A STRUCTURAL AND DYNAMICAL STUDY OF LATE-TYPE, EDGE-ON GALAXIES. I. SAMPLE SELECTION AND IMAGING DATA

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ABSTRACT

We present optical (B and R) and infrared (K_s) images and photometry for a sample of 49 extremely late-type, edge-on disk galaxies selected from the Flat Galaxy Catalog of Karenchentsev et al. Our sample was selected to include galaxies with particularly large axial ratios, increasing the likelihood that the galaxies in the sample are truly edge-on. We have also concentrated the sample on galaxies with low apparent surface brightness in order to increase the representation of intrinsically low surface brightness galaxies. Finally, the sample was chosen to have no apparent bulges or optical warps so that the galaxies represent undisturbed, “pure disk” systems. The resulting sample forms the basis for a much larger spectroscopic study designed to place constraints on the physical quantities and processes that shape disk galaxies. The imaging data presented in this paper have been painstakingly reduced and calibrated to allow accurate surface photometry of features as faint as 30 mag arcsec^{-2} in B and 29 mag arcsec^{-2} in R on scales larger than 10". Because of limitations in sky subtraction and flat-fielding, the infrared data can reach only to 22.5 mag arcsec^{-2} in K_s on comparable scales. As part of this work, we have developed a new method for quantifying the reliability of surface photometry, which provides useful diagnostics for the presence of scattered light, optical emission from infrared cirrus, and other sources of nonuniform sky backgrounds.

Key words: galaxies: formation — galaxies: fundamental parameters — galaxies: irregular — galaxies: spiral — galaxies: structure

1. INTRODUCTION

Basic physics must be responsible for final differentiation of galactic structure. Mass, angular momentum, density, environment, and metallicity all must contribute to the shape and relative proportions of the disk and spheroid structures observed today. While the tremendous diversity of the galaxy population suggests a bewildering level of complexity in the details of galaxy formation, the existence of broad patterns, such as the fundamental plane or the Tully-Fisher relation, gives some hope that the overall structure of galaxies is controlled by large-scale physics and thus can be explained and constrained with observation.

Disk galaxies represent some of the best possible laboratories for exploring the physics that controls galaxy formation. Spiral disks are less corrupted by dissipation and angular momentum transport than comparable elliptical galaxies, and thus they better preserve the initial conditions from which they were formed. Likewise, the disks of spiral galaxies extend far out into their dark matter halos and thus can be used to probe the shape and extent of the accompanying dark matter, which in turn places strong constraints on theories of dark matter and structure formation. Finally, only in spirals can we directly observe galaxy formation in process, particularly among late-type spiral disks and low surface brightness galaxies, which, from their colors, IR surface brightnesses, and gas content, seem to be forming stars for nearly the first time.

To place observational constraints upon the process of galaxy formation, we have begun a comprehensive program to study the dynamics, gas content, metallicity, and stellar populations of a sample of late-type, bulgeless disk galaxies. This population forms a structurally uniform sample, allowing us to isolate changes in the physical properties of the galaxies (i.e., mass, angular momentum, etc.) independent of changes in morphology. By avoiding systems with bulges, we also limit the degree to which the baryonic component of the galaxy may have been affected by dissipation or angular momentum transport during formation.

We have selected these galaxies from a large catalog of edge-on galaxies, described below in § 2. By selecting the galaxies edge-on, we can ensure that the galaxies are free of strong warps, which could indicate a recent interaction or a nonequilibrium configuration. The galaxies in our sample should therefore be well relaxed and largely undisturbed. Furthermore, while the edge-on view of a galaxy can clearly identify it as a disk, it disguises the face-on morphology, masking the presence or absence of spiral arms, bars, or star formation regions. Thus, the selection of an edge-on sample should be unbiased with respect to these transient features. Finally, the edge-on orientation of these galaxies allows direct study of their vertical structure. The vertical structure of galactic disks contains information on the balance between the surface density of the disk, the vertical velocity dispersion of the stars, and the density structure of the halo. Thus this sample will provide constraints (albeit highly interdependent constraints) on the internal dynamics of the disk and the flattening of the halo (Spitzer 1942; van der Kruit & Searle 1982; Bahcall 1984; Zasov, Makarov, &
was originally selected by visual inspection of the O POSS greater than 7, and major axis lengths of The FGC (1993), a catalog of 4455 edge-on galaxies with axial ratios of Karanchentsev, Karanchentseva, & Parnovsky structural properties until a later paper in the series. We delay a full analysis of the galaxy colors and photometry, with a complete analysis of the errors and uncertainties. We present the sample, the imaging data, and the resulting photometry, with a complete analysis of the errors and uncertainties. We delay a full analysis of the galaxy colors and structural properties until a later paper in the series.

2. SAMPLE SELECTION

The sample was selected from the Flat Galaxy Catalog (FGC) of Karanchentsev, Karanchentseva, & Parnovsky (1993), a catalog of 4455 edge-on galaxies with axial ratios greater than 7, and major axis lengths of >0.6. The FGC was originally selected by visual inspection of the O POSS plates in the north (δ > −27°) and the J films of the ESO/SERC survey in the south (δ < −17°). Galaxies from the ESO plates are known as the FGCE and have slightly different properties due to small differences in the plate material. From the combined FGC/FGCE catalog, we selected galaxies which appeared both bulgeless and low surface brightness on the Digitized Sky Survey (DSS) and which showed no signs of inclination (major to minor axis ratio a/b > 8) or interaction. Unfortunately, our selection criteria were not uniformly successful, as the images in § 7 and Figure 3 will show. Because of the low resolution of the DSS, ≤10% of the galaxies that met the original selection criteria showed small bulges which were not apparent on the DSS or dust lanes which masked a high surface brightness disk (e.g., FGC 446, 1043, 1440, and E1371). As these galaxies will be useful for some aspects of our extended scientific program, we have retained them in the sample but treated them separately when appropriate. One galaxy that we had originally chosen for the survey, FGC E1550, showed a pronounced integral sign–shaped warp in our initial R band imaging and was removed from the sample. The final sample is listed in Table 1 along with positions and orientations as given in the FGC.

