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INFRARED OBSERVATIONS OF LINER GALACTIC NUCLEI[1]

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ABSTRACT

Energy distributions from 1 to 20 μm are presented for a sample of galaxy nuclei all meeting the spectroscopic definition for LINERs (low-ionization nuclear emission-line regions). Shortward of 5 μm, most of the nuclei show only stellar emission with normal colors, but at 10 and 20 μm, most nuclei show dust emission. The dust luminosities are correlated with the Hα luminosities and are consistent with the hypothesis that the same ultraviolet source ionizes the emission-line gas and heats the dust. The dust almost certainly does not compete strongly for ionizing photons. The ionizing source cannot have a spectrum consisting of a single power law extending from infrared to soft X-ray wavelengths. The observations thus strongly favor photoionization models in which the ionizing source is intrinsically weaker than in Seyfert nuclei.

Subject headings: galaxies: nuclei — galaxies: photometry — infrared: sources

I. INTRODUCTION

The term "LINER" was introduced by Heckman (1980) to describe the nuclei of galaxies with emission-line ratios dissimilar both to Seyfert nuclei and to normal H II regions. These nuclei are very common in nearby spiral galaxies and perhaps in radio galaxies. "LINER" is an acronym for "low-ionization nuclear emission-line region," which refers to the relative prominence of low-excitation forbidden lines. This prominence distinguishes the LINERs from Seyfert galaxy nuclei. The LINERs also differ from low-excitation H II regions, which are found in the nuclei of some galaxies, in that the forbidden emission lines are relatively strong compared to the permitted lines.

The origin of the LINER phenomenon is unknown, but there are two main competing proposals. Koski and Osterbrock (1976) and Fosbury *et al.* (1978) explained the line ratios in NGC 1052 as the result of a shock moving at about 130 km s^{-1}. Heckman (1980) found this explanation consistent with his data on many nuclei. More recently, models involving photoionization rather than shocks have been advanced (Ferland and Netzer 1983; Halpern and Steiner 1983; Péquignot 1984). In order to account for the line ratios, the ionizing spectrum must be broader than a single blackbody, and all successful models have employed a power-law component. Shock models and photoionization models are both consistent with the ratios of the strong emission lines. The different models predict differences in the weak lines, but these lines are hard to measure and are often confused by underlying stellar absorption features.

Two classes of photoionization models for LINERs have been presented. The key parameter in these models is the "ionization parameter," defined as the ratio of photon density (per logarithmic frequency interval) to atom density at the surface of the emitting gas cloud. Line emission similar to that in LINERs results when the ionization parameter (in models where it is taken to be a constant) is less than $10^{-3.5}$, while greater values lead to line ratios similar to those observed in Seyfert nuclei. Ferland and Netzer (1983) proposed that a low ionization parameter could result from a low-luminosity central ionizing source or from greater distance between the ionizing source and the gas clouds than is typical of Seyfert nuclei. Péquignot (1984) presented similar models, allowing for the gas clouds to have a range of distances from a central source. The assumption that density and ionization gradients are present is strongly supported by observations of emission-line widths in LINERs and in a similar galactic nucleus (Filippenko 1985; Filippenko and Halpern 1984). Halpern and Steiner (1983) proposed that dust obscuration with a covering factor exceeding 0.9 might reduce the ionization parameter enough to give the observed line ratios, although they remarked that a low-luminosity central source would have the same effect.

Infrared observations offer a possibility for distinguishing among the explanations for the LINER phenomenon. In the model of an obscured ionizing source, the radiation absorbed by dust would be emitted in the infrared. If the covering factor is large, this would constitute most of the luminosity of the nucleus. In the model of a weak or distant photoionizing source, the amount of infrared emission would depend on the dust-to-gas ratio and the spectrum of the ionizing source. In the model of shock heating, there would be no reason to expect dust emission, because grain heating by gas is relatively inefficient.

In an earlier paper (Lawrence *et al.* 1985, hereafter Paper I), we presented a first reconnaissance of the infrared properties of

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six LINER nuclei. This paper presents infrared observations of 23 additional LINER galaxy nuclei, including six new detections at 10 μm and six at 20 μm, along with a more detailed analysis of the whole set.

II. THE SAMPLE

A large fraction of luminous spiral and elliptical galaxies have LINER nuclei (e.g., Heckman 1980; Keel 1983*a*). These nuclei typically have optical luminosities one or two orders of magnitude smaller than Seyfert nuclei. The established definition of a LINER nucleus is that the [O II] doublet λ3727 must be stronger than the [O III] λ5007 line and that the [O I] λ6300 line must be at least one-third as strong as λ5007 (Heckman 1980). Baldwin, Phillips, and Terlevich (1981) investigated line ratios in different classes of active nuclei and found that if one of these criteria is met, the other will nearly always be met also. A few Seyfert galaxies, however, have [O II] stronger than [O III]. Other line ratios can also be used to distinguish the LINERs, including [N II] λ6584 to Hα, λ5007 to Hβ, and λ6300 to Hα. Of course, for a nucleus to be recognized as a LINER, the emission lines must be above some minimum strength compared to the stellar continuum. The cutoff in equivalent width is undoubtedly approximate, but we estimate it to be about 2 Å in λ6584.

The galaxy nuclei discussed in this paper are from a complete, apparent magnitude–limited sample of galaxies. The sample consists of all galaxies listed in the RC2 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) north of declination $-15°$ and having total blue magnitudes B_T brighter than 12.0. This sample has been studied by Heckman, Balick, and Crane (1980) for all galaxies north of 40° and by Keel (1983*a*) for spiral and irregular galaxies south of 40°. All galaxies in our selected sample that have been recognized as LINERs are listed in Table 1. The galaxies in Table 1 meet (within the observational uncertainties) at least one of the standard oxygen line ratio requirements for LINERs, and the other is not contradicted by existing observations. Furthermore, the other line ratios discussed by Baldwin *et al.* (1981) are consistent with classification as LINERs. We therefore consider that nearly all of the galaxies in Table 1 meet the spectroscopic definition of LINERs, although measuring additional line ratios might find one or two slightly outside the strict definition.

Table 1 is by no means complete, however. Keel (1983*a*) classified numerous nuclei with weak emission lines as LINERs, apparently on the basis that λ6584 is stronger than Hα, but these have been omitted from Table 1 unless observations of either λ6300 or λ3727 are available. Such observations are available (Heckman, Balick, and Crane 1980; Keel 1983*c*) for those spiral nuclei and those elliptical nuclei north of 40° having the greatest emission-line equivalent widths. Even within these restrictions, the incidence of LINER nuclei is quite high, amounting to about 20% of the spiral nuclei and 40% of the 20 elliptical nuclei north of 40°. (Keel did not study many elliptical or S0 nuclei, so Table 1 is definitely incomplete for such galaxies south of 40°.) This incidence refers primarily to bright, massive galaxies because the sample is magnitude-limited rather than volume-limited.

Several galaxies that have previously been considered LINERs are omitted from Table 1. Absent are NGC 4258 and NGC 5194, which Heckman (1980) called "transition cases." These galaxies have λ6300 at or below the cutoff for LINERs, and the other line ratios are more typical of Seyfert galaxies. They should probably be classed as Seyfert 2 nuclei. Paper I discussed NGC 2110 and 5033 as LINERs, but both are rejected here. NGC 2110 is not in our sample because it is not listed in the RC2; even if it were listed, the line ratios (Shuder 1980) do not quite meet the criteria for LINERs. This nucleus probably should be classified Seyfert 1.8 or 1.9. NGC 5033 also lacks strong enough [O I] λ6300 (Shuder 1980; Stauffer 1982) to meet the definition of a LINER. Since the broad component of Hα is relatively strong, this nucleus should probably be classified Seyfert 1.5. NGC 660 is a borderline case, especially after removal of the stellar absorption underlying λ6300 (Keel 1983*c*), but pending measurements of [O II] λ3727 we have omitted this nucleus.

III. OBSERVATIONS

All of the observations are listed in Table 2, which gives the date, beam size, and telescope used. Magnitudes are given relative to standard stars chosen from the lists of Elias *et al.* (1982) and Tokunaga (1984). The magnitudes have been converted to flux densities based on the calibration given by Wilson *et al.* (1972); use of the newer calibration by Rieke, Lebofsky, and Low (1985) would increase the 10 and 20 μm flux densities by 7%. The energy distributions of those nuclei measured at both 10 and 20 μm are plotted in Figure 1, unless plots were given in Paper I.

Observations at the Multiple Mirror Telescope were made with the standard infrared photometer (Rieke 1984). The chopping secondaries were set to 30″ in elevation, and the beam size was 5″. Enough standard stars were observed to derive transformations from the instrumental *JHK* magnitude system to the CIT (Elias *et al.* 1982) system. For the range of colors covered by the standard stars, the only transformation needed is:

$$(J-K)_C = (J-K)_0/1.066\ , \tag{1}$$

where the subscript "C" denotes the CIT system and the subscript "0" denotes the instrumental system. This transformation should be accurate to within 0.02 mag, and it has been applied to all MMT observations reported here. The MMT measurements indicated as 3.5 μm were actually made with a filter 0.2 μm wide centered at 3.4 μm. All of the standard stars and all of the galaxies except NGC 7479 have similar colors in this wavelength region, so the magnitudes should be nearly the same at 3.4 and 3.5 μm. For uniformity, the magnitudes have been converted to flux densities at an effective wavelength of 3.5 μm.

At the IRTF, observations from 1.25 to 5 μm were made with the RC2 indium antimonide detector system. Observations at 10 and 20 μm were made with a bolometer detector and filters 5.1 and 9 μm wide, respectively. The chopper distance was 30″ in declination. The UKIRT observations were made with similar detector systems and a chopper spacing of 20″ in declination. Magnitudes in Table 2 are on the instrumental system. The 1.25–3.5 μm filters at the UKIRT are identical to those at the IRTF, and for both telescopes the $J-K$ and $H-K$ colors listed in Table 3 have been transformed to the CIT system using preliminary equations derived by A. Longmore for the UKIRT. For the range of colors under consideration, the results agree with published color equations (Longmore 1984).

Table 2 also lists observations from the literature. For wavelengths through 3.5 μm, generally only the observations with the smallest available beam sizes are included, while all obser-

TABLE 1

BRIGHT NORTHERN LINER GALAXY NUCLEI

Galaxy	RA	Dec	Type	Ref.	Dist. (Mpc)	B_T	EW[N II] (Å)	$F_{[N\ II]}$	$F_{H\alpha}$
								(10^{-14} ergs s^{-1} cm^{-2})	
NGC0404	1 6 39.3	35 27 10	S0-?	ks	0.7a	11.05	1.4	6.1	10.7
NGC1052	2 38 37.0	-8 28 5	E4	F	20.8	11.50		21.3	20.3
NGC2681	8 49 57.85	51 30 12.9	SAB0/a	h	18.5b	11.10			
NGC2685	8 51 40.73	58 55 32.8	SB0p	h	24.5	11.90			
NGC2768	9 7 44.69	60 14 33.9	E6?	H	24.5	10.90	2.8	3.0	1.1
NGC2787	9 14 49.29	69 24 51.0	SB0+	h	14.8:	11.80			
NGC2841	9 18 35.76	51 11 25.4	Sb?	Hk	18.5b	10.10	4.3	8.5	5.9
NGC2985	9 45 53.80	72 30 45.4	Sab	h	24.5:	11.25			
NGC3031	9 51 26.97	69 18 06.3	Sab	H	4.5b	7.75	11.3	58.6	42.3
NGC3079	9 58 35.4	55 55 11	SBc	hs	20.5b:	11.20	14.0	2.2	1.9
NGC3169	10 11 38.70	03 43 3	Sa p	k	23.0	11.25	4.1	9.1	5.9
NGC3368	10 44 6.9	12 5 5	SABab	K	21.8b	10.10	2.8	10.0	5.6
NGC3623	11 16 18.6	13 22 00	SABa	k	21.8b	10.17	2.1	2.2	1.4
NGC3642	11 19 25.05	59 20 55.9	Sbc?	H	20.1b	11.60	6.6	3.7	12.5
NGC3718	11 29 49.91	53 20 39.1	SB0/ap	h	20.1b	11.26			
NGC3898	11 46 36.27	56 21 44.2	Sab	h	20.1b	11.70	1.7	2.7	3.4
NGC3992	11 55 00.78	53 39 11.2	SBbc	h	20.1b	10.60			
NGC3998	11 55 20.91	55 43 55.7	S0?	HK	20.1b	11.55	7.4	16.5	18.8
NGC4036	11 58 53.06	62 10 26.6	S0-	H	26.0	11.40	8.6	10.8	5.8
NGC4096	12 3 28.93	47 45 25.3	SABc	h	14.4b	11.02			
NGC4111	12 4 31.06	43 20 36.9	S0+?/	H	20.1b	11.50	2.7	7.9	4.7
NGC4125	12 5 36.69	65 27 8.4	E6p	h	26.7:	10.70			
NGC4192	12 11 15.4	15 10 23	SABab	K	19.5a	10.86	6.1	6.0	4.8
NGC4216	12 13 21.67	13 25 38.1	Sb/	K	19.5a	10.91	1.1	3.0	2.2
NGC4278	12 17 36.5	29 33 26	E1+	H	14.4b	11.15	9.6	15.8	12.3
NGC4303	12 19 21.67	4 45 3.5	SABbc	wS?	19.5a	10.21	9.8	21.4	36.3
NGC4419	12 24 24.67	15 19 25.8	SBa	s	19.5a	11.95	4.2	5.5	
NGC4438	12 25 13.5	13 17 11	S0/ap	KS	19.5a	10.85	21.1	12.6	11.7
NGC4450	12 25 58.22	17 21 41.6	Sab	s	19.5a	10.94	2.6	4.4	6.2
NGC4486	12 28 17.8	12 39 58	cD	H	19.5a	9.56	16.5	15.9	6.9
NGC4501	12 29 27.74	14 41 44.2	Sb	ks?	19.5a	10.27	6.7	11.0	4.9
NGC4565	12 33 51.8	26 15 50	Sb?/	k	14.4b:	10.30	2.6	1.9	1.7
NGC4569	12 34 18.53	13 26 16.9	SABab	kS	19.5a	10.23	8.9	28.2	30.9
NGC4579	12 35 12.6	12 5 40	SABb	KS	19.5a	10.61	8.0	23.4	8.1
NGC4589	12 35 28.97	74 27 59.3	E2	h	30.8	11.80			
NGC4594	12 37 23.37	-11 20 53.3	Sa/	hk	19.5a	9.27	3.1	24.0	9.1
NGC4736	12 48 31.90	41 23 31.5	Sab	h	14.4b	8.85			
NGC4826	12 54 16.9	21 57 18	Sab	ks?	4.6b:	9.35	5.5	23.4	23.4
NGC5005	13 8 37.6	37 19 25	SABbc	S	21.0b	10.64	19.9	41.7	22.4
NGC5055	13 13 34.86	42 17 35.2	Sbc	h	10.3b	9.30			
NGC5195	13 27 52.4	47 31 48	I0 p	h	10.3b	10.53	2.6	6.8	10.9
NGC5371	13 53 33.61	40 42 22.8	SABbc	H	34.0b	11.40	4.5	2.4	1.5
NGC5474	14 3 14.91	53 54 6.0	Scd p	h	7.5b	11.35			
NGC7217	22 5 37.87	31 6 52.4	Sab	kS?	18.2:	11.10	4.7	10.5	2.3
NGC7479	23 2 26.41	12 3 11.0	SBc	k	37.4:	11.70	9.4	5.2	6.5

NOTES.—Positions given to 0".1 were measured at the MMT and have an uncertainty of ~0".5 with respect to a nearby SAO star. The position of NGC 1052 is from Gallouet *et al.* 1975 and has uncertainties of ±5" in R.A. and ±2" in decl. The remaining positions are from Dressel and Condon 1976 and are uncertain by ±4".

The line ratios are from the sources given in col. (5). The lowercase letters indicate that only one of the two oxygen line ratios that define the LINER class was verified:

F Fosbury *et al.* 1978
K, k Keel 1983*c*
W Huchra, Wyatt, and Davis 1982
H, h Heckman, Balick, and Crane 1980
S, s Stauffer 1982

The distances (col. [6]) are from the following sources: a, Sandage and Tammann 1968, 1971, 1974*a*, *b*; b, infrared Tully-Fisher method (Aaronson and Mould 1983; Aaronson *et al.* 1982*b*); no indication, kinematic distance corrected for Virgo flow.

TABLE 2A

INFRARED MEASUREMENTS OF LINERs

Object Name Co-ordinate	Common	1.2μm J Mag. mJy±er.	1.65μm H	2.2μm K	3.5μm L	4.8μm M	10.1μm N	20.2μm Q	Date Telescope	Aperture or Reference
0106+354	NGC0404	9.38	8.71	8.57						48″
		269±11	322±10	231±7						Frogel et al. 1978
							>7.0		1984 Sep 23	6″
							<60		IRTF	
0238-084	NGC1052	9.88	9.23	8.96	8.69				1978 Feb 20-24	15″
		171±2	200±2	162±2	93±10					McAlary et al. 1979
		10.37	9.56	9.28	9.02					9″
		108±4	147±6	120±5	69±3					Glass and Moorwood 1985
							6.45	3.58	1980-81	4″
		49±3	66±4	51±3	38±3	30±4	97±14	359±55		Becklin et al. 1982
										6″
							190±30			Rieke and Low 1972
									1981	5″.8
				82.5±4	56±3	48±4				Rieke et al. 1982
										8″
		85±3	109±3	96±2	68±2		118±13	379±76		Rieke et al. 1982
0849+515	NGC2681	10.20	9.52	9.22	9.03				1983 Dec 18	5″
		126±6	152±8	127±6	68±4				MMT	
							6.21	>3.38	1984 Jan 14	6″
							121±18	18.4±432	IRTF	
								4.5	1984 Mar 7	8″
								154±31	UKIRT	
0851+589	NGC2685	11.33	10.69	10.49	10.36				1983 Dec 18	5″
		44±2	52±3	39±2	20.1±2.2				MMT	
							>7.50		1984 Jan 14	6″
							11.1±12.3		IRTF	
0907+602	NGC2768	11.24[a]	10.58[a]	10.37[a]	10.18[a]				1983 Dec 18	5″
		48±2	57±3	44±2	24±1.7				MMT	
		10.21	9.49	9.24						15″
		125±4	157±5	125±4						Frogel et al. 1978
							>7.59		1984 Jan 14	6″
							16.0±11.4		IRTF	
0914+694	NGC2787	10.78	10.07	9.86	9.61				1983 Dec 18	5″
		74±4	92±5	71±4	40±2.9				MMT	
0918+510	NGC2841	10.23	9.48	9.21	8.88				1982 Oct 14	8″
		123±5	158±5	128±5	79±6					Lawrence et al. 1985
		10.39	9.73	9.52	9.28				1983 Dec 18	5″
		106±5	126±6	96±5	54±3				MMT	
		9.18	8.44	8.16						22″
		332±40	412±50	335±40						Glass 1976
							>8.11		1983 Feb 5	6″
							14±7			Lawrence et al. 1985
							>7.13		1984 Jan 16	6″
							26.6±17.4		IRTF	
										5″.7
							<90			Rieke and Lebofsky 1978

TABLE 2A—*Continued*

Object Name Co-ordinate	Common	1.2μm J Mag. mJy±er.	1.65μm H	2.2μm K	3.5μm L	4.8μm M	10.1μm N	20.2μm Q	Date Telescope or Reference	Aperture
0945+725	NGC2985	11.14	10.48	10.31	10.16				1983 Dec 18	5″
		53±3	63±3	47±2	24.2±1.8				MMT	
0951+693	NGC3031	9.39	8.72	8.36	8.06				1983 Dec 18	5″
	(M81)	267±13	319±16	281±14	167±8				MMT	
										5″7
							86±15		Rieke and Lebofsky 1978	
0958+559	NGC3079	11.85	10.52	9.77	9.16	9.38			1983 Feb 7	6″
		28±2	61±4	77±5	61±4	27±6			Lawrence *et al.* 1985	
							5.46	3.55	1983 Feb 5	6″
							250±30	380±60	Lawrence *et al.* 1985	
1011+037	NGC3169									
1044+120	NGC3368	9.07	8.26	8.07						22″
		367±44	502±60	364±44					Glass 1976	
1116+133	NGC3623			8.72						30″
				200±6					Grasdalen 1975	
										5″7
							<67		Rieke and Lebofsky 1978	
1119+593	NGC3642	12.35	11.66	11.42	11.16				1983 Dec 18	5″
		17.5±0.9	21.2±1	16.8±1	9.6±0.9				MMT	
1129+533	NGC3718	11.32	10.50	10.15	9.83				1983 Dec 18	5″
		45±2	62±3	54±3	33±2.6				MMT	
							>7.66		1984 Jan 14	6″
							22.2±10.6		IRTF	
1146+563	NGC3898	10.87	10.16	9.86	9.88				1983 Dec 18	5″
		68±3	85±4	71±4	31±2.3				MMT	
1155+536	NGC3992	11.82	11.09	10.88	10.69				1983 Dec 18	5″
		28.5±1.4	36±2	28±1.4	14.8±1.7				MMT	
										5″7
							<75		Rieke and Lebofsky 1978	
1155+557	NGC3998	10.16	9.50	9.25	8.99				1983 Dec 18	5″
		131±7	155±8	124±6	71±4				MMT	
		9.91	9.19	8.99						10″8
		165±5	207±6	157±5					Longmore and Sharples 198	
		9.46	8.73	8.46						15″
		256±8	325±10	254±8					Frogel *et al.* 1978	
							7.14		1984 Jan 14	6″
							52±12		IRTF	
							7.11		1984 Jan 16	6″
							53±12		IRTF	
							7.76	3.84	1984 Mar 6	8″
							29±16	282±96	UKIRT	
1158+621	NGC4036	11.02	10.39	10.04	9.74				1983 Dec 18	5″
		59±3	68±3	60±3	36±3.2				MMT	
							7.88[b]		1984 Jan 16	6″
							26.1±10.6		IRTF	

TABLE 2A—*Continued*

Object Name Co-ordinate	Common	1.2µm J Mag. mJy±er.	1.65µm H	2.2µm K	3.5µm L	4.8µm M	10.1µm N	20.2µm Q	Date Telescope or Reference	Aperture
1203+447	NGC4096	12.84	12.15	11.87	11.41				1983 Dec 18	5″
		11.2±0.6	13.5±0.7	11.1±0.6	7.6±1.0				MMT	
							>7.60		1984 Jan 14	6″
							11.2±11.2		IRTF	
1204+432	NGC4111	10.07	9.40	9.18	8.97				1983 Dec 18	5″
		143±7	170±9	132±7	72±5				MMT	
		10.09	9.42	9.18	8.92				1983 Dec 20	5″
		140±9	167±11	132±9	76±6				MMT	
							7.95		1984 Jan 16	6″
							24.5±8.7		IRTF	
1205+654	NGC4125	10.66	10.01	9.81	9.61				1983 Dec 20	5″
		82±6	97±6	74±5	40±4				MMT	
										5″.7
							<102		Rieke and Lebofsky 1978	
1211+151	NGC4192									6″
	(M98)						100±30		Rieke and Low 1972	
							7.59		1982 Mar 19	6″
							34±17		Scoville et al. 1984	
1213+134	NGC4216	10.57	9.74	9.47	9.27				1984 Apr 15	5″
		90±4	125±6	101±5	55±4				MMT	
							>7.15		1982 Mar 19	6″
							29±17		Scoville et al. 1984	
1217+295	NGC4278	10.32	9.62	9.37						7″.5
		116±3	143±4	110±3					Frogel et al. 1978	
		10.41	9.71	9.49						7″.2
		104±3	128±4	99±3					Longmore and Sharples 1982	
							>7.59		1980 May	6″
							<34		Puschell 1981	
1219+047	NGC4303	11.21	10.42	10.21	9.79				1984 Apr 15	5″
	(M61)	50±2	67±3	51±3	34±2				MMT	
				10.04	9.77				1984 Apr 16	5″
				60±3	35±2				MMT	
		10.72	10.07	9.70					1980 Mar 29	10″
		78±4	92±5	82±6					Balzano and Weedman 1981	
										6″
							240±60		Rieke and Low 1972	
										5″.7
							83±14		Rieke and Lebofsky 1978	
							6.68		1982 Mar 19	6″
							78±17		Scoville et al. 1984	
1224+153	NGC4419	11.21	10.39	10.06	9.71				1984 Apr 15	5″
		50±2	68±3	59±3	37±2				MMT	
							6.31	3.38	1984 Mar 7	8″
							111±11	431±65	UKIRT	
							6.02		1982 Mar 19	6″
							145±17		Scoville et al. (1984)	

TABLE 2A—*Continued*

Object Name Co-ordinate	Common	1.2μm J Mag. mJy±er.	1.65μm H	2.2μm K	3.5μm L	4.8μm M	10.1μm N	20.2μm Q	Date Telescope or Reference	Aperture
1225+132	NGC4438	10.97	10.08	9.77	9.53				1983 Feb 7	6″
		62±4	91±6	77±5	43±3				Lawrence et al. 1985	
				8.55						30″
				234±9					Grasdalen 1975	
							7.68	>3.75	1983 Feb 6	6″
							32±8	96±100	Lawrence et al. 1985	
							7.03		1982 Mar 19	6″
							57±17		Scoville et al. 1984	
1225+173	NGC4450	11.41	10.71	10.39	10.12				1984 Apr 15	5″
		41±2	51±3	43±2	25±2				MMT	
							8.10		1982 Mar 19	6″
							21±17		Scoville et al. 1984	
1228+126	NGC4486	10.72	9.99	9.76						7″.5
	(M87)	80±2	102±3	77±2					Frogel et al. 1978	
		11.07	10.35	10.09						7″.2
		57±2	71±2	57±2					Longmore and Sharples 1982	
							6.36		1980 May	6″
							106±19		Puschell 1981	
										6″
							60±21		Rieke and Low 1972	
										5″.7
							30±8		Rieke and Lebofsky 1978	
1229+146	NGC4501	11.05	10.33	10.06	9.77				1984 Apr 16	5″
		58±3	72±4	59±3	35±2				MMT	
										5″.7
							<78		Rieke and Lebofsky 1978	
							>7.15		1982 Mar 19	6″
							17±17		Scoville et al. 1984	
1233+162	NGC4565									5″.7
	edge on						<86		Rieke and Lebofsky 1978	
1234+134	NGC4569	10.56	9.93	9.64	9.25				1984 Apr 16	5″
	(M90)	91±5	105±5	86±4	56±4				MMT	
		10.33	9.67	9.36					1980 Mar 28	10″
		112±6	133±7	112±8					Balzano and Weedman 1981	
							6.42	3.36	1984 Mar 7	8″
							100±11	439±70	UKIRT	
										6″
							170±30		Rieke and Low 1972	
										5″.7
							100±18		Rieke and Lebofsky 1978	
							6.12		1982 Mar 19	6″
							131±17		Scoville et al. 1984	
1235+121	NGC4579	10.84	10.08	9.79	9.41	9.51			1983 Feb 7	6″
	(M58)	70±4	91±6	75±5	48±3	24±9			Lawrence et al. 1985	
							6.88	>3.9	1983 Feb 6	6″
							67±9	56±90	Lawrence et al. 1985	
							6.88		1982 Mar 19	6″
							66±17		Scoville et al. 1984	

TABLE 2A—*Continued*

Object Name Co-ordinate	Common	1.2μm J Mag. mJy±er.	1.65μm H	2.2μm K	3.5μm L	4.8μm M	10.1μm N	20.2μm Q	Date Telescope or Reference	Aperture
1235+744	NGC4589	11.27	10.61	10.36	10.04				1984 Apr 16	5″
		47±2	56±3	45±2	27±2				MMT	
1237-113	NGC4594	9.49	8.70	8.64	8.17				1983 Dec 21	5″
		242±24	325±33	217±22	151±15				MMT	
		9.53	8.67	8.52	8.29					7″.2
		234±12	334±17	242±12	135±7				Ellis <u>et al.</u> 1982	
		8.15	7.36	7.08	6.81					22″
		857±103	1149±138	907±109	481±48				Glass 1976	
							7.62		1984 Jan 16	6″
							33.1±11.3		IRTF	
										5″.7
							<69		Rieke and Lebofsky 1978	
1248+413	NGC4736	9.20	8.51	8.21	7.94				1984 Apr 16	5″
	(M94)	318±16	387±19	322±16	187±9				MMT	
		9.54	8.77	8.49	8.25	8.37			1984 May	5″
		232±12	304±15	249±12	140±7	69±5			Roche and Aitken 1985	
		8.50	7.75	7.50					1980 Mar 30	10″
		605±30	778±39	620±43					Balzano and Weedman 1981	
		8.19	7.47	7.22	6.95	7.36			1978 Feb 20-24	15″
		803±13	1003±9	801±6	464±8	174±51			McAlary <u>et al.</u> 1979	
										6″
							180±30		Rieke and Low 1972	
										5″.7
							130±21		Rieke and Lebofsky 1978	
										4″.3
							88±13		Roche and Aitken 1985	
1254+219	NGC4826	10.22	9.37	9.05	8.94	9.22			1983 Feb 7	6″
	(M64)	124±7	175±12	148±9	74±5	31±7			Lawrence <u>et al.</u> 1985	
		9.51	8.68	8.34					1980 Mar 30	10″
		239±12	330±17	286±20					Balzano and Weedman 1981	
		8.82	7.87	7.72						22″
		463±56	718±86	503±60					Glass 1976	
							6.39	4.11	1983 Feb 5/6	6″
							105±12	226±62	Lawrence <u>et al.</u> 1985	
										6″
							94±26		Rieke and Low 1972	
										5″.7
							65±16		Rieke and Lebofsky 1978	
1308+373	NGC5005	9.87	8.99	8.66					1980 Mar 30	10″
		171±9	248±12	213±215					Balzano and Weedman 1981	
1313+422	NGC5055	10.35	9.79	9.67	9.27				1983 Dec 18	5″
		111±6	119±6	84±4	55±3.4				MMT	
							>7.64		1984 Jan 16	5″
							13.1±10.8		IRTF	
										5″.7
							64±16		Rieke and Lebofsky 1978	

TABLE 2A—*Continued*

Object Name Co-ordinate	Common	1.2μm J Mag. mJy±er.	1.65μm H	2.2μm K	3.5μm L	4.8μm M	10.1μm N	20.2μm Q	Date Telescope	Aperture or Reference
1327+475	NGC5195		8.82	8.40	7.91				1970 June 26	10″
			291±23	271±19	192±40				Penston 1973	
										6″
				160±10	110±20	140±40	290±60		Rieke and Low 1972	
										4″.3
							160±24		Roche and Aitken 1985	
										5″.7
							290±6(extended)		Rieke 1976	
										8″.5
							430	570±16	Lebofsky and Rieke 1979	
1353+406	NGC5371	11.95	11.26	11.04	10.83				1983 Dec 18	5″
		25±1	31±2	24±2	13±3.5				MMT	
				10.24						30″
				49±3					Grasdalen 1975	
1403+539	NGC5474	14.80	14.19	14.01	>12.23				1983 Dec 18	5″
		1.83±0.09	2.13±0.1	1.54±0.08	<3.6				MMT	
2205+32	NGC7217	11.01	10.25	9.99	9.77				1982 Oct 15	8″
		60.0±2.4	78±3	62.6±2.5	35±2				UKIRT	
		11.08	10.36	10.14	10.02				1983 Dec 18	5″
		56±3	70±4	55±3	27±1.5				MMT	
2302+120	NGC7479	12.33	11.55	11.17	10.36				1983 Dec 18	5″
		17.7±0.9	24±1	21±1	20.1±1.4				MMT	
							5.39	2.35	1984 Jan	6″
							263±19	1114±5	IRTF (Tokunaga, 20″ chop)	

TABLE 2B

LINERs Too Faint for Main Sample

Object Name Co-ordinate	Common	1.2μm J Mag. mJy±er.	1.65μm H	2.2μm K	3.5μm L	4.8μm M	10.1μm N	20.2μm Q	Date Telescope	Aperture or Reference
0335+096	Anon	13.26	12.41	11.99	11.65				1982 Oct 15	8″
z=0.04		7.5±0.3	10.6±0.4	9.9±0.4	6.1±0.9				UKIRT	
0931+103	NGC2911	11.78	11.06	10.78	10.59				1983 Dec 18	5″
α = 09 31 05.14		29.5±1.5	37±2	30±2	16.3±1.4				MMT	
δ = 10 22 31.0										
							>7.70		1984 Jan 14	6″
							12.4±10.3		IRTF	

[a] Because of a failure to record the time of a focus change, these measurements may be miscalibrated in the sense that the correct values are 0.11 mag brighter than the values given. The colors should be correct.

[b] NGC 4036 was also measured on 1984 Jan 14 with a result of −68 ± 19 mJy. The negative result was not caused by incorrect pointing of the telescope, which was verified to be beamswitching correctly between the two chopped images. Either a mistake was made in determining the sign of the beamswitching or there might be a strong source separated from this nucleus by about the chopper distance, which was 30″ north-south.

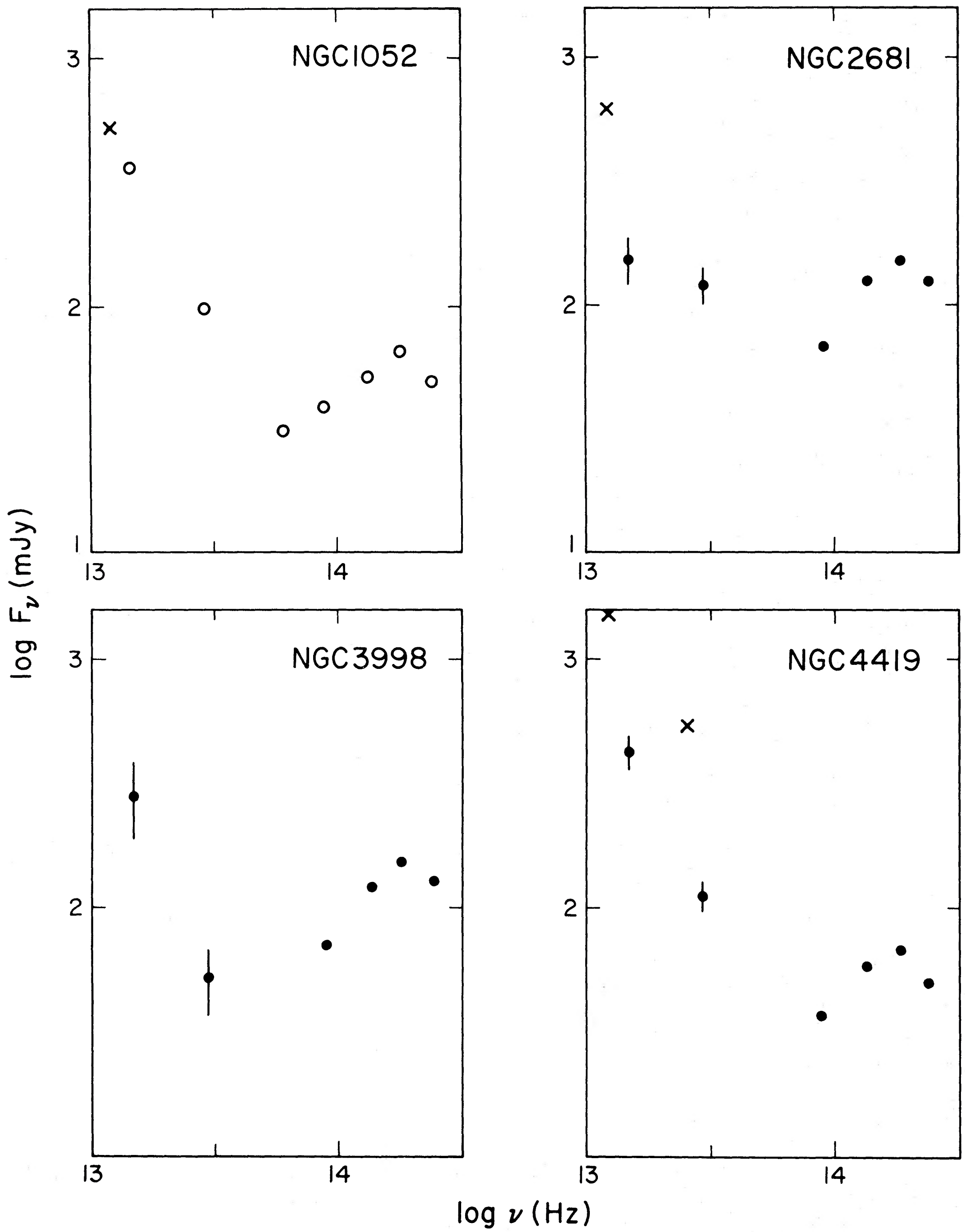

FIG. 1*a*

FIG. 1.—Flux density of LINERs measured at 10 and 20 μm. The open and filled circles denote measurements with small beam sizes (Table 2). The X's denote *IRAS* measurements, and the arrows indicate the existence of *IRAS* measurements that are above the limits of the plots. For NGC 4736, the filled circles denote measurements with 5″–6″ beams, and the open circles denote measurements with a 15″ beam. For NGC 5195, the different symbols refer to beam sizes of 6″ and 8″.5–10″, respectively. Where both 10 and 20 μm measurements exist, the plots show the 10 μm measurements made at the same time as the 20 μm measurements.

vations are listed at the longer wavelengths. Where possible, published observations were converted to magnitudes and then to flux densities using the same calibration as for our observations. Where no calibration is given or implied in the published observations, Table 2 lists only the flux density. Different authors have used calibrations that differ by up to about 20%, but such differences do not affect the conclusions of this paper.

After this paper was submitted, Cizdziel, Wynn-Williams, and Becklin (1985) presented new 2.2 and 10 μm measurements that include 10 of the LINERs discussed here. The new measurements are not included in Table 2 but agree in all cases of overlap. Two nuclei not previously measured at 10 μm, NGC 3368 and 5005, are included in the work of Cizdziel *et al.* The results agree with those for other nuclei discussed below, and the conclusions of this paper are not changed.

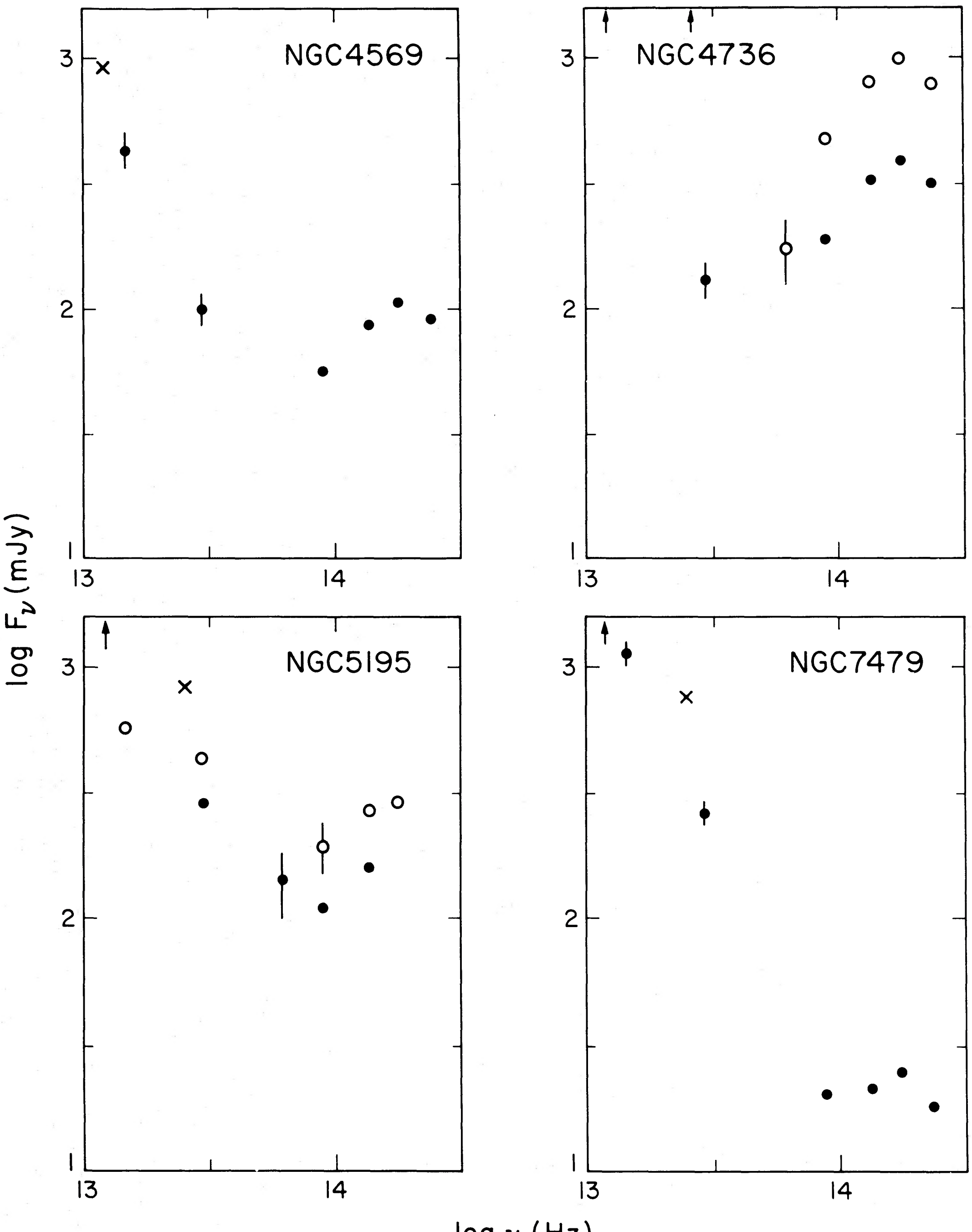

FIG. 1*b*

IV. DISCUSSION

a) Distances

For most of the galaxies listed in Table 1, it was possible to derive distances based on group membership. Such a determination should be more accurate than a determination for an individual galaxy. Group assignments from Huchra and Geller (1982) account for 35 of the 45 galaxies, and assignments from Geller and Huchra (1983) account for two more. The distances of nongroup galaxies are indicated by a colon in Table 1.

Distances were whenever possible determined from the infrared Tully-Fisher method (Aaronson and Mould 1983; Aaronson *et al.* 1982*b*), which should be more accurate than Hubble law distances for such nearby galaxies. For the nearest groups, which are used as calibrators for the Tully-Fisher distances, distances were taken from Sandage and Tammann (1968, 1971, 1974*a*, *b*). Specifically, NGC 404 is a member of the M31 group, whose distance was taken from Sandage and Tammann (1971). The distance of the NGC 3031 (M81) group was taken from Sandage and Tammann (1968). For the remaining groups and individual galaxies, distances were determined from the tabulated mean radial velocities (Huchra

TABLE 3

COLORS OF LINER NUCLEI

NGC	K	J−K	H−K	K−L	L−M	L−N	N−Q
1052	10.21			0.54	0.40:	3.22:	2.9
2681	9.22	0.98	0.30	0.19		2.82:	1.7
2685	10.49	0.84	0.20	0.13		<2.86	
2768	10.37	0.87	0.21	0.19		<2.59	
2787	9.86	0.92	0.21	0.25			
2841	9.52	0.87	0.21	0.24		0.85:	
2985	10.31	0.83	0.17	0.15			
3031	8.36	1.03	0.36	0.30		1.48:	
3079	9.77	(2.08	0.75)	0.61	−0.22:	3.70:	1.9
3642	11.42	0.93	0.24	0.26			
3718	10.15	1.17	0.35	0.32		<2.17	
3898	9.86	1.01	0.30	−0.02			
3992	10.88	0.94	0.21	0.19		<3.96	
3998	9.25	0.91	0.25	0.26		1.86:	3.9
4036	10.04	0.98	0.35	0.30		1.86:	
4096	11.87	0.97	0.28	0.46:		<3.81	
4111	9.18	0.90	0.23	0.23		1.00:	
4125	9.88	0.85	0.20	0.20		<3.28	
4216	9.47	1.10	0.27	0.20		<2.12	
4278	9.37	0.95	0.25			<1.78	
4303	10.13	1.00	0.21	0.35:		3.10:	
4419	10.06	1.15	0.33	0.35		3.50:	2.9
4438	9.77	1.08	0.32	0.24		2.02:	<3.8
4450	10.39	1.02	0.32	0.27		2.02:	
4486	9.76	0.96	0.23				
4501	10.06	0.99	0.27	0.29		<2.62	
4569	9.64	0.92	0.29	0.39:		2.89:	3.1
4579	9.79	0.95	0.30	0.38	−0.10:	2.53	<3.0
4589	10.36	0.91	0.25	0.32			
4594	8.64	0.85	0.06	0.47		0.57:	
4736	8.21	0.99	0.30	0.27	−0.41:	1.93:	
4826	9.05	1.05	0.33	0.11	−0.28:	2.55:	2.3
5055	9.67	0.68	0.12	0.40		<1.63	
5195	8.40		0.42	0.49:	0.92:	3.07:	1.8
5371	11.04	0.91	0.22	0.21			
5474	14.01	0.79	0.18				
7217	10.14	0.94	0.22	0.12			
7479	11.17	1.16	0.38	0.81		4.97	3.0
Anon	11.99			0.34			
2911	10.78	1.00	0.28	0.19		<2.89	

NOTES.—All $J-K$ and $H-K$ colors shown are in the CIT system except NGC 3079. Differences in photometric systems may account for some of the variance in other colors. The $L-N$ color is not corrected for the possibly different beam sizes used. Colon indicates the uncertainty is greater than 0.10 mag. Upper limits are 3 σ.

and Geller 1982; Geller and Huchra 1983; RC2). Velocities were translated to distance based on a Virgo infall model (Aaronson *et al.* 1982*a*) with an infall velocitiy of 250 km s^{-1} and a Hubble constant of 67 km s^{-1} Mpc^{-1}. These parameters give good agreement for three groups with distances determined from other indicators (Sandage and Tammann 1974*a*, *b*) and with the Tully-Fisher distances. We therefore believe that the distances used are on a consistent scale. The only exception is the group HG 56, which contains NGC 3368 and 3623. The Tully-Fisher distance, based on five galaxies, is 21.8 Mpc, while the redshift distance of the group is 11.8 Mpc. The two LINER galaxies have much lower velocities than the group average, and the smaller distance has been adopted.

The resulting distances are strongly concentrated near the distance of the Virgo Cluster, here taken to be about 20 Mpc. At this distance, the usual beam sizes of 5″–6″ correspond to linear dimensions of 500–600 pc. Because so many of the galaxies are at similar distances, the discussion that follows can use either observed or intrinsic fluxes with little difference in the results.

b) Near-Infrared Colors

The near-infrared colors of the LINER nuclei are much the same as those of normal galaxies, implying that the LINER phenomenon has not had a detectable effect on the stellar population within a radius of 250 pc of the nucleus. Figure 2 shows the $J-K$ versus $H-K$ diagram for the LINER nuclei. The ellipse indicates the mean and dispersion of the colors of a comparison sample.

A suitable comparison sample is available from Aaronson (1977): spiral nuclei from the HBC or Keel samples, not known to be LINERs or other types of strong emission galaxies, and measured with beam sizes smaller than log $A/D(0) \leq -0.90$. (Different comparison samples, such as those of Glass 1984 or Willner *et al.* 1984, would give the same results.) There are 30 galaxies in the adopted comparison sample, two of which,

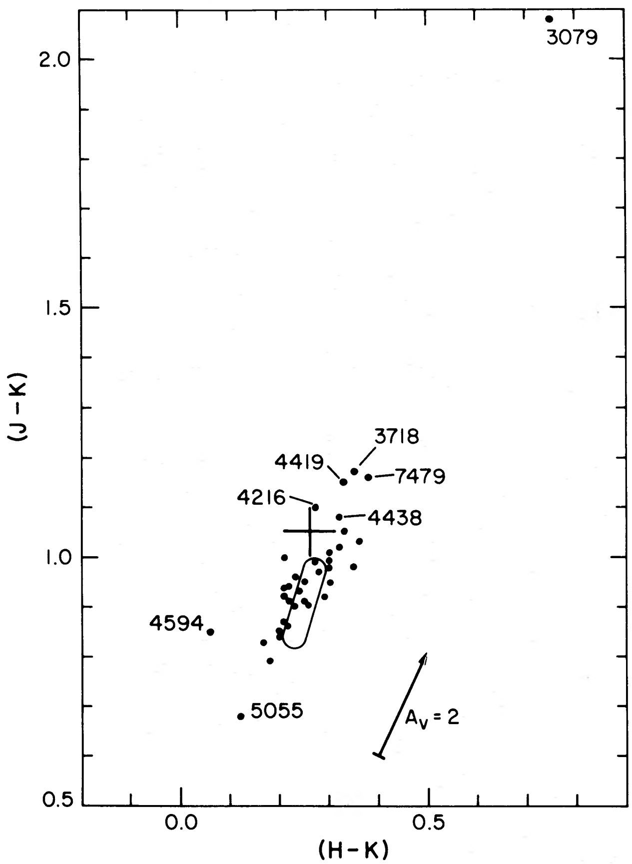

FIG. 2.—Two-color diagram for the LINER nuclei. All colors plotted are on the CIT system. The arrow indicates the reddening vector, the cross denotes the colors of a sample of normal galaxies (Willner *et al.* 1984), and the curve encloses the region of most of the galaxies in the comparison sample from Aaronson (1977) discussed in the text.

NGC 5907 and 3628, are redder than the rest. The former has the highest inclination of any galaxy in the sample, and the latter is described by Keel (1983*a*) as edge-on. We conclude that reddening provides a plausible explanation for the colors of these nuclei, although emission from nuclear H II regions cannot be excluded. NGC 2146 was omitted from the comparison sample because it has an obscured H II region nucleus (Keel 1984). An unpublished spectrum obtained at the Mount Hopkins 1.5 m telescope shows strong Hα, [N II], and [S II] emission with weak Hβ and [O III] emission.

The actual color distributions of the LINER nuclei and the comparison sample are identical except for the reddest four nuclei shown in Figure 2. (The dispersion in the LINER sample is slightly larger than in the comparison sample, but this is undoubtedly because most of the LINERs were observed at the MMT, where photometric precision is typically not as good as with conventional telescopes.) The reddest LINER nucleus, NGC 3079, is in a highly inclined galaxy and is heavily reddened (Paper I). Its near-infrared colors are consistent with normal intrinsic colors and a reddening of $A_V \approx 10$ mag. NGC 1052 also has a red nuclear component and has been discussed in detail by Rieke, Lebofsky, and Kemp (1982) and by Becklin, Tokunaga, and Wynn-Williams (1982). It is therefore not discussed below, nor is it included in Figures 2 and 3, because we cannot transform the measurements to the same photometric system.

The remaining three relatively red LINER nuclei can be explained either by about 2 visual mag more reddening than the other nuclei or by a cooler stellar population, perhaps due to higher metallicity. Reddening in the Milky Way is insufficient to account for the excess extinction. The three red LINER nuclei are all in galaxies of lower inclination than are either of the red nuclei in the comparison sample. We therefore conclude that the red colors are properties of the nuclei rather than of the surrounding galaxies. One of the red LINERs, NGC 7479, has excess infrared emission at 3.5 μm, and a small amount of emission at 2.2 μm could account for the red colors. The other two galaxies have normal $K-L$ colors. The Hα/Hβ ratio should be measured in these three galaxies to see if reddening is a substantial factor. Direct study of the stellar population could also be interesting, but it might be difficult to obtain sufficiently good spectra.

Even at wavelengths as long as 3.5 μm, almost all of the LINER nuclei have the same colors as normal galaxy nuclei. Figure 3 shows a two-color diagram that includes the $K-L$ color. *L* band measurements of normal galaxy nuclei with which to compare the LINER nuclei are regrettably rare. The cross shows results (Willner *et al.* 1984) for a very small sample of normal nuclei. As in Figure 2, most of the dispersion is along the reddening line. NGC 7479 is again the exception, showing a clear excess over stellar colors at 3.5 μm. It shows considerable dust emission at longer wavelengths, and its large ratio of 10 μm (dust) to 1.6 μm (stellar) emission is similar to many starburst and Seyfert 2 nuclei (Paper I). It is thus natural to interpret the 3.5 μm emission as due to dust, and the likely presence of some emission at 2.2 μm is no surprise. Its optical spectrum (Keel 1983*c*), total line luminosity, and probably line morphology (Keel 1983*b*) do not distinguish NGC 7479 from the many LINERs without 3.5 μm dust emission. It is somewhat surprising that no other LINER nuclei show dust emission at 3.5 μm, but we note that other nuclei having the same 10–3.5 μm slope as NGC 7479 would not be seen at 3.5 μm because of their relatively larger flux from starlight (Fig. 1).

The lack of emission of most LINER nuclei at 3.5 or 5 μm limits the amount of hot dust that can be present. Most of the nuclei show substantial dust emission at longer wavelengths, and the lack of 3.5 or 5 μm emission implies an upper limit on the typical dust temperature of about 350 K. Evidently the dust is far enough from the heat sources to prohibit short wavelength emission. A typical luminosity absorbed and reradiated by dust is 10^{42} ergs s^{-1}; if this represents the entire heating of the grains, they must be between 0.1 and 1 pc from a single source and correspondingly closer if there are multiple heating sources. These distances are comparable to the distances of broad line clouds in Seyfert nuclei and much less than distances thought appropriate for narrow line emitting clouds. In view of the evidence for high densities in LINERs (Filippenko 1985), we regard the small distances as a possibility for some nuclei.

c) Mid-Infrared Emission

Paper I and the additional data in Table 2 show that emission at 10 μm and longer wavelengths in excess of starlight is common for LINER nuclei. The 10 and 20 μm measurements together with the upper limits on any nonstellar component at 3.5 or 5 μm imply a curved spectrum, and therefore the most likely source of the excess emission is thermal radiation by dust (Paper I). There are, however, many possible reasons for dust

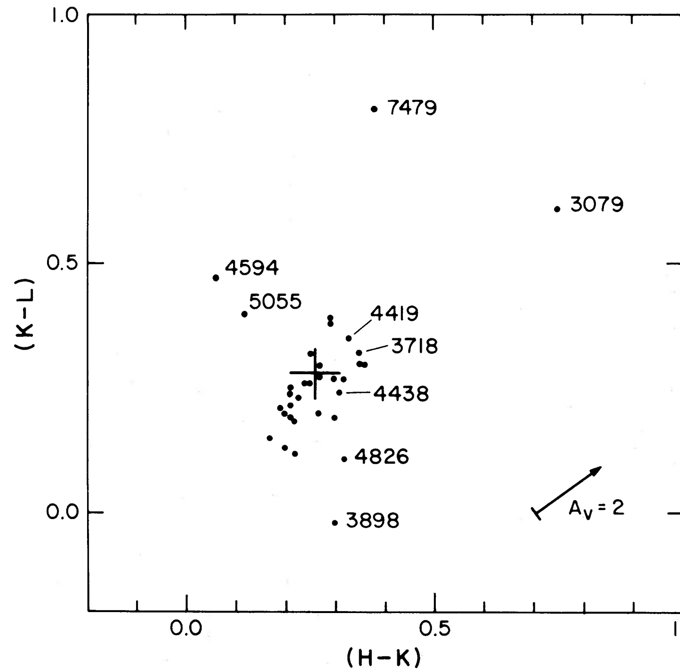

FIG. 3.—Two-color diagram for the LINER nuclei, this time including the $K-L$ color. Symbols have the same meanings as in Fig. 2.

emission from galactic nuclei, and whether the excess radiation is directly related to the LINER phenomenon must be examined. This section discusses the general characteristics of the dust emission, the frequency of its occurrence, and the correlation with emission lines. The next section examines whether a single source could both heat the dust and ionize the gas responsible for the emission lines.

One approach is to examine the relative frequency of dust emission in LINER and non-LINER nuclei. If dust emission is more common in the LINERs, one would conclude that the LINER phenomenon must be responsible for much of the dust emission. Testing this hypothesis is difficult, however, because of the lack of adequate comparison samples. The largest unbiased study at 10 μm was presented by Scoville *et al.* (1983), who measured 53 galactic nuclei in the Virgo Cluster. We consider only the 29 nuclei in common with the Keel (1983*a*) sample, because only for these is there adequate spectroscopic information to distinguish the LINERs. This constraint also limits the sample to the intrinsically brightest galaxies and thus avoids confusion by any possible correlation of luminosity with both LINER status and 10 μm emission. We also eliminate from consideration NGC 4388, which has a Seyfert nucleus and is the brightest galaxy measured by Scoville *et al.* (1983). Figure 4 gives histograms of 10 μm flux densities for the LINER and non-LINER nuclei. The noise in the measurement of each nucleus was the same, and not all of the nuclei were detected individually. Indeed, some of the measurements gave negative results, as expected if the true fluxes are small compared to the measurement noise.

Figure 4 suggests that the LINER nuclei indeed tend to be brighter than non-LINER nuclei. For example, seven of nine LINERs, but only eight of 19 non-LINERs, have 10 μm flux densities above the 1.5 σ level. Some of the non-LINER nuclei have emission lines in ratios indicating the presence of H II regions, from which some 10 μm emission will result. The LINERs, however, are selected against having a strong component arising from normal H II regions. Consideration of the presence of H II regions strengthens the suggestion that the phenomenon causing the optical lines also gives rise to the infrared emission. In this small sample, however, the statistical significance of that result is not as high as it might seem. Two tests of whether two samples are drawn from the same population are the Kolmogorov-Smirnov test and the Mann-Whitney "*U*-test." Neither test requires that the data be binned, as they are in Figure 4 for illustration. Both tests imply

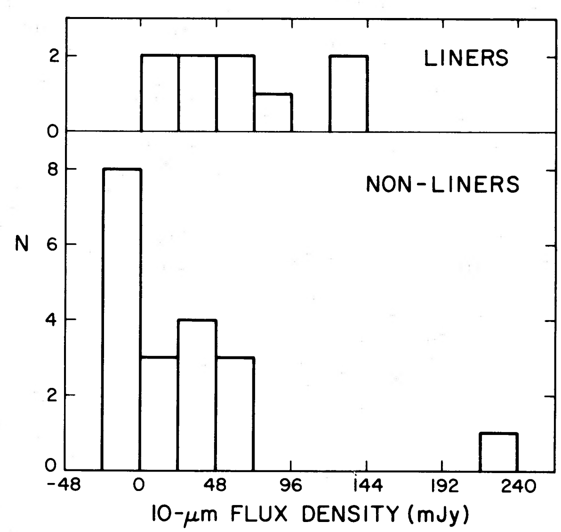

FIG. 4.—Histogram of 10 μm flux densities of LINER and non-LINER nuclei in the Virgo Cluster. The data are from Scoville *et al.* (1983), who measured each nucleus with the same noise level. The bin size corresponds to 1.5 times the measurement noise, and nuclei in the two lowest bins are likely to have individual flux densities smaller than 2 or 3 times the measurement noise. The brightest nucleus is NGC 4536, which has strong emission lines characteristic of photoionized H II regions.

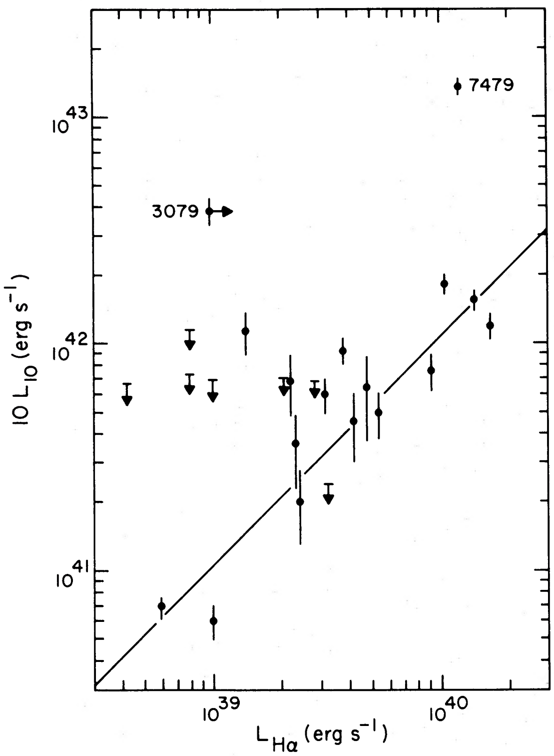

FIG. 5.—Plot of 10 μm luminosity (λF_λ) versus Hα luminosity for LINER nuclei. Upper limits shown are 3 σ, and the arrow on NGC 3079 indicates that a large correction for reddening is needed. The line indicates the expected luminosity of dust that absorbs and reradiates all of the energy from an ionizing source taken to have a power-law spectrum with a slope of 1.5. For nuclei measured more than once at 10 μm, the weighted average of all measurements is plotted.

that the differences between LINERs and non-LINERs are significant at the 95% level.

Another approach is to see whether the 10 μm luminosities of the nuclei in our sample are correlated with the emission-line luminosities. Such a correlation would be expected if both line and dust emission are due to the same underlying source. Figure 5 shows a plot of the luminosities for all nuclei in our sample having both available. A plot with fluxes instead of luminosities would be nearly equivalent, because most of the galaxies are at nearly the same distance. Figure 5 shows that there is not a tight correlation between the two quantities, but the lower envelope of the plot does slope up to the right. Indeed, there are *no* nuclei that have strong Hα and weak 10 μm emission. We interpret this as evidence that the LINER phenomenon gives rise to a minimum amount of dust emission, but LINER nuclei can coexist with other phenomena that also cause emission at 10 μm. In order to quantify the relationship, we ignore other processes and look simply for the slope of the best fit to the data in Figure 5 and in a similar plot using [N II]. (NGC 3079 has been omitted because of the large extinction affecting the emission lines, and NGC 7479 has been omitted because the near-infrared data are direct evidence of an additional emission process.) Applying the "detections and bounds" maximum likelihood method (Avni *et al.* 1980; see Fabbiano, Feigelson, and Zamorani 1982), we find that the 10 μm luminosity is correlated with both the Hα and [N II] luminosities with greater than 3 σ significance. The best-fit slope is in both cases unity. Since the nuclei with weak lines but strong 10 μm fluxes would weaken these correlations but are not contrary to our hypothesis, we consider the existence of a statistically significant correlation to be good evidence that the LINER phenomenon indeed gives rise to 10 μm emission.

There is ample evidence that the infrared emission is not the same in all nuclei. One difference is in the 10–20 μm slopes or color temperatures. Paper I found that in a small sample of LINERs, the 10–20 μm slopes were similar and flatter than in starburst or type 2 Seyfert nuclei. NGC 2681 snd 5195 are additional LINERs with flat slopes. However, we have now found examples of LINER nuclei having steeper slopes between 10 and 20 μm, although still flatter than the steepest slopes found for starburst and Seyfert 2 nuclei. Examples of nuclei with steep slopes are NGC 1052, 3998, 4419, 4569, and 7479. The last and possibly the first of these might be discounted because of their unusual near-infrared properties, but the others cannot. Too few objects have been observed to say whether there is a continuous distribution of slopes or two distinct groups, but LINERs clearly have heterogeneous energy distributions. Carswell *et al.* (1984) found evidence for different ionizing spectra in two radio-bright LINER nuclei. Further investigation is needed to determine whether there is a connection between ionizing spectrum and infrared properties.

Another possible difference is in the angular sizes. The emission in NGC 3079, for example, is extended on a scale of several hundred parsecs (Paper I). NGC 5195 was also noted by Rieke (1976) to be extended. NGC 1052, on the other hand, is indistinguishable from a point source (Becklin, Tokunaga, and Wynn-Williams 1984). For both NGC 3079 and 5195, however, a substantial fraction of the flux could come from a point source. Figure 6 presents the observations of NGC 3079 compared with the beam profile.

It is intriguing that the two sources known to be extended both have flat 10–20 μm slopes, while NGC 1052, the one known point source, has a steep slope. The available information on the spatial extent of the optical emission lines (Keel 1983*b*; Heckman *et al.* 1983) is limited and possibly irrelevant to the 10 μm extent; for NGC 1052, the emission lines are extended (Fosbury *et al.* 1978) over a much larger region than the 10 μm emission (Becklin, Tokunaga, and Wynn-Williams

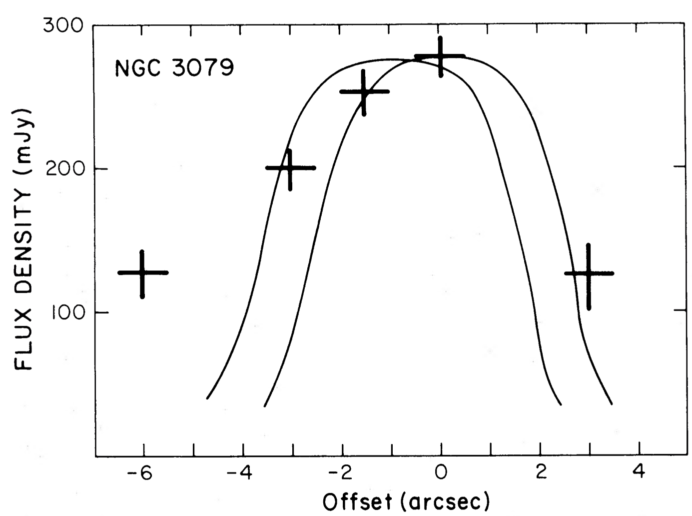

FIG. 6.—Measurements of NGC 3079 at 10 μm as a function of position. The curves indicate the point source response in two positions. Although the source is definitely extended, a considerable portion of the flux could come from a point source component.

1982). Nevertheless, optical line measurements do not contradict the hypothesis that flat spectrum sources may be more extended than ones with steep spectra.

d) Luminosity and Ionization

This section shows that it is possible for a single energy source both to ionize the line-emitting gas and to heat the infrared-emitting dust. An ionizing source with approximately a power-law spectrum has frequently been suggested to explain the optical spectra of LINERs and similar nuclei (Ferland and Netzer 1983; Halpern and Steiner 1983; Halpern and Filippenko 1984). For the rough comparison below, we assume that such a source exists, that all of the ionizing photons are absorbed by hydrogen gas, and that all of the energy emitted shortward of 0.5 μm (corresponding to $A_V \approx 1$ in the nucleus) is absorbed by dust and reemitted in the infrared. (The last assumption is a good approximation because at most a small fraction of the energy can emerge in the Balmer and higher line series.) In view of the observed energy distributions, we also assume that the 10 μm flux densities give an adequate indication of the infrared luminosities. This simple scenario may underestimate the infrared luminosity by neglecting any emission at wavelengths much longer than 10 μm, but it likewise underestimates the power available to supply that luminosity by neglecting ionizing photons absorbed by dust rather than by gas.

The observed line fluxes determine the number of ionizing photons and thus the luminosities of the ionizing sources. Ferland and Netzer (1983, eq. [2]) give an expression for the equivalent width of Hβ. Inserting the wavelength dependence of the power law, $F_\nu \propto \nu^{-\alpha}$, and a typical ratio H$\alpha$/H$\beta$ = 3 gives

$$\left(\frac{F_\nu}{\text{mJy}}\right) = 4.7 \times 10^{-3}\alpha\left(10.97\,\frac{\lambda}{\mu\text{m}}\right)^{\alpha}\left(\frac{F(\text{H}\alpha)}{10^{-14}\ \text{ergs s}^{-1}\ \text{cm}^{-2}}\right). \tag{2}$$

The luminosity at wavelengths shorter than 0.5 μm, where dust absorption is likely to be significant, is then given by integrating equation (2):

$$L = 2.8L(\text{H}\alpha)\left(\frac{\alpha}{\alpha-1}\right)\left(\frac{16}{3}\right)^{\alpha}, \tag{3}$$

where $\alpha > 1$. This luminosity has a broad minimum at $\alpha \approx 1.42$, about the same value as the power-law index of 1.5 suggested to explain the emission lines (Ferland and Netzer 1983). This minimum luminosity is indicated in Figure 5. Although we regard the apparent excellence of the agreement between the observed 10 μm luminosity and the calculated ultraviolet luminosity as fortuitous, the observations clearly support the assumption that the source of the ionizing photons is also responsible for heating the dust. Moreover, the dust must not compete strongly with the gas for ionizing photons. If it did, the emission lines would be weaker and the dust emission larger, resulting in most of the points falling considerably above the line in Figure 5. The dust luminosities estimated in Figure 5 do not include any luminosity that may emerge as considerably longer wavelengths than 10 μm, but the measured ratios of 20 μm to 10 μm flux densities suggest that far-infrared emission from the nuclei is likely to be negligible.

The observations do not require that the ionizing source have a power-law spectrum; on the contrary, the observations rule out any such spectrum that extends from infrared to soft X-ray wavelengths. The most sensitive limits on a potential power-law component in the infrared are set by the 3.5 μm observations. Most of the 3.5 μm flux is from stars, but a limit on any nonstellar component can be derived from the assumption that all of the 2.2 μm flux is from stars with a $K-L$ color of 0. The resulting upper limits are plotted in Figure 7 along with lines indicating the expected flux density from power laws of various slopes. About half of the upper limits are inconsistent with a power law as steep as slope 1.5, and two nuclei, NGC 4303 and 4826, have such small infrared flux densities that a spectral index flatter than 1.2 is required. Moreover, the power-law flux density estimates are based on only those ionizing photons absorbed by gas; if a substantial fraction escape, the ionizing source must be brighter by a corresponding factor. At 10 μm, the results are similar but less stringent. We conclude that the ionizing sources must generally be characterized by a spectral index flatter than 1.5 and probably flatter than 1.2 between the Lyman limit and the infrared.

The relatively flat slope required by the infrared observations cannot extend into the soft X-ray region. Figure 8 shows the available X-ray fluxes of LINERs. Most of the observations were made with the *Einstein* IPC, which had a spatial resolution worse than 1′; the fluxes are then upper limits for the nucleus, because much of the X-ray emission must come from the galaxy disk. (For NGC 4438, for example, the upper limit would be a factor of 3 above the nuclear flux actually measured—Kotanyi, van Gorkom, and Ekers 1983.) The few points measured with arcsecond resolution are also plotted. As can be seen, most of the measurements require that any power-law component have a slope steeper than 1.5. Absorption of X-rays affects this result only insofar as the absorption of X-rays in our line of sight exceeds the absorption of ultraviolet radiation as seen from the line-emitting region.

The failure to detect the ionizing source in either the infrared or in X-rays implies that its spectrum cannot consist of a single power law. One possibility is that the LINERs are shock heated after all, so no power-law source is expected. Shock heating, however, gives no obvious explanation for the observed dust emission. The other possibility is that the photoionization source has a different spectral shape than a power law. A hot blackbody-like component could supply the ionization without violating the infrared or X-ray upper limits. Indeed Péquignot (1984) found that postulating such a component gave the best match to the observed line ratios for NGC 1052. Such a component has been found by Malkan and Sargent (1982) in the spectra of some Seyfert 1 nuclei and QSOs; if a similar component exists in LINERs, the 3.5 μm and X-ray upper limits for many nuclei require that it be larger with respect to any power-law continuum than the blackbody-like component in 3C 273. Another possibility is the existence of a break in the spectrum between the infrared and ultraviolet. This behavior is commonly observed for BL Lacertae objects (Cruz-Gonzalez and Huchra 1984), which have much higher luminosities and where the central source is probably being observed directly. The turnover is thus consistent with the view that the LINER phenomenon is simply a low-luminosity version of the same process that produces other active nuclei. Another possible heating and ionizing source would be a population of extremely hot stars (Terlevich and Melnick 1985).

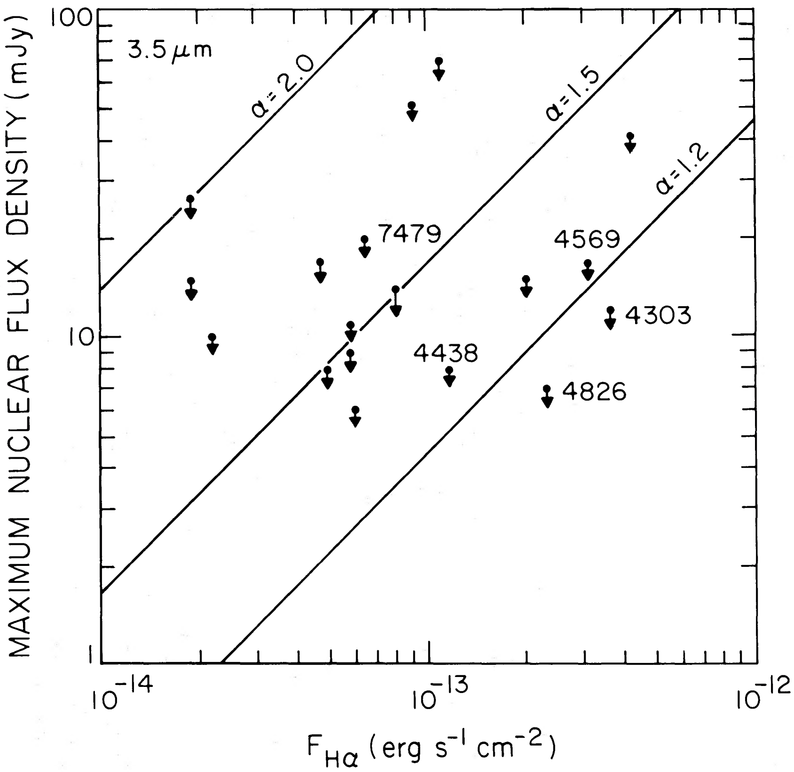

FIG. 7.—Maximum 3.5 μm flux density from a nonthermal component of LINER nuclei vs. Hα flux. Only upper limits are given, because the 3.5 μm measurements are consistent with all of the flux being from stars (or from dust for NGC 7479). NGC numbers of a few nuclei are indicated.

Many LINER galaxies emit an order of magnitude more luminosity beyond 20 μm than was considered above (Rickard and Harvey 1984; *IRAS Point Source Catalog*). These large luminosities cannot be powered by the nuclei unless the emission lines greatly understate the nuclear luminosities. However, all of the far-infrared measurements used large beam sizes, 40″–50″ for Rickard and Harvey (1984) and even larger for *IRAS*. Figure 1 shows the 12 and 25 μm measurements from the *IRAS Point Source Catalog* as well as the 10 and 20 μm measurements with small beam sizes. As can be seen, the large beam measurements give much larger fluxes. Most likely, the galaxy disks are giving a considerable contribution to these measurements; the disk is certainly the major contributor for NGC 3079, which has a far-infrared size of 30″ (Low, Gillett, and McCarthy 1984). Even the measurements of NGC 1052, which shows a relatively small difference between large and small beams, may contain a considerable contribution from the galaxy outside the nucleus (Neugebauer *et al.* 1984). Far-infrared measurements in a small beam would be of considerable interest, especially as the Halpern and Steiner (1983) model would predict relatively large fluxes. Such measurements probably cannot be made with existing instruments.

V. CONCLUSIONS

LINER nuclei show dust emission at wavelengths of 10 μm and longer. In contrast to many Seyfert nuclei, however, starlight rather than the long wavelength emission dominates the luminosity. The 1.25–3.5 μm colors show no differences between the stellar populations of the LINER nuclei and normal spiral nuclei.

The correlation between dust and line luminosities in the LINER nuclei and the amount of dust emission imply that the same ultraviolet source photoionizes the gas and heats the dust. For most nuclei, the observed dust luminosities are small enough that the dust must not compete strongly with the gas for ionizing photons, except in the unlikely cases of a very narrow ionizing spectrum or very large far-infrared luminosity from the nucleus. The observations thus favor models in which the gas is photoionized by a weaker or more distant central source than is typical of Seyfert nuclei, rather than models in which the ionization parameter is reduced by dust absorption.

Observations in the infrared and soft X-ray regions show no trace of a putative ionizing source with a power-law spectrum, except possibly for a very few nuclei. Four nuclei have good enough upper limits to preclude such a spectrum unless a special geometry produces much higher than expected X-ray absorption. A more plausible explanation for the absence of a power-law component is that the ionization results from a hot thermal spectrum as might be found for an accretion disk (Péquignot 1984) or a population of high-temperature stars (Terlevich and Melnick 1985). Carswell *et al.* (1984) concluded that different ionizing spectral shapes were required in different LINER nuclei. Understanding the physical origin or origins of the LINER ionization will require investigation of how the infrared properties, both size and energy distribution, are related to the ionizing spectrum.

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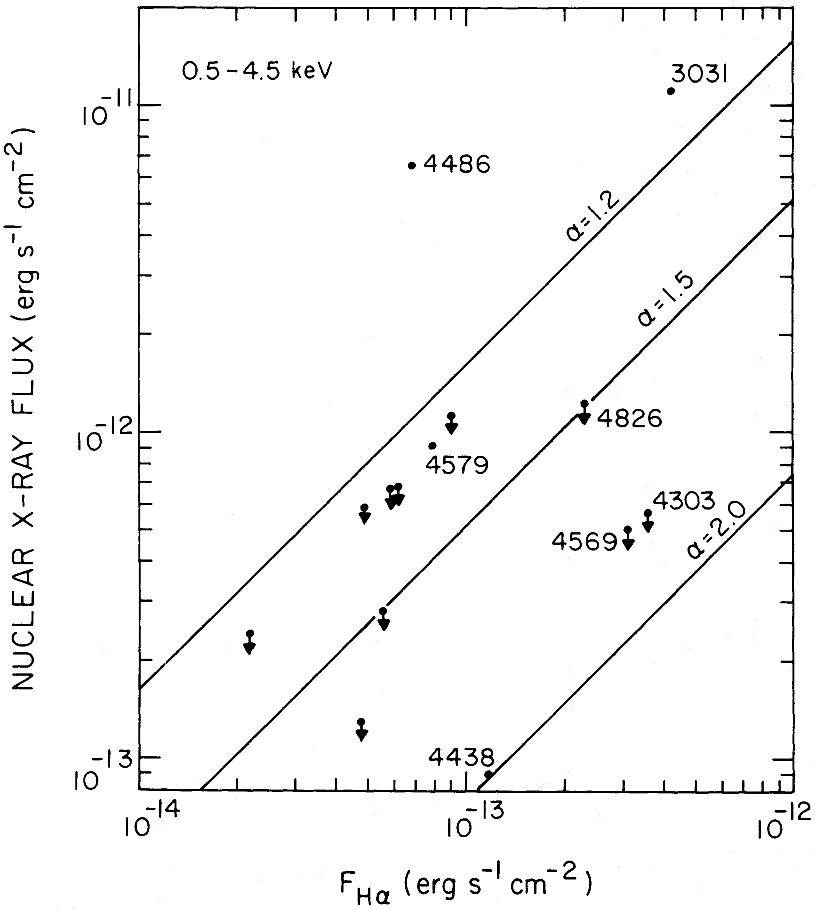

FIG. 8.—X-ray flux from LINER nuclei vs. Hα flux. Upper limits indicate observations with the *Einstein* IPC, which generally includes a substantial contribution from the galaxy disk. The points indicate observations with the HRI; all of these except those of NGC 4486 (M87—Schreier *et al.* 1982) are consistent with a point source component. Other observations come from Forman (1985), Elvis and Van Speybroeck (1982), Long and Van Speybroeck (1983), and Kotanyi *et al.* (1983). Small corrections have been applied where the observed energy range differs from that used in the figure. The lines indicate the expected flux of power-law components bright enough in the ultraviolet ionize the line-emitting gas; the lines are labeled with the corresponding slopes.

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