

NEAR-INFRARED LOW-RESOLUTION RADIAL LUMINOSITY DISTRIBUTIONS OF NEARBY ACTIVE GALAXIES

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Received 16 March 1992; revised 7 May 1992

ABSTRACT

We present low-resolution near-infrared (NIR) radial brightness and color profiles of a small sample of nearby Seyfert, starburst, and LINER galaxies. These profiles are used to determine extranuclear NIR colors and to determine the nuclear flux in the observing aperture. We find that the NIR nuclear continua in some Seyferts (NGC 3227 and NGC 5506) are well fit by a reddened power law with flat indices ($\alpha \sim 0.0$ – 0.5) and substantial reddening ($A_V \sim 5$ – 10 mag), implying that the continua suffer from more extinction than does either the broad-line region or the narrow-line region. In a Seyfert 2 (NGC 1068), there is not only excess nuclear emission (in the K and L bands) relative to the host galaxy brightness profile, but also a central depression (in the J and H bands). Excess nuclear emission relative to the surrounding galaxy is also present in two starbursts (NGC 520 and NGC 2782) and seems to be due to hot dust, or hot dust together with H II-region emission. Finally, we find evidence for violent star formation on kpc scales around the nucleus in each of the activity classes, that is to say in six of the nine galaxies studied.

1. INTRODUCTION

Previous studies of active spiral galaxies have been primarily aimed at describing the continuum and spectroscopic properties of the nuclei, while relatively little attention has been paid to the surrounding galaxy. The preponderance of disturbed morphologies in active galaxies (Simkin *et al.* 1980; Arsenault 1989; MacKenty 1990) induces one to believe that the galaxies surrounding active nuclei are rarely quiescent systems. Indeed, peculiar morphology is typically associated with enhanced star formation and the relationship between nuclear activity and violent star formation is neither clear nor understood.

Although optical color indices are indicators of star formation (e.g., Larson & Tinsley 1978), they are affected by extinction, population age, and chemical composition. In contrast, the near-infrared (NIR) bands suffer minimally from these influences and are relatively insensitive to the effects of star formation of the kind seen in quiescent spiral disks.¹ Indeed, the NIR colors of normal spiral nuclei represent a composite old stellar population (which will hereafter be referred to as a “normal late-type stellar population”) and, consequently, the spread of NIR colors in normal spiral galaxies is relatively small and does not change appreciably with morphological type (e.g., Johnson 1966; Aaronson 1978; Griensmith *et al.* 1983; Glass 1984; Frogel 1985). Although small-scale (≤ 1 kpc) NIR color gradients may be present in disk galaxies (e.g., Frogel 1985), large-scale (few kpc) color gradients are not gen-

erally observed in either early or late-type spirals (Giovanardi & Hunt 1988; Giovanardi & Hunt, in preparation). However, in galaxies with violent star formation, where star formation rates are much higher than those seen in normal spiral disks, NIR imaging shows that colors present spatial gradients and are generally much redder than those of normal spirals (e.g., Telesco *et al.* 1991; Stanford & Balcells 1990; Hutchings *et al.* 1990; Carico *et al.* 1990; Eales *et al.* 1990). NIR color gradients are also observed in interacting disk galaxies (Bushouse & Werner 1990), and Joseph *et al.* (1984) found that the K – L color in interacting galaxies is much redder than that of a normal late-type stellar population; they attributed the color excess to warm dust in emission associated with violent star formation induced by the interaction.

Factors that may influence *extranuclear* NIR colors include thermal emission from ionized gas in H II regions, hot dust in emission, anomalously red or blue stellar populations, and dust extinction. Violent star formation is typically associated with these phenomena, and, conversely, red extranuclear colors are observationally evident in galaxies where violent star formation is occurring (see above). Therefore, the invariance of NIR colors in quiescent systems provides a diagnostic tool for investigating violent star formation in the inner regions of active galaxies. In practice, away from the nucleus any deviation from normal late-type stellar population colors can be attributed to enhanced star formation.

Several previous studies of the NIR characteristics of active systems have relied on multiaperture photometry to ascertain the presence of radial color gradients and abnormal NIR colors of the surrounding galaxy (e.g., Glass & Moorwood 1985; McAlary & Rieke 1988). However, be-

¹Although J – K has been used to indicate metallicity, the maximum of the range of trends with abundance is roughly 1.0 typical of that seen in normal spiral galaxies (Thuan 1983; Bothun *et al.* 1984).

cause of obvious constraints on aperture size, these studies could not properly sample extranuclear regions on scales of a few kpc. Moreover, contamination by the nuclear emission makes multiaperture determinations of extranuclear colors uncertain and not commensurate with the photometric accuracy achievable with nuclear measurements. This issue will be discussed further in Sec. 3.

We present low-resolution NIR radial brightness and color profiles of a small group of nearby Seyfert, starburst, and LINER galaxies. These profiles not only provide an accurate determination of extranuclear NIR colors with which to investigate the frequency of extranuclear enhanced star formation in active galaxies, but are also used to subtract the galaxy contribution from the central aperture measurements. Thus, nuclear properties are derived from observed quantities, and not from assumptions about either the host galaxy colors or brightness distribution.

In what follows, we first describe the observing procedure and data reduction. These are followed by an illustration of the NIR color-color plots, the brightness and color radial profiles and the models used to fit them, together with a brief discussion of their limitations. Properties of individual galaxies and of their nuclear components are described in detail. Finally, we present a discussion of the results and our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

The observations were performed at the 1.5 m $f/20$ Infrared Telescope at Gornergrat (TIRGO). The single-element InSb detector is positioned behind J ($1.2\ \mu\text{m}$), H ($1.6\ \mu\text{m}$), K ($2.2\ \mu\text{m}$), and L' ($3.8\ \mu\text{m}$) broadband filters with diaphragms in the focal plane defining the aperture dimensions. Detector, filters, and diaphragms are cooled to solid-nitrogen temperature. Characteristics of the telescope and instrument are described in Salinari (1982) and Hartill *et al.* (1985). The coordinates of the galaxies' centers were taken from Clements (1981) if available, or from Dressel & Condon (1976). The infrared signal was "peaked-up" in all cases, resulting in positions that were typically within 5 arcsec of the nominal galaxy center. The luminosity distribution of each galaxy was sampled along the major axis with a 17 arcsec aperture and a 10 arcsec separation between each data point; the adopted position angles are those given Grosbøl (1985) or in the Uppsala General Catalogue (Nilson 1973). Because of lack of telescope time, only in one case (NGC 1068) was the luminosity distribution measured in both directions relative to the nucleus. At each position, each filter band was observed successively.

Sky subtraction was performed with a wobbling secondary at a frequency that varied from 2.1 to 12.5 Hz according to the integration time for the individual measurement. The modulation direction was parallel to the minor axis with an amplitude of 2.5 arcmin. Linear variations in the sky emission were eliminated by beam switching using two opposing reference beams along the modulation direction. We checked for stars in the reference beam both by scrutinizing the POSS prints and the on-line image intensifier

of the guiding system; when there was possibility of contamination, we either altered slightly the modulation amplitude or used the opposite semimajor axis or both. Since the data-acquisition system provides simultaneous sky measurements, reference-beam contamination was continuously monitored; contamination from external regions of the galaxy was never measurable.

Photometric calibration was performed by observing several standard stars nightly to determine zero points and atmospheric extinction coefficients. Magnitudes are given in the CIT photometric system (Elias *et al.* 1982) which, to within measurement errors, is indistinguishable from the intrinsic filter system in use at the TIRGO (Hunt *et al.* 1987).

The magnitudes corrected for atmospheric extinction were corrected for Galactic extinction according to Sandage (1973b) using the interstellar extinction curve given in Rieke & Lebofsky (1985). K dimming in the J and H bands was accounted for using the formulas given in Frogel *et al.* (1978) and velocities reported in NED.² For the L' band, the K correction was calculated by convolving a typical K5 III stellar spectrum (Strecker *et al.* 1980) with the TIRGO L' filter and results in a K correction of $-2.7z$. The K correction for the K band was calculated in the same way and also gives a correction of $-2.7z$.³ The reported magnitudes are the weighted mean of the observations, corrected for Galactic extinction and K dimming;⁴ they are not corrected for internal extinction.

When a galaxy was observed on only one occasion, the reported errors are calculated by adding in quadrature the photon-counting errors and the standard deviation of the ensemble of standard star observations on the night of interest. When a galaxy was observed more than once, the quoted error is the error of the mean of the ensemble of observed magnitudes.

The sample comprises nine nearby active galaxies. Two of the nine galaxies are Seyfert 1's (Sy 1's) (NGC 4151, NGC 3227), one is a Seyfert 1.9 (NGC 5506), one is a Seyfert 2 (NGC 1068), three are starbursts (NGC 520, NGC 2146, NGC 2782), and two are LINERs (NGC 7177, NGC 7331). Their general properties are reported in Table 1. The corrected magnitudes and colors are given in Table 2; to minimize effects of atmospheric variation, the $J-H$ and $H-K$ colors were always calculated using pairs of successive measurements. Figure 1 presents the radial profiles graphically. In what follows, we will use "central" to refer to the measurement in our observing aperture of the magnitude of the galaxy (NIR peaked-up) center.

The observed central magnitudes and colors were compared with photometry in the literature (McAlary *et al.*

²The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the U.S. National Aeronautics and Space Administration.

³For a spectrum with a power-law index of -4 and $z \leq 1$, the K correction in the K band is $-3.3z$, as given in Frogel *et al.* (1978).

⁴When the source spectrum does not resemble that of a late-type star, the applied K correction may be inappropriate; in the worst case, we estimate that the applied correction is wrong by ~ 0.03 mag, which is within the photometric errors.

TABLE 1. Sample galaxies.

NGC	RH Type	Activity	Opt. Size [arcmin]	<i>i</i> [deg]	P.A. [deg]	V_H [km s ⁻¹]	D [Mpc]	Other Names
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
520	P	*-b	5.0×2.0	66	135 ^b	2162	26	Arp 157, VV 231
1068	(R)SA(rs)b	Sy2	9.0×8.0	28	106	1153	12	Arp 37, M77
2146	SB(s)ab P	*-b	5.9×4.9	34	128	903	15	
2782	SAB(rs)a P	*-b	4.2×3.2	40	90	2550	36	Arp 215
3227	SAB(s)a P	Sy1	6.5×4.5	46	153	1165	18	Arp 44, VV 209a
4151	(R')SAB(rs)ab:	Sy1	7.0×6.0	31	134	999	17	
5506	Sa P sp	Sy1.9	2.9×1.0 ^a	70	90 ^b	1829	27	Mrk 1376
7177	SAB(r)b	LINER	3.3×2.0	53	82	1145	16	
7331	SA(s)bc	LINER	11.4×4.0	70	171 ^c	819	12	

Column 1: NGC number.

Column 2: Revised Hubble morphological classification from RC2.

Column 3: Type of nuclear activity; starburst (*-b), Seyfert (Sy), and Liner.

Column 4: Blue major and minor diameters from UGC.

Column 5: Inclination respect to the line of sight (0° for face-on) as defined by the ratio of the red diameters.

Column 6: Position Angle (eastward of North) of the major axis from Grosbøl (1985).

Column 7: Heliocentric velocity from NED.

Column 8: Redshift distance for $H_0=75$ km s⁻¹ Mpc⁻¹. The reduction to the Local Group and the correction for the Virgocentric inflow are computed as in Giovanardi & Hunt (1988).

Column 9: Number in other relevant catalogs.

NOTES: ^aOpt. size from RC2. ^bP.A. estimated from P.O.S.S. ^cP.A. from UGC.

1979; Joseph *et al.* 1984; Willner *et al.* 1984; Glass & Moorwood 1985). For comparable apertures, the central K magnitudes differ by 0.09 ± 0.10 mag; without NGC 4151 (McAlary *et al.* 1979), the difference becomes 0.06 ± 0.06 mag. The central colors agree very well with respective mean differences in $J-H$ and $H-K$ of 0.002 (± 0.05) and -0.05 (± 0.07), irrespective of the photometric system (cf., Bessel & Brett 1988).

3. DATA ANALYSIS

3.1 NIR Colors

To better ascertain the presence of radial color gradients and to determine the average colors of the host galaxy, we calculated the arithmetic mean of the NIR colors for galactocentric distances ≥ 1 kpc. The color difference between the nucleus and the mean host galaxy color was also calculated. These results are given in Table 3. Radial color and brightness profiles for each source as a function of galactocentric distance are presented in Fig. 2. The dotted line connecting the points in the brightness profiles is the best-fit model that will be discussed in the following section.

