ABSTRACT

The Ursa Major Cluster appears to be unevolved and made up of H I-rich spiral galaxies such as those one finds in the field. B, R, I, K′ photometry has been obtained for 79 galaxies, including 62 in a complete sample with $M_I^{b,i} < -16^{m}5$ (with a distance to the cluster of 15.5 Mpc). The K′ information is particularly important for the present discussion because it is not seriously affected by obscuration. There is reasonably convincing evidence that the distribution of exponential disk central surface brightnesses is bimodal. There is roughly an order of magnitude difference in the mean luminosity densities of high and low surface brightness disks. Disks avoid the domain between the high and low surface brightness zones. The few intermediate surface brightness examples in the sample all have significant neighbors within a projected distance of 80 kpc. The high surface brightness galaxies exhibit a range $-21^{m} < M_I^{b,i} < -17^{m}$, while the low surface brightness galaxies are found with $-19^{m} < M_I^{b,i} < -17^{m}$ that are indistinguishable in luminosity–line width plots have very distinct locations in surface brightness–scale length plots. The existence of separate high and low surface brightness families suggests that there are discrete radial configurations that are stable. Galaxies are driven into one of these regimes. The high surface brightness state has a lower luminosity cutoff. It is likely that the high surface brightness galaxies are dominated by dissipational matter at their centers, while the low surface brightness galaxies are dark matter dominated. The high surface brightness family subdivides into those with and without substantial bulges. In either case, these galaxies have essentially the same exponential disk central surface brightnesses. Evidently, there are two thresholds, probably controlled by angular momentum content or transfer. Passing from high to low specific angular momentum, there is first the transition from low surface brightness to high surface brightness regimes, and then the transition from exponential disk to disk plus bulge regimes.

Subject headings: dark matter — galaxies: clusters: individual (Ursa Major) — galaxies: formation — galaxies: photometry — galaxies: structure

1. FREEMAN’S LAW

Evidence will be presented that the luminosity densities of the disks of galaxies are bimodally distributed. By inference, the mass distributions would also be bimodally distributed. If true, then the distinction between high and low surface brightness (HSB and LSB) systems is a fundamental phenomenon that any theory of galaxy formation should be required to explain.

The surface brightness of galaxy disks falls off exponentially with radius (de Vaucouleurs 1959). Freeman (1970) considered many of the most familiar nearby spiral and S0 galaxies and pointed out that if fits to the main body of disks are extrapolated to the centers, then the central surface brightnesses have values in the B band of $\mu_B^{0} \approx 21.65$ mag per square arcsec with a very small dispersion. Today, many exceptions are known to Freeman’s law, inevitably on the LSB side. It has been argued that the constancy of central surface brightness values was an artifact either of obscuration (Jura 1980), bulge disk decomposition methods (Kormendy 1977), or selection effects that narrow the range of observed surface brightnesses (Disney 1976; Allen & Shu 1979). Van der Kruit (1987) made a strong case for a peak in agreement with Freeman’s discovery, although he appreciated that there are LSB galaxies that are discordant. The current dominant point of view is that there is a rather flat distribution of central surface brightnesses from $\mu_B^{0} \sim 20$ down to the faintest accessible levels (McGaugh, Bothun, & Schombert 1995; McGaugh 1996; de Jong 1996a). The details of this distribution have not been well determined because of selection effects.

Wide-field photographic surveys select for high surface brightness (HSB) galaxies within a preferred “visibility” window, in the vocabulary of Disney & Phillips (1983). Special efforts are necessary to find LSB objects (Impey, Bothun, & Malin 1988; Irwin et al. 1990; Davies et al. 1994; Schwartzzenberg et al. 1995). These efforts amply demonstrate the ubiquity of LSB galaxies, but often the distances to these objects are unknown, and it is not easy to achieve a normalization of the counts per surface brightness bin per unit volume element. Going back a bit, the first big compilation of LSB galaxies was by van den Bergh (1959, 1966). Redshifts for these galaxies were obtained by Fisher & Tully (1975), who made it clear that many of the objects in this class are big and intrinsically luminous; the brightest in that sample have $M_B \sim -20$. A big compendium of nearby LSB galaxies is provided by Fisher & Tully (1981). Quite a few samples have been compiled since that time, for example, the new catalog by Impey et al. (1996), which includes objects to $z \sim 0.1$.

This new study contains two observational elements that appear to be important. One is the nature of the sample: we have a statistically significant data set that is complete to an
absolute magnitude limit drawn from an environment dominated by H ii-rich, mostly noninteracting disk galaxies. The other element has to do with the passbands of the photometric material: we combine K' imaging with B, R, I optical imaging.

The raw data have been published in Paper I of this series (Tully et al. 1996). There is a description of the Ursa Major Cluster in that reference. The region is unusual in a favorable way. Clusters are nice because if objects are at a common distance, then an apparent threshold corresponds to an absolute threshold. However, it is suspected that cluster environments affect the properties of the constituent galaxies, for example, to produce the correlation of galaxy types with local density (Dressler 1980). Yet it was argued in Paper I that the Ursa Major Cluster may be so young that its members are representative of a “field” population. The velocity dispersion of the cluster is only 148 km s$^{-1}$, whence the characteristic crossing time is $0.5H_0^{-1}$. There is no concentration toward a core, no large elliptical galaxies, and only a few moderate S0 galaxies, and the spirals have normal gas properties. Next to the Virgo Cluster, the Ursa Major Cluster contains by far the largest concentration of spiral galaxies of any bound region in the Local Supercluster. Hence, there is the possibility that all galaxies in the volume of the cluster can be surveyed down to some absolute limit and that these galaxies will be reasonably representative of objects in the low-density parts of the universe.