The resulting distribution of morphological types and surface brightness classes (I = high surface brightness, IV = low surface brightness), both as given by the FGC, are plotted in Figure 1, along the with the distributions for the entire FGC catalog. Clearly our sample is biased toward later types and lower surface brightnesses than the FGC as a whole. We have also plotted the distributions of blue axial ratios for our sample in Figure 2. Our subsample has a higher mean axial ratio than the catalog as a whole, betraying our selection bias for the most nearly edge-on galaxies. It may also reflect our choice of late morphological types; an analysis of the FGC by Kudrya et al. (1994) shows that the galaxies in the FGC become progressively thinner with later Hubble types, with the limiting axial ratio varying from (a/b)max = 14.1 for Sb galaxies to (a/b)max =
27.0 for Sd’s. This trend toward intrinsically thinner galaxies with increasing Hubble type is also seen by de Grijs (1998). The apparent bias toward large axial ratios may also result from our selection of lower surface brightness galaxies. LSBs are known to have larger disk scale lengths than normal galaxies with similar rotation speeds (Zwaan et al. 1995) and consequently may have larger axial ratios as well.

Many of the galaxies in our sample were previously observed in single dish H I observations with Arecibo. For our \(8^h < \text{R.A.} < 19^h\) sample (spring observing season), we concentrated on those galaxies that had H I detections and which were relatively nearby (\(V \lesssim 5000 \text{ km s}^{-1}\)), giving us better spatial resolution for both imaging and spectroscopy. During the fall, slightly more than half (20 of 32) of our sample galaxies had existing H I observations. Overall, 77% of the galaxies in our survey have published single-dish H I observations. When available, the heliocentric velocity and the corrected line width at 50% peak flux (\(W_{50,c}\)) are listed in Table 1. The majority of these are from a large survey of FGC galaxies observed at Arecibo by Giovanelli, Avera, &...
Karachentsev (1997). These are supplemented with measurements for FGC 164 from Schneider et al. (1990), for FGC 84 and 2264 from Matthews & van Driel (2000), and for FGC 349 from Haynes et al. (1997).

In addition to H i observations, a very small number of the galaxies in our sample (FGC 446, FGC 1043, and FGC 2217) were detected as part of the IRAS Faint Source Catalog (Moshir et al. 1989; F03422+0544, F10131+0734, 18356+1729, respectively). In order of increasing 60 µJy flux, FGC 1043 is detected in both 60 µ and 100 µ bands, with flux of 0.23 Jy and 0.65 Jy, respectively; FGC 446 is only detected at 60 µ, with flux of 0.38 Jy; and FGC 2217 is detected at 25 µ and 60 µ, with flux of 0.17 Jy and 1.25 Jy, respectively. All of the detections and upper limits are consistent with spectra that rise in $\nu_f$ toward 100 µ.

While our sample galaxies are exceptionally useful probes of the properties of galaxies over a spectrum of mass and surface brightness, they by no means constitute a statistical sample of any sort. They are not drawn randomly from the FGC, and thus their properties are not representative of that catalog as a whole. Because our selection of a subsample was far from unbiased, the sample cannot be used for any analysis of the numbers of galaxies of different surface brightnesses. Likewise, the sample cannot be used to study the incidence of warping at moderately bright surface brightness levels.

Finally, our subsample of the FGC includes galaxies with peak $B$-band surface brightnesses (viewed edge-on) between 21.5 and 23 mag arcsec$^{-2}$—i.e., between the face-on value of the characteristic Freeman (1970) surface brightness and the surface brightness limit of the FGC survey data. Thus, this limited range of $B$-band surface brightness can become a selection effect that can influence some results, such as apparent trends in color and extinction. These biases will be considered explicitly.

3. OPTICAL OBSERVATIONS, DATA REDUCTION, & PHOTOMETRIC CALIBRATION

3.1. Optical Imaging

All optical observations of the FGC sample were made with the 2.5 m du Pont Telescope on Las Campanas, during the nights of 1997 September 22 and 23 and 1998 March 29 and 30, using a thinned Tektronix 2048 $\times$ 2048 CCD (Tek5) with 0.259 pixels, a gain of $\sim$2.4 DN per electron, and read noise of $\sim 7$ e$^-$. The conditions were photometric for the duration of all four nights. For each galaxy, a series of three exposures was taken through both a Johnson $B$ and a Kron-Cousins $R$ filter, with the position of the telescope shifted by more than 2$'$ between exposures to minimize large- and small-scale flat-fielding variations, cosmic rays, and cosmetic defects on the CCD. Typical exposure times for the fall subsample were 300 s per frame in $B$, and 120 s per frame in $R$, for combined exposure times of 15 minutes and 6 minutes, respectively. In order to maximize our chances of detecting extended stellar halos in the nearby spring sample, our exposure times for the spring sample were 2–3 times longer.

While the 1998 March observations were made during new Moon, the 1997 September observations were made with 40%–50% Moon illumination for the second half of each night. During the night of 1997 September 23 time limitations forced us to image FGC 164, 215, 225, 256, 349, 436, 442, and 446 while the Moon was up; as a result of the increased sky brightness, the $B$ images of these galaxies are noticeably shallower. Typical sky brightnesses without Moon were 22.2 $\pm$ 0.2 mag arcsec$^{-2}$ and 20.6 $\pm$ 0.2 mag arcsec$^{-2}$ in $B$ and $R$, respectively, and 21.5 $\pm$ 0.5 mag arcsec$^{-2}$ and 19.9 $\pm$ 0.5 mag arcsec$^{-2}$ after the Moon had risen fully. The total exposure times, sky brightnesses, seeing FWHMs, and fluctuation levels of the reduced images are listed in Table 2.

3.2. Image Reduction

Each raw image has a bias level consisting of a time-variable mean which changes by $\pm 1$ DN between images and causes $\pm 0.5$ DN vertical structure along columns. There is also a stable component, which is a small exponential decay over the first 150 pixels in every row. The time-variable bias level can be identified in the 30 columns of overscan taken in each image. To remove it, we fitted the average of these columns with a 10th order polynomial and subtracted this fit column by column. A bias image was then made by averaging 15–20 overscan-subtracted, zero-second exposures, with two iterations of $\pm 3$ $\sigma$ rejection to remove cosmic rays. This image was then smoothed with a 1 $\times$ 4 boxcar to reduce pixel-to-pixel noise to $\sim 0.3$ DN and then subtracted from each image to remove the stable exponential structure. Dark frames show that the dark current in the CCD is less than 0.5 DN per 900 s exposure with no two-dimensional structure evident. No dark correction was therefore applied.