Color-color diagrams are useful preliminary diagnostics for ascertaining the contribution of nonstellar radiation to the observed colors. Although the difference between power law and dust thermal emission is not observationally apparent,⁵ both are certainly distinguishable from the ef-

fects of extinction and from the contribution of H II regions or blue stars. In addition, the fraction of nonstellar radiation in a given aperture can be estimated.

Figure 3 shows the central and extranuclear colors of these galaxies; $J-H$ vs $H-K$ is displayed in Fig. 3(a) and $H-K$ vs $K-L$ in Fig. 3(b). Note that the $K-L'$ color is transformed to $K-L$ ($3.5 \mu\text{m}$) using the Bessel & Brett (1988) transformation. The ellipse indicates the mean and typical spread of normal galaxy colors (Aaronson 1978; Glass 1984; Giovanardi & Hunt 1988). Also shown in Fig. 3 are theoretical mixtures of normal galaxy colors with nonstellar emission processes, a blue stellar population (e.g., A stars), and extinction.

3.2 Modeling of the Radial Brightness Distribution

Traditionally, galaxy brightness profiles have been fit with empirical functions which usually include an exponential disk and a (de Vaucouleurs) spheroid (Boroson 1980; Kent 1985; Kodaira *et al.* 1986). Ideally, we could determine the four best-fit parameters (two scale lengths and two surface brightnesses) using a nonlinear least-squares fit or an iterative technique (Kormendy 1977). In practice, these observations are not amenable to either method for two reasons: (1) the limited resolution and sensitivity of these profiles and the concomitant small number of data points renders the convergence of two-component least-square fits unreliable if not impossible; and (2) iterative fits rely on differential weights of the respective components in regions where either one or the other component dominates. Since our profiles never ex-

⁵This is strictly true only for "normal" power-law indices and dust temperatures.

TABLE 2. NIR photometry.

Name	#	r	J	H	K	L	J-H	H-K	K-L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
NGC 520	4	0"	11.67±0.02	10.61±0.01	10.02±0.01	8.36±0.16	1.06±0.03	0.58±0.02	1.58±0.16
	2	10"	11.98 0.05	11.15 0.05	10.77 0.01		0.88 0.01	0.39 0.05	
	2	20"	12.82 0.05	12.06 0.01	11.85 0.01		0.80 0.04	0.22 0.03	
	2	30"	13.63 0.13	12.82 0.08	12.67 0.03		0.84 0.05	0.13 0.05	
	2	40"	14.51 0.09	13.82 0.03	13.67 0.01		0.72 0.06	0.14 0.02	
	1	50"		14.63 0.12					
NGC 1068	6	0"	8.70±0.01	7.81±0.02	6.96±0.01	4.56±0.01	0.89±0.01	0.84±0.01	2.39±0.02
	4	10"	9.59 0.17	8.87 0.13	8.18 0.17	6.10 0.14	0.90 0.03	0.45 0.07	1.79 0.01
	3	20"	10.82 0.12	10.09 0.10	9.86 0.10	9.65 1.09	0.84 0.02	0.30 0.04	
	3	30"	11.59 0.07	10.94 0.07	10.68 0.07		0.73 0.01	0.25 0.01	
	2	40"	12.23 0.06	11.61 0.13	11.37 0.12		0.70 0.02	0.23 0.01	
	2	50"	12.83 0.09	12.26 0.12	11.96 0.15		0.67 0.03	0.24 0.04	
	2	60"	13.47 0.05	12.78 0.12	12.47 0.18		0.77 0.02	0.23 0.06	
	1	70"	13.91 0.10	13.20 0.06	12.78 0.08		0.71 0.12	0.42 0.10	
NGC 2146	5	0"	10.21±0.02	9.07±0.02	8.44±0.02	7.49±0.06	1.15±0.01	0.59±0.01	1.01±0.05
	3	10"	11.02 0.07	9.90 0.05	9.18 0.07		1.18 0.03	0.59 0.04	
	3	20"	11.77 0.05	10.84 0.04	10.20 0.03		0.99 0.04	0.51 0.03	
	2	30"	12.32 0.04	11.51 0.02	11.06 0.08		0.85 0.03	0.37 0.04	
	2	40"	12.76 0.06	12.10 0.03	11.73 0.05		0.71 0.06	0.31 0.05	
	1	50"	13.32 0.06	12.54 0.04	12.26 0.06		0.78 0.07	0.27 0.08	
	2	60"	13.60 0.02	12.86 0.04	12.65 0.03		0.75 0.08	0.23 0.08	
	2	70"	13.76 0.02	13.17 0.07	12.89 0.09		0.57 0.10	0.27 0.11	
NGC 2782 (17")	1	80"	13.86 0.09		13.10 0.08				
	3	0"	11.16±0.03	10.41±0.01	10.07±0.04	9.09±0.19	0.76±0.03	0.33±0.03	0.89±0.19
	1	10"	12.45 0.05	11.49 0.06	11.30 0.07		0.96 0.08	0.19 0.09	
	2	20"	13.37 0.24	12.69 0.35	12.51 0.27		0.72 0.02	0.20 0.08	
	2	30"	14.31 0.12	13.62 0.13	13.41 0.10		0.65 0.01	0.25 0.03	
NGC 2782 (21")	1	40"	14.94 0.12		13.79 0.11				
	2	0"	10.94±0.02	10.21±0.01	9.90±0.01	8.51±0.21	0.73±0.02	0.32±0.01	1.39±0.21
	2	20"	12.79 0.38	12.25 0.38	11.85 0.36		0.58 0.01	0.34 0.03	
	1	40"	14.36 0.12	13.77 0.11	13.70 0.11		0.59 0.16	0.07 0.16	
	1	60"		14.22 0.11					
NGC 3227	1	80"		15.70 0.47					
	2	0"	10.61±0.02	9.83±0.05	9.37±0.01	8.20±0.24	0.79±0.03	0.46±0.05	1.18±0.24
	2	10"	11.38 0.03	10.77 0.05	10.58 0.06	8.62 0.22	0.63 0.03	0.19 0.08	1.96 0.23
	1	20"	12.17 0.03	11.53 0.04	11.27 0.06		0.64 0.05	0.26 0.07	
	1	30"	12.79 0.04	12.07 0.04	11.82 0.06		0.72 0.06	0.25 0.07	
NGC 4151	1	40"	13.09 0.04	12.43 0.04	12.23 0.07		0.66 0.06	0.20 0.08	
	3	0"	10.14±0.03	9.35±0.03	8.78±0.04	7.27±0.18	0.79±0.02	0.58±0.01	1.51±0.14
	2	10"	11.37 0.07	10.61 0.04	10.32 0.09		0.76 0.03	0.30 0.05	
	1	20"	12.80 0.08	12.03 0.06	11.87 0.06		0.77 0.10	0.16 0.09	
	2	30"	13.39 0.11	12.74 0.06	12.61 0.07		0.65 0.04	0.13 0.01	
NGC 4151	1	50"	13.75 0.08	13.10 0.08	12.84 0.08		0.65 0.11	0.26 0.11	

TABLE 2. (continued)

Name	#	r	J	H	K	L	J-H	H-K	K-L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
NGC 5506	5	0"	11.18±0.02	9.78±0.02	8.64±0.01	6.79±0.05	1.40±0.01	1.14±0.01	1.84±0.04
	2	10"	12.24 0.06	11.51 0.01	11.21 0.04	9.42 0.01	0.75 0.07	0.36 0.07	1.74 0.09
	2	20"	12.80 0.01	12.06 0.01	11.84 0.02		0.73 0.01	0.22 0.02	
	1	30"	13.00 0.05	12.28 0.04	12.02 0.04		0.72 0.06	0.26 0.06	
	1	40"	13.23 0.06	12.47 0.05	12.35 0.04		0.76 0.08	0.12 0.06	
	2	50"	13.82 0.44	13.44 0.52	13.18 0.48		0.56 0.08	0.30 0.04	
NGC 7177	4	0"	10.34±0.01	9.54±0.01	9.29±0.01	8.43±0.12	0.79±0.01	0.26±0.01	0.80±0.12
	3	10"	11.00 0.08	10.42 0.11	10.12 0.11		0.71 0.03	0.31 0.02	
	3	20"	12.43 0.04	11.78 0.04	11.59 0.06		0.65 0.02	0.17 0.04	
	3	30"	13.16 0.03	12.39 0.09	12.27 0.05		0.72 0.11	0.16 0.04	
	2	40"	13.93 0.01	13.34 0.10	13.05 0.17		0.55 0.10	0.26 0.07	
	2	50"	14.80 0.11	14.19 0.05	13.91 0.07		0.69 0.07	0.26 0.12	
	2	60"		15.05 0.08					
NGC 7331	6	0"	9.20±0.01	8.45±0.01	8.16±0.02	7.90±0.05	0.76±0.01	0.31±0.02	0.29±0.07
	3	10"	9.83 0.11	9.06 0.09	8.73 0.10		0.77 0.02	0.22 0.01	
	3	20"	10.70 0.04	9.88 0.02	9.54 0.03		0.79 0.05	0.32 0.04	
	3	30"	11.18 0.08	10.29 0.03	9.91 0.01		0.88 0.05	0.37 0.01	
	3	40"	11.54 0.08	10.68 0.04	10.29 0.04		0.88 0.06	0.38 0.01	
	2	50"	11.88 0.07	11.00 0.10	10.62 0.09		0.88 0.03	0.35 0.01	
	2	60"	12.30 0.12	11.42 0.08	11.08 0.06		0.87 0.04	0.37 0.03	
	2	70"	12.62 0.08	11.69 0.10	11.37 0.09		0.96 0.03	0.32 0.01	
	2	80"	12.84 0.04	12.03 0.07	11.69 0.08		0.84 0.04	0.33 0.01	
	1	90"	13.14 0.06	12.39 0.03	12.03 0.04		0.76 0.07	0.36 0.05	
	1	100"	13.69 0.07	12.83 0.04	12.52 0.06		0.98 0.15	0.37 0.07	
	1	110"	13.94 0.09	13.20 0.04	12.95 0.08		0.75 0.10	0.25 0.09	
	1	120"	14.09 0.10	13.32 0.06			0.78 0.12		

Column 1: NGC number.

Column 2: Number of measurements, which if # > 1 indicates measurements on at least 2 different nights.

Column 3: Galactocentric distance of the aperture center in arcsec.

Column 4-7: CIT magnitudes measured within the observing aperture in the J, H, K, and L bandpasses and their 1- σ errors.

Column 8-10: NIR colors and 1- σ errors.

NOTE: The observing aperture is 17 arcsec except for NGC 2782 which was observed with both 17 arcsec and 21 arcsec apertures.

tend beyond a fractional radius⁶ of ~ 0.4 , when there is a substantial spheroid component the disk never dominates these profiles. In addition, the low spatial resolution makes the parameters of small scale-length spheroids difficult if not impossible to determine.

We therefore adopted the simplistic approach of single component models and for each galaxy in each band generated separate model grids for both disks and spheroids. These fits should not be interpreted as an accurate structural decomposition but only as a tool to determine the galaxy contribution to the central magnitude and as quantitative indicators of the variation of the profile shapes with wavelength band.

⁶We use "fractional radius" to denote the galactocentric distance normalized to the galaxy's optical major radius from Table 1.

Only extranuclear data points were considered in the calculation of χ^2 for the model grids; the nuclear component luminosity is easily determined *a posteriori*. Inclination (projection) effects and beam smearing were compensated for by calculating from the model distribution the flux within the observing aperture. The reduced χ^2 , χ^2_{ν} (normalized sum of the weighted square of the residuals), was calculated for a complete range of possible values for the surface brightness and scale length defining the model. Errors on the fitted parameters were estimated by the increment in the parameter that resulted in a unit increase of χ^2 . Results of the model grids are given numerically in Table 4 and graphically in Fig. 2 (for the band with the lowest χ^2_{ν}).

We have performed numerical simulations to determine how wrong the single-component fits can be at the center.