The K' (2.2 μm) imaging provides the second important resource for this study. A 256 × 256 HgCdTe detector was used in wide-field modes, providing fields of view up to 9'. The photometry in the infrared is not significantly affected by obscuration, and it measures the light from old populations, which is presumably more closely tied to the total mass than the light of young populations.

It has long been appreciated that Freeman’s law, if true, provides strong constraints on galaxy formation scenarios. However, a galaxy modeler could not be sure if s/he was being asked to reproduce a real effect or an observational artifact. It is hoped that the present discussion will help revive the focus on an important characteristic of galaxies with the introduction of a couple of curious new elements.

2. SURFACE BRIGHTNESS–SCALE LENGTH DIAGRAMS

A compilation of photometric data can be found in Paper I for 79 galaxies projected within a 7.5 circle and with $700 < V_{helio} + 300 \sin l \cos b < 1210$ km s$^{-1}$. Of these, 62 galaxies define a complete sample with $M_B^i < -16.5$. CCD B, R, I photometry is available for all 79 galaxies. There is imaging K' photometry available for 60 of the 62 galaxies in the complete sample and for 10 of the 17 fainter galaxies. Absolute magnitudes are based on an assumed distance modulus of 30.95, corresponding to a distance of 15.5 Mpc. Hence, 1' = 75 pc. This distance is compatible with a complex velocity field map of the Local Supercluster with a global value of $H_0 = 85$ km s$^{-1}$ Mpc$^{-1}$ (Tully et al. 1997).

2.1. Photometric Parameters

One-dimensional projected surface brightness profiles were derived by averaging the surface brightness in concentric ellipses of constant position angle and ellipticity chosen to match the outer isophotes. The surface brightness profiles were fitted by a straight line of the form

$$ \mu' = \mu_0' + 1.086(r/r_d) $$

corresponding to an exponential profile of the form

$$ L'(r) = L_0' e^{-r/r_d} $$

If a bulge was detected, the inner region of the profile was excluded from the fit, and $\mu_0'$ was determined by extrapolation. Hence, the fall-off of surface brightness with radius $\mu(r)$ in a given passband $\lambda$ is described by two parameters: the surface brightness at the center of the galaxy, $\mu_0$, and the exponential scale length, $r_d$. Typically, 4 to 6 scale lengths are observed above the outer limiting isophote. It is known that giant elliptical galaxies are poorly fitted by an exponential form (de Vaucouleurs 1959), but there are no giant elliptical galaxies in the Ursa Major Cluster. There are some moderate-luminosity early-type systems that are classified as S0. It is possible to provide at least a crude exponential fit to the main bodies of these galaxies, although inevitably there are substantial bulge components at the centers. It is known that dwarf galaxies, whether irregular or elliptical, can be reasonably approximated by exponential profiles (Binggeli, Sandage, & Tarenghi 1984). Hence, it has been possible to measure the parameters $\mu_0$ and $r_d$ in all available bands for all the galaxies in the sample.

Plots of the positions of galaxies in the domain of these two parameters are informative. We begin in Figure 1 with the directly observed parameters, i.e., with no corrections for inclination effects. The solid symbols denote members of the complete sample, and the crosses are associated with fainter galaxies. The diagonal lines are loci of constant magnitudes since for an exponential disk

$$ m_\lambda = \mu_0 - 2.5 \log 2\pi b/a - 5 \log r_d $$

where the observed minor-to-major axial ratio of a galaxy is $b/a$. The lines are drawn to coincide with the completion boundary, defined in B and roughly transformed to the other bands. The curved lines in the B panel are in the spirit of the visibility limits discussed by Disney & Phillipps (1983). Following from Paper I, the magnitude above the limiting isophote is

$$ m_{lim} = m_T - 2.5 \log \left( 1 - \left[ 1 + \frac{(\mu_{lim} - \mu_0)}{0.1086} \right] e^{-\frac{(\mu_{lim} - \mu_0)}{0.1086}} \right) $$

(4)

Here $(\mu_{lim} - \mu_0)/0.1086$ is the number of scale lengths above the limiting isophote $\mu_{lim}$. If we substitute for $m_T$ and assume the face-on case $b/a = 1$, then

$$ r_d = 0.2 \left( \frac{\mu_0 - 2.5 \log 2\pi - m_{lim}}{-2.5 \log \left( 1 - \left[ 1 + \frac{(\mu_{lim} - \mu_0)}{0.1086} \right] e^{-\frac{(\mu_{lim} - \mu_0)}{0.1086}} \right)} \right) $$

(5)

We consider that we have completion brighter than $m_{lim} = 14^{m}.5$. Our fundamental reference is the Uppsala General Catalogue of Galaxies (Nilson 1973). According to Cornell et al. (1987), this catalog measures diameters to $25^a4^m0^s7$ at B, and, according to van der Kruit (1987), it measures diameters to $26^a0^m0^s7$ at B. In the following, we assume that there is completion to $\mu_{lim} = 25^{m}.5$. With these assumptions for $m_{lim}$ and $\mu_{lim}$, equation (5) provides the relation between $r_d$ and $\mu_0$ plotted as the lower limiting curve in Figure 1. The top left limiting curve is imposed by the requirement that galaxies have diameters larger than 1' at
the limiting isophote. In this case,

\[ r_d(\mu_{\text{lim}} - \mu_0)/1.086 > 30' \],

that is, the scale length times the number of scale lengths above the limiting isophote must exceed a radius of 30'.