Pixel-to-pixel flat fields were generated separately for each night using dome flats. The resulting flat fields were divided into all bias subtracted images, including twilight flats. Except for large-scale illumination changes due to the relative changes in the telescope and dome positioning, differences between the dome flats on adjacent nights were less than 0.3%, peak to peak. To enable faint surface photometry over reasonably large areas ($1'-2'$), we have taken particular care with the large scale flat-field calibration of our images. To remove large-scale illumination features and to correct for the difference in color between the night sky and the dome flats, twilight sky flats and night sky flats were created. The $B$- and $R$-band twilight sky flats contained over 100,000 counts, cumulative.

The night sky flats were made by averaging the science exposures after rescaling them to a common mean sky level and using IRAF’s CCDCLIP rejection with a grow radius of 10–30 pixels to eliminate stars, galaxies, and cosmic rays; roughly 30 images per night were used in this average. As the object galaxies were moved by several arcminutes between exposures, the target objects were rejected cleanly, and roughly 75% of the images could usefully contribute to the flat field in any region of the CCD. We then median-smoothed the combined images on a $\sim 2''$ scale to reduce the pixel-to-pixel noise to $\sim 0.001$ DN ($\sim 28$ mag arcsec$^{-2}$ for a sky level of 20.5 mag arcsec$^{-2}$), while preserving the large-scale illumination correction. With the exception of one dust feature, the twilight and night sky flats had peak-to-peak amplitude of less than 0.5% (corresponding to roughly 26.5 $R$ mag arcsec$^{-2}$ or 28.3 $B$ mag arcsec$^{-2}$).

For the moonless portion of the 1997 September observations, the illumination was very uniform, and correction with twilight flats alone yielded images in which no repeating large-scale structures were evident at the 0.5% level between the flat-fielded science images. Diffuse optical emis-
tion from Galactic cirrus could clearly be detected in some of the lower latitude fields, immediately suggesting that flat-fielding residuals were small. High-frequency structure (e.g., dust “donuts”) in the $R$-band twilight flat was isolated by dividing a heavily smoothed version (26 pixels) of the flat into the original. This provided a high-frequency color correction to the dome flats, the maximum amplitude of which was $\leq 1\%$.

Because of the color change of the sky after moonrise, separate night sky flats were generated from and applied to the $B$- and $R$-band 1997 September observations taken after moonrise. Night sky flats were also applied to all of the 1998 March observations, for which the color and illumination of the twilights were not a good match to the night sky during science observations.

The images were aligned by matching SExtractor (Bertin & Arnouts 1996) positions for all objects in the $R$ and $B$ images. The resulting pairs were used to shift the images into accurate alignment with one of the $R$-band images, using IRAF’s GEOMAP and GEOTRANS packages. All images were then averaged together with $\pm 4\sigma$ rejection to produce the final images. To simplify later analysis, both $B$ and $R$ band images were rotated to orient the galaxy horizontally. The required rotation was identified by measuring the position of each galaxy at more than four locations.
along the disk in the R-band image. Finally, a $982 \times 982$ subsection was extracted from each image, centered on the galaxy.

3.3. Photometric Calibration

Photometric calibration for the optical observations was straightforward because of the nearly ideal conditions during the run. At least two separate Landolt (1983, 1992) standard fields were observed at the beginning and end of the night, at a variety of exposure times, and at air masses between 1.1 and 2.5. At least two more sets of standard observations were made during the course of each night, giving a total of 35–57 individual standard star measurements per night through each filter. The fluxes of the standard stars were measured within the 14" diameter aperture used by Landolt. For the fall run, the photometric solution was made assuming a constant zero point and color term, with an air-mass term allowed to vary night to night. For the spring run, the zero point, color term, and air mass were allowed to vary each night; the resulting terms agreed to within $\pm 1 \sigma$. Residuals from the best-fit photometric solutions were typically $\sigma_m = 0.012–0.020$. The resulting solutions are given in Table 3.

Few of the galaxies in our sample have been extensively observed in the optical. As a result, we have few means to check our calibration for consistency with other authors. One galaxy from our sample, FGC E1371, was also studied in the ESO-LV catalog (Lauberts & Valen汀 1989; ESO-LV 3380010). The reported ESO-LV magnitudes are $B_{25}$(Cousins) = 18.15 $\pm$ 0.09, $B_{26}$(Cousins) = 17.95 $\pm$ 0.09, $R_{25}$(Cousins) = 16.22 $\pm$ 0.09, and $R_{26}$(Cousins) = 16.06 $\pm$ 0.09. In our filter system (Johnson B, Cousins R), we find $B_{24}$(Johnson) = 18.27, $B_{26}$(Johnson) = 18.04, $R_{24}$(Cousins) = 16.23, and $R_{26}$(Cousins) = 16.21, giving offsets of +0.12, +0.09, +0.01, and +0.15 from the ESO-LV measurements. These results are consistent within the errors ($\pm 0.15$ for our sample).

4. INFRARED OBSERVATIONS, DATA REDUCTION, AND PHOTOMETRIC CALIBRATION

4.1. Infrared Imaging

The infrared observations of the FGC sample were made with the du Pont 2.5 m telescope at Las Campanas Observatory, using an updated version of the IRCAM camera originally described in Persson et al. (1992), with the upgraded camera being similar to the P60IRC described by Murphy et al. (1995). The IRCAM, which consists of a Rockwell NICMOS3 $256 \times 256$ HgCdTe chip with 40 $\mu$ pixels, was operated at f/7.5, giving 0′348 pixels and an 89′ field of view. All observations were made through the $K_s$ filter (developed by M. Skrutskie and described in the appendix of Persson et al. 1998), which cuts off at $\sim 2.2 \mu$ to reduce the thermal background by a factor of 2. All observations took place during three runs: 1997 September 21–22, October 10–14, and 1998 April 13–14. Observing conditions on usable nights were as follows: September 21 and 22, photometric; October 10, clear for the first half of the night; October 11, photometric with high winds and poor seeing; October 14, photometric with very high winds and a 7.8 earthquake in the middle of the night; April 13, nonphotometric; and April 14, photometric. The electronics for the camera were replaced between the fall 1997 runs and the spring 1998 run, changing the gain from $4.8 e^-ADU^{-1}$ to $7.5 e^-ADU^{-1}$ and requiring a new linearity correction.

