We present near-infrared (NIR) broadband and color images of 26 galaxies which host Seyfert 1 (Sy1), Seyfert 2 (Sy2), or starburst nuclei (SBNs). The study is focussed on properties of the host galaxies rather than their nuclei and, to this end, careful attention is paid to photometric accuracy and to reliable measurements of the low-surface-brightness outer disk. Inspection of the elliptically-averaged radial brightness and color profiles reveals that: (i) the NIR mean colors of the inner and outer disks of Seyferts and starbursts are consistent with a normal late-type stellar population, and do not differ significantly with activity class; (ii) the color gradients in the outer disks are similar both in sign and magnitude to those observed in normal spirals; (iii) red “ridges” in the inner parts of the J – H profile are evident in the majority of SBNs, but only in a few Sy1s, and in no Sy2s; (iv) circumnuclear blue “dips” in the J – H profile are seen only in Sy2s. We then construct color images and find ridges, rings, and filaments, not evident in the broadband images, in the inner disks of SBNs and in NGC 7469, a Seyfert 1. The application of a simple model to these features yields evidence for both dust extinction and excess 2-μm emission. Color-color diagrams of individual pixels confirm these results, and also show that the stellar mix in most of the Sy2s comprises a conspicuous contribution from an intermediate-age (3 – 5 × 10⁸ yrs) population. In conclusion, it appears that ongoing star formation in the inner disks of SBNs is signalled by the presence of dust (and gas); the absence of such features in both Seyfert types implies that star formation episodes are either absent or very old. However, while the blue colors of Sy2s suggest that a burst of star formation did, in fact, occur not more than 10⁹ yrs ago, the normal colors of Sy1s imply that any starforming episodes must be significantly older.

1. Introduction

The relationship of a Seyfert nucleus to its host galaxy is one of the outstanding questions in the study of active galactic nuclei (AGNs). Properties of the Seyfert galaxy such as mass and

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luminosity concentration, morphological type, relative dominance of the bulge and disk components, metal abundance, and total luminosity may be expected to influence nuclear activity and perhaps in turn be affected by it.

The connection between Seyfert activity and intense star formation is a further outstanding question. The standard model for a Seyfert nucleus invokes accretion onto a massive compact object (cf. Rees 1977; Malkan 1983). Either this scenario or a nuclear burst of star formation (e.g., Terlevich et al. 1992) requires a reservoir of gas and an efficient way to concentrate the gas into small nuclear regions on time scales that are comparable with the duration of the activity. Given that high rates of star formation seem to be causally linked to high gas surface densities (Elmegreen 1987; Larson 1985; Kennicutt 1989), one would expect nuclear activity, whatever its cause, to be frequently associated with intense star-forming episodes. There are some indications from observations that star formation is enhanced in the circumnuclear regions and disks of Seyfert galaxies (Rodriguez-Espinosa, Rudy, & Jones 1987; Wilson 1988; Hunt & Giovanardi 1992), although other observations appear to contradict this (Heckman et al. 1989; Carone 1992).

The problem of fuel supply and transport involves large quantities of mass, \( \times 10^7 \) to \( \times 10^9 \) \( M_\odot \), most of which must be somehow brought in from extra-nuclear regions. Current wisdom places the origin of this gas in the galactic disk (e.g., Shlosman, Begelman, & Frank 1989; Barnes & Hernquist 1991), but the mechanism by which the gas is transported into the nuclear regions of the galaxy must reduce specific angular momentum of the gas by \( \times 10^4 \) since viscous processes become important only on very small spatial scales (\( \ll 10 \) pc) (Hernquist 1989; Shlosman et al. 1989). It seems likely on both observational (e.g., Simkin et al. 1980) and theoretical (Heller & Shlosman 1994) grounds that the nuclear source is fed by disk gas, swept inwards by large-scale non-axisymmetric perturbations in the gravitational potential. These perturbations could arise from intrinsic global instabilities or from tidal interactions, and should be associated with irregular morphology, bars, rings, twisted isophotes, or oval distortions. Observational evidence for such non-axisymmetric structures in active galaxies is mounting (e.g., Simkin et al. 1980; MacKenty 1990; Moles, Marquez, & Perez 1995), but studies restricted to optical wavebands have some fundamental limitations.

The advantages of studying galaxies in the near-infrared (NIR) bands have long been known: (i) the energy output of a normal stellar population is dominated by old red giants and therefore peaks around 1 \( \mu \)m; and (ii) dust extinction is substantially reduced at these wavelengths. For both reasons, the NIR properties of galaxies tend to be more homogeneous and well-defined than in the optical, and the NIR wavelength bands are thus ideal when searching for bars or oval distortions. Indeed, specific cases of so-called NIR bars are becoming more and more numerous (e.g., NGC 253, Scoville et al. 1985; NGC 1068, Thronson et al. 1989; M 82, Telesco et al. 1991; NGC 7469, Mazzarella et al. 1994). NIR wavelengths also facilitate studies of circumnuclear regions in AGNs because the contrast between the stellar and non-thermal contributions is maximized. On the other hand, a 2.2 \( \mu \)m \( K \)-band excess can point to the hot dust that is sometimes associated with violent star formation (e.g., Joseph et al. 1984; Hunt & Giovanardi 1992). The chief difficulty with such observations has been with the sensitivity and number of pixels of infrared detectors. When IRCAM became operational on the UK Infrared Telescope (UKIRT), a number of groups (including ours) recognized the opportunity to overcome these problems much more effectively than had heretofore been possible.

We have adopted an observational approach to address the connection between an active nucleus and its host galaxy. In this paper, the first of a series, we present NIR images of 26 galaxies which host Seyfert (Sy) or starburst nuclei (SBNs, e.g., Feldman et al. 1982). Subsequent papers will describe the structural components of these galaxies together with the analysis of the non-axisymmetric features in the images (Paper II), and the amplitudes and colors of the Seyfert and starburst nuclei (Paper III). Here we discuss the sample selection in \( \S2 \), followed by a description
of the observations and our data reduction and analysis in §3. In particular, we determine, independently of the background subtraction, NIR disk colors and color gradients of the galaxies in our sample, and compare their properties, in §4, with those of normal spirals. We also present in §4 NIR color images of the central regions of these galaxies which reveal structures visible only in the colors.

Unlike most previous NIR imaging studies of Seyferts (Kotilainen et al. 1992a, 1992b; Kotilainen & Ward 1994; Alonso-Herrero, Kotilainen, & Ward 1995 – hereafter collectively KW; Zitelli et al. 1993; Danese et al. 1992 – hereafter collectively ZD), this project was designed to investigate properties of the host galaxies. Hence deep images, acquired at the UKIRT, were obtained in three bands to measure the low-surface-brightness outer disk. The galaxies’ distances were constrained in the sample selection (see below) so that, in most cases, it was possible to image the outer disks without using mosaics. As a result, the range of distances, and spatial resolution, of each activity-class subsample is similar, and within a class varies by roughly a factor of two. Finally, special care was paid to the determination of the background level and to photometric corrections so that disk colors could be accurately determined and compared to the wealth of normal galaxy photometry in the literature.