The galaxies of the complete sample seem already to fall into two zones in each of the color panels of Figure 1. As one progresses from B, through R and I, to K, the two zones become more separated. The higher surface brightness galaxies tend to be redder, so the differences between HSB and LSB objects are accentuated with observations toward the infrared.

2.2. Inclination Corrections

Inclination effects can be confusing at optical bands because surface brightness path length and obscuration variables play off against each other. Happily, at K' obscuration is negligible, and it can be anticipated that projection effects on surface brightness are simply described by geometric considerations. It is expected that the central surface brightnesses of galaxies viewed face-on can be described by

\[ \mu_{0}^{\text{H}} = \mu_0^{\text{F}} - 2.5C^{\text{H}} \log (b/a) \).

Here, the coefficient C ranges from 0 for an opaque system to 1 for a transparent system. The superscript i means that an inclination correction has been applied. It can be anticipated that \( C^{K'} \sim 1 \) at K' and \( C^{A} \) is progressively smaller as one goes toward shorter wavelengths. In transparent systems the geometric effect of longer line-of-sight path lengths in edge-on cases augments surface brightnesses, but if the systems are not transparent, then the geometric augmentation is offset by the increased obscuration in edge-on cases.

In fact, if one distinguishes between edge-on and face-on galaxies in Figure 1 (triangles and circles, respectively), there is an immediately evident separation between the two inclination groups on the K' plot that weakens at I and R and is almost washed out at B. It is exactly this effect that is anticipated by the formulation of equation (7). Estimates of \( C^{A} \) can be derived by looking for the best agreement between edge-on and face-on galaxies in the various passbands. Given the apparent separation of galaxies into two surface brightness zones, we split the sample at \( \mu_0^{K'} = 17^{m}5 \) and, moreover, consider only the 62 galaxies of the complete sample. For the HSB and LSB subsamples separately, we then varied \( C^{A} \) to find minima in the dispersion of central surface brightnesses. Figure 2 illustrates the variations in
rms dispersion with the choice of the parameter C, for the HSB subsample in (a) and for the LSB subsample in (b). The variation of \(C^\lambda\) behaves as expected for the 39 galaxies in the HSB subsample (38 at \(K\) and \(I\)). There is a minimum dispersion at \(K^\prime\) with \(C^{K^\prime} = 1\) corresponding to the transparent model. Progressively toward shorter wavelengths, dispersion minima occur at \(C^I = 0.61\), \(C^R = 0.52\), and \(C^B = 0.23\). At minimum, the rms dispersions are approximately 0.583 at \(R\) and \(I\) and approximately 0.583 at \(B\) and \(K^\prime\). For comparison, Valentijn (1990) found \(C^B \sim 0.2\) for Sb–Sc types, and Peletier & Willner (1992) found \(C\) near the transparent regime at \(H\) band.

If the same test is applied to the 23 galaxies of the LSB subsample (22 at \(K\)), the results are more uncertain but consistent with the proposition that these systems are transparent. It is seen in Figure 2b that the rms dispersion is minimized with \(C^\lambda\) in the range 0.64–0.78, with no systematic dependence on \(\lambda\). Since \(C^\lambda\) does not increase with increasing \(\lambda\), we conclude that obscuration is not a factor for this subsample. The deviation from \(C = 1\) is taken to be a statistical aberration. Almost certainly, \(C^K\) should equal unity, and the measured minimum is most deviant from unity in this case. We accept that \(C^\lambda = 1\) at all passbands for the LSB subsample. Dispersions about the mean surface brightnesses are 0.59 to 0.71, but these values may be affected by incompleteness on the low surface brightness side. Surface brightness means and dispersions are recorded for the various subsamples and passbands in Table 1.

Figure 3 is the equivalent of Figure 1, but now with the inclination adjustments of equation (7) applied. In this new figure, the HSB galaxies are distinguished as the filled symbols and the LSB galaxies are identified by open symbols. The separation between the two groups is formally made at \(\mu^{K^\prime} = 18.05\). In the \(K^\prime\) panel, large symbols identify galaxies with large bulges (concentration index from Paper I \(C_{82} > 5\)). It is seen that the HSB and LSB domains are each restricted in surface brightness and extended in scale length. There are histograms of the surface brightness distributions shown in Figure 4. The one HSB system, as defined at \(K^\prime\), that overlaps with the LSB sample at \(B, R, I\) is the anomalous galaxy NGC 3718, which will be discussed later.