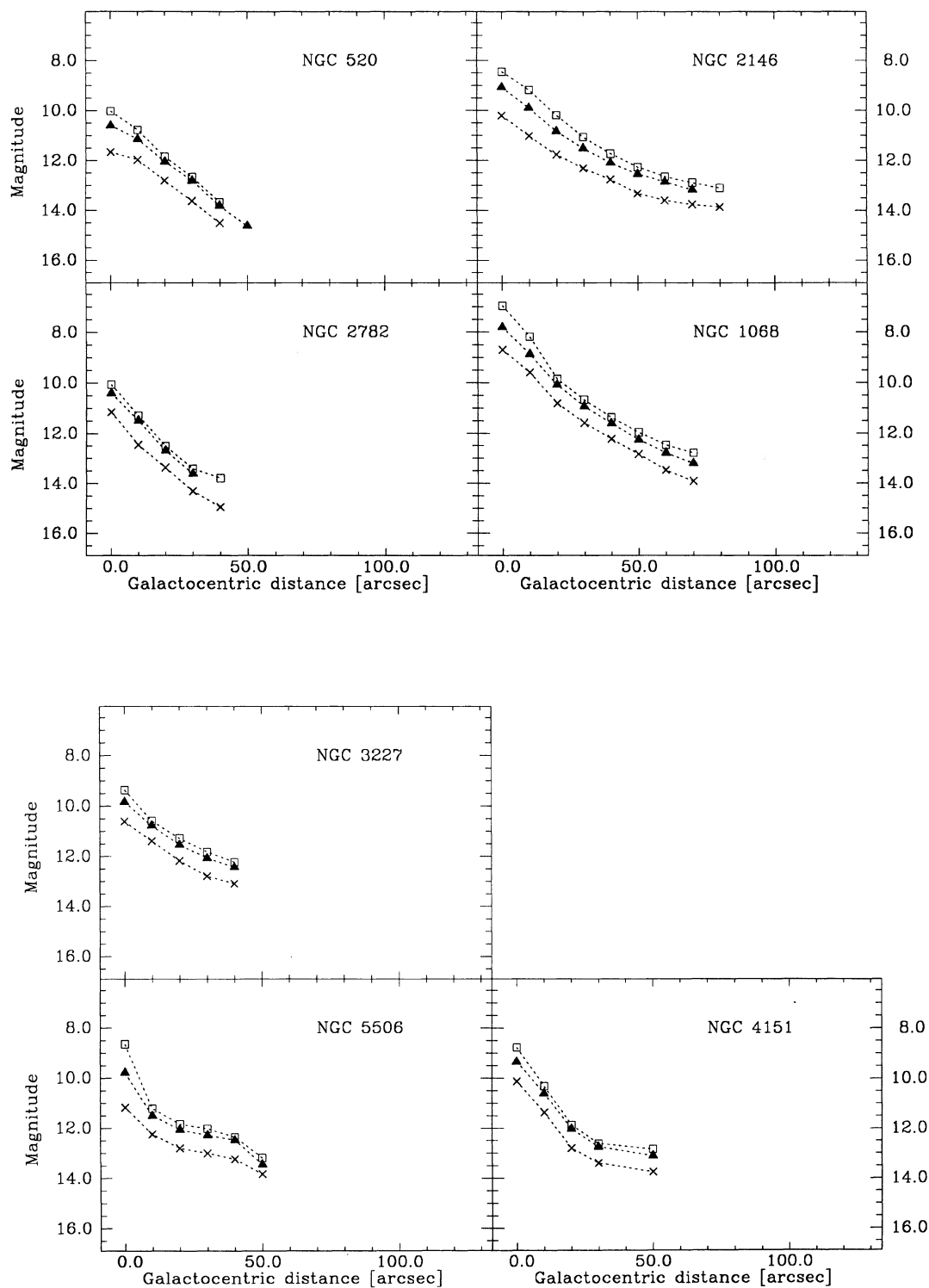


FIG. 1. Radial luminosity profiles based on 17 arcsec aperture measurements; open squares for the *J* band, filled triangles for *H*, and × for *K*. The magnitudes (in the CIT system) are corrected for extinction within our Galaxy and for *K* dimming. The data points are connected by dashed lines to help visualize the profile shape in the various bands. Panel a presents Sy2 and starburst galaxies, panel b Sy1's, and panel c the LINERs.

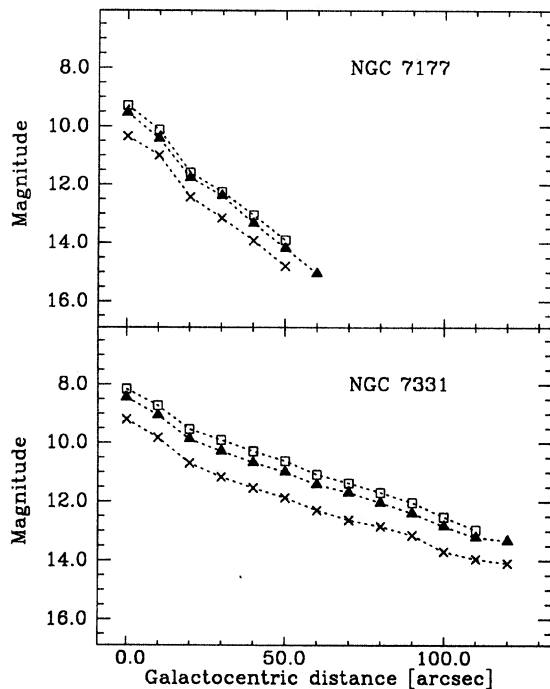


FIG. 1. (continued)

In the case of a pure bulge fit to a truly composite profile, the extrapolation of the bulge to the center underestimates the galaxy contribution. This is because the subtraction of an exponential disk from a given radial luminosity distri-

bution steepens the remaining profile. Therefore, the contribution of the galaxy to the central magnitude estimated with a pure bulge fit is smaller than that estimated from a bulge+disk fit. When a pure disk is fit to a truly composite profile, the extrapolation of the disk to the center again underestimates the galaxy contribution; this is due to the fast decline of the bulge brightness in the central regions.

The main aim of the fitting procedure was to estimate the quiescent stellar contribution in the observing aperture to the observed central magnitude. If our fits do not accurately reflect the global brightness profile, the accuracy of the extrapolations of the galaxy fits to the nucleus is questionable. We maintain that whenever the profiles in at least two bands are well fit by a single component with the same scale length/effective radius to within the errors, we can reliably use the profile extrapolation to the center to derive properties of the nuclear component. Therefore, individual cases must be carefully scrutinized, and this will be done in Sec. 4.

3.3 Derivation of Nuclear Properties

Various techniques have been devised to derive broadband optical and NIR nuclear properties of active galaxies. Single-aperture or multiaperture photometry, together with certain assumptions about the colors and the brightness distribution of the surrounding galaxy, provide nuclear-to-galaxy flux ratios and nuclear colors (e.g., Color-Given, Galaxy-Growth-Curve-Given: Sandage 1973a; Penston *et al.* 1974; Glass & Moorwood 1985; McAlary & Rieke 1988). Images in the optical bands af-

TABLE 3. Extranuclear colors.

Name (1)	$\langle J-H \rangle_o$ (2)	$\langle H-K \rangle_o$ (3)	$(J-H)_n - \langle J-H \rangle_o$ (4)	$(H-K)_n - \langle H-K \rangle_o$ (5)
NGC 520	0.79 ± 0.06 (3)	0.16 ± 0.05 (3)	0.27	0.42
NGC 1068	0.72 0.04 (5)	0.27 0.08 (5)	0.17	0.57
NGC 2146	0.73 0.10 (5)	0.29 0.05 (5)	0.42	0.30
NGC 2782	0.69 0.05 (2)	0.23 0.04 (2)	0.07	0.10
NGC 3227	0.67 0.04 (3)	0.24 0.03 (3)	0.12	0.22
NGC 4151	0.65 0.00 (2)	0.20 0.09 (2)	0.14	0.38
NGC 5506	0.69 0.09 (4)	0.23 0.08 (4)	0.71	0.91
NGC 7177	0.65 0.09 (3)	0.23 0.06 (3)	0.14	0.03
NGC 7331	0.86 0.08 (10)	0.34 0.04 (9)	-0.10	-0.03

Column 1: NGC number.

Column 2: Average J-H color, and 1- σ dispersion, of the extranuclear regions. Only measurements encompassing areas with galactocentric distance >1 kpc were included; the number of observed points included in the average is reported in parenthesis.

Column 3: Same as in Column 2 but for H-K.

Column 4: Difference between the J-H color observed at the center, $(J-H)_n$, and the average outer color $\langle J-H \rangle_o$.

Column 5: Same as in Column 4 but for H-K.

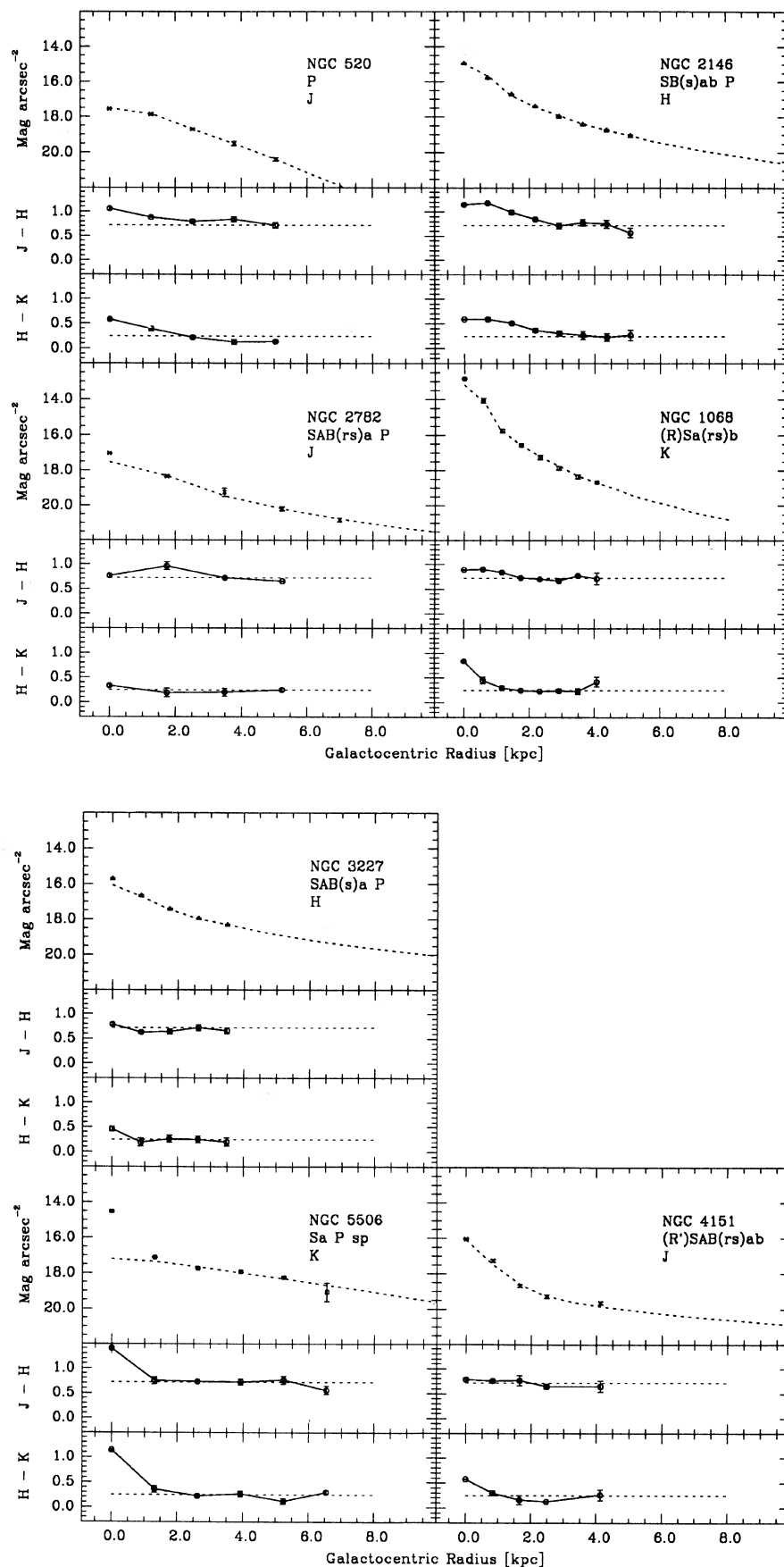


FIG. 2. Radial luminosity and color distributions and comparison with model fit. For each galaxy the upper panel shows the data points (converted to surface brightness units) with 1σ errors. The dashed line represents the model fit used to derive the nuclear component. Only the wavelength band with the best χ^2_ν is shown. The lower panels illustrate the radial trend of the observed NIR colors (not from fitting); the dashed horizontal line marks the average value for normal spirals, $J-H=0.72$, $H-K=0.25$.