2. Sample Selection

The Seyfert galaxies studied here belong to the spectroscopically-defined CfA sample (Edelson 1987; Huchra & Burg 1992). To ensure that the galaxies could be successfully observed with the small-format (62×58) array in the UKIRT camera (IRCAM1), we imposed a constraint on redshift, $z \geq 0.015$. Such a constraint ensured that the galaxies would be close enough so that we could resolve relatively small spatial structures, but distant enough so that they would not overfill the IRCAM array. We have obtained images in three colors of more than half (9/17 Sy 1’s and 8/14 Sy 2’s) of the subsample of those galaxies in the CfA sample with $z \geq 0.015$. For two particularly large galaxies—NGC 5674 and 1335+39—we obtained mosaics. The observed sample was selected essentially randomly from the CfA list, and, as mentioned above, spans a range of about a factor of two in distance; Table 1 gives the global properties of the observed galaxies. Distances are computed from the redshifts, correcting for infall according to Geller & Huchra (1983), with a Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

To test the alleged connections between starburst activity and AGNs, we also imaged galaxies with starburst nuclei in the same redshift range. These were selected from the survey of SBNs taken from Balzano (1983) and Mazzarella & Balzano (1986). It should be emphasized that this starburst sample, selected for bright compact nuclei with HII-region-like spectra, was chosen primarily for a comparative analysis with Seyferts. Since Seyfert activity, as such, is a strictly nuclear phenomenon, we felt that the starburst comparison was more appropriate for nuclear starbursts, and hence galaxies with extended starburst regions were not included in the sample. In any case, one must keep in mind that the Markarian lists from which these surveys are drawn suffer from a selection bias (UV excess) which does not apply to the CfA sample. Nevertheless, it has the advantage of being homogeneously selected, and allows us to search for peculiarities shared by galaxies that host Seyfert or starburst nuclei. We have observed nine of the 43 SBNs with $z \geq 0.015$ in the Mazzarella & Balzano and Balzano lists.

Finally, in order to compare our results with a control sample, we have extracted from the diameter-selected sample of normal spirals of de Jong & van der Kruit (1994) those galaxies with well-defined spiral types between Sa and Sc, excluding S0 galaxies, Sd’s, and irregulars. To this subsample, we applied the same redshift criterion as before and obtained a set of 30 galaxies. Of these, eight have UKIRT IRCAM images in two NIR broadbands (H and K), and de Jong has
3. Observations, Data Reduction, and Analysis

Data were obtained during the course of ten nights on the UKIRT with IRCAM1 (April 1990, March 1991, September 1991); of these five nights were useful, and, for the most part, photometric. The camera was based on an InSb Santa Barbara 62×58 array, and we adopted a pixel size of 0.62 arcsec. 23 of the galaxies were imaged in the three broadband filters, \( J \), \( H \), and \( K \); two were imaged in \( H \) and \( K \) only, and one in \( H \). The average seeing in the \( K \)-band was FWHM=1.3 arcsec, and no data were obtained with seeing worse than 1.8 arcsec (FWHM).

A typical observing sequence consisted of five exposures ON-source, interleaved with five empty sky exposures offset at least 90 arcsec from the center of the galaxy. Usually no more than 120 s was spent in one telescope position, and this time was divided into a number of coadds to ensure that the nuclei were not saturated and that the images were background limited. With one exception (1614+35), galaxies were never observed at airmasses > 1.5. Dark exposures were acquired every two or three hours throughout the night, as the dark current varied substantially (at least in the first few hours); for each night, we were careful to acquire at least one dark exposure taken with the same integration time and coadds as each of the source exposures. Bias exposures taken before each integration were automatically subtracted by the double-correlated read-out algorithm of the data acquisition system. Typical total integration times are around 300-500 s, and are given individually in Table 1.

As we wanted our images to be flat to better than \( 1 \times 10^{-3} \), we paid close attention to the flat fielding and dark current subtraction. Dark current was determined by performing, for each night, a pixel-by-pixel linear regression on all the bias-subtracted dark exposures. We thus obtained two fitted frames, a slope and an intercept, which we then scaled and subtracted from each (bias-subtracted) science frame. Tests show that the fits tend to reduce the noise introduced in the image reduction, as opposed to using an average dark frame acquired with similar observing parameters. These fits are interpolations, not extrapolations, as we acquired dark frames at all of the object integration times used during a night.

After dark current subtraction, flatfields were constructed from pairs of sky frames acquired before and after each source exposure. Each object frame was divided by the normalized (to the image median), averaged pair of temporally adjacent sky frames, then registered and averaged, after adjusting the offset sky level to a common median. To optimize the signal-to-noise of the final images, we chose to use a simple average, rather than a median, since the flat fields were different for each source image, the sky positions were chosen to be empty fields, and the field-of-view was small. We found no residual stars in the final object frames.

Bad pixels were eliminated in the first approximation by a bad-pixel list derived from an analysis of the dark frames, and the correction for these entailed substitution with the median of its (eight) neighbors. Remaining bad pixels were eliminated manually from the final images with linear interpolation. All image reduction was performed with IRAF and the STSDAS packages\(^2\).

3.1. Photometric Calibration and Corrections

During the photometric nights, standard stars taken from the UKIRT Bright Standard List (see Casali & Hawarden 1992) were observed every two hours. Each standard star was measured in

\(^2\)IRAF is the Image Analysis and Reduction Facility made available to the astronomical community by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under contract with the U.S. National Science Foundation. STSDAS is distributed by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS 5-26555.
two positions on the array. The zero-point flux calibrations were typically accurate to 0.05 mag in $J$, 0.04 mag in $H$, and 0.03 mag in $K$. The stability of the system was very good; zero points did not differ by more than a few percent from one night to the next during a run. Airmass corrections were applied to the standard stars and program objects using the mean UKIRT extinction coefficients of 0.10, 0.05, and 0.07 mag airmass$^{-1}$ in $J$, $H$, and $K$, respectively.

We applied a number of corrections to the photometric calibration given by the airmass corrected standard star observations. The first involves the chromatic change in the IRCAM pixel scale. While the nominal pixel scale in the $K$-band is 0.62 arcsec$^3$, chromatic effects in the IRCAM optical train make the $J$-band and $H$-band pixels larger by 4% and 1%, respectively, and change the nominal calibration to mag arcsec$^{-2}$ by 0.022 in $H$ and 0.085 mag in $J$.

To analyze galaxy colors and compare them to those of normal galaxies in the literature, we applied three additional corrections to the data. First, we transformed the UKIRT photometry to the CalTech-CTIO (CIT) photometric system (Frogel et al. 1978; Elias et al. 1982). Such a transformation affects mainly the UKIRT $J$ filter as it is somewhat bluer than that of the CIT (Casali & Hawarden 1992). We adopted the CIT system as it is one frequently used in observations of normal galaxies (e.g., Frogel 1985), and is the one on which the UKIRT standard system is based. Second, we corrected for Galactic extinction using the Burstein-Heiles values of the $B$-band extinction given in the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991; RC3), together with the interstellar extinction curve of Cardelli et al. (1989).

The final correction was the $K$ correction for redshift determined according to the precepts of Persson, Frogel, & Aaronson (1979). These are based on the rather red (equivalent to a late-type K III star) colors of normal galaxies, and are roughly linear with $z$ for small redshifts: $-0.5 z$, $-3.5 z$, and $+3.3 z$ for $J - H$, $H - K$, and $K$, respectively. For a redshift of 0.03, they are $-0.015$ for $J - H$ and $-0.11$ mag for $H - K$. The transformed (to CIT) colors corrected for Galactic extinction and redshift will be referred to as $(J-H)_0$ and $(H-K)_0$.