Observations were made by looping the camera through successive sets of six exposures of 20 s (2 minutes total) at various positions, typically shifting the telescope by one-half of the camera field of view ($\sim 35′−45′$) between exposure loops. Because of the thinness of the FGC, our mosaic pattern allowed at least part of the galaxy to be on the chip during every exposure, giving us high observing efficiency without affecting our ability to create sky frames. The shifts were in the direction that maximized the overlap between the chip and the galaxy (i.e., galaxies aligned east-west were dithered north-south). This strategy will limit our ability to reliably interpret faint infrared structures more than 20′ above the planes of the galaxies. However, given the existence of low-level ghosting in the IRCAM and the faintness of the FGC subsample, such scientific inquiries are beyond the limits of the data, regardless.

Total exposure times varied widely for our galaxies. In keeping with the wide range in $K_s$-band surface brightness, which spanned 4 mag arcsec$^{-2}$, the most massive galaxies were well exposed in only 12 minutes of observations, while the lowest mass galaxies were still barely detectable after several hours of integration. Table 4 lists the UT dates of all our observations, along with the exposure times and estimates of the photometric quality (discussed in §4.2).

4.2. Image Reduction

Before processing, all images were linearized using scripts kindly supplied by S. E. Persson. (These scripts differed slightly between 1997 and 1998, because of the change in electronics.) The linearization was tested with data taken during the night of 1997 October 12 while the dome was closed on account of bad weather. For count levels less than 20,000 counts pixel$^{-1}$, the linearized data were linear to better than 0.1%; for reference, our typical sky levels in 20 s exposures were 6000 counts pixel$^{-1}$ or less. The linearization procedure was not tested during the 1998 run.

All loops of exposures at a single position and exposure time were averaged together using $\pm 5 \sigma$ rejection to remove cosmic rays. Dark frames were created each night by combining loops of 50–100 exposures at every exposure time used for our science observations and were subtracted from the appropriate images. On the night of 1998 April 14, darks were taken in both the evening and morning and were found to differ by $\sim 15\%$; no explanation for this variation was evident, and the two sets of darks were simply averaged together. The data from 1997 September 20 were reduced using darks taken the following night.

Dome flats were derived most nights and divided into the summed, dark-subtracted images. Exceptions were the
| FG C | Exp Time (minutes) | Date (UT) | FWHM $_{\text{major}}$ ($K_s$) (arcsec) | $a/b_{\text{PSF}}$ | P.A.$_{\text{PSF}}$ (deg) |
|------|-------------------|-----------|------------------------------------------|-------------------|--------------------------|
| 31   | 48                | 970921    | 1.1                                      | $1.5 \pm 0.6$     | $-85 \pm 35$             |
| 36   | 16:               | 971011    | 0.7                                      | $1.1 \pm 0.1$     | $-53 \pm 39$             |
| 51   | 22:               | 971011    | 1.3                                      | $1.7 \pm 0.1$     | $46 \pm 37$              |
| 84   | 36                | 970922    | 0.7                                      | $1.1 \pm 0.1$     | $-52 \pm 14$             |
| 130  | 12:               | 971011    |                                          | $85 \pm 2$        | $77 \pm 35$              |
| 143  | 20:               | 971011    |                                          | $1.1 \pm 0.1$     | $-73 \pm 100$            |
| 164  | 24                | 971012    | 1.1                                      | $1.1 \pm 0.1$     | $47 \pm 17$              |
| 215  | 18                | 970922    |                                          | $53 \pm 39$       | $100 \pm 3$              |
| 225  | 30                | 971012    | (1.2)                                    | $(1.2 \pm 0.2)$   | $(18 \pm 18)$            |
| 227  | 24                | 970921    |                                          | $1.1 \pm 0.1$     | $81 \pm 80$              |
| 256  | 24:               | 971011    |                                          | $1.1 \pm 0.1$     | $84 \pm 60$              |
| 277  | 30                | 970921    | 1.1                                      | $1.1 \pm 0.1$     | $-84 \pm 86$             |
| 30   | 971015            |           |                                          |                   |                          |
| 310  | 24                | 970921    | 0.8                                      | $1.7 \pm 0.7$     | $71 \pm 23$              |
| 349  | 36:               | 971011    | 0.9                                      | $1.1 \pm 0.1$     | $-70 \pm 20$             |
| 395  | 24                | 970921    | 0.8                                      | $1.5 \pm 0.4$     | $34 \pm 10$              |
| 436  | 24                | 970922    | 1.0                                      | $1.1 \pm 0.1$     | $-63 \pm 46$             |
| 442  | 12:               | 971011    |                                          | $1.5 \pm 0.7$     | $85 \pm 69$              |
| 449  | 12:               | 971012    | (0.8)                                    | $(1.2 \pm 0.2)$   | $(59 \pm 59)$            |
| 780  | 24                | 980415    | 1.2                                      | $1.2 \pm 0.2$     | $-33 \pm 15$             |
| 901  | 18:               | 980414    |                                          |                   |                          |
| 913  | 18                | 980415    | 0.9                                      | $2.0 \pm 0.6$     | $86 \pm 58$              |
| 979  | 12                | 980415    | 1.0                                      | $1.0 \pm 0.1$     | $-26 \pm 23$             |
| 1043 | 12                | 980415    | 1.0                                      | $1.8 \pm 0.6$     | $-11 \pm 5$              |
| 1063 | 18                | 980415    | 1.1                                      | $1.5 \pm 0.5$     | $89 \pm 5$               |
| 1285 | 18                | 980415    | 1.0                                      | $1.0 \pm 0.1$     | $-52 \pm 5$              |
| 1303 | 12:               | 980414    |                                          | $1.2 \pm 0.3$     | $78 \pm 19$              |
| 1415 | 10                | 980415    | 1.0                                      | $1.2 \pm 0.4$     | $27 \pm 58$              |
| 1440 | 10                | 980415    | 1.1                                      | $2.0 \pm 0.7$     | $-58 \pm 37$             |
| 1642 | 12:               | 980414    |                                          |                   |                          |
| 1863 | 18                | 980415    | 1.2                                      | $1.5 \pm 0.5$     | $-52 \pm 5$              |
| 1945 | 12:               | 980414    |                                          | $1.5 \pm 0.6$     | $83 \pm 61$              |
| 1948 | 12:               | 980414    |                                          |                   |                          |
| 1971 | 18:               | 980414    |                                          | $1.9 \pm 0.7$     | $82 \pm 72$              |
| 2131 | 18                | 980415    | 1.1                                      | $1.6 \pm 0.6$     | $59 \pm 47$              |
| 2135 | 18                | 980415    | 1.2                                      | $1.4 \pm 0.1$     | $69 \pm 4$               |
| 2217 | 12                | 980415    | 1.0                                      | $1.3 \pm 0.2$     | $59 \pm 56$              |
| 2264 | 12                | 980415    | 1.0                                      | $1.4 \pm 0.2$     | $12 \pm 4$               |
| 2292 | 24                | 970921    | 0.9                                      | $1.3 \pm 0.2$     | $91 \pm 26$              |
| 2367 | 18                | 971011    | 1.1                                      | $1.1 \pm 0.2$     | $87 \pm 49$              |
| 2369 | 36                | 970921    | 1.0                                      | $1.2 \pm 0.2$     | $59 \pm 75$              |
| 2548 | 36                | 970921    |                                          |                   |                          |
| 2558 | 18:               | 971012    |                                          | $1.2 \pm 0.2$     | $28 \pm 7$               |
| 2568 | 36                | 971012    | 0.5                                      | $1.1 \pm 0.2$     | $-26 \pm 20$             |
| 310  | 24                | 971011    |                                          | $1.4 \pm 0.1$     | $60 \pm 3$               |
| 320  | 30                | 971012    | 0.9                                      | $1.1 \pm 0.1$     | $59 \pm 14$              |
nights of October 10 and 11, for which dome flats taken during the night on October 12th were used. The dome flats from October 10 and 11 were obtained during the daytime, with much warmer temperatures, and approached the level of nonlinearity. Dome flats taken on the night of April 13 produced large-scale illumination residuals relative to twilight flats taken on April 14. Dome flats taken on April 15 were used instead. (No dome flats were taken on April 14 because the calibration lamps broke.) After dark subtraction and flattening, known bad pixels were replaced with locally interpolated values. Henceforth, we will use “images” to refer to these co-added, calibrated frames, and not the individual loop subexposures.