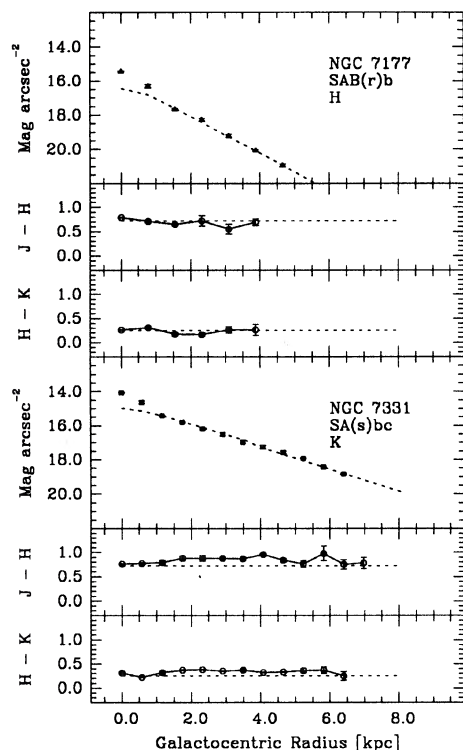


FIG. 2. (continued)

ford a more detailed description of the host galaxy since the galaxy surface-brightness profile can be fit with a bulge + disk model to derive nuclear and galaxy (optical) colors as well as relative flux ratios (e.g., Malkan & Filippenko 1983; Yee 1983; MacKenty 1990). These can then be extrapolated to the NIR assuming standard galaxy colors (Ward *et al.* 1987a).

All of these methods suffer from limitations. Neither mixing curves with single-aperture photometry nor optical imaging extrapolated into the NIR take into account non-standard galaxy colors. The use of multiaperture photometry with standard growth curves relies on the invariance of the galaxy brightness profile, regardless of individual galaxy characteristics (e.g. the bulge-to-disk luminosity ratio, disk scale length, bulge effective radius). Reddening of the nuclear component is neglected in all the above methods, although there are indications of substantial nuclear extinction (Ward *et al.* 1987a).

We take advantage of the NIR brightness distributions reported here to determine properties of the nuclear component of these systems. The method consists of fitting the NIR brightness profile and extrapolating the fit to the nucleus; this will provide an estimate of the nuclear-to-galaxy flux ratio in each of the bands observed. We then have the nuclear component colors together with the relative flux ratios; in the case of nonthermal nuclei these can be used to derive power-law spectral indices ($S_\nu \propto \nu^{-\alpha}$) and nuclear reddenings.

This method is, in principle, analogous to that used with multiaperture photometry. However, for a given measure-

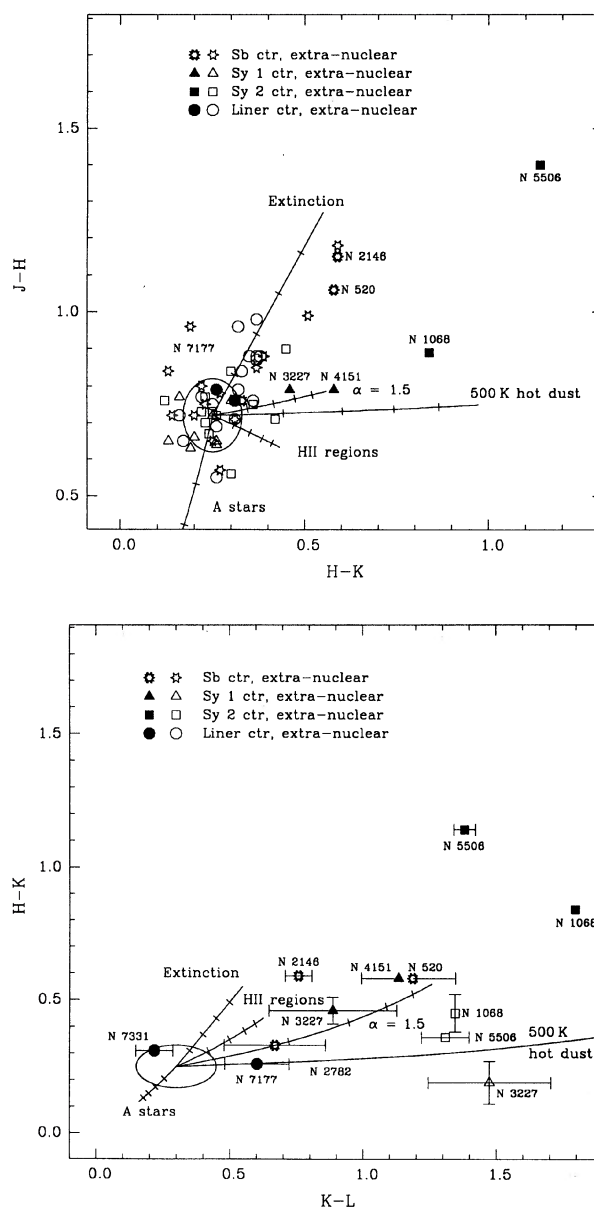


FIG. 3. NIR color diagrams. The colors observed in the sample galaxies, both at the center and at the extranuclear positions, are reported with different symbols according to different types of activity. The $K-L'$ color is transformed to $K-L$ ($3.5 \mu\text{m}$) using the Bessel & Brett (1988) transformation. The ellipse indicates the mean and typical spread of normal galaxy colors (Aaronson 1978; Glass 1984; Frogel 1985; Giovanardi & Hunt 1988). Error bars are drawn only if > 0.03 . Also shown are theoretical mixtures of galaxy colors with nonstellar emission processes (power law, $S_\nu \propto \nu^{-\alpha}$, with $\alpha = 1.5$; H II regions; dust emission at 500 K), with a blue stellar population (A-type stars), and with the effects of extinction (external screen). The mixing curves were calculated using a monochromatic approximation and the flux calibration given in Wilson *et al.* (1972). The emitting dust was assumed to be optically thin with emission coefficient $\propto \nu$. The extinction was calculated assuming an external screen and the extinction curve of Rieke & Lebofsky (1985). Colors of 0.0 were assumed for the A stars. The NIR colors of H II regions (including free-free, free-bound, and two-photon emission) were taken from Willner *et al.* (1972) (see also Thuan 1983, Sibille *et al.* 1974). The tick marks along the mixing curves indicate fractional contributions to the K band in units of 0.2 relative to the quiescent stellar contribution in the observing aperture. The ticks along the extinction line correspond to unit increments of A_V .

TABLE 4. Single component fits.

Name	Band	#	Disk			Spheroid		
			λ [kpc]	μ_0 [mag arcsec ⁻²]	χ^2_ν	R_e [kpc]	μ_e [mag arcsec ⁻²]	χ^2_ν
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
NGC 520	J	4	1.48 ± 3%	16.66 ± 0.04	0.5 ^a	3.80 ± 20%	19.56 ± 0.07	8.7
	H	5	1.48 1%	15.94 0.02	2.9	2.80 13%	18.09 0.02	47.
	K	4	1.31 1%	15.36 0.09	113.	—	—	—
NGC 1068	J	7	1.10 ± 14%	15.82 ± 0.07	8.4	1.24 ± 13%	16.85 ± 0.06	2.4
	H	7	—	—	—	1.30 17%	16.31 0.07	0.9
	K	7	1.40 56%	15.35 0.02	30.	1.27 6%	15.92 0.10	0.4 ^a
NGC 2146	J	8	—	—	—	8.76 ± 2%	20.75 ± 0.22	5.8
	H	7	1.54 ± 8%	15.80 ± 0.05	40.	4.63 8%	18.88 0.12	1.8 ^a
	K	8	—	—	—	2.48 5%	17.25 0.04	4.2
NGC 2782	J	4	2.20 ± 10%	17.45 ± 0.05	1.6	7.70 ± 3%	20.99 ± 0.14	0.5 ^a
	H	3	—	—	—	4.99 4%	19.42 0.06	0.1
	K	4	2.20 10%	16.31 0.04	10.	6.49 10%	19.63 0.16	1.1
NGC 3227	J	4	1.70 ± 10%	16.80 ± 0.03	36.	12.94 ± 11%	21.34 ± 0.15	2.3
	H	4	—	—	—	15.15 17%	20.89 0.20	0.3
	K	4	1.70 5%	15.94 0.05	3.7	16.17 14%	20.75 0.22	0.3 ^a
NGC 4151	J	4	—	—	—	—	—	—
	H	4	1.23 ± 1%	16.00 ± 0.06	113.	4.22 ± 7%	16.99 ± 0.01	30. ^b
	K	4	—	—	—	—	—	—
NGC 5506	J	5	4.90 ± 12%	18.02 ± 0.11	11.	—	—	—
	H	5	2.77 4%	16.70 0.03	66.	28.10 ± 1%	21.55 ± 0.05	33.
	K	5	3.86 6%	16.79 0.06	22. ^a	—	—	—
NGC 7177	J	5	1.00 ± 4%	16.46 ± 0.13	20.	1.38 11%	17.97 ± 0.25	7.5
	H	6	0.98 2%	15.82 0.05	6.7 ^a	0.96 8%	16.65 0.30	11.
	K	5	0.96 8%	15.51 0.09	10.	—	—	—
NGC 7331	J	12	1.71 ± 4%	15.76 ± 0.11	5.1	4.38 9%	18.70 ± 0.17	5.3
	H	12	1.67 2%	14.91 0.03	6.5	3.78 8%	17.66 0.15	15.
	K	11	1.65 1%	14.57 0.03	4.3 ^a	3.78 11%	17.22 0.17	14.

Column 1: NGC number.
Column 2: Photometric bandpass.
Column 3: Number of points included in the fit.
Column 4: Exponential scale length of the exponential disk best-fit.
Column 5: Central surface brightness of the exponential disk best-fit.
Column 6: Reduced χ^2 of the exponential disk best-fit.
Column 7: Effective radius of the $r^{1/4}$ spheroid best-fit.
Column 8: Effective surface brightness of the $r^{1/4}$ spheroid best-fit.
Column 9: Reduced χ^2 of the $r^{1/4}$ spheroid best-fit.

NOTES: ^aFit shown in Fig. 2. ^bThe profile shown in Fig. 2 refers to a composite fit with $\lambda = 7.79$ kpc, $\mu_0(J)=19.56$, $R_e=1.64$ kpc, and $\mu_e(J)=19.25$.

ment signal-to-noise ratio, multiaperture photometry measures the outer regions of the galaxy much less accurately than do brightness profiles. Moreover, observing diaphragms of at least 2 arcmin would be required to sample the galaxy to the galactocentric distance covered by the brightness profiles. By fitting brightness profiles, the galaxy contribution to the observed nuclear properties is more accurately determined. The NIR colors of both the galaxy and the nucleus are derived from the observations, not from assumptions about host galaxy properties. Details of the calculations are given in the Appendix. The uncertainty in the nuclear properties derives mainly from the uncertainty in the model fitting as discussed in the previous section.

4. RESULTS

4.1 NIR Colors

The salient features emerging from the NIR color inspection (Figs. 2 and 3 and Table 3) are as follows.

(i) The Seyfert 2 and the Seyfert 1.9 show distinctly redder central colors than both Sy 1's.⁷ As noted in Glass & Moorwood (1985), the Sy 1 nuclear colors are roughly consistent with a typical stellar population together with a low-luminosity (power law) nucleus, while the Sy 1.9 and Sy 2 colors are not so simply interpreted.

(ii) Almost all the extranuclear positions of the four Sy galaxies, with the notable exception of NGC 1068, lie within the range of normal galaxy colors in the $J-H$, $H-K$ diagram. In contrast, where data are available (NGC 1068, NGC 3227, NGC 5506), the extranuclear $K-L$ color is abnormally red.

(iii) Two of the three starburst nuclei (NGC 520 and NGC 2146) suffer from some amount of internal extinction and may contain an anomalously red stellar population or hot dust in emission or both. These same two galaxies exhibit color excesses consistent with internal extinction in several extranuclear points, i.e., on scales > 1 kpc.