We have compared synthetic-aperture photometry obtained from our calibrated images with photometry in the literature. The sense of all the comparisons is us - them in units of magnitudes; NGC 7469 has been excluded from the comparison because of its known NIR variability (e.g., Lebofsky & Rieke 1980). The agreement with the photometry for the four galaxies in common with Balzano & Weedman (1981) is good with $\Delta K = -0.03 \pm 0.12$, and similar values in $J$ and $H$ (8.5 arcsec aperture). The agreement with other single-element photometer observations is similar: $\Delta K = -0.07$ for NGC 3362 (9 arcsec, Glass & Moorwood 1985) and $\Delta K = -0.08$ for NGC 5548 (10 arcsec, Hunt et al. 1994). For the three galaxies common to this work and ZD, the photometry agrees reasonably well with $\Delta K = 0.17 \pm 0.17$ (5 arcsec), a difference within their estimated accuracy of 0.1 to 0.15 mag. Two galaxies are also common to this work and KW, and the agreement of the photometry is good with $\Delta K = -0.05 \pm 0.06$ (12 arcsec). All things considered, we estimate the effective uncertainty in our absolute calibration to be around 0.1 mag.

### 3.2. Profile Extraction

Elliptically-averaged radial surface brightness profiles were extracted from the images (before sky subtraction, see below) by first fitting the central peak of the galaxy in each filter with an axisymmetric two dimensional gaussian. The center was then fixed, and ellipses were fitted to the outer $J$ isophotes; the ellipticities and position angles were determined by measuring the best-fitting ellipse at the 21 $J$-mag arcsec$^{-2}$ isophote. This isophotal level is roughly 100 times fainter than the sky and corresponds approximately to the $3\sigma$ noise limit of the images. We preferred to fix the

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3We were unable to check this as we lacked the large field-of-view necessary to perform astrometry. See, for example, de Jong (1995).
ellipse parameters, instead of letting them vary radially, so that we could better compare profiles in
the different passbands. The major-axis increment of the radial profiles was defined to be 1 pixel,
or 0.62 arcsec (K-band).

Radial brightness profiles in the J band, and radial color profiles are presented in Fig. 1,
together with grey-scale images with contours of the J-band image overlayed. Images and profiles
in Fig. 1 are all shown after the sky subtraction described in the following section.

3.3. Outer Disk Colors, Color Gradients, and Sky Level Determination

Because accurate surface photometry of the outer disks of these galaxies requires sky level
determinations accurate to better than one part in 1000, after much experimentation we adopted a
new procedure for measuring the sky for each galaxy. Although it utilizes one powerful constraining
assumption, which might not always be valid, it has the advantages of speed, simplicity, objectivity,
and great precision.

We have exploited the techniques outlined in Sparks & Jørgensen (1993) to determine, indepen-
dently of sky level, mean colors and dimensionless color gradients in the outer disk. We then
incorporated these as fixed parameters in a simultaneous $\chi^2$ fitting procedure of the outer parts of
the J-, H-, and K-band surface brightness profiles. The constraining assumption alluded to before
is that the outer part of each of the profiles is described simply by the sum of a constant sky level
and an exponential law \[ I(r) = I(0) \exp \left(-r/r_0\right) \]. We therefore fit the three profiles simultaneously
for five parameters, the sky levels in each of the three bands, and the surface brightness and scale
length of the disk in one band. The average colors and color gradients, derived independently,
constrain the disk fits in the remaining bands. Details of the method are given in Appendix A.

As an after-the-fact justification for this technique, we note that nearly all of the profiles,
In magnitude vs. radius (i.e., logarithmic vs. linear) plots, are extremely well characterized by
very straight lines over the outer two thirds to three quarters or more of their points (see Fig. 1).
In fact, we do not have any cases where the outer half of the profile is not well described by an
exponential law, a behavior similar to that generally observed in normal spiral disks (e.g., Freeman

3.4. Inner Disk Colors

In addition to the outer disk colors obtained independently of sky subtraction as described in
the previous section, we also determined colors of the “inner disks”. This was done by calculating
averages of the radial color profiles between 4 arcsec and 3 kpc. An inner limit of 4 arcsec was used
as the color profiles show that, for bright and red nuclei, the nuclear colors can contaminate the
galaxy profile out to roughly this apparent radius (see in Fig. 1, for example, Mkn 530 and Mkn
817). The outer radius was the lower limit of the radial range used to fit for the average colors and
color gradients in the outer disk (see Appendix A). Photometric corrections, as described in Section
3.2, were applied to both inner and outer disk colors. The colors, thus obtained, are reported in
Table 2, along with mean values for each activity type obtained by simple averages over all the
galaxies in each subsample.

3.5. Two-Dimensional Color Images

To construct the color images, very accurate alignment is necessary. Because the small field-
of-view of IRCAM1 minimizes the probability of having stars in the galaxy field, we were forced
to align images using other techniques. To determine the alignment offsets, we first subjected the
images to a $3 \times 3$ bi-linearly interpolated magnification; the exact expansion factor varies from band to band as it is necessary to take into account the different pixel sizes in the different bands.

The shifts were then determined in two ways: (i) from the maximum of the two-dimensional cross-correlation function of the expanded (sky-subtracted flux) images, and (ii) from the relative shifts of the peak of the galaxy emission, as determined by a two dimensional axisymmetric gaussian fit. In all but a few cases, the two methods of determining the relative alignment gave similar results, implying that the nuclei are not sufficiently reddened to be offset spatially in the different NIR passbands. In those few cases where the two methods did not give consistent shifts, usually where there was structure in the color images or objects on the edge of the frame, we aligned the images assuming that the peaks of the galaxy emission in the different wavebands coincide. Finally, the magnitude images were registered to a fraction of a (magnified) pixel using polynomial interpolation and subtracted. In this way, we generated color images in $J - K$ and $J - H$.

A sample of these color images is shown in color in Plate 1. The remainder are shown in Fig. 1 as grey scale plots, with the direct $J$-band image adjacent.

4. Results

We defer a detailed analysis of the general morphology, the radial brightness profiles, and the non-axisymmetric features of the broadband images to Paper II (Chapter 10). Here we discuss the average disk colors, color gradients, and the structure in the color images. Note that the mean colors and color gradients are measured from azimuthally averaged major-axis profiles, rather than from virtual-aperture photometry.

4.1. Average Disk Colors

We find no significant difference in inner or outer disk colors between type 1 and type 2 Seyferts, nor between the Seyferts and the SBNs. More specifically, although Seyfert 2s may have slightly blue colors (see Table 2), the outer disk colors of all three classes are consistent with those of normal spiral disks as shown in the two-color diagram in Fig. 2; the sample medians ($J - H = 0.68$ and $H - K = 0.22$) are equivalent to those found by other groups for normal spiral galaxies (Griersmith, Hyland, & Jones 1982; Glass 1984; Frogel 1985; Giovanardi & Hunt 1988; Giovanardi & Hunt 1996).

The inner disk colors of type 1 Seyferts and SBNs tend to be slightly redder in $J - H$ than those of the outer disk, and lie at the blue end of the range of NIR colors of Sa’s, dominated by massive metal-rich bulges (Giovanardi & Hunt 1996). Indeed, what we call “inner disk” colors should probably be called colors of the bulge (see also Terndrup et al. 1994). In any case, the spread in both sets of colors is remarkably small, given that these galaxies host active nuclei. We show the $H - K$ colors of the inner disk as histograms in Fig. 3. All four (Sy 1’s, Sy 2’s, SBNs, normal spirals) of our color distributions are indistinguishable, in mean and scatter, from each other.