These plots include the adjustments for inclination effects, so care is needed in one regard. In the cases of \(B, R, I\) the coefficients \(\lambda^\lambda\) are different for the HSB and LSB regimes (see Table 1). The effect of the inclination corrections is to make the adjusted surface brightnesses of edge-on galaxies \(\mu^\lambda\lambda \geq \mu^\lambda_0\). The larger the value of \(C^\lambda\), the

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**TABLE 1**

| Filter | Complete subsample of isolated galaxies | N | \(\langle \mu_0 \rangle\) | rms | N | \(\langle \mu_0 \rangle\) | rms |
|--------|----------------------------------------|---|----------------|-----|---|----------------|-----|
| \(B\)  | 24 | 20.60 | ±0.52 | ... | 14 | 22.77 | ±0.46 |
| \(R\)  | 24 | 19.50 | ±0.55 | ... | 14 | 21.87 | ±0.41 |
| \(I\)  | 24 | 18.94 | ±0.54 | ... | 14 | 21.36 | ±0.46 |
| \(K\)  | 23 | 17.15 | ±0.40 | ... | 13 | 19.85 | ±0.39 |
larger the shift. In the case of the $B$, $R$, $I$ passbands, since $C_{\text{LSB}} > C_{\text{HSB}}$, there is a separation of the HSB and LSB groups introduced by the inclination adjustments. On the one hand, there is a reasonable basis for making the separate inclination corrections to HSB and LSB systems. On the other hand, it makes it dangerous to argue that the gap between HSB and LSB systems is real when part of the separation is introduced by these corrections. Hence, the $K'$ material takes on a particular importance. Our tests indicate that both the HSB and LSB galaxies are in the transparent regime, so the two groups receive the same inclination treatment. Moreover, the HSB systems turn out to be redder than the LSB systems, so the separation between the two kinds of galaxies is most easily distinguished in the infrared.

The color and reddening variations provide a reconciliation with the claims by Peletier & Willner (1992) that the range of observed surface brightness at $B$ is small because of dust absorption and is more considerable at $H$ where disks are almost transparent. If no corrections for inclination are made, then the scatter is smallest at $B$ because absorption and projection effects offset each other. Once suitable corrections are made, then the scatter is comparable in each band from $B$ to $K'$ for the separate HSB and LSB families. However, the HSB and LSB families move apart as one progresses from the blue to the infrared since HSB types are redder than LSB types. Hence, if the separate families are not distinguished, then the dispersion in surface brightnesses seems to increase as one progresses to the infrared.

Could the bimodality be an artifact of our fitting of the exponential disks since we have not attempted bulge–disk decompositions? The large bulge systems are flagged in Figure 3, and the bimodality is seen to remain in those without bulges. It is argued by de Jong (1996b) and Courteau, de Jong, & Broeils (1996) that the exponential representation of bulges is at least as justified as an $r^{1/4}$ representation, whence de Jong shows that our “marking the disk” fits give an unbiased disk characterization relative to a bulge/disk decomposition, with an uncertainty of about 0.2. A greater potential error arises in our case because the $K'$ photometry is cut off at smaller radii by sky noise. If there is a substantial bulge, then the disk fitting range is restricted, and there is a bias toward too steep a slope through inclusion of some of the bulge in the disk. Hence, the measure of $\mu_0$ may be too bright. The concern here is whether bulge galaxies could have been moved from the gap to the HSB domain erroneously. The $K'$ luminosity profile fits of Paper I have been reconsidered from a conservative perspective by asking how far $\mu_0$ values could be pushed toward the gap. In fact, in several of the bulge systems it is warranted to take fainter $\mu_0$ values. Changes from Paper I are recorded in Table 2. A couple of systems are
FIG. 4.—Histogram of inclination-adjusted central disk surface brightnesses for B, R, I, K'. The HSB component of the histogram is filled. Means for the HSB and LSB components are indicated. NGC 3718 is identified as HSB at K' but lies with the LSB at B, R, I.

TABLE 2

| PGC   | Filter | Paper I | Revised |
|-------|--------|---------|---------|
|       |        | μ₀     | rₚ      | μ₀     | rₚ      |
| 35202 | K'     | 19.31  | 19.6    | 19.9   | 26      |
| 36866 | K'     | 17.04  | 7.1     | 18.0   | 9       |
| 37073 | K'     | 17.09  | 7.9     | 17.8   | 11      |
| 37163 | K'     | 16.90  | 9.3     | 17.3   | 10      |
| 37550 | B      | 21.91  | 13.1    | 22.26  | 14.5    |
| 37550 | R      | 20.78  | 11.7    | 21.19  | 13.0    |
| 37550 | I      | 20.25  | 11.2    | 20.63  | 12.3    |
| 37550 | K'     | 18.19  | 7.9     | 18.56  | 8.8     |
| 37553 | B      | 21.06  | 16.6    | 21.42  | 18.0    |
| 37553 | R      | 20.22  | 17.5    | 20.60  | 19.2    |
| 37553 | I      | 19.88  | 20.0    | 20.30  | 22.5    |
| 37553 | K'     | 17.87  | 14.6    | 18.34  | 17.1    |
| 37618 | K'     | 16.04  | 8.9     | 16.4   | 10      |
| 37719 | K'     | 14.70  | 11.0    | 17.0   | 18      |
| 38068 | K'     | 16.72  | 30.2    | 16.9   | 33      |
| 38392 | K'     | 16.15  | 19.7    | 15.82  | 18.0    |
| 38440 | K'     | 15.63  | 23.9    | 16.02  | 26.3    |
| 39237 | K'     | 16.51  | 7.2     | 16.74  | 7.7     |
| 38503 | K'     | 17.11  | 12.1    | 17.8   | 15      |
| 38507 | K'     | 18.26  | 5.7     | 19.1   | 9       |
| 40228 | K'     | 15.91  | 19.7    | 16.8   | 25      |

moved into the surface brightness gap, but the changes are not significant.