(iv) The nuclei of the LINER galaxies are both within the spread of normal galaxy colors while the extranuclear positions of one (NGC 7331) lie roughly along the extinction track.

(v) In the outer regions of the (five) galaxies which do not show evidence for extranuclear extinction, the NIR colors are slightly bluer than those of normal spirals ($J-H = 0.67 \pm 0.02$, $H-K = 0.23 \pm 0.02$).

For the four galaxies which exhibit extended red JHK colors (NGC 520, NGC 2146, NGC 1068, and NGC 7331),⁸ mean extinction at 1–2 kpc away from the nucleus can be inferred from the colors assuming a typical late-type

stellar population. In these objects, the implied visual extinction, A_V , at ~ 1 kpc or more from the nucleus ranges from 1 to 2.5 mag. These observations suggest that values of $A_V \gg 1$ are not confined to nuclei and may be common in the inner regions of actively star-forming galaxies.

4.2 Nuclear Components

The profile fits of only five galaxies (NGC 520, NGC 1068, NGC 2782, NGC 3227, and NGC 5506) allowed a reliable⁹ subtraction of the galaxy contribution from the central magnitude. The derivation of the nuclear component flux densities is given in Table 5 and shown graphically in Fig. 4. In NGC 1068, the central magnitudes in the J and H bands fell significantly below the extrapolated galaxy contribution; the implications of this will be discussed in the following section.

As described in the Appendix, we fit each set of nuclear flux densities with power laws and with reddened power laws. The lack of an L -band profile precludes direct subtraction of the galaxy from the central flux. To derive the nuclear component L -band flux density, we therefore assumed a galactic $K-L=0.3$ (Glass 1984; Joseph *et al.* 1984). As a result, the L -band nuclear flux density is more uncertain than those in the remaining bands. The fits are given in Table 5; the reddened power-law fits for NGC 3227 and NGC 5506 are shown as the long-dashed lines in Fig. 4.

The mean apparent spectral index for NGC 3227, 1.4, is identical to the median low-frequency spectral index for the PG quasars given in Neugebauer *et al.* (1987); NGC 5506, with a mean apparent spectral index of 2.2, is very red. Both Seyfert nuclei are well fit by a flat reddened power law ($\alpha=0.5$ for NGC 3227, and 0.0 for NGC 5506), with residuals that are more than three times smaller than those with a mean power law. The nuclear extinctions, A_V , implied by these fits are quite substantial, with $A_V=4.5$ mag for NGC 3227 and $A_V=10.7$ mag for NGC 5506.

The reddened power-law fits are clearly not realistic for the starburst nuclear components. For NGC 520, the fitted spectral index is very blue with a large visual extinction; the residuals are between 0.2 and 0.5 mag. For NGC 2782, the fitted α corresponds to a red spectrum, but the fitted extinction is negative! Although the reddened power-law model may be appropriate for the Seyfert nuclear components, it is clearly not so for the starbursts.

Also shown in Fig. 4 are the spectra of a normal late-type stellar population, H II-region emission (Willner *et al.* 1972), and optically thin dust emission (with emission coefficient $\propto \nu$). Comparisons of these with the starburst nuclear components will be discussed in the following section.

4.3 Individual Galaxies

In the following, we discuss in detail the model fits of the brightness profiles together with salient individual characteristics, and compare results derived here with

⁷Both Sy 1's are at approximately the same distance as NGC 1068 (Sy 2), so that the contribution of the host galaxy should be comparable.

⁸The differing spatial resolution caused by a fixed observing aperture could result in redder extranuclear colors in nearby objects since the angular extent of the (red) central region is larger. This does not seem to be the case here as two of the three Seyferts (excepting NGC 5506) which show no evidence for red extranuclear colors are closer or at approximately the same distance as the galaxies with red extranuclear colors. The two LINERs also lie roughly at this distance (~ 15 Mpc).

⁹The fits for NGC 5506 are poor, but the nucleus is extremely dominant.

TABLE 5. Nuclear components.

Name	r_K	N_J [mJy]	N_H [mJy]	N_K [mJy]	N_L [mJy]	J-H	H-K	K-L	< α >		α		A_V [mag]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)		(11)		(12)	
NGC 520	0.75	0.9	13.5	26.2	61.6	3.4	1.2	1.8	3.7±1.2		-2.1±2.1		28.9±9.7	
NGC 2782	0.43	13.0	14.3	17.5	24.5	0.6	0.7	1.2	0.6	0.1	0.9	0.1	-1.4	0.2
NGC 3227	0.71	16.7	31.6	45.8	74.9	1.2	0.9	1.4	1.4	0.2	0.5	0.2	4.5	1.1
NGC 5506	10.7	31.4	95.4	198.4	338.2	1.7	1.3	1.4	2.2	0.4	0.0	0.3	10.7	1.3

Column 1: NGC number.

Column 2: K-band ratio of the nuclear flux to the galactic contribution in the observing aperture.

Column 3-6: Nuclear flux densities in the NIR bandpasses assuming the Wilson et al. (1972) flux calibration.

Column 7-9: NIR colors of the nuclear component.

Column 10: Apparent mean spectral index between the J and L bandpasses.

Column 11: NIR spectral index from fit to reddened power-law.

Column 12: Visual extinction from fit to reddened power-law.

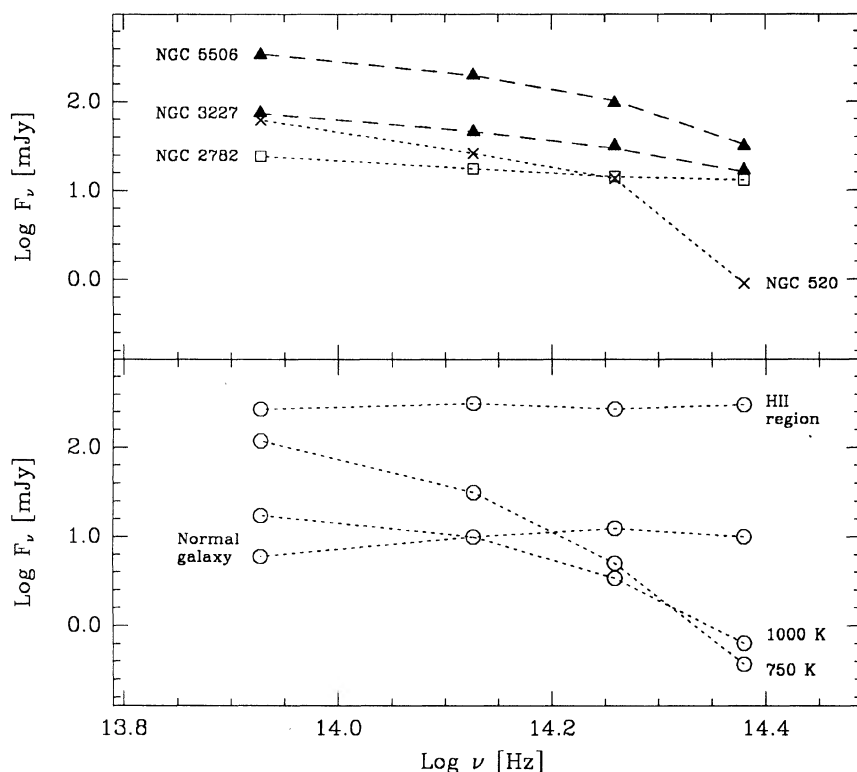


FIG. 4. Broadband spectral behavior of the nuclear components. Shown in the upper panel are the flux densities in the J , H , K , and L bands derived for the nuclear component of the four galaxies for which such determination was possible. The L -band flux (transformed from L') is computed assuming a standard $K-L$ color of the galaxy of 0.30. The long-dashed lines connecting the spectra of NGC 3227 and NGC 5506 correspond to the best-fit reddened power law reported in Table 5. The short-dashed lines are visual aids only. In the lower panel for comparison are the spectral distributions of (i) a standard galaxy ($J-H=0.72$; $H-K=0.25$; $K-L=0.30$); (ii) optically thin dust emission, with emission coefficient $\propto \nu$, at 750 and 1000 K; and (iii) a typical H II-region emission ($J-H=0.52$; $H-K=0.66$; $K-L=0.69$). The lower-panel spectra are arbitrarily displaced in the vertical direction.

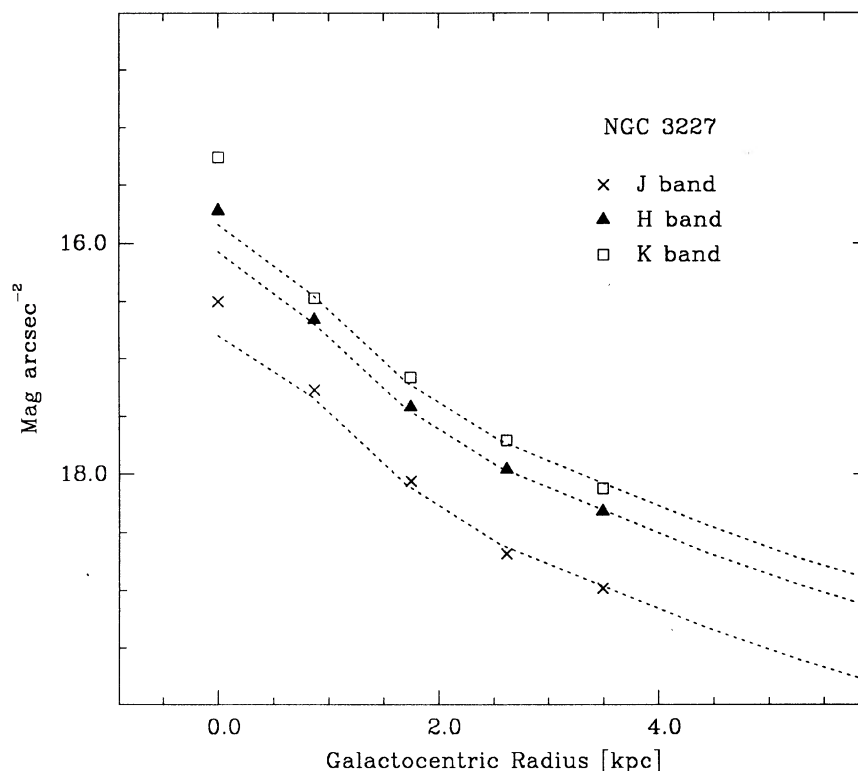


FIG. 5. Surface-brightness profiles of NGC 3227. Shown are the data points and the (dashed) lines referring to the pure spheroid best fits (excluding the central point). To compare with the data, the model $r^{1/4}$ spheroid is convolved with a 17 arcsec aperture, and the same effective radius $R_E=15.7$ kpc is assumed for the three wavelength bands.

those reported in the literature. As defined in the Appendix, r_K is the nuclear-to-galaxy flux ratio in the observing aperture.

4.3.1 NGC 3227 (Seyfert 1)

NGC 3227 (Arp 94) is a nearby interacting galaxy with an elliptical companion, NGC 3226; the companion shows no evidence of nuclear activity or enhanced star formation. It is an atypical Seyfert 1 as its hard x-ray luminosity is only slightly greater than that of NGC 1068 (Ward *et al.* 1987b). The spheroid fit for NGC 3227 is statistically significant in both the H and the K bands with the same effective radii to within the errors. Our observed profile matches well that observed by Terlevich *et al.* (1990) in the narrow band red continuum. It is of interest that the best-fit spheroid for this galaxy has an unusually large effective radius, R_E , (0.92 in units of fractional radius, or 13.9 kpc). This could result from the tidal distension induced by the interaction (Kormendy 1977); the CO distribution also shows evidence for tidal interaction with the companion elliptical (Meixner *et al.* 1990). In any case, the fitted R_E is at the large end of the range of values for normal spirals (e.g., Kodaira *et al.* 1986).

The galaxy brightness profiles predicted by adopting for the J band the R_E fitted in the H and K bands are presented in Fig. 5. The observed profiles are also shown and the nuclear excess relative to the galaxy is evident. The derived

nuclear flux densities in the H and K bands are in overall agreement with those in McAlary & Rieke (1988), while the J -band estimate is lower than those in McAlary & Rieke (1988) and in Ward *et al.* (1987a); both these groups note that the star light in NGC 3227 was underestimated by their techniques.¹⁰ The extinction, $A_V=4.5$, that results from the reddened power-law fit to the nucleus is higher than those found by Ward *et al.* (1987b) using NIR spectral line ratios [$A_V=2.3$ for the broad-line region, (BLR); $A_V=1.7$ for the narrow-line region, (NLR)], which suggests that the NIR nuclear continuum originates well inside the BLR (see also Carleton *et al.* 1987).