Our result contradicts both ZD and KW, who found Seyfert host galaxies to have a normal distribution in $J - H$, but with an $H - K$ color which: (i) is redder on average than in normal galaxies; and (ii) has a substantially wider dispersion than is observed in normal spirals. There are two possible reasons for this contradiction: the first is that both ZD and KW used colors determined from annular rings somewhat close to the nucleus (2.5 to 3.9 arcsec radii, and 3 to 6 arcsec radii, respectively), so that there is a chance of spillover from the bright non-stellar AGN (cf., color profiles in Fig. 1). The second possible reason for the disagreement is that both groups neglected to apply the $K$ correction; as mentioned in Section 3.2, this correction is seven times larger for the $H - K$ color than for $J - H$, so that not applying it would result in colors substantially normal in $J - H$, but redder than normal in $H - K$. 

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Fig. 3.— Color-color diagram of the mean inner and outer disk corrected colors for each activity class; the error bars correspond to the spread (standard deviation) of the colors within each activity class. Circles show Seyfert 1s; squares Seyfert 2s; and triangles SBNs; filled symbols indicate the “inner” disk, and open symbols the outer disk. Dotted lines show the spread of colors for elliptical and Sc systems (Frogel 1985), and for Sa’s (Giovanardi & Hunt 1996). The locus of the K correction is also shown (departing from the average colors), with z-increments of 0.01 shown by crosses. A visual extinction of 1 mag is shown by the arrow in the lower right-hand corner.

We have checked this last hypothesis by correcting for redshift the host galaxy colors reported in ZD and KW. They found sample medians for the host galaxy colors of 0.77 (ZD) and 0.71 (KW) for J − H and 0.45 (ZD) and 0.49 (KW) for H − K. After applying the K-correction, the sample medians are substantially unchanged in J − H: 0.75 (ZD) and 0.71 (KW), but are significantly different in H − K: 0.36 (ZD) and 0.32 (KW). The corrected H − K values are shown in the histogram in Fig. 3. The corrected colors of both groups coincide very well with our result for Sy 1s (inner disk), and the peaks of the distributions are consistent with colors of normal galaxies.

4.2. Color Gradients

A visual inspection of the azimuthally averaged radial color profiles illustrated in Fig. 1 shows that of eight galaxies with starburst nuclei, six present red circumnuclear “ridges” in the J − H color. In contrast, only three of eight galaxies with type 1 Sy nuclei and none of the type 2 Sy nuclei shows the same tendency. Another phenomenon is shown only by the Sy 2’s: namely, a circumnuclear blue “dip” in the J − H color. We will discuss these trends in more detail in connection with the structure in the color images (§4.3).
Fig. 4.— Histograms of the corrected inner disk \((H - K)_0\) color as a function of activity type. The top two panels show colors taken from Kotilainen & Ward (1994) and from Danese et al. (1992), after correcting for \(K\)-dimming as described in the text. The bottom panel shows (corrected) normal spiral colors derived from the radial profiles in de Jong & van der Kruit (1994).

**Inner vs. Outer Colors**

The inner and outer NIR disk colors are plotted against one another in Fig. 4; the solid line in the figure indicates equality. The majority of type 1 Seyferts and SBNs present \(J - H\) colors which are redder within 3 kpc than those in the outer disk; in contrast, the majority of type 2 Seyferts show bluer \(J - H\) colors in the inner disk. The trend for redder \(J - H\) in the inner regions is weak in any case, with a mean amplitude of \(0.02 - 0.03\) (see also Fig. 2). The change in \(H - K\) from inner to outer disk shows more variation, as something like half the galaxies have redder and half have bluer \(H - K\) in the inner part; this behavior in \(H - K\) is also seen in the de Jong & van der Kruit normal spirals (denoted by \(\times\) in Fig. 4).

The color behavior shown by the galaxies in our sample is similar to that of normal spirals. Terndrup et al. (1994) analyzed \(J\) and \(K\) images of normal spirals and found that bulge (roughly equivalent to our “inner”) and disk (outer) \(J - K\) colors are roughly the same. Their data are shown by \(\times\) in the \(J - K\) panel of Fig. 4. The redder inner disk \(J - H\) colors in Sy 1’s and SBNs are evident in the middle panel, as all but three lie above the equality line. The effect is diluted in the \(J - K\) color, however, and the behavior shown by our galaxies is similar to that of Terndrup et al.’s sample. Multiaperture photometry also shows that bulge NIR colors tend to resemble those of the disk component, with redder colors in the inner (few kpc) regions (Griersmith et al. 1982; Frogel 1985). We, therefore, hesitate to attribute the slightly redder inner disk colors seen in Sy
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Fig. 5.— Corrected inner and outer disk colors. The upper-left panel shows $J-K$; the upper-right panel $J-H$; and the lower panel $H-K$. The solid line indicates equality. Seyfert 1s are shown by circles; Seyfert 2s by squares; and SBNs by triangles. Typical error bars are shown in the upper left corner of each plot. In the $J-K$ panel, crosses show normal spirals from Terndrup et al. (1994); in the $H-K$ panel, crosses show normal spirals from de Jong & van der Kruit (1994).

Seyfert 1’s and SBNs to processes associated with the active nucleus or star formation, as it seems more plausible that the redder colors are due to effects which occur also in normal spirals, that is a red bulge component which dominates the inner regions, or extinction, or both.

Outer Disk Gradients

The color gradients measured for sky subtraction (see Appendix A) are also of interest in their own right. To interpret the results from the generalized polynomial fitting procedure we used to derive them, we first need to impose a parametric model for the disk light. This is easily accomplished using the generalized exponential given in Sparks (1988):

$$I(s) = I_e \exp[-\alpha(s^\gamma - 1)]$$  \hspace{1cm} (9.1)

where $s$ is a dimensionless radius, $r/r_e$, and $r_e$ is the effective (half-light) radius. For an exponential disk, $\alpha = 1.68$ and $\gamma = 1$ (see Sparks 1988). Following Sparks & Jørgensen (1993), we suppose that the radial profile is described by Eq. 9.1 at a first wavelength with scale length $r_e$ and at a second wavelength with scale length $r'_e = r_e + \Delta r_e \equiv r_e(1 + \Delta s)$. The second-order term, $a_2$, in the
Fig. 6.— Outer disk gradients as a function of activity type. The plotted quantity is the fractional change in scale length $\Delta s$, obtained from the second-order term $a_2$ in the Tchebyshev polynomial fit to the flux-flux profiles as described in the text and in Appendix A; error bars are the formal errors associated with the polynomial fit. The upper-left panel shows $J - K$; the upper-right panel $J - H$; and the lower panel $H - K$. The activity type spacing is arbitrary, and Seyfert 1s are shown by circles; Seyfert 2s by squares; and SBNs by triangles (and denoted by “activity type” 3). For convenience, a zero gradient is shown by the horizontal dotted line.

Tchebyshev polynomial fit to the fluxes at two different wavelengths is simply related to $\Delta s$:

$$\Delta s \approx \frac{3}{\gamma} \approx -3 a_2$$

(9.2)

The $a_2$’s for our sample are given in Table 3, together with the mean radius over which the gradient was determined. Fig. 5 shows the fractional scalelength change $\Delta s$ as a function of activity type, with Sy’s denoted by 1 and 2, SBNs by 3, and normal galaxies by 4.