Sky subtraction and image alignment was performed with a modified version of the DIMSUM V2.0 package. First, a running sky image was created from the median of every six adjacent sets of co-added images, and then subtracted from the central image of the time series. At the beginning and end of each time series, no fewer than four adjacent images were used to create the sky image. Next, a rough offset was calculated using the centroid of a single star in each image, and then refined using IMALIGN with all stars available in the frame. These offsets were used to align the frames and then co-add them into a single image. The deep image was then used to create a mask of all objects. While the standard DIMSUM masking procedure works well for compact, reasonably well-exposed objects, it was necessary to modify DIMSUM’s masking procedure to create appropriate masks for the extended, low surface brightness galaxy in the frame. The masks were then deregistered and used to create refined sky images for each frame. The new sky-subtracted images were then realigned and co-added to produce the final image. During the final alignment, the images were expanded by a factor of 4 to avoid loss of resolution when shifting the images. For images of standard stars, a sky image was created from all science exposures for the night and then scaled to the image median and subtracted. The resulting IR images were then realigned and adjusted with the optical R band images using IRAF’s GEOMAP and GEOTRANS packages. To reduce uncertainties in aligning a single image, after one pass through all of the data, the mean scale factor was derived for the transformation between \( K_s \) and \( R \). The images were then realigned using the fixed scale factor.

While the seeing during our infrared run (\(~1.1\)) was not ideal, our final image resolution was also affected by the difficulty in aligning some of our images. Many of the galaxies were at sufficiently high Galactic latitude that there were no bright stars visible in the individual images. As the galaxies themselves were often invisible in 120 s exposures, and the du Pont control software did not record pointing position until 1999, some of the co-added images were aligned using underexposed faint stars, leading to non-spherical PSFs in the co-added frames. We were also troubled by high east-west windshake, compounding this problem. To account for this, we have fitted all stars in our \( K_s \) images with elliptical Gaussian profiles. The PSF was measured for all available stars selected from \( R \)-band SExtractor catalogs (CLASS_STAR > 0.9). The mean properties of the PSF were calculated using the brightest half of the stars (as measured in \( K_s \), iteratively rejecting outliers at the \( \pm 3 \sigma \) level. In Table 4, we report the resulting mean FWHM along the major axis of the PSF ellipse, the axis ratio of the PSF ellipse, and the position angle of the ellipse, measured relative to the position angle of the galaxies. Thus, galaxies whose \( K_s \) PSFs have position angles less than \( 45^\circ \) will have worse seeing along the plane of the galaxy than perpendicular to the plane. In general, because of the paucity of bright stars in our images, the higher order shape parameters for the PSF are not particularly well measured in most cases (given that they are based upon two to five faint stars). Values within parentheses are based upon only a single star, and entries marked with an ellipsis had no stellar objects within the frame.

For galaxies whose images were obtained over the course of two or more nights, we reduced the images for each night separately. The final image was a weighted sum of the images from separate nights.

### 4.3. Photometric Calibration

Calibration was performed using the faint standard star sequence established by Persson et al. (1998). Each standard star was moved through the four quadrants of the chip to reproduce differences between the four amplifiers. Sets of standards were observed at the beginning and end of each night and usually three to five times during the course of the night. The fluxes of the standards were measured within 10” diameter apertures, as in Persson et al. (1998).

For the 1997 data, a single magnitude zero point and color term was found by simultaneously solving the four nights with high photometric quality and allowing the extinction term for each night to vary separately. The resulting photometric solutions and associated errors (\(~0.02\) mag) are given in Table 5. Because of the updated electronics between 1997 and 1998, the solution for the one photometric night in 1998 was derived independently.

Even in nonphotometric conditions (i.e., any cloud cover visible in any part of the sky), standards were monitored to test our ability to judge the level of cloud cover. The derived “photometric” solutions for the parts of nonphotometric nights that were judged to be reasonably clear are listed in parentheses in Table 5. In general, the solutions are nearly

### Table 4—Continued

| FGC     | Exp Time (minutes) | Date (UT) | FWHM\(_{\text{major}}\) (\(K_s\)) (arcsec) | \(a/b_{\text{PSF}}\) | P.A.\(_{\text{PSF}}\) (deg) |
|---------|--------------------|-----------|--------------------------------------------|----------------|--------------------------|
| E1440 . . | 30                 | 970922    | 1.1                                        | 1.2 ± 0.2       | −67 ± 20                 |
| E1447 . . | 16                 | 971015    | ...                                        | ...             | ...                      |
| E1498 . . | 30                 | 970921    | 0.9                                        | 1.2 ± 0.1       | −44 ± 12                 |
| E1619 . . | 18                 | 971011    | 1.1                                        | 1.1 ± 0.1       | 74 ± 4.2                 |
| E1623 . . | 18                 | 971011    | 0.9                                        | 1.1 ± 0.1       | 25 ± 25                  |

**Note:** Single colons (:) indicate data taken during clear portions of nonphotometric nights. Double colons (:) indicate data taken during nonphotometric conditions. See discussion in §4.3.
identical to those derived for the photometric nights, suggesting that the parts of the night which we considered to be clear had transparencies comparable to truly photometric conditions. As a further test, we made plots of the sky level as a function of time during our science exposures. On the photometric nights, the sky level was very stable, varying extremely slowly and smoothly. By comparing our observing logs to plots of the sky level during partially cloudy nights, we found that the presence of clouds produced obvious, rapid variations in the sky level. We used the combination of our observing notes and plots of the sky level to judge the degree of photometric accuracy reported in Table 4.

Unlike the $B$- and $R$-band results, we were unable to find any infrared observations of our sample galaxies in the literature with which to compare our global calibration. While roughly one-fourth to one-third of our sample is visible in the existing 2MASS survey (Skrutskie et al. 1997), these galaxies are so faint and diffuse that they had not been cataloged or photometered at the time this paper was submitted.

We have, however, checked our photometric calibration internally. For roughly half of our sample, we obtained images over two or more nights. This was particularly true for the galaxies with the faintest $K_s$-band surface brightnesses, which required much deeper observations. We have performed aperture photometry on all fields observed on separate nights in order (1) to test the consistency of our photometry and (2) to correct observations taken in non-photometric conditions. The mean amplitude of night-to-night variations among the photometric observations and the “questionable” observations (marked by a single colon in Table 4) were identical ($\Delta m = 0.04$) and were all within the 2 $\sigma$ uncertainties defined by photon counting and the photometric calibration. There were also no consistent offsets between nights (i.e., the offsets were just as likely to be negative as positive). Only the nonphotometric observations marked with double colons in Table 4 showed significant variations, with $\Delta m_{\text{FGC}143} = 0.09$, $\Delta m_{\text{FGC}256} = 0.31$, $\Delta m_{\text{FGC}901} = 0.55$, and $\Delta m_{\text{FGC}1971} = 0.28$. The zero points of these nonphotometric images were adjusted accordingly before they were co-added with the photometric data. We also did not include the data for FGC 1303 from 980415 and for FGC 277 from 971015, as unfortunately, the subimages could not be properly aligned.

5. MASKING

In order to facilitate analysis of the galaxy profiles at low light levels, we generated a mask for each image to identify regions contaminated by interloping sources (stars, galaxies, meteor trails, etc.). The masks were made using our $R$ band images, which typically had the highest signal to noise. First, SExtractor (Bertin & Arnouts 1996) was used to identify all objects in the frame. Using the reported ellipticities and isophotal areas, we masked elliptical regions around all detected objects (except for the immediate vicinity of the central galaxy where objects were masked by hand to avoid masking H II regions associated with the galaxy). We increased the size of the masked regions by a factor of 3, producing a factor of 9 increase in the area and thus reducing any contamination from interloper objects at low light levels.

The resulting masks were then visually inspected, and edited by hand to remove any remaining sources of contamination in all three bands (i.e., $B$, $R$, & $K_s$). Examples of these include objects that fell on top of or very near to a galaxy (a problem in lower latitude fields), meteor trails, diffraction spikes from bright stars, poorly removed bad columns, obvious scattered light from stars just off the field, and regions that were not covered in all three subexposures used to make the final optical images. There is some ambiguity about removing faint “contaminating” objects close to the galaxy, given the natural confusion between faint intervening galaxies and small H II regions within the galaxy. This confusion is highest in the furthest outskirts of the galaxies, which are known to harbor faint H II regions in spite of having little diffuse optical emission (e.g., Ferguson et al. 1998). We typically mask these regions when there was no diffuse emission connecting the faint object to the main galaxy. Given that these sources are all extremely faint, their inclusion or exclusion will make little difference in the total magnitude of the galaxy. They may slightly affect the shapes of the faintest isophotes, however.

We also generated a second set of masks to generously encompass the faintest possible isophotes of the main FGC galaxy. These masks are used to exclude all possible contributions from the galaxy when measuring the background sky.

Finally, for each galaxy, identical masks were used for all bands, so that all analysis was restricted to the same portions of the images.

6. SKY SUBTRACTION

After the $B$ and $R$ images were flattened using the combination of dome flats, twilight flats, and super–sky flats, there remained residual diffuse low surface brightness structure visible in many of the images. These structures varied significantly from image to image and are thus not due to variations in the illumination or the response of the CCD. In most cases, the position of the structure shifts with the sky in the series of dithered images, suggesting that these
sky fluctuations are an astronomical source and not a calibration problem. These remaining variations are most likely the result of a combination of scattered light from stars beyond the field of view and optical emission from the 100 μ cirrus (e.g., Guhathakurta, Tyson, & Majewski 1990). These unavoidable sources of nonuniform background represent a fundamental limit on our ability to trace the structure of galaxies to extremely low surface brightnesses [μ(R) > 28 mag arcsec\(^{-2}\)].

Because these sources are additive, we have made a first-order attempt to subtract them from the B and R images by fitting a plane to the 982 × 982 pixel subregion around each galaxy. The images were masked with both the background object mask and the galaxy mask (§ 5), leaving only sky pixels in the resulting image. A plane was then fitted to the unmasked background, using iterative rejection of outliers. The resulting slopes implied a variation across the 4:2 region of typically fainter than Δμ > 29 B mag arcsec\(^{-2}\) and Δμ > 27 R mag arcsec\(^{-2}\). These surface brightness variations are also characteristic of the smaller scale structures found in some of the images.

We chose not to perform a further background subtraction on the K\(_s\) band images. Because of the smaller field of view of the infrared images and our generous masking of the galaxy region, the number of unmasked “background” pixels was small, leading to unrepresentative fits to the overall background. The unmasked pixels were typically found in the outskirts of the image, which were sampled by a much smaller number of subimages, and thus were of lower signal to noise and more prone to statistical variations in the sky level. Furthermore, given the higher level of ghosting and scattered light in the IRCAM (compared to the optical CCD camera) and the brighter IR sky, remaining sky variations are more likely to be calibration problems than true astronomical signals. Experiments quickly revealed that fitting the sky background with the same procedure used for the optical bands created gradients across the central field, rather than eliminating them.

7. ISOPHOTES AND INTEGRATED MAGNITUDES

Before defining magnitudes for the galaxies in our sample, it was necessary to define isophotal contours for photometry. Using IDL, we defined contour levels in the masked, unsmoothed image, down to an isophote level of 3σ above the sky. To trace the contours to fainter limits, we developed a variable smoothing method, wherein the image was smoothed with a Gaussian ellipse whose size was adjusted to preserve constant signal to noise in the resulting image, with the maximum smoothing length fixed to a width of 15 pixels (3:9) and a 3:1 axial ratio oriented along the major axis of the galaxy. Note, however, that while smoothing was used to set the shape of the faintest isophotes, photometry was performed only on the unsmoothed images. We also did not correct the levels of the isophotes to compensate for foreground Galactic extinction; the isophotes therefore refer to an apparent surface brightness, rather than one intrinsic to the galaxy.

The resulting isophotes are plotted in Figure 3. The plots clearly show the transition between using smoothed and unsmoothed isophotes, as individual pixels mark the edge of the latter and smoother contiguous lines mark the former. Occasionally, contours skirt the perimeters of masked stars, leading to odd shapes in the isophotes. To partially compensate for the flux lost to masking and to better trace the isophotes, we derived approximate smooth models for the galaxies in an attempt to “fill” in the masked regions. As this process is necessarily uncertain, we include the magnitude of the flux added by the model in our uncertainties; rarely is this contribution the dominant source of error.

Using these isophotes, we have derived isophotal magnitudes in B, R, and K\(_s\). We present these in Table 6 for our sample, uncorrected for Galactic extinction. We give magnitudes in reference to a specific isophotal level in each band (μ\(_{lim}(B) = 27\) mag arcsec\(^{-2}\), μ\(_{lim}(R) = 26\) mag arcsec\(^{-2}\), and μ\(_{lim}(K\(_s\)) = 22\) mag arcsec\(^{-2}\)) in order to facilitate comparison with other comparable observations, most notably the Ursa Major cluster sample of Verheijen (1997). Because the isophotal areas associated with these limits are a strong function of the filter bandpass, we also give magnitudes in B, R, and K\(_s\), which are calculated within the area of the μ\(_{lim}(R) = 25\) mag arcsec\(^{-2}\) isophote; these magnitudes should be used when determining colors for the sample. In a few cases, because of somewhat shallower observations or larger problems with scattered light (e.g., FGC 2292), the reference isophotes were not reliably determined; these cases are left blank in Table 6. Because projection makes the galaxies in this edge-on sample appear brighter, the isophotes of our sample probably occur at larger radii than they would if seen face-on and are thus comparable to fainter isophotes for less inclined galaxies. We have chosen not to correct the final magnitudes listed in Table 6 to either total or face-on values, as such conversions would be highly uncertain.

In calculating the magnitudes, we have included the color term in the zero point by first calculating the magnitudes assuming a mean color of *B − R ~ 1* and *J − Ks ~ 1* and then making a second-order correction (typically less than 0.02) based upon the resulting color of the galaxy within the μ\(_{lim}(R) = 25\) mag arcsec\(^{-2}\) isophote. As we did not have information on the J − K\(_s\) colors of the sample, we made no further correction to the infrared K\(_s\) magnitudes.

Because the amplitude of Galactic extinction corrections tend to be a function of time and a matter of taste, we have listed E(B − V) from Schlegel, Finkbeiner, & Davis (1998) in Table 6, but have not included the associated correction in the B, R, or K\(_s\) values in Table 6.

7.1. Uncertainties and Reliability of Faint Isophotes

There are three main sources that contributed to the uncertainties given in Table 6. First are the photometric calibration uncertainties σ\(_m\) given in Tables 3 and 5, which are typically ≤ 0.02 in the optical and ≤ 0.05 in the infrared. The value of σ\(_m\) is the rms scatter around the photometric solution and is an empirical measurement of the characteristic error in an individual measurement. Thus σ\(_m\) is a conservative estimate of the photometric uncertainty associated with any single observation.