4.3.2 NGC 4151 (Seyfert 1) and NGC 5506 (Seyfert 1.9)

None of our profiles for either of these galaxies is amenable to single-component fits (see Fig. 2). We can, however, remark on the nuclear dominance in the central aperture.

NGC 4151 is the archetype of intermediate Seyfert galaxies with both broad and narrow emission lines (Veilleux

¹⁰The abnormally large effective radius of this galaxy causes an overestimation of the nuclear component because the light contained in successively smaller apertures changes less than that predicted by a standard galaxy growth curve. Consequently, more light is attributed to the nuclear component than ought to be and the galaxy light in the observing aperture is underestimated.

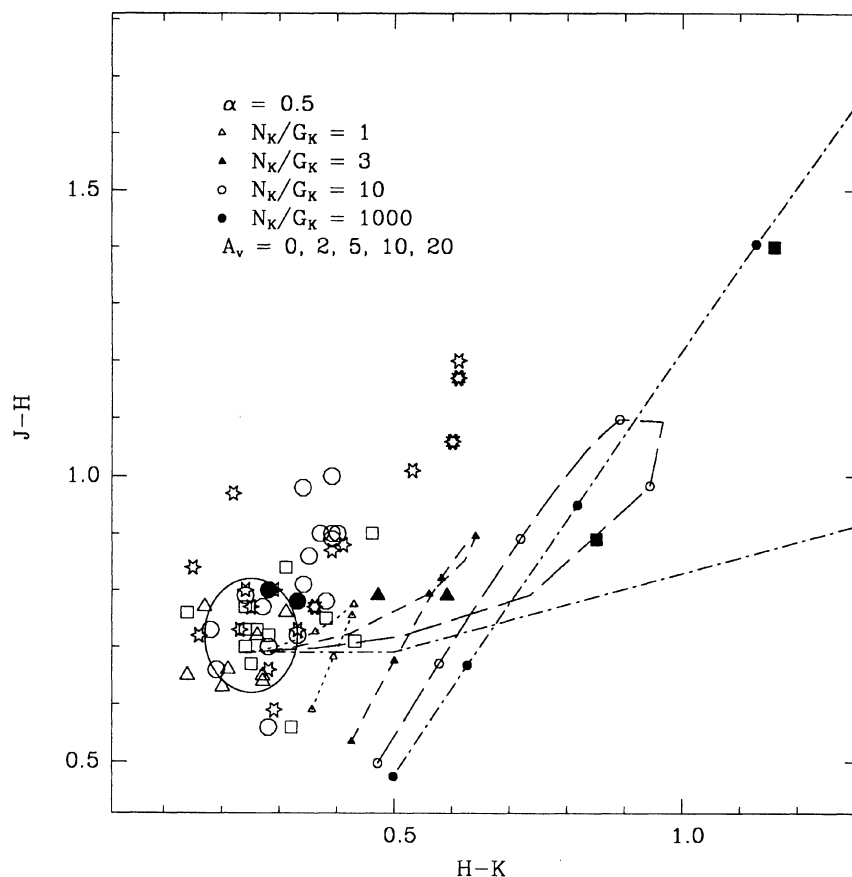


FIG. 6. Nuclear extinction in the $J-H$ vs $H-K$ diagram. This is similar to Fig. 3(a) but with the mixing curves obtained by varying the (strictly nuclear) extinction of an $\alpha=0.0$ power law. Each curve refers to a different nuclear (power law) relative contribution, r_K , within the observing aperture and is labeled according to the ratio in the K band of the nuclear (N_K) and the galaxy (G_K) contribution; here N_K is the intrinsic nuclear luminosity before extinction. The starting (lower) point of each curve refers to no nuclear extinction ($A_V=0$), and the locations of some fixed A_V values are marked on each curve. The nuclear extinction is assumed not to affect the galaxy contribution, and the galaxy colors are those of NGC 5506 given in Table 3. Symbols for the galaxy observations are as in Fig. 3.

1991). The nuclear emission is rather faint and, from the NIR color-color diagram shown in Fig. 3, is consistent with a power law of roughly 1.5 and an $r_K \approx 1$.

NGC 5506 is an x-ray selected Seyfert (edge on) with weak broad emission lines and narrow emission lines similar to those in Seyfert 2's (Blanco *et al.* 1990). Both continuum studies and optical and NIR spectra show evidence of nuclear extinction of several magnitudes (Moorwood & Salinari 1981; Wilson *et al.* 1985; Blanco *et al.* 1990). If we adopt the pure disk model for NGC 5506 shown in Fig. 2, we derive $r_K \approx 11$ and $r_J \approx 2$ (see Table 5), which suggest a dominant and extremely red nucleus. Figure 6 shows the results of model calculations (see Table 5 and Appendix) for the colors that result from a nonthermal nucleus with a spectral index of 0.0, extinction of only the nucleus, and the mean extranuclear colors of NGC 5506. Also shown in Fig. 6 are the observed colors; the nucleus of NGC 5506 is the solid square in the upper-right corner. Both the reddened power-law fit given in Table 5 and the model calculations shown in Fig. 6 give an estimate of the nuclear extinction, $A_V \sim 10$, which is slightly higher than the $A_V = 6$

reported in Blanco *et al.* (1990) for the BLR, but is roughly consistent with that implied from the gas column density towards the hard x-ray source ($A_V \sim 12$ mag, Pounds 1989).

4.3.3 NGC 1068 (Seyfert 2)

NGC 1068 (M77, 3C71, Arp 37) is probably the best-studied Seyfert 2 galaxy as a result of its proximity (~ 10 Mpc) and its concomitant large apparent size. Our spheroid fit for NGC 1068 is statistically significant with the same R_E in both the H and the K bands. The galaxy colors from the model fit are $J-H=0.67$ and $H-K=0.32$, consistent with those of normal spirals. Figure 7 shows the J -, H -, and K -band data together with the best-fit spheroid (with the same R_E in all three bands). The central K -band magnitude exceeds that predicted by the model (by 0.35 mag) while a central depression is evident in the J - and H -bands (0.39 and 0.18 mag, respectively). If we interpret this depression as due to extinction, we can derive A_V from the differences in each band between the observed central

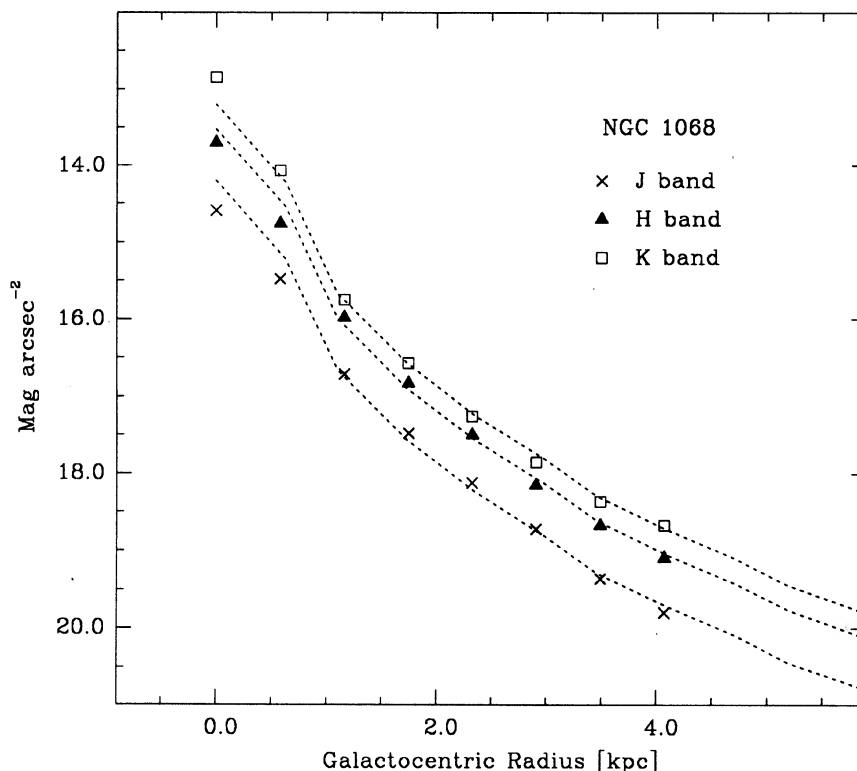


FIG. 7. Surface-brightness profiles of NGC 1068. Same as in Fig. 5. In this case the model spheroid has an $R_e = 1.27$ kpc.

magnitude and the fit. A_V 's derived in this way from the J and H bands are 1.4 and 1.0 mag, which are consistent with the central extinction measured by previous studies (Neugebauer *et al.* 1980; Young *et al.* 1988b; Oliva & Moorwood 1989; Kennicutt & Pogge 1990). Instead, the K -band excess must include some additional contribution such as hot dust; such interpretation is also supported by the position of the nucleus of NGC 1068 in the color-color diagrams shown in Fig. 3 (see also Scoville *et al.* 1988; Thronson *et al.* 1989). The interpretation of the J - and H -band depressions and the K -band excess will be discussed in the following section.

Optical profiles of this galaxy have been published by Van Houten (1961) and Schild *et al.* (1985). They are plotted together with our K -band profile fit in Fig. 8. For a better comparison we have convolved our K -band model spheroid with a Gaussian seeing disk of 2.4 arcsec (that quoted in Schild *et al.*); overall, the agreement between the profiles is remarkably good.¹¹

NGC 1068 is the only Seyfert where we find anomalously red JHK colors away from the nucleus. The radial color gradients seem to follow the discontinuity between inner and outer disk structure noted in Schild *et al.* (1985). The inflection in the optical surface brightness profile co-

incides with the radius at which the NIR color profiles become approximately flat (see Fig. 8). Therefore, the red NIR colors seem to be associated with the circumnuclear disk thought to be the site of vigorous star formation.

4.3.4 NGC 520, NGC 2146, and NGC 2782 (Starbursts)

NGC 520 (Arp 157), NGC 2146, and NGC 2782 (Arp 214) each present peculiar morphology and are probably merging systems (Stanford & Balcells 1990; Hutchings *et al.* 1990; Pompea & Rieke 1989; Pompea & Rieke 1990). Two of the three possess prominent dust lanes (NGC 520 and NGC 2146) or extended H I emission (NGC 2146 and NGC 2782) (Smith 1991; Young *et al.* 1988a). Only two sets of brightness profiles resulted in good fits (NGC 520 and NGC 2782), while those for NGC 2146 gave χ_ν of 2 or more (see Table 3).

Figure 9 presents the best fits with a common scale length in the three NIR bands for NGC 520. The best-fit colors of the galaxy are those of normal spirals with $J-H = 0.72$ and $H-K = 0.28$. Clearly, the K -band profile for NGC 520 shows a significant nuclear excess, while the J -band central magnitude is within the errors of the fit. The colors for the nuclear component (see Table 5) are not well matched by either optically thin or optically thick single-temperature dust emission. If we ascribe the nuclear emission to a dust mixture, such as in Galactic H II regions (Natta & Panagia 1975), then the inferred $60 \mu\text{m}$ flux exceeds by 75% that measured by *IRAS*. If the dust is

¹¹We note that our photometry agrees exactly with that (within the same aperture) in Glass & Moorwood (1985) and reasonably well (0.11 mag) with that quoted in Scoville *et al.* (1988); the colors in both cases are in good agreement (< 0.05 mag difference).