We included a given outer-disk color gradient in the sky fits if it was determined with a S/N $\geq 3$. Using this same criterion, we find that 4 of 9 Sy 1’s, 2 of 8 Sy 2’s, and 6 of 8 SBNs present significant non-zero gradients in at least one of the two colors. In the normal spirals, for which we only have $H - K$, we find 2 of 8 with significant non-zero gradients. The sign of the gradient in each of the four samples is evenly distributed, with half of the significant gradients positive and half negative. It seems that the largest gradients seen in Fig. 5 are from $J$ to $H$ and in the positive sense, but the galaxies that present the largest gradients are those for which the assumption of an exponential disk is probably not valid: namely 1614+35, Mkn 575, and Mkn 496. The first two are systems with prominent bars, and the third is the result of a merger.
Although we used a different method to derive color gradients, we can compare our results to those found by Terndrup et al. (1994) for normal spirals. For a color gradient of the form:

$$\Delta (\mu_J - \mu_K) = \beta \Delta \log r$$  \hspace{1cm} (9.3)

we find, from Eq. 9.1 and assuming an exponential disk, that:

$$\beta \approx 4.2 \langle s \rangle \Delta s$$  \hspace{1cm} (9.4)

The mean value of $s$, $\langle s \rangle$, can be defined as the mean radius of the interval used for the determination of $a_2$. Terndrup et al. measured disk gradients roughly from 0.8 to 1.8 of $r_0$ (disk exponential folding length), so that we assume an $\langle r \rangle/r_0$ of 1.3. Since $\langle r \rangle/r_0 = 1.68 \langle s \rangle = 1.3$, we have $\langle s \rangle = 0.77$, and $\beta \approx 3.25 \Delta s$. The largest $\beta$'s in their sample are positive with amplitudes of 0.6–0.7, corresponding to a fractional scale length change of around 0.2 from $J$ to $K$, comparable to the largest value we find for our galaxies. Moreover, the gradients for normal galaxies found by Terndrup et al. are roughly evenly distributed between positive and negative values, as are the gradients measured here. It appears that the color gradients in our galaxies are more or less normal, both in sign and amplitude.

### 4.3. Structure in the Color Images

Although quantitative analyses of galaxy images are usually based on azimuthally-averaged data, not all photometrically interesting structures possess azimuthal symmetry. In fact we have found some of these in the two-dimensional images.

In several cases there is a clear color gradient which is not radial, but azimuthal or more complex. Inspection of Fig. 1 shows cases where the $J - K$ color weakly delineates spiral structure (e.g., 1335+39, Mkn 334, Mkn 533, Mkn 307), or bars (e.g., 1614+35, NGC 5674, and Mkn 575). The $J - K$ images also show more exotic structures like rings and filaments in one type 1 Seyfert (NGC 7469), and in five SBns (Mkn 496, Mkn 545, Mkn 717, Mkn 732, Mkn 912).

Such non-axisymmetric red structure in active galaxies can be caused primarily by two mechanisms: dust extinction or excess 2μm emission (dust in emission or HII regions, see also Hunt & Giovanardi 1992). We have investigated the alternatives of extinction or excess emission for the galaxies in our sample by applying a simple model to the color images. First, we compute the optical depth pixel-by-pixel from the $(J - H)_0$ color image by assuming that the dust is in front of the stars emitting the NIR flux (see Telesco et al. 1991); then we apply the extinction so derived to the $(H - K)_0$ image. Assuming that a red $H - K$ color is due to reddened stellar emission + some non-stellar processes that emit only in the $K$-band, we can derive an image that maps the excess (over the reddened stellar) $K$-band emission:

$$\left(\frac{H - K}{K}\right)_{\text{obs}} = \left(\frac{H - K}{K}\right)_{\text{0(stars)}} + 1.086 \left(\tau_H - \tau_K\right) + 2.5 \log \left[1 + \frac{\Sigma_K(\text{excess})}{\Sigma_K(\text{stars})}\right]$$  \hspace{1cm} (9.5)

where $\Sigma_K$ is the $K$-band surface brightness in flux units of the excess and stellar radiation. The excess is given as the last term in Eq. 9.5. We calculated the visual optical depth, $\tau_V$, by applying the Cardelli et al. (1989) interstellar extinction curve, and, instead of adopting the corrected outer disk colors as the intrinsic colors, we used the sample medians of 0.68 (in $J - H$) and 0.22 ($H - K$). The sample medians were preferred to the individual corrected colors for each galaxy as we found that the azimuthally averaged outer disk colors can frequently be as much as 0.1 redder than those outside the red structures. The implication is that even azimuthal averages can be affected by sufficiently significant structure in the colors.
The assumption of the dust acting as a foreground screen instead of being uniformly mixed with the stars (hereafter denoted by “true”) simplifies the calculation of the $K$-band excess, but underestimates the dust optical depth (e.g., Mathis 1970); moreover, such an assumption may spuriously imply excess long-wavelength emission when, in fact, there is none. We have therefore checked the validity of the simple screen model on these two points: (i) how well the optical depth $\tau_V$ estimated by the screen model corresponds to the “true” one; and (ii) how the amplitude of any spurious excess emission varies with $\tau_V$. The results of these checks are given in Appendix B, and show that, for inferred “screen” $\tau_V \lesssim 2.0$, there is a simple multiplicative factor ($\sim 2.3$) relating the “true” and “screen” $\tau_V$. Under these conditions the spurious implied excess emission fraction (the error on the last term in Eq. 9.5) $\lesssim 0.01$. Hence, as long as the “screen” optical depths $\lesssim 2.0$ and the excess emission fractions $\gtrsim 0.05$ ($5\sigma$), the excess should be real. We emphasize that, while seemingly quantitative, this technique is really only a qualitative estimate of both the extinction and excess $K$-band flux. We use it to diagnose the presence of dust and excess $2\mu$m emission, not to make definitive statements about the amplitude of the optical depth or precise estimates of the quantity of non-stellar emission, as both quantities strongly depend on the assumed intrinsic colors, the geometry of the dust and stars, and the properties of the excess emission such as dust temperature and emissivity.

Spiral structure, bars, and lens distortions

The spiral arms in 1335+39, Mkn 307, Mkn 334, and Mkn 533 are characterized by $\Delta(J - K) \approx 0.14-0.18$ across the arm. These are similar to the color changes across the spiral-arm dust lanes in M 51 reported by Rix & Rieke (1993) who find $\Delta(J - K)$ ranging from 0.13 to 0.21. Our simple model gives (screen) $\tau_V$ ranging from 0.3 to 0.6 in the arms, which correspond to “true” optical depths $\tau_V$ between 1 and 2. We note that these inferred “true” optical depths are roughly a factor of two lower than those derived by Rix & Rieke who applied a detailed radiation-transfer model to multicolor optical and NIR data; evidently, even the internal extinction model tends to underestimate the true extinction. We find no evidence for excess $K$-band emission in the arms. Oval distortions and bars show less obvious color trends. The two galaxies with clear oval or lens distortions, Mkn 1243 (Sy 1) and Mkn 732 (SBN), show negligible $J - K$ color gradients associated with the lens, as the $J - K$ color image for Mkn 1243 is roughly axisymmetric and that for Mkn 732 is confused by the circumnuclear ring (see below). The bars in 1614+35, Mkn 575, and NGC 5674, on the other hand, all show roughly 0.14-0.18 of reddening in $J - K$ along the bar. Again, taken at face value, these color gradients correspond to (“true”) optical depths in the $V$ band between 1 and 2. Again, as for the spiral arms, neither bars nor oval distortions show evidence for excess $K$-band flux.

