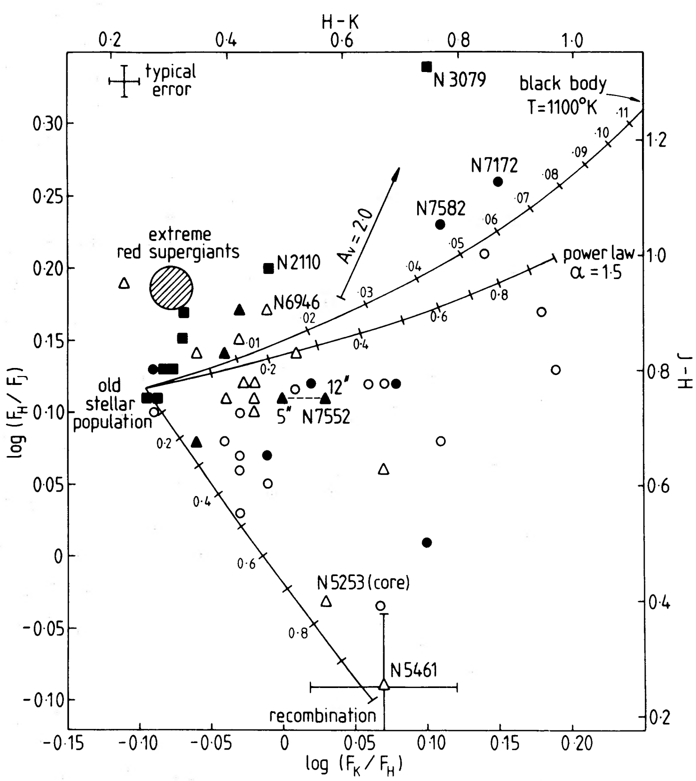

FIG. 3.—Near-infrared two-color diagram. *Squares*, Liners; *circles*, high-excitation galaxies; *triangles*, starburst nuclei. Our own data are plotted as solid symbols. Other data are from Balzano and Weedman (1981), Rieke (1978), Moorwood and Glass (1982), and Lebofsky and Rieke (1979). The extragalactic H II region NGC 5461 is also plotted (Blitz *et al.* 1981). The mixing curves are graduated according to fractional contribution at J.

The *JHKL* colors of most of the Liners are consistent with a normal bulge stellar population. This is not surprising since the optical emission-line spectra in Liners are generally weaker than those in the other two categories. The prominent exception is NGC 2110, which can be seen in Figure 3 to be consistent with a reddened mixture of old stars and either a power law or hot dust.

There are links between at least some Liners and type 1 Seyferts: X-ray emission, broad Hα wings, variability, and photoionization calculations. It may be that Liners are in general weak type 1 Seyfert galaxies, with IR emission from dust heated by a central source. The 10 μm luminosities of the Liners are in the range 1–100 times their soft X-ray luminosities (Halpern and Steiner 1983). This ratio is consistent with the bulk of the soft X-rays being absorbed and reradiated in the infrared, as suggested by Halpern and Steiner (1983). There are two problems with this hypothesis. First, our discovery of extended 10 μm emission in NGC 3079 (see notes to Table 2 and Fig. 2) surely requires a distributed heating source, perhaps an accompanying starburst. Second, the Liners are typically much nearer than our other program galaxies, so there may be a substantial scale effect, e.g., if we are sampling characteristically different fractions of point and extended sources.

b) Starburst Nuclei

The five objects in this class with strong emission lines have IR flux distributions roughly similar to NGC 5461: flat *JHKLM*, steep *NQ* ($\alpha \approx 2$–4). The 10–20 μm slope for these objects tends to be steeper than that of the Liners (Fig. 4). The weak starburst galaxy NGC 7723 has *JHKL* colors of a normal old stellar population. Unfortunately, no *NQ* measurements were made of this object. In detail, however, the *JHKL* flux distributions show a variety of shapes and differ significantly from NGC 5461. In its near-infrared colors (Fig. 3) the extragalactic H II region NGC 5461 appears to be dominated by recombination radiation. None of the starburst nuclei, however, lie on the old stars plus recombination mixing curve. There are three likely reasons:

1. It is possible that 2–3 mag of visual extinction have reddened them away from the recombination line. We can test this possibility using the observed flux of Hβ, and an extinction derived from Hα/Hβ, to predict the flux density at *L* (where stellar contamination should be least). The results are shown in Table 3. The predictions fail, in all cases, to account for the observed F_L (even after correction for possible stellar contributions), on average, by an order of magnitude. The true extinction may be much larger than implied by Hα/Hβ. A discrepancy of some size seems to be universal for extragalactic H II regions, judging by the relative values of Hα, Hβ, and the flux density at 5 GHz (Israel and Kennicut 1980). However, the correction needed for our objects ($\Delta A_v \approx 1$–4) is much greater than for NGC 5461 ($\Delta A_v \approx 0.3$). Moreover, using $A_{\mathrm{H}\beta}$ calculated from $F_L/F_{\mathrm{H}\beta}$, the implied true luminosities of Hβ become extremely large, of the order 10^{42-43} ergs s^{-1}, comparable with the most luminous type 1 Seyfert galaxies.

2. A second possibility is that another component altogether is dominating the near-infrared emission of starburst nuclei. Within errors, the $J-H$, $H-K$ colors of starbursts are consistent with a small fraction of either a power law or a hot blackbody component mixed with old stars.

3. A third intriguing possibility is that the starburst nuclei may contain a substantial population of red supergiants. Red supergiants evolve from massive stars, and so will be present shortly after a burst of star formation. In Figure 4 we show the colors of the reddest such stars (McGregor and Hyland 1981; colors have been converted from the AAT system to the CIT system). Many of the starburst nuclei fall on a mixing line between these colors and those of NGC 5461. If the red supergiant interpretation is correct, it provides the first evidence purely on the basis of IR colors that "starburst" nuclei really are powered by star formation. Comparison of optical excitation (e.g., O III/Hβ) with IR colors, especially a CO index, could lead to an estimate of the age of a starburst.

c) High-Excitation Nuclei

These objects are quite varied in their infrared properties. At least three distinctive energy distributions are seen. I Zw 92 and Mrk 273 appear roughly similar to the starburst nuclei: flat *JHKLM*, steep *NQ*. Their $N-Q$ colors are closer to those of the starburst nuclei than those of the Liners (Fig. 4). 5C 3.100 appears similar to I Zw 92 and Mrk 273 in its *JHKL* colors but was not observed at longer wavelengths. By contrast, the two galaxies known to be hard X-ray (2–20 keV)

TABLE 3

RECOMBINATION CALCULATIONS FOR STARBURST CANDIDATES

Name (1)	F_L (mJy) (observed) (2)	$A_{\mathrm{H}\beta}$ (mag) (from Hα/Hβ) (3)	F_L (mJy) (predicted) (4)	$A_{\mathrm{H}\beta}$ (mag) (required) (5)	$L_{\mathrm{H}\beta}$ (ergs s^{-1}) (implied) (6)
NGC 6764	8–16	2.3	0.2–0.9	≥4.6	$\geq 1.1 \times 10^{42}$
NGC 1614	40–58	4.0	0.3–1.3	≥7.7	$\geq 1.9 \times 10^{43}$
NGC 7552	27–56	1.8	1.9–8.1	≥3.1	$\geq 1.4 \times 10^{42}$
NGC 7714	11–22	1.9	0.9–4.0	≥3.0	$\geq 2.2 \times 10^{42}$
I Zw 92	3–5	0.5	0.1–0.4	≥2.7	$\geq 8.7 \times 10^{42}$
Mrk 273	12–19	3.9	0.5–2.0	≥5.8	$\geq 3.4 \times 10^{43}$
Mrk 359	15–21	1.6	0.1–0.3	≥5.8	$\geq 2.8 \times 10^{43}$
NGC 5461 (central 6″ core)	$F_K = 2.7$	0.6	0.7–2.0	≥0.9	$\geq 1.1 \times 10^{40}$

NOTE.—Data for galaxies from Table 2 and references quoted therein. NGC 5461 data from Blitz *et al.* 1981 and Peimbert and Spinrad 1970.

Col. (2).—The smaller number is the excess at *L*, having removed the largest possible stellar contribution which would not exceed observed flux at *J*, *H*, or *K* (assuming average normal galaxy colors).

Col. (4).—The two values are extreme predictions based on a range of assumptions about temperature, excitation, and He abundance (see Appendix).

As closely as possible, all values used correspond to ~6″–8″ regions.

sources (NGC 7172 and 7582) have power-law IR flux distributions, similar to type 1 Seyfert galaxies. Both of these galaxies are edge on spirals and are probably obscured broad-line objects (see Lawrence and Elvis 1982). NGC 5929 shows only normal galaxy *JHKL* colors, although it has a strong optical emission line spectrum (Huchra, Wyatt, and Davis 1982). Mrk 359 is ambiguous in its near-infrared colors, as it is in its optical classification (see notes to Table 2), but some process other than stellar emission dominates.

For those objects that resemble NGC 5461, a problem arises in the simple interpretation of the flat *JHKL* emission as recombination plus stellar emission, in the same sense as for the starburst nuclei. Table 3 shows that, compared to Hβ, the observed flux density at *L* is more than an order of magnitude too large. Unlike the case of the starburst nuclei, however, the presence of high-excitation emission lines lends weight to the idea that a weak nonthermal component may dominate the flux density at *L*. For an H II region ionized by a nonthermal source, whether the near-IR colors are dominated by recombination or the nonthermal power law will depend on a large number of factors: e.g., the slope of the power law, gas geometry, reddening, and whether or not the central source is still "switched on." Examining the *JHK* colors of these high-excitation nuclei (Fig. 3), we can see that they certainly do not have the same spread of colors as the starburst nuclei. There is a possible, but by no means unique, division into two broad groups. The first group lies on a line between red supergiants and recombination radiation, but further along the line than the "starburst" nuclei. These could actually be younger, higher excitation starbursts. The second group falls on a line between a power-law and recombination radiation, and these are more likely to be true active nuclei of some kind.

V. CONCLUSIONS

The low-excitation (Liner) nuclei are dominated by a typical stellar population from 1 to 5 μm but show strong excesses at 10 and 20 μm. In the one nucleus that was mapped, the 10 μm emission is extended. In this and two other cases the 10–20 μm slope must turn over to fit the 5 μm data. An explanation in terms of thermal dust emission thus seems most natural, although the dust may be heated by a central nonthermal source. The starburst nuclei have flat spectra in the near-infrared and a steep rise through 10–20 μm. The gross features probably represent a combination of stellar emission and thermal dust emission powered by stars. Recombination, and possibly nonthermal emission, may contribute in some cases. The "high-excitation" galaxies are not a homogeneous group. The label "type 2 Seyfert" should be used carefully. Some of these objects are obscured type 1 Seyfert galaxies, others may be high-excitation starbursts.

Our preliminary survey has shown that even low-luminosity activity in galaxy nuclei can give rise to strong infrared emission. In particular, the existence of 10 μm excesses in Liners (which occur in one-third of spiral galaxies) weakens the common assumption that such excesses indicate a burst of star formation (e.g., Rieke and Lebofsky 1978; Scoville *et al.* 1984); thermal gas and dust emission may also be powered by a weak nonthermal source.

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APPENDIX

RECOMBINATION CALCULATIONS

The expected *colors* of recombination radiation have been calculated by A. Campbell and are used here as a private communication. These calculations included free-free, free-bound, and strong lines and folded the result through the known shape of UKIRT filters. The predictions of *absolute* flux at 3.5 μm were calculated for this paper. The calculation was monochromatic, but was made several times with various assumptions about temperature (we used $T = 5000$, 10,000, and 20,000 K), excitation (for low excitation we assume all He is in the form of He II, whereas for high excitation it is all He III), and He abundance [we used $N(\text{He})/N(\text{H}) = 0.1$ and 0.25].

Temperature-averaged free-free Gaunt factors for 3.5 μm at the various temperatures were read from the graphs of Karzas and Latter (1961). The formulae to calculate free-free and free-bound continua were taken from Tucker (1975). Free-bound Gaunt factors were assumed to be 1.0 throughout. Hβ recombination coefficients were taken from Osterbrock (1974). The He II contribution is simply proportional to the relative abundance by number, for both free-free and free-bound; the contribution per ion is similar to H II. For He III, however, the contribution per ion is 4 times as large for free-free, and twice as large for free-bound.

As a check against earlier results of Willner *et al.* (1972) we also calculated the free-free continuum at 5 GHz, using the formula of Tucker (1975) for radio Gaunt factors. For $T = 10{,}000$ K, high excitation (He III only), and $N(\text{He})/N(\text{H}) = 0.1$, we find the 3.5 μm/5 GHz flux density ratio to be 0.27, in good agreement with the value 0.26 found by Willner *et al.* (1972). Reasonable temperature and excitation changes can alter this value between ~ 0.2 and ~ 0.3, however. The range of predicted values listed in Table 3 corresponds to the smallest and largest of the 12 values calculated for the various temperature, excitation, and abundance assumptions.

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