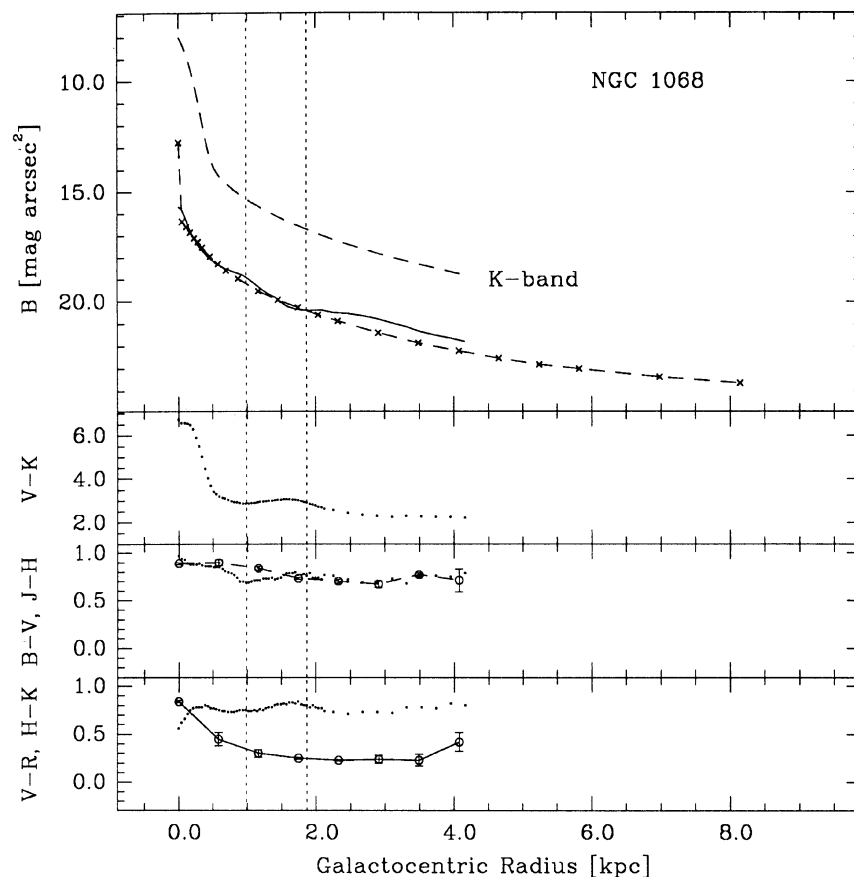


FIG. 8. Comparison of optical and NIR surface-brightness profiles of NGC 1068. In the upper panel the upper dashed curve is the K -band surface-brightness profile from our pure spheroid best fit convolved with a Gaussian seeing disk of $\text{FWHM}=2.4''$. The solid line is the B band azimuthally averaged profile of Schild *et al.* (1985) at the same resolution. The lower dashed curve and $\times$ symbols refer to the photographic blue major axis profile from Van Houten (1961). The $V-K$ panel reports the color profile from our K -band best fit and the V -band data in Schild *et al.* Also reported are the radial trends of $B-V$ and $V-R$ from Schild *et al.* and, with coarser sampling, our data (not from the fits) radial trends for the $J-H$ and $H-K$ colors. The two vertical dashed lines mark the inner edge of the circumnuclear disk and the outer edge of the low surface-brightness region surrounding it, as noted by Schild *et al.*

hotter than in typical H II regions, then the extremely (for hot dust) red $J-H \geq 3.4$ must still be explained. ($J-H \geq 3.4$ corresponds to color temperatures $T_c \leq 800$ K while $H-K=1.2$ and $K-L=1.8$ imply $T_c \sim 1450$ and 1100 K, respectively.) The form of the spectrum shown in Fig. 4 does, however, suggest that hot dust contributes substantially to the nuclear emission of NGC 520 (as has been suggested by Stanford & Balcells 1990).

The NIR brightness profiles of NGC 2782 are well fit by a pure spheroid. Kent (1985) provides a bulge+disk profile decomposition in the r band for this galaxy. The profile resulting from his decomposition is shown in Fig. 10 together with the NIR data and our pure spheroid fit. The pure spheroid fit follows closely Kent's prediction except for the outer regions (where the NIR profile is not constrained). The r -NIR colors are constant with radius (as are the NIR colors, see Fig. 2). NGC 2782 is the only starburst galaxy of the three studied here that does not present red extranuclear colors.¹²

We have determined the nuclear component luminosi-

ties for NGC 2782 both using Kent's decomposition and our pure spheroid fit. The ratio in the K -band of nuclear-to-galaxy luminosity in the observing aperture is 0.3 and 0.5, for the decomposition and the pure spheroid, respectively. In both cases, we find the nuclear component to have $J-H \approx 0.5$ and $H-K \approx 0.7$; these colors are within 0.06 mag of those for H II-region emission given in Willner *et al.* (1972). They are also very similar to those of violent star formation regions reported by Melnick *et al.* (1985). The $K-L$ color of 1.2 is redder (0.5 mag) than that of H II-region emission, and may arise, at least in part, from hot dust emission.

Because of the poor fit for NGC 2146, we were unable to determine properties of the nuclear component. However, extranuclear colors from the NGC 2146 color profiles show evidence for significant extinction as far as 3 kpc from the nucleus. From the $J-H$ colors, we estimate an $A_V \approx 4$ mag at the nucleus, and $A_V = 2.5$ mag at 1.3 kpc from the center, in agreement with Young *et al.* (1988a, 1988b) and Hutchings *et al.* (1990).

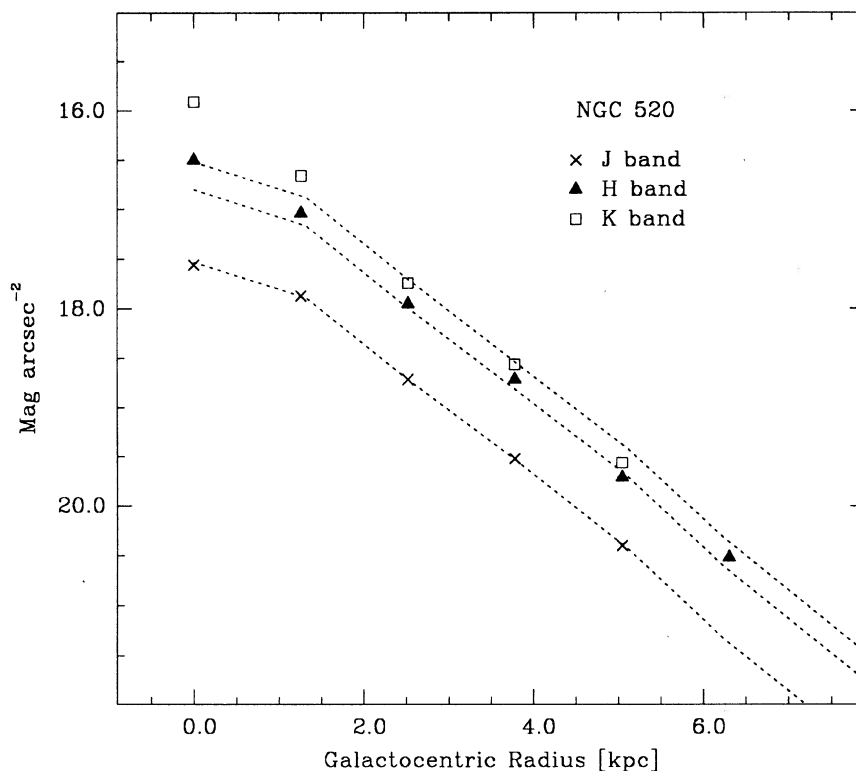


FIG. 9. Surface brightness profiles of NGC 520. Same as in Fig. 5, but for a pure disk best fit. The exponential scale length adopted for all the three bandpasses is $\lambda = 1.48$ kpc.

4.3.5 NGC 7177 and NGC 7331 (LINERs)

The nucleus of NGC 7177 is intermediate between low-ionization and H II-regionlike classes (Keel 1983a). Emission-line imaging shows a stellar nucleus and patchy circumnuclear emission associated with H II regions (Pogge 1989). NGC 7331 is classified as an “[N II]-type” LINER (Keel 1983a), although it may satisfy strict LINER criteria (Keel 1983b). It shows a diffuse circumnuclear disk of line emission with an extent of around 20 arcsec (Keel 1983b; Pogge 1989).

Neither set of NIR profiles is amenable to single-component fits. This is seen in the disk fits shown in Fig. 2; both galaxies possess a non-negligible spheroid.

For NGC 7331, Boroson (1980) gives a blue profile decomposition which is compared with the NIR profiles in Fig. 11. We have calculated the extinction inferred from the $B-H$, $J-H$, and $H-K$ colors assuming as unreddened colors those of the outer range of our profiles.¹³ These extinction estimates are also shown in Fig. 11. As can be seen in the figure, the radial trend of the extinction is the same in the different bands. The extranuclear $B-H$ colors are redder than those implied by the measurements of late-type spirals by Skrutskie *et al.* (1985), as are the $J-H$ and $H-K$ colors reported here. We therefore argue

¹³ $B-H=3.5$, $J-H=0.77$, $H-K=0.30$.

that heavy extinction is present in NGC 7331 as far as 5 kpc from the nucleus, an extension much larger than that of the circumnuclear disk of emission-line gas.

5. DISCUSSION

In the Seyfert galaxies where we were able to derive nuclear properties (NGC 3227 and NGC 5506), the nuclear component seems relatively flat and substantially reddened. These NIR nuclear spectra are similar to those seen in some quasars (Neugebauer *et al.* 1987), and they exhibit similar behavior at low frequencies, that is the observed flux at $3.5 \mu\text{m}$ is lower than that predicted by extrapolating a simple power law from higher frequencies (in this case J , H , and K). Instead, the spectra are well fit by reddened power laws. If the reddened power-law fits are interpreted at face value, the Seyfert nuclei in this study suffer from substantial extinction that seems disassociated from the surrounding galaxy; the host galaxy colors, if anything, are slightly bluer than those of normal spirals. In addition, the extinction of the NIR nuclear continuum exceeds that of the BLR and the NLR.

The high 10 and $2.2 \mu\text{m}$ luminosities in NGC 520 and NGC 2782 (Condon *et al.* 1982; Devereux 1987, 1989) place these two galaxies at the luminous end of the “M82-type” starbursts investigated by Devereux (1989). When

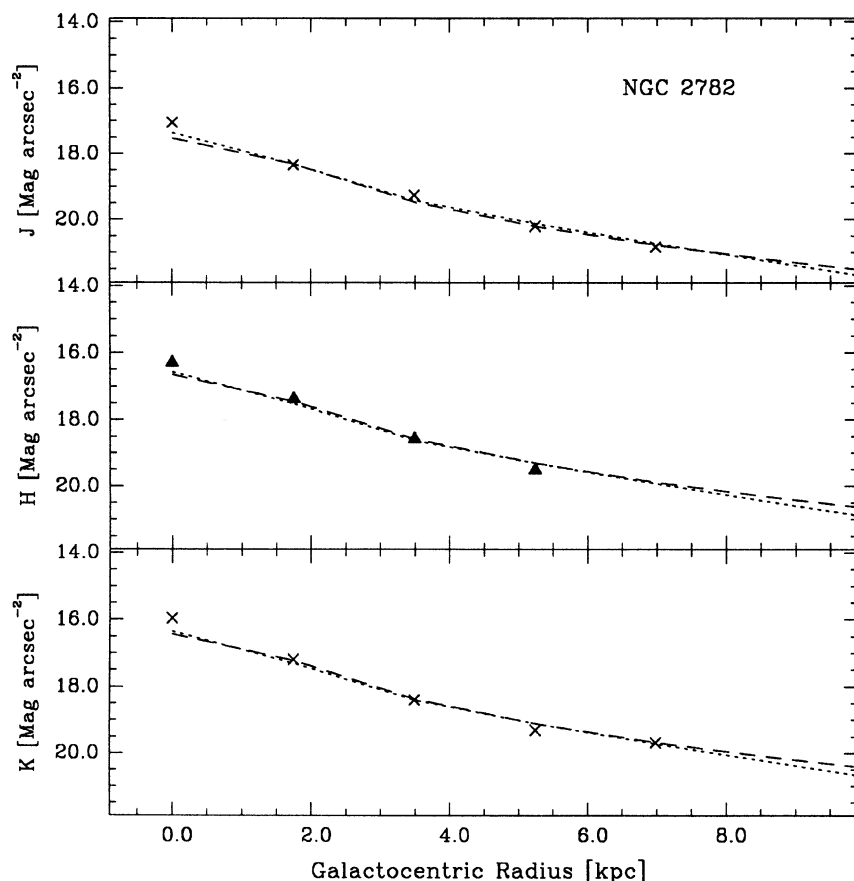


FIG. 10. Surface-brightness profiles of NGC 2782. In the three panels, one for each bandpass, the data points are shown together with two model profiles. The dotted line refers to our pure spheroid best fit with $R_c=5.0$ kpc for all bandpasses. The dashed line is the profile resulting from the bulge + disk decomposition of Kent (1985). Both profiles have been convolved with a 17 arcsec aperture.

the starburst is “intense” ($\geq 6 \times 10^8 L_\odot$ at $10 \mu\text{m}$), red supergiants may dominate the nuclear emission at $2.2 \mu\text{m}$. Neither the nuclear spectrum of NGC 2782 nor NGC 520 seem to be consistent with any stellar colors, either reddened or not.¹⁴ The J , H , and K colors in NGC 2782 are reproduced to within 0.06 mag by an H II-region spectrum (e.g., Willner *et al.* 1972), while the L -band nuclear flux is almost twice as much as that predicted. In NGC 520, if the nuclear excess is to be attributed to red supergiants, then a large visual extinction is necessary (≥ 15 mag) for consistency in all three colors. From Fig. 4, however, it seems plausible that the excess is due to dust emission with a distribution of temperatures. The nuclear components of both NGC 2782 and NGC 520 do not, therefore, seem to be readily attributable to stellar emission, but rather to nebular emission + hot dust (in NGC 2782) or to hot dust with a distribution of temperatures (NGC 520).