Rings, ridges, and filaments

Perhaps the most striking features revealed in the color images are the rings and filaments in the SBNs. Of eight SBNs with $JHK$ colors, five show red circumnuclear rings (Mkn 545, Mkn 717, Mkn 732, Mkn 912), non-axisymmetric circumnuclear ridges (Mkn 496), or filaments (Mkn 545). These galaxies also show the circumnuclear “ridge” in the $J - H$ color profile noted in §4.2. Of eight type 1 Seyferts, only NGC 7469 shows an extended red circumnuclear ring+ridge (and circumnuclear ridges in the color profiles); none of the type 2 Seyferts presents similar structure. We note that such features in the SBNs are particularly surprising since the SBNs were selected for their nuclear properties (see §2), not for evidence of any extended starburst region. All of these features provide evidence for dust in extinction and excess $2\mu$m emission. Fig. 6 shows contour plots of the $\tau_V$ maps, together with maps of the excess $K$-band emission. While the
knots in the outer regions are due to noise, the contiguity of the inner contours implies that the features in both the optical depths and in the excess emission correspond to real features. Values for (screen) $\gamma$ in the rings, ridges, and filaments ranges from 0.2 to roughly 1.5, corresponding to “true” visual optical depths of up to 3 or 4. Excess emission fractions in these features range from 0.1 to 0.3 or more; the implication is that, locally, excess nonstellar emission can comprise as much as 30% of the stellar $K$-band emission.

Red $JHK$ extranuclear colors observed primarily in starbursts were also noted in previous studies. Forbes et al. (1992), on the basis of NIR images of LINERS and starbursts, found evidence for variations in obscuration in starbursts and hot dust close to the nucleus. Low resolution maps of the NIR radial color distribution in Seyferts and starbursts (Hunt & Giovanardi 1992) show red extranuclear $JHK$ colors only in starbursts, colors that are consistent with internal extinction, emission by hot dust, or both.

Color-color diagrams

To confirm the nature of the features described in the preceding subsections, we have produced pixel-by-pixel color-color diagrams for our sample galaxies. The pixels are extracted directly from the $(J - H)_0$ and $(H - K)_0$ images, and representative examples are shown in Fig. 7, together with mixing curves for various physical processes. To conserve some spatial information, we have coded the nuclear regions ($R \leq 4$ arcsec) as filled circles, the circumnuclear regions (4 arcsec < $R \leq 3$ kpc, “inner disk”) as open circles, and the outer regions (3 kpc < $R \leq 11$ arcsec) as points. Indeed, the inferences made in the preceding paragraphs are borne out by the color-color diagrams. In particular, the colors in one type 1 Seyfert NGC 7469 and in six SBNs (the five with non-axisymmetric features noted above and Mkn 575 with a bar) lie along the extinction vector.

The nature of the excess $K$-band emission can also be investigated with the color-color diagrams. Roughly constant $J - H$ colors together with red $H - K$ indicate hot dust, while bluer than normal $J - H$ and red $H - K$ suggest nebular emission probably from HII regions. Of the six galaxies that show evidence in the color images for excess emission, five show red $H - K$ extranuclear colors associated with normal stellar population $J - H$. We attribute the excess $K$-band emission in these systems to hot dust. Only in Mkn 912 (SBN) does the rather blue $J - H$ color together with red $H - K$ suggest that nebular emission causes the 2$\mu m$ excess.

Finally, the color-color diagrams enable us to discern colors associated with an intermediate-age population arising from a past burst of star formation (shown in the mixing curves as “Aged Burst” and “A stars”). Five of the seven type 2 Seyferts with $JHK$ colors have the blue colors that signify a conspicuous contribution from a “fossil” starburst. We note that the azimuthally-averaged profiles lend support for bluer colors in the inner regions of Seyfert 2s: (i) a subset of these galaxies also show the circumnuclear blue “dip” noted in §4.2; (ii) the mean colors of Seyfert 2 inner disks tend to be slightly bluer than those of Seyfert 1s and SBNs (sample mean of 0.67 vs. 0.70–0.71), although no claim for significance was made because of the 0.03–0.05 scatter; (iii) the mean Seyfert 2 inner disk colors are bluer than those of the outer disk (see Fig. 2), an unusual trend not observed in the Seyfert 1s or the starbursts studied here, nor in normal spirals (e.g., Frogel 1985). In contrast with the Seyfert 2s, only two type 1 Seyferts and three SBNs show clear evidence in the color-color diagrams for blue colors associated with an intermediate-age stellar population.

5. Discussion and Conclusions

Our study is focussed on the galaxies hosting active nuclei, rather than the active nuclei themselves; we were particularly careful in the analysis to avoid contamination by the nucleus, and to obtain images and color images as precise as possible even at low surface brightness.
Our main results are as follows. The average colors, both of the outer and the inner disks, are fully consistent with being independent of activity class, and equal to those of normal spiral galaxies. This is at variance with previous studies, which found $H - K$ redder by $\approx 0.1$ magnitude in the inner regions of active galaxies. We have shown that most of this discrepancy arises from the neglect of the redshift correction: when the correction is made, the previous data become compatible with the present results.

The outer disk color gradients are compatible with those of normal spirals. The color gradients in the outer disks, and the color differences between inner and outer disk, do not show any clear cut trend. In $J - H$, we find marginal evidence of red inward differences in Seyfert 1s and starbursts, and of blue inward differences in Seyfert 2s; however, given the smallness of the effect, and the uncertain results about NIR color gradients in normal galaxies, a pixel-by-pixel color analysis is required.

Two methods have been used to investigate the presence of dust in these galaxies. We have looked for dust features in absorption ($J - H$ redder than normal) and in emission ($H - K$ still redder than normal after dereddening), with the constraint that reliable features should follow simple connected patterns. Such features are seen primarily in the inner disks of starburst galaxies; in the other activity classes, only NGC 7469 shows dust in absorption and in emission, in accordance with its well-established circumnuclear starburst (Mazzarella et al. 1994; Genzel et al. 1995). The implication of this is that in the starbursts, gas associated with the dust we observe has been swept in from the outer disk, piling up in locations in the inner disk that perhaps correspond to dynamical resonances. Such dust (and gas) is not observed in the inner disks of typical Seyferts.

We have also plotted small areas of each galaxy disk on a color-color diagram, in order to enhance the visibility of localized, non-axisymmetric color features which would be smeared out in the averaging process. We find that the inner disk blueing of Seyfert 2s, alluded to above, is due to patches spread along the “Aged Burst” mixing line. Population synthesis models (e.g., Leitherer & Heckman 1995; see Fig. 7) indicate that the blue colors observed in the Seyfert 2s correspond to ages of roughly a few $\times 10^8$ years after a burst of star formation. Systematic differences between Seyfert 1s and Seyfert 2s with respect to the star formation activity have been reported previously, indicating that Seyfert 2s are star-forming and Seyfert 1s are not (e.g., Maiolino et al. 1995). Previous work also suggests that star formation in Seyfert 2s is “fossil” (Glass & Moorwood 1985; Taniguchi & Mouri 1992; Dultzin-Hacyan & Benitez 1994; Oliva et al. 1995), and age indicators such as the one proposed by Oliva et al. (1995) should prove useful in this context.

In conclusion, on a scale of a few kiloparsecs from the center, starburst galaxies show ongoing star formation, signalled by the presence of hot dust; Seyfert 2s exhibit “fossil” star formation activity, a few hundred Myr old, signalled by the presence of an old starburst component in addition to a normal population; and, finally, Seyfert 1s do not show any sign of activity either ongoing or fossil exceeding that of normal spirals. It is to be stressed that most of the evidence appears in the pixel-by-pixel analysis, and is strongly diluted or completely washed out by averaging over large disk areas; furthermore, nothing can be deduced from our data concerning possible star formation activity in the immediate vicinity of the nucleus, where superior angular resolution would be needed.