The second source of uncertainty comes from the area lost to masking of stars on or near the galaxy or to the small area of the K\(_s\) image (smaller than the extent of the R-band isophotes in some cases). Both effects cause flux to be underestimated. In most instances, the galaxies in our sample are at high enough Galactic latitude that few foreground stars overlap even the faintest isophotes of the galaxy, and thus this is usually not a problem. However, we have attempted to correct for this effect by using the smoothed models described above to interpolate within the masked regions.
Fig. 3. — $B$ (bottom left), $R$ (top), and $K_s$ (bottom right) images and contour diagrams of the 49 galaxies of our sample. The contour levels are separated by 1 mag arcsec$^{-2}$, with the dark reference contour drawn at $\mu_K = 27$ mag arcsec$^{-2}$, and $\mu_K = 21$ mag arcsec$^{-2}$ in the bottom left, top, and bottom right contour images, respectively. The solid circle in the top right of each image has a diameter equal to the FWHM of the point-spread function for that image. The horizontal line in the bottom left of the top $R$-band image is equal to 1 kpc if the galaxy is at a distance of $\frac{V_c}{H_0}$; we have taken the recessional velocity $V_c$ from the published single dish $\text{H I}$ measurements described in § 2 (if available) or from our long slit $\text{H \alpha}$ spectroscopy. At isophotal levels where there is sufficient signal to noise, contours are defined from the unsmoothed image. However, fainter isophotes are defined using a smoothed version of the image (see § 7). Tick marks are given at every 5 arcsec. The light gray shading under the contours indicates regions that were masked. All galaxies are displayed with an identical exposure time and image stretch.

While this process is uncertain, it is at least a step in the right direction. Furthermore, the magnitude of the correction gives some indication of the magnitude of the uncertainty. Typically, these corrections are less than 0.05 magnitudes.

The final, most subtle, and dominant source of uncertainty comes from sky subtraction. If the level of the sky is wrong, then this contributes/removes additional light to/from the galaxy in proportion to the area of the isophote used for photometry. To set the uncertainty in the sky subtraction, we have analyzed the noise properties of the unmasked “sky” pixels (see § 6) for a variety of boxcar smoothing lengths $L$ (Fig. 4). For an uncorrelated, uniform sky background, the standard deviation of the sky pixels $\sigma_{sky}$ will decrease with increasing smoothing lengths as $1/L$; this relation is plotted as the dashed line in Figure 4. For a highly correlated, nonuniform sky background, $\sigma_{sky}$ will be constant as long as $L$ is smaller than scale of the nonuniformity and the Poisson fluctuations in the smoothed image are smaller than the amplitude of the nonuniformity (for example, imagine a step function in brightness across the image). Mathematically, for a given power spectrum of background sky fluctuations, the predicted distribution of $\sigma_{sky}(L)$ can be calculated in analogy to the “counts-in-cells” formalism developed for large-scale structure analysis (e.g., Peebles 1980). The inclusion of the correlated background increases the variance above that predicted for pure Poisson fluctuations by adding a term involving the integral of the correlation function over the smoothing area. In each image, we can therefore assess the level of residual structure in the sky and its origin from the behavior of $\sigma_{sky}(L)$ shown in Figure 4. These plots also indicate the reliability of surface photometry at various length scales.

The plots of $\sigma_{sky}(L)$ in Figure 4 reveal a number of facts about our data. First, there is indeed correlated structure in the sky, as revealed by the deviation of the measured curves from the $1/L$ behavior expected for a uniform Poisson background. The presence of such structures is not too sur-
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praising, given that we fully expect to have residual contamination from scattered light and from stars and galaxies that lie below our detection threshold.

Second, the similarity of the $B$- and $R$-band $\sigma_{sky}(L)$ curves, down to the faintest surface brightnesses, suggests that the deviation from the $1/L$ Poisson expectation does not result from uncertainties in flat-fielding, at least for the optical imaging. Large-scale flat-fielding errors would be expected to differ between the two bands, leading to shape variations for observations taken through different filters. These shape variations would be consistent, however, for all galaxies observed on a single night. Although we do see occasional variations in between the shape of the $B$ and $R$ curves (e.g., FGC 51), these variations are not consistent with other galaxies observed on the same night. Thus, they are more realistically interpreted as being variations in the scattered light in the different bands (see below), given that the pointing centers are not identical for the subimages used to make the $B$ and $R$ images.

Third, we also see many cases where the curve is rolling over to flat as we approach the amplitude of the background sky variations. In some cases (e.g., FGC 227, 2548, E1371, E1404, and E1440), optical emission from 100 $\mu$ cirrus is clearly visible in the frame. In others (see FGC 51, 238 DALCANTON & BERNSTEIN Vol. 120
2264, and 1642), scattered light is a large problem in one of the subimages. In all of these cases, $\sigma_{\text{sky}}(L)$ rolls over at large smoothing lengths, as expected, and reveals the characteristic brightness of the structure.

Finally, the plots in Figure 4 clearly demonstrate the well-known difficulties with attempting to do reliable infrared surface photometry of nearby galaxies. The small field of view of IR detectors, the brightness and variability of the IR sky, and the difficulty in constructing reasonable dome flats all conspire to make the prospect of accurate faint surface brightnesses photometry daunting, if not practically impossible with current detectors. The $K_s$-band $\sigma_{\text{sky}}(L)$ curves deviate in shape from the optical curves at relatively small smoothing lengths ($\sim 5''$) and bright surface brightnesses ($\mu_{K_s} \lesssim 22 \, \text{mag arcsec}^{-2}$), demonstrating the limitations of our $K_s$-band data at large scales and faint surface brightnesses. Because of mosaicking, the signal to noise of the $K_s$ images tends to degrade toward the outskirts of the image, away from the galaxy. The estimates of the sky uncertainty come from these outer regions and will thus be biased toward higher values. Thus, sky subtraction near the galaxy is likely to be somewhat better than indicated by Figure 4.

To treat the contribution that the uncertainties in sky
subtraction make to the magnitudes in Table 6, we take the faintest reliably determined value of $\sigma_{sky}(L)$ (i.e., the highest point in each curve plotted in Fig. 4) as being characteristic of the error in our determination of the sky. We then calculate the uncertainty in the total flux over the isophotal area.

8. SUMMARY

In this first of a series of papers, we have described our sample of edge-on, late-type disk galaxies. As we have demonstrated, the optical and infrared imaging data on these galaxies are exceptionally well characterized and will be well suited for upcoming analysis of the structural properties of the sample, down to very faint surface brightness limits  

$$[\mu(B) \sim 29.5 \text{ mag arcsec}^{-2}, \ \mu(R) \sim 29 \text{ mag arcsec}^{-2}].$$

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FIG. 4.—Continued
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