¹⁴The A_V of ~ 2 mag for NGC 2782 inferred from the nuclear Balmer decrement (Balzano 1983) is, in any case, inconsistent with heavy reddening.

Knowledge of the galaxy luminosity distribution makes possible the distinction between *color* and *emission* excesses. In NGC 1068, the red central colors in our observing aperture are not simply the result of excess emission but also of a depression relative to the extrapolated galaxy profile. We have investigated the possibility that the depression in the J and H bands is due to extinction by the same dust that contributes to the K -band excess. In the limiting case of an (infinite optical depth) absorbing screen of a given radius, r_c , that completely obscures the galactic light, we can suitably integrate the fitted galaxy profile to obtain r_c . In this way, we derive the minimum radius of the absorbing region, $r_c=85$ pc. Assuming the observed $2.2 \mu\text{m}$ excess arises from the same region, we derive an upper limit for the temperature of the dust, $T_d=305$ K. If the optical depth is less than infinite, the linear dimension, r_c , the dust temperature, T_d , and the optical depth are inter-related so that, for fixed r_c , the optical depth implied by the observed J -band depression together with the observed K -band emission constrain the dust temperature: $T_d < 300$ K.

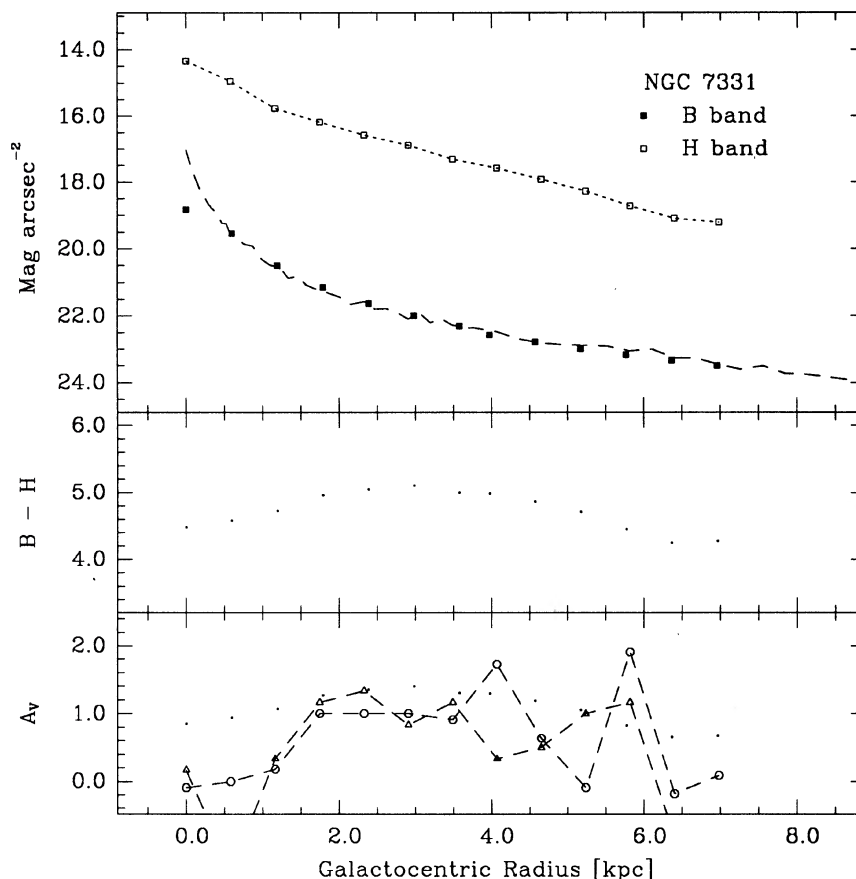


FIG. 11. Comparison of optical and NIR surface brightness profiles of NGC 7331. In the upper panel are shown our H -band data converted to surface-brightness units. The short-dashed line simply connects the H -band data and does not represent any model fit. The B band azimuthally averaged profile from Boroson (1980) is shown as the long-dashed line. The points marked by filled squares are obtained by convolving with a 17 arcsec aperture the model profile resulting from Boroson's decomposition. The $B-H$ panel shows the radial trend of the $B-H$ color (in a 17 arcsec aperture) obtained from the data marked by the squares (open and filled) in the upper panel. The A_V panel shows the radial trend of the visual extinction computed by assuming standard colors throughout the galaxy ($J-H=0.77$; $H-K=0.30$; $B-H=3.50$) and imputing any deviation from such values to extinction. The dots represent the A_V estimate from $B-H$, the circles from $J-H$, and the triangles from $H-K$. The standard colors assumed are the average of those in the three outermost points in the galaxy. The extinction curve used is the one of Rieke & Lebofsky (1985).

The extinction inferred from the H -band depression is inconsistent with that inferred from the J band (from 50% to a factor of 4 lower according to the assumed geometry). This discrepancy can be mitigated only if the same source that emits in the K band also radiates in H ; for thermal sources, T_d must be ~ 1000 K. The $K-L$ nuclear color of 3.0 implies a $T_d \sim 750$ K. Thus, the observations are inconsistent with dust clouds at a single temperature; two components are necessary. These could be either two single-temperature components (one at ~ 300 K and one at ~ 1000 K), a dust cloud complex with a radial temperature distribution such as that described in Jones *et al.* (1977), or a thermal source at 300 K together with nonthermal nuclear emission as suggested by Tresch-Fienberg *et al.* (1987).

Spatially extended JHK excesses are seen in the Seyfert 2 (NGC 1068), two starbursts (NGC 520, NGC 2146),

and one LINER (NGC 7331). NGC 520, NGC 1068, and NGC 2146 are known sites of extranuclear vigorous star formation (Stanford & Balcells 1990; Balick & Heckman 1985; Schild *et al.* 1985; Young *et al.* 1988a). It therefore seems likely that the red extranuclear JHK colors of the LINER (NGC 7331) are associated with a spatially extended episode of a similar kind. As seen in Fig. 3, the nuclear colors of three of the galaxies with JHK extranuclear color excesses (NGC 520, NGC 2146, and NGC 1068) also require excess K -band emission, presumably by hot dust.

Spatially extended $K-L$ excesses are seen in all of the galaxies where an extranuclear L' measurement was possible (NGC 1068, NGC 3227, NGC 5506). Joseph *et al.* (1984) has used $K-L > 0.5$ as a diagnostic for nuclear star formation; the excess L emission is thought to be due to warm dust (> 100 K). In each of the galaxies measured,

$K-L$ (transformed to $3.5 \mu\text{m}$) > 1.3 , thus falling well above the criterion adopted by Joseph *et al.* Dust at a few hundred K cannot be maintained more than 100 pc from a $10^{44} \text{ erg s}^{-1}$ central source (see Davidson & Netzer 1979; Carleton *et al.* 1987), so that warm dust a few kpc from the nucleus must be heated locally. We therefore attribute these extranuclear $K-L$ excesses to violent star formation in the inner regions of these galaxies.¹⁵ Clearly, more sensitive off-nuclear L -band measurements are needed for ascertaining the frequency of such extranuclear star formation in active galaxies.

6. SUMMARY AND CONCLUSIONS

The NIR radial luminosity distributions of a small group of active galaxies have been used to derive their nuclear properties and extranuclear colors. We find the following.

(i) The nuclear components of the Seyfert galaxies are consistent with flat ($\alpha \sim 0.0-0.5$), highly reddened ($A_V \sim 5-10 \text{ mag}$) continua. In both cases, the derived extinction for the NIR nuclear continuum is greater than those of the BLR and the NLR.

(ii) The nuclear components of the starburst galaxies are consistent either with H II-region emission together with hot dust emission or with hot dust at a variety of temperatures.

(iii) NGC 1068 shows a nuclear color excess that is due to a depression in the J - and H -band and K -band emission relative to the galaxy profile. We attribute this to two distinct components: one at $\sim 300 \text{ K}$ and one with a hotter spectrum.

(iv) Spatially extended violent star formation as indicated by extended red $JHKL$ colors seems to be present in one or more galaxies in each activity class, that is to say in six of the nine galaxies studied.

Dust clearly plays an important role in the observed properties of active galaxies, both in the nuclear regions and on kpc scales around the nucleus. Effects of dust extinction or hot dust emission or both are evident in seven of the nine galaxies studied. We also find that star formation on kpc scales may be associated with different forms of nuclear activity.

We would like to thank Marco Salvati for a critical reading of the manuscript, and the TIRGO Telescope-Time-Assignment Committee for generous allocations of telescope time.

APPENDIX

Presented here is the method adopted in this study for determining the nuclear fluxes in each band together with the simple models used to fit them. We first define the

¹⁵6 cm maps in Condon *et al.* (1982) show that these three galaxies are highly centrally concentrated at radio wavelengths so that the $3.5 \mu\text{m}$ extranuclear emission is much too large to be due to nonthermal or thermal gas emission. We also note that Joseph *et al.* (1984) found that the galaxies with a $K-L$ excess almost always have normal $H-K$ colors.

observed central magnitude, d_i , and the galaxy contribution, f_i , in each band:

$$d_i = -2.5 \log(G_i + N_i), \quad (1)$$

$$f_i = -2.5 \log(G_i), \quad (2)$$

where G_i is the galaxy flux predicted by the profile fit extrapolated to the center and N_i is the nuclear component to determine. G_i and N_i are monochromatic flux densities at the effective wavelengths, λ_i , of the filter bands; G_i is the galaxy contribution in the observing aperture. i denotes the filter bands, J , H , and K .

The difference in central magnitude gives the nuclear-to-galaxy flux ratio, r_i , in each band:

$$r_i = N_i/G_i = \text{dex}[-0.4(d_i - f_i)] - 1 \quad (3)$$

and knowledge of the galaxy contribution (from the profile fits) gives the nuclear flux densities and colors:

$$\rho_{ij} = N_i/N_j = (G_i/G_j) \frac{r_i}{r_j}. \quad (4)$$

These colors can then be modeled in the conventional way by calculating the individual apparent power-law spectral indices ($\nu \propto \nu^{-\alpha}$) assuming there is no extinction:

$$\alpha_{ij} = \frac{\ln(\rho_{ij})}{\ln(\lambda_i/\lambda_j)}, \quad (5)$$

(where i and j refer to two wavelength bands), by simultaneously solving for the mean apparent spectral index, or by simultaneously solving the set of color equations (one for each color) for the optical depth and the power-law spectral index. These equations are defined by the ratio of the nuclear fluxes:

$$N_i/N_j = \left(\frac{\lambda_i}{\lambda_j}\right)^\alpha e^{-\tau_i + \tau_j} \quad (6)$$

which gives the color equation

$$\ln \rho_{ij} = \alpha \ln(\lambda_i/\lambda_j) + \tau_V(\epsilon_i - \epsilon_j), \quad (7)$$

where ϵ_i and ϵ_j are the ratios of the optical depths in the i and j bands relative to the V band (e.g., Rieke & Lebofsky 1985).

If we fix α , then we can solve directly for the optical depth, τ_V . Otherwise, the above set of equations can be solved simultaneously for α and τ_V .

When the radial brightness profile is unavailable, as is usually the case in the L band, the procedure is still applicable by assuming a standard color (in this case $K-L$) for the galaxy. For the L band, Eq. (3) is then replaced by

$$r_L = \frac{r_K + 1}{\text{dex}(-0.4X)} - 1, \quad (8)$$

where $X = (K-L)_{\text{obs}} - (K-L)_{\text{gal}}$. The derivation of ρ_{KL} (Eq. 4) follows naturally.

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