The emerging picture is that of a starburst-Seyfert evolutionary connection, although not so global and not so tight in time as previous studies would have implied. The starburst activity appears to involve restricted regions of the inner disk in the pre-Seyfert phase; this spatially-confined activity is however capable of feeding matter to the nucleus on a time scale comparable with the lifetime of the starburst, and Seyfert activity begins. The reason why the Seyfert 2s appear to precede in time the Seyfert 1s is perhaps only statistical (e.g., Maiolino et al. 1995): a ‘young’ active nucleus should be surrounded by matter contributed recently by the starburst, and injected into non-equatorial orbits; then the lines of sight to the center should have a high probability of being obscured. At later times the accretion flow should settle in a thinner configuration, and
obscuration-free lines of sight should become more numerous.

Recent theoretical work seems to support this scheme. Heller & Shlosman (1994) have studied the evolution of the gas distribution in globally unstable galactic disks and found that gas inevitably builds up within the inner $\sim 100$ pc on timescales of $\lesssim 1$ Gigayear. A circumnuclear /nuclear burst of star formation and the creation of a supermassive object in the galaxy’s center are almost certainly the consequence of such a central gas concentration. Their models further suggest that the formation of a black hole would follow the episode of star formation, which is what seems to emerge from our observations.

While an evolutionary link between starburst and Seyfert activity seems likely, we can only speculate about the relationship between “active” and quiescent galaxies. Many lines of evidence indicate that episodes of star formation can cause the structural components of galaxies to evolve over time. For example, disks can become more compact by inward gas transport and subsequent star formation (e.g., Kormendy 1993). Interestingly, steep inner disks have been noted to be associated with active star-forming galaxies (Boroson 1981). Bulges may also be built up by similar evolutionary processes: as pointed out by Kormendy (1993), steep $r^{1/4}$ brightness gradients associated with disk-like dynamics; triaxial bulges in disk-like barred galaxies; and Population I material in “bulges” all imply that the distinction between bulges and disks is not as sharp as was previously thought. Statistical evidence also leads to the conclusion that galaxies initially without massive bulges can form them as a consequence of galaxy interaction and the ensuing star formation episode (Elmegreen, Elmegreen, & Bellin 1990). Evidently, if a galaxy disk is subject to perturbations in its gravitational potential, subsequent redistribution of the disk gas can give rise to bursts of star formation which may alter the galaxy’s physiognomy. In the end, it is conceivable that starburst and Seyfert activity may be transient, but inevitable, phases in the normal evolution of galactic systems.

We would like to thank C. Aspin for scientific and moral support; the UKIRT technical staff for cheerful competence and timely assistance; and the SERC PATT for generous allocations of telescope time. We are also grateful to R. de Jong for providing profiles and images of the galaxies in his sample, and to J. van Hardy for his insightful comments.

A. Determination of Sky Levels, Outer Disk Colors, and Color Gradients

Analysis of cuts along the sides of some of the images shows that we have succeeded in flattening them to $0.1–0.2\%$ in $J$ and $H$, and $0.08–0.09\%$ in $K^4$. At this level then, the sky in each frame is presumed to be an additive constant at every pixel. As pointed out by Sparks & Jorgensen (1993), some intrinsic galactic properties can be measured even when the absolute levels of the sky brightness are not known in any of the filters. This capability is most evident when the flux at a given wavelength at each pixel is plotted against the corresponding flux for that pixel at another wavelength. The slope and curvature of this linear flux vs. linear flux plot are independent of the additive offsets of the sky. Consider the fluxes $f_1$ and $f_2$ in two different filters:

$$f_2 = c_0 + c_1 f_1 + c_2 f_1^2$$

The first order coefficient $c_1$ is the average color (or flux ratio) of the galaxy. The second order coefficient $c_2$ measures a dimensionless color gradient. Unfortunately, ordinary polynomials are not suitable for the parameterization of scalelength changes with $c_2$ as described in the text. Instead,

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$^4$These are, in fact, upper limits to the true image flatness, as in most cases, faint galaxy emission is evident even on the edge of the array.
we must exploit an orthogonal set of polynomials (Sparks & Jørgensen 1993):

\[ n_2 = \frac{a_0}{2} + \sum_{i=1}^{4} a_i T_i(n_1) \]  

(A2)

where \( n_1 \) and \( n_2 \) are the scaled fluxes (to the interval \([-1,1])\) and the \( T_i \) are the Tchebyshev polynomials.

To determine the mean disk color, we performed second-order linear regressions on the flux-flux data sets; each data set consists of the profile extracted as defined in the previous section, and there is one data set for each filter. All fits were limited to galactocentric distances \( R > 3 \) kpc. The first-order coefficient \( c_1 \) is determined by the least-squares fitting routine with a typical error bar of only a few percent of its value. To determine the mean color gradient, following Sparks & Jørgensen (1993), we fit up to fourth-order Tchebyshev polynomials to the two scaled flux-flux data sets (as before limiting the fits to those points with \( R > 3 \) kpc). The curvature term in these fits \( a_2 \) has a typical uncertainty of 0.01, that is to say a 3% difference in scale length between the two wavebands.

While these sky-independent parameters are important in themselves, we also exploited them to determine the unknown sky level of our images. In practice, after having determined the mean disk colors and color gradients, we then used these parameters as the inputs to a second least-squares fitting procedure. For a given galaxy, we simultaneously fitted, in a weighted least-squares sense, to the outer parts (\( R > 3 \) kpc) of the \( J \), \( H \), and \( K \)-band surface brightness profiles the sum of a constant sky level and an exponential law \( [I(r) = I(0) \exp(-r/r_d)] \). All of these profiles were fitted before any sky subtraction. The constant sky brightnesses in each waveband were three of the five free parameters to be fitted; the remaining two were the parameters that describe the exponential disk (central surface brightness and exponential folding length) in one band. The brightness profiles of the other two wavelengths were also forced to be exponential, but with two modifications which were not free fitting parameters. First, the average color in the fitting range of radius was fixed to be equal to the color we found in the earlier polynomial fit described above. Second, the color gradient was fixed by the second-order coefficient, which determines by how much the disk scale length at the longer wavelength differs from that in \( J \).

The simultaneous fitting of the three different profiles in a self-consistent way gives very robust results because the problem is highly over-constrained. Thus formal errors\(^6\) on the five free parameters are exceedingly small: typically 0.03%–0.1% in the sky levels, 0.5% in the disk central surface brightness \( I(0) \), and 3% in the exponential scale length \( r_d \). The sky levels thus determined are always lower than the median values along the edges of the image, and their errors are consistent with the (upper limits of the) flatness we measure along the row-column cuts at the edges of the images. We emphasize that the fits always started at an inner radius of 3 kpc, and went out to the last measured profile point (see Fig. 1).

### B. Extinction Models: Foreground Dust Screen vs. Uniformly Mixed Dust and Stars

Most analyses of extinction in galaxies have been based on the assumption that the dust resides in a foreground screen. Such an assumption simplifies the calculation of the unknown optical depth

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\(^5\)For the two galaxies where we have only \( H \) and \( K \), we fit the disk to the \( H \) band, and imposed the average color and color gradient to the \( K \)-band disk. For the single galaxy (Mkn 719) where we have only an \( H \)-band image, we used the minimum curvature method described in Hunt (1993) to determine the sky level.