2.3. An Environmental Effect

Having identified the separate HSB and LSB families, we wondered whether there was any environment difference between the two, so we looked at surface brightness properties as a function of proximity to nearest neighbor. Figure 5 shows the amazing result. In the top panel for each bandpass, the inclination-adjusted central disk surface brightness is plotted against the projected distance to the nearest significant neighbor. To be "significant," we require that the neighbor have at least 10% of the luminosity of the galaxy under consideration. For this discussion, we draw attention to the K' panels where the situation is clearest. Remarkably, all of the intermediate surface brightness systems have projected near neighbors. For the approximately two-thirds of the sample that do not have a significant close companion, the separation into HSB and LSB classes is compelling.

The middle panels for Figure 5 repeat the histograms of Figure 4 but only include the 38 of 62 galaxies (36 of 60 at K') in the complete sample with a nearest significant neighbor more distant than 80 kpc in projection. Histogram
means and dispersions are recorded in Table 1. The solid curve in the $K'$ panel illustrates a completeness expectation. The histogram would have this shape if there was a uniform population of the $\mu_0^{\text{K,'}} - r_d$ domain for $0.8 < \log r_d < 1.6$ and $\mu_0^\text{K,'} > 17^\text{m}$. The fall-off from the peak is described by the transposition of the curve defined by equation (5) and illustrated in the $B$ panel of Figure 1. The bottom panels in Figure 5 show the same information for the 24 galaxies in the complete sample with a nearest significant neighbor closer than 80 kpc in projection.

For the isolated galaxies, there is a gap at $K'$ between HSB and LSB types of $1^\text{m}5$, which contains three galaxies where roughly 20 might be expected. The dispersion about the separate peaks is $\sigma = 0.40$. There is an evident difference with respect to the representative completeness expectation. This remarkable figure demonstrates that the HSB-LSB bimodality is highly significant in galaxies that are relatively isolated today. These galaxies have transit times greater than $10^\text{yr}$ with another galaxy.

The sample is drawn from a cluster, but one that appears to be dynamically young; so much so that in Paper I it was argued that the galaxies may be representative of a field population. The relatively isolated galaxies that display the bimodality most clearly are probably most similar to galaxies in the field. By contrast, the much more scattered distribution of surface brightnesses for the galaxies with projected neighbors is strong evidence that interactions can substantially redistribute the luminous matter in disks.

We can summarize this section with the suggestion that the disk components in each state is a full factor of 10. The evidence for bimodality is particularly strong if only relatively isolated galaxies are considered. The HSB family lie sufficiently far from the completion limits on the $\mu_0 - r_d$ plots that our census of this family is probably near to complete. In contrast, the LSB family is badly intersected by the completion limits, and our census of that family must be quite incomplete.

3. BACK TO THE LITERATURE

It has been appreciated for some time that there are departures from Freeman’s law, to the extent that the acronyms LSB and HSB have become familiar coinage for low and high surface brightness systems. However, it had never been proposed that there was a discrete difference between LSB and HSB galaxies. Rather, it was supposed that there was a continuum of surface brightness properties (see McGaugh 1996; de Jong 1996a) and that the designations LSB and HSB described objects on either side of an ill-defined dividing line (Davies et al. 1988a; McGaugh & Bothun 1994; de Blok, van der Hulst, & Bothun 1995). See McGaugh (1996) for a more elaborate categorization.

In retrospect, astronomers have long been able to distinguish LSB from HSB galaxies on a qualitative basis. Figure 6 illustrates the correlation between surface brightness and morphological type designations. With overwhelming coincidence, galaxies typed S0–Sc are classed HSB and galaxies typed Scd–Im are classed LSB. The few exceptions tend to be rather anomalous and hard to define morphologically. The HSB/LSB separation at $\mu_0^{K,'} = 18^\text{m}5$ takes the S0 galaxy NGC 4117 to the LSB class, but this limit is subjective and could be revised. Evidently, the
density of the disk has a distinct signature in the appearance of a galaxy. For one thing, the HSB systems may saturate at the centers on photographic images, while the LSB systems do not. There must also be manifestations in the organization of spiral structure.

Our claim of bimodality is consistent with the study by van der Kruit (1987). His sample was somewhat smaller, with distance effects, and was based on J-band photographic material with quoted uncertainties in $\mu_0$ of $\pm 0.3$. He saw enough of a difference between early and late types that he fitted separate distributions to the two, but he did not draw attention to these separations or make any suggestion that the two types were distinct. Van der Kruit made inclination adjustments on the assumption that the disks are transparent, which closes the gap in $\mu_0$ between the HSB and LSB families. Consider the B-band panel of our Figure 5. If we assumed that HSB galaxies are transparent at B, then the HSB subsample would shift to lower surface brightnesses (more positive values) by $0^\circ.6$ in the mean. The LSB subsample remains where it is because it was already assumed that these galaxies are transparent. Hence, the two subsamples would begin to merge. The mean for the LSB part would be approximately $21^\circ.2$, not so different from van der Kruit's approximately $21^\circ.5$ for S0–ScII (translating from J to B) and Freeman's (1970) $21^\circ.65$ for a blend of mostly HSB and a few LSB objects.

De Jong (1996a) presents a similar plot to our Figure 6 with his Figure 3. It can be seen, on the one hand, that our results are consistent with his and, on the other hand, that his sample of mostly earlier types would not convincingly reveal bimodality.

If we are seriously proposing a distinct separation of disk types into two families, then it is an appropriate moment to try to understand the relationship between these families and the kinds of galaxies that have been revealed by other surveys. In terms of luminosity–surface brightness–scale length properties, it might be argued that there are as many as six families of galaxy types.

1. Type 1, giant boxy elliptical galaxies.—Galaxies of this class do not have significant disks and are not well described by the exponential luminosity-radius description. If exponential curves were force-fitted in such cases, presumably these systems would be given values at least as bright or brighter than HSB disks and comparable scale lengths. There are no such galaxies in our sample.

2. Type 2, high surface brightness disks.—Normal spiral and S0 galaxies, the majority of our complete sample, are of the HSB type. It can be debated if "disky" elliptical galaxies belong in this group or with type 1.

3. Type 3, low surface brightness disks.—Galaxies typed Scd to Irregular are of this LSB class, which constitutes

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**Fig. 6.** Correlation between surface brightness families and morphological types: filled symbols, HSB; open symbols, LSB; crosses, fainter than complete sample limit. Large symbols denote galaxies with bulges: concentration index $C_4 > 5$. NGC 3718 is the unusual galaxy discussed in connection with the type 6, large LSB systems. The S0 galaxy identified as LSB by the delineation between surface brightness regimes at $\mu_0 = 18.5$ is NGC 4117. Otherwise, the LSB systems are typed Scd or later. The central disk surface brightnesses are similar for bulge and nonbulge HSB systems.
one-third of our complete sample and one-half of our overall sample. The examples we know about are inevitably H I-rich. Our study does not explore the full domain of this class at faint $\mu_0$ and low $r_d$.

4. Type 4, dwarf spheroidal galaxies.—Galaxies of this type are known in the Local Group and related objects are found in abundance in such clusters as Virgo (Binggeli et al. 1984; Impey et al. 1988) and Fornax (Ferguson & Sandage 1988; Davies et al. 1988a; Irwin et al. 1990). The vast majority of these systems are H I poor. The location of this class in the $\mu_0 - r_d$ parameter space is shown in Figure 7 with the superposition of the Fornax Cluster samples of Davies et al. (1988a) and Irwin et al. (1990). The domain of these dwarfs is essentially entirely below our completion limit. Galaxies of types 3 and 4 must overlap in surface brightness and scale length properties, and the relationship between the two groups remains to be clarified. It has been argued (Wirth & Gallagher 1984; Kormendy 1985) that dwarf spheroidal galaxies are a distinct family from large elliptical galaxies.

5. Type 5, compact dwarfs.—Blue and red compact dwarfs are known to exist (Zwicky 1964). The best example of a blue compact dwarf in our sample is PGC 37045 = 1148 + 48 = Markarian 1460. UGC 6805 may be a reasonable example of a red compact dwarf. These two objects are fainter than our completion limit. There is still a very poor inventory of these kinds of galaxies. Red compact dwarfs may be related to giant elliptical galaxies, and blue compact dwarfs may be related to dwarf irregular galaxies.

6. Type 6, large low surface brightness galaxies.—Malin 1 (Bothun et al. 1987) is an extreme example of what seems yet to be a rare class of galaxies. Other examples have been reported by Davies, Phillipps, & Disney (1988b) and Sprayberry et al. (1995b), and representatives of these objects have been located in Figure 7. Galaxies of this class can have extreme properties because of low values of $\mu_0$ and large values of $r_d$. The objects known to date are distinguishable from galaxies of type 3 because they are relatively red and have prominent bulges. Both types 3 and 6 contain H I. It is possible that we have one galaxy of this type in our sample, albeit not so extreme. NGC 3718 is quite anomalous in comparison with the rest of our objects. It has by far the largest exponential scale length in all passbands and has a relatively low disk central surface brightness. It is red and has a big bulge, which causes it to be classified Sa, but the galaxy could be considered too pathological to be fitted into the Hubble sequence. Schwarz (1985) has shown that this otherwise relatively isolated galaxy could be interacting with NGC 3729. It has not been suggested in other cases that the large LSB class is involved in interactions.

In summary of this section, galaxies with distinctive properties inhabit distinctive parts of the $\mu_0$-$r_d$ diagram. In particular, galaxies we think of as "normal" disk systems are reasonably isolated from other types in this parameter space. These normal galaxies can be quantitatively specified by their $\mu_0$, $r_d$ properties. We should ask how this segregation of properties has occurred.

4. A CORE SURFACE BRIGHTNESS–LUMINOSITY RELATION

This section stands a bit apart. The disk component can get lost at the centers of some galaxies that have large bulges. In Paper I, we tabulated for each galaxy the surface brightness within an ellipse with a major axis radius of 4′ and a minor axis radius in proportion to the inclination of the galaxy. At the distance of Ursa Major, 4′ = 300 pc. This parameter that we call $\mu_0$ is a metric surface brightness, a measure of the density of light at the centers of all our galaxies. It is the cumulation of the light of disks and of any bulge. Active nuclei, and possibly bars, will contribute to $\mu_0$. At K′, the parameter should not be strongly affected by obscuration.

Tight correlations are seen in Figure 8, which shows all the available data at K′ band. In the top panel, there is the relationship between the $\mu_0$ parameter and the disk central surface brightness, $\mu_0$, where the superscript indicates that a correction for inclination has been made. This inclination correction is applied to the disk component only; i.e., the flux from the bulge contribution to $\mu_0$ is not modified with inclination. The two parameters, $\mu_0$ and $\mu_4$, scatter about the 45° equality line if there is no bulge component, but $\mu_4 < \mu_0$ if there is a bulge component in addition to the disk component. Only types earlier or equal to Sab among the HSB subsample have significant bulge components. In Figures 8b and 8c, the K′ magnitude is plotted against the $\mu_4$ core surface brightness parameter, and tight correlations are found. The same data are shown in the two panels, but in (b) the types Sab and earlier are emphasized with big symbols, and in (c) the types Sb and later are emphasized with big symbols. The correlations are particularly tight with these separations by type.

These plots are a diversion from our main theme, but it is worthwhile to remember that, while the disk central surface...
brightnesses of HSB galaxies may have a small scatter, the disk-plus-bulge (plus possible active nucleus) central surface brightnesses display a wide range. In our small sample, there are separate strong correlations between $\mu_0$ and $M_K^*$ for types S0–Sab and SB–Im.

5. LUMINOSITY FUNCTIONS

A convenient description of the luminosity function of galaxies is provided by the Schechter (1976) formulation. However, there is growing evidence that this two-parameter curve is too simple. Samples that are fitted only to $M_b \lesssim -16^m$ are adequately described with the Schechter parameter $x \simeq -1.0$ (Davis & Huchra 1982; Tully 1988; Loveday et al. 1992; Marzke et al. 1994), which is the case if there are equal numbers in equal logarithmic bins at faint luminosities. However, there have been claims that the luminosity function turns up, possibly dramatically, at the faint end (Sandage, Binggeli, & Tammann 1985; Driver et al. 1994; Marzke et al. 1994). In other words, the luminosity function for all galaxies combined may have a concave shape that the Schechter formulation will not accommodate.

It is interesting to see the separate contributions to the total luminosity function according to the HSB and LSB categories that have been identified. Figure 9 shows the luminosity functions of the separate HSB and LSB components and the sum of all types. Overall, the luminosity function is rather flat to the completion limit of $M_b = -16^m$. The separate components have very different forms. The HSB component cuts off above the completion limit, while the LSB component is rising sharply at the completion limit.

This result is not surprising given the strong correlation between the surface brightness classes and morphological types, as shown in Figure 6. Sandage et al. (1985) have demonstrated the differences in luminosity functions between morphological types. See also Binggeli, Sandage, & Tammann (1988) for a review, and Marzke et al. (1994). The Binggeli, Sandage, & Tammann (1988) review recalls the historical debate over the bell-shaped function found by Hubble (1936) versus the faint-end exponential shape advocated by Zwicky (1942). It has been appreciated that Hubble was drawing upon a sample dominated by HSB objects, while Zwicky was impressed that LSB, faint galaxies did exist but were strongly selected against. There are some basic points of agreement. Binggeli et al. (1988) find bell-shaped luminosity functions for types E–Sc, as we do for the HSB family, and as Hubble found for samples dominated by HSB galaxies. Binggeli et al. (1988) and Marzke et al. (1994) find luminosity functions to be steeply increasing at the faint end for irregular or dwarf spheroidal systems, as we find for the LSB family and as Zwicky anticipated.

The HSB-LSB distinction does put a new twist on the debate. It was not clear before why one should be impressed by the decomposition of the luminosity function by type carried out by Binggeli et al. Let us restrict our considerations to either the H i–rich disk systems or the H i–poor ellipsoidal systems separately. If there is a continuum of properties along one of these branches, then the type decomposition may just be providing an alternative description of the Hubble sequence rather than telling us something fundamental about galaxy formation. For example, suppose the sequence from Sa to Im is basically a continuous mass sequence. More massive galaxies are more
organized, have bigger bulge components, get an earlier type classification, and are more luminous. The least massive, less luminous galaxies are too small to maintain spiral structure and have a late-type classification. Naturally then, there would be differences in the luminosity functions of the different types, and earlier types will have cutoffs at the faint end. The luminosity function differences between types might just be telling us about thresholds for the maintenance of spiral structure or the formation of bulges: issues to do with resonances or disk instabilities, perhaps. The ensemble luminosity function might be viewed as providing a more global constraint on the mass spectrum and galaxy formation.

The HSB-LSB dichotomy provides a better understanding of the origins of the historic debate and enhances the interest in the separation of luminosity functions by type. If there really were a continuum of surface brightness properties among disk systems, then the extreme bias of early and even modern surveys in favor of E–Sc types at the expense of Sd–Im types is hard to understand, the “visibility” arguments of Disney & Phillipps (1983) notwithstanding. The situation makes more sense if there is a distinct gap in the detectability of the early and late types, as follows from what we are finding. Moreover, the gap has to be explained. The step from Sc to Sd may involve a discontinuity in formation processes. For example, what if there is a step in mass-to-light ratio between the Sc and Sd types (a possibility discussed in the next section)? Then the ensemble luminosity function would not be a simple reflection of the more fundamental mass function. A kink in the ensemble luminosity function between the domains of HSB and LSB dominance might be a signature of a break between different ways that disks form.

6. LUMINOSITY–LINE WIDTH RELATIONS

Although the possibility of surface brightness bimodality has come as a surprise, part of the original motivation for our study was to understand why galaxies can lie together on a luminosity–H I profile line width plot (Tully & Fisher 1977) yet be quite removed from each other on a surface brightness–scale length plot. The luminosity–line width relations are seen in Figure 10 for the fraction of our sample that satisfies our type, inclination, and H I profile quality criteria (34 galaxies). The HSB galaxies are denoted by filled symbols; the LSB galaxies, by open symbols.

In all the passbands, it can be seen that there is a 2^m–3^m domain of overlap between HSB and LSB galaxies and that there is no significant difference of each type from the mean correlations. The HSB systems are redder than the LSB systems, so the HSB types do progressively brighten relative to the LSBs as one steps toward the infrared. The galaxies in the overlap region are given box symbols so that they can be tracked in the next plot, Figure 11. This figure is a repetition of Figure 3, except now the galaxies given box symbols in Figure 10 are identified with identical symbols here. These figures illustrate the point made in the previous paragraph. Galaxies that are mixed together in luminosity–line width diagrams separate to the distinct HSB and LSB zones on the \( \mu_0 - r_d \) diagrams.

Three specific HSB-LSB pairs are illustrated in Figure 12. Each of these pairs lies close together on the luminosity–line width diagrams. See the objects labeled 1, 2, and 3 in Figures 10 and 11. The I-band inclination-adjusted surface brightnesses are shown in Figure 12, and the distinct differences between the HSB and LSB families are evident.

The HSB-LSB overlap in Figure 10 is part of the mystery of the tightness of luminosity–line width relations. The coincidence between LSB and HSB systems has been noted by Sprayberry et al. (1995a) and Zwaan et al. (1995). Zwaan et al. (1995) make the following point if galaxies are built homologously. Compare systems with the same luminosity \( L \) and maximum rotation velocity \( V_{\text{obs}} \) but different \( \mu_0, r_d \). Then the indicative mass, \( M \propto (V_{\text{obs}}^{max})^2 r_d \), is greater for the LSB galaxy with large \( r_d \) than the HSB galaxy with small \( r_d \), though the luminosities are the same. That is, \( (M/L)_{\text{LSB}} > (M/L)_{\text{HSB}} \). This argument is in line with other evidence that late-type galaxies have larger mass-to-light ratios than early types (Carignan & Freeman 1988; Persic & Salucci 1988).

If the velocity field is responding to just the matter distributed in an exponential disk, then the velocity maximum induced by this disk, \( V_{\text{max}} \), will occur at 2.1\( r_d \) (Freeman 1970). With this consideration, we can generalize that there

![Fig. 9.—Luminosity functions in B band. (a) The HSB subsample is shaded and embedded in the luminosity function for the entire sample. There is completion at \( M_b^{\text{H}} = -16.6^m \). The cutoff of the HSB luminosity function by \( M_b^{\text{H}} \sim -17^m \) is unlikely to be an observational artifact. (b) The LSB subsample is shown as an open histogram embedded in the ensemble function. The LSB component begins at \( M_b^{\text{L}} \sim -19^m \) and rises steeply to the completion limit.](image-url)
are three possible cases: (1) if the potential within a few \( r_d \) is dominated by mass in an exponential disk then the observed \( V_{\text{obs}} \) should occur at \( r \sim 2.1 r_d \), (2) if the potential is dominated by the halo \( V_{\text{obs}} \) will probably occur at \( r > 2.1 r_d \), since the halo is expected to be more extended than the light, and modeling will probably give \( V_{\text{disk}} \) and \( V_{\text{max}} \), and (3) if in addition to the self-gravitating exponential disk there is a central bulge then \( V_{\text{obs}} \) should be pulled inward to occur at \( r < 2.1 r_d \).

We can look at the information about velocity fields in the literature. The HSB-LSB pair NGC 2403–UGC 128 was studied by de Blok & McGaugh (1996) because they share the same \( V_{\text{max}} \) and \( L \). The HSB object NGC 2403 has an exponential disk scale length about one-third that of the LSB object UGC 128. The luminosity is sufficiently concentrated in the HSB case that the stellar mass that can be associated with the light is enough to produce the observed velocities. Such is not the situation with the LSB case. The resolution in the case of UGC 128 is not fully satisfactory (beam \( \sim 2r_d \)), Verheijen (1997) has Westerbork HI synthesis maps of all the galaxies, both HSB and LSB, in the overlap region of \(-17^m > M_B > -19^m \) of the Ursa Major sample. Figure 13 provides a preview of a small bit of the HI information available to us. Velocity-radius contour maps are shown for the triplet of galaxies tracked in Figures 10 and 11.

The three galaxies used in this figure were chosen as representatives of the three generalized cases outlined two paragraphs above. We will try to make the case that NGC 3949 is an example of a self-gravitating exponential disk system without a substantial bulge. This galaxy is in the HSB family. It is offered as an example of case 1 above and will be referred to as the “exponential HSB” class. UGC 6973 has an HSB disk and, additionally, has a significant central excess of light. It is offered as an example of case 3, the “exponential HSB plus bulge” class. NGC 3917 is drawn from the LSB family. It will be shown that the disks of such galaxies do not make an important dynamical contribution. This object is an example of case 2, the “LSB” class.

The bottom panels of Figure 13 demonstrate decompositions of the rotation curves into the contributions associated with the stellar component, assuming \( M/L_{K_s} = 0.4M_{\odot}/L_{\odot} \), the interstellar gas component (negligible in all these examples), and what is left over, hence attributed to a dark halo. The choice \( M/L_{K_s} = 0.4M_{\odot}/L_{\odot} \) was made to give a “maximum disk” fit (van Albada & Sancisi 1986) of the velocities associated with the luminous matter to the