\(^6\)Assuming a \( \chi^2 \) increment equal, not to 1, but rather to the 1\( \sigma \) confidence level for a five-parameter fit (i.e., 5.9), e.g., Lampton, Margon, & Bowyer (1976).
\( \tau \) from reddened colors as the relations are linear (e.g.):

\[
(H - K)_{\text{obs}} = (H - K)_{\text{stars}} + 1.086(\tau_H - \tau_K).
\]  
(B1)

As has been amply pointed out (e.g., Mathis 1970; Boroson 1981; Tully & Fouqué 1985; Disney et al. 1989), a more realistic configuration would have the dust interspersed with the stars, making a determination of \( \tau \) from reddening more complex. In the simple case of a uniform slab in which the dust is distributed among the stars, the reddening equation becomes:

\[
(H - K)_{\text{obs}} = (H - K)_{\text{stars}} - 2.5 \log \left( \frac{\tau_K(1 - e^{-\tau_K})}{\tau_H(1 - e^{-\tau_H})} \right).
\]  
(B2)

Given a certain reddening and assuming a standard extinction curve, we can compare the optical depth inferred for the two above configurations (Eq. B1 and Eq. B2). Such a comparison is shown in Fig. 9a, and the onset of non-linearity is clearly evident for “slab” (uniform mix of dust and stars) \( \tau_V \approx 2 \). At slab \( \tau_V \approx 5 \), a linear extrapolation of the slope (2.3) at \( \tau_V = 0 \) results in a discrepancy of 0.3 between slab and screen optical depths, or 15% of “screen” \( \tau_V \). Slab optical depths are always greater than screen \( \tau_V \): by roughly a factor of two for small (screen) \( \tau_V \), and by more than a factor of four for (screen) \( \tau_V \approx 4 \).

In §4.3, we described the method we used for estimating excess (over the reddened stellar colors) 2\( \mu m \) emission. Assuming an intrinsic stellar color, we first derive the local optical depths from the \( J - H \) image. These optical depths are then used to deredden the \( H - K \) image, and any color excess over the assumed intrinsic stellar color is ascribed to excess \( K \)-band emission. The results reported are those based on the assumption of a foreground dust screen instead of the more realistic mix of dust and stars, and such an assumption may yield a spurious excess.

To estimate the influence of such an effect, we can proceed as follows. Assume there is no \( K \)-band excess; then, for a given \( \tau_V \), we can compute the reddening in \( J - H \) and in \( H - K \) for the case of the foreground screen. We can also derive the \( \tau_V \) needed to produce the same \( J - H \) reddening for the case of the uniform slab (e.g., Fig. 9a). But, in this case, the resulting \( H - K \) reddening will be greater than that for the screen model. Hence, under the premise that the uniform slab model corresponds to the “truth”, the assumption of a foreground screen will result in a spurious \( H - K \) color excess. Fig. 9b shows this spurious excess as a function of screen optical depth. It appears that the assumption of a foreground screen results in an erroneous \( H - K \) color excess \( \lesssim 0.01 \) for screen \( \tau_V \lesssim 2 \). Therefore, we conclude that, as long as we derive \( \tau_V \lesssim 2 \) or so, the spurious \( K \)-band excess is on the order of 1% of the stellar emission; this is also the (1-\( \sigma \)) limit and accuracy to which our method can estimate the \( K \)-band non-stellar contribution.

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Fig. 7.— Extinction and excess emission maps. The left panel shows contour plots of the visual optical depth $\tau_V$, and right panel the excess 2$\mu$m emission, both obtained from the simple screen model described in the text. (Additional galaxies can be viewed in the electronic version of the published paper.) The $\tau_V$ contours run from 0 to 2 with increments of 0.2, and from 0 to 1 with 0.1 increments for the excess. They are overlayed on the $J$-band magnitude image, and arcsec increments in R.A. and Dec. are shown on the coordinate axes. Notes on individual galaxies: 
(i) Mkn 496: extinction peaks between the two continuum maxima, while a ridge of excess emission is evident to the NE of the main nucleus;  
(ii) Mkn 545: NE and SW filaments spiraling in towards nucleus, culminating in a circumnuclear ring (cf. Fig. 1) that is overshadowed by the $J$-band image;  
(iii) Mkn 732: dust extinction and emission to the SW of nucleus, roughly coincident with the end of the oval distortion;  
(iv) Mkn 912: broad ridge of excess emission to the S of nucleus, together with a small amount of extinction;  
(v) NGC 7469: circumnuclear extinction and hot dust emission extends to the N and S of nucleus – may coincide with the inner spiral noted by Mazzarella et al. (1994); noteworthy the northern extinction and emission “ridge”.
Fig. 8.— Color-color diagrams of individual pixels from selected color images. Pixels with distance $R$ from nucleus $\leq 4''$ shown by filled circles; $4'' < R \leq 3$ kpc shown as open circles; and $3$ kpc $< R < 11''$ by points. Also shown are theoretical mixtures of galaxy colors and non-stellar emission processes (power-law, $S_{\nu} \propto \nu^{-1.5}$; HII regions; thermal dust emission at 600 K), an intermediate-age stellar population (A-type stars), the effects of extinction (external screen), and of varying strengths of a starburst component at a post-starburst age of $3 \times 10^8$ yrs (Leitherer & Heckman 1995). 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 Cardelli et al. (1989). Colors of 0.0 were assumed for the A stars. The NIR colors of HII 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 galaxy contribution. The ticks along the extinction line correspond to unit increments of $A_V$; the ticks along the aged burst line correspond to order-of-magnitude increments (1, 10, 100) in the fractional contribution of the starburst component to the $V$-band relative to the galaxy contribution. The open circle at the lower end of the burst only line indicates a post-starburst age of $10^7$ yrs, and the curve ends at $3 \times 10^8$ yrs where it coincides with the aged burst line dominated by the starburst.
"Slab" visual optical depth and spurious $H - K$ color excess vs. "screen" optical depth $\tau_V$. 
"Slab" refers to a uniform slab with dust interspersed with stars, and "screen" to a foreground screen of dust. a) The ordinate is the slab $\tau_V$ that would produce the same amount of $J - H$ reddening as the screen $\tau_V$ in abscissa. The dotted line is the linear extrapolation of the slope (2.26) at zero optical depth. b) The ordinate is the spurious $H - K$ color excess that results from the assumption of a foreground screen of optical depth $\tau_V$ in abscissa, instead of a uniform slab of dust and stars. $\Delta(H - K)_{(\text{excess})} = 2.5 \log \left[ 1 + \frac{\Sigma_{K}^{(\text{excess})}}{\Sigma_{K}^{(\text{stars})}} \right] \approx \frac{\Sigma_{K}^{(\text{excess})}}{\Sigma_{K}^{(\text{stars})}}$ for small non-stellar emission fractions. The dotted line emphasizes the 1% amplitude of the spurious excess emission fraction at screen $\tau_V \approx 2$. 

Fig. 9.
Fig. 1.— $J$-magnitude images, $J - K$ color images, and elliptically-averaged radial brightness and color profiles. Galaxies are grouped by activity type, with Seyfert 1s followed by Seyfert 2s and SBNs. For each galaxy, the $J$-band image is shown in the upper left panel; the $J - K$ (expanded, see text) color image in the lower panel; and the $J$-band brightness, $J - H$, $H - K$, and $J - K$ color profiles in the upper right panel. The broadband images are contoured from 23 to 16 $J$-mag arcsec$^{-2}$, and the color $J - K$ images from 0.4 to 1.35. The horizontal dotted line in each of the color profiles corresponds to the average outer disk color as determined from the flux-flux plots (Appendix A); the vertical dotted line indicates the 3 kpc cutoff between “inner” and outer disk. The dashed lines shown in the brightness and color profile panels give the disk fits described in Appendix A. All magnitudes and colors are those observed, before application of the photometric corrections described in the text. For additional figures, see electronic version of the published paper.
Fig. 2.— $J$-band and $J-K$ images of representative SBNs. The top panel shows Mkn 496; the middle panel Mkn 732; and the bottom Mkn 545. The color table shows brighter and redder regions as white, and fainter and bluer regions as green. The white features in the outer parts of the color images are due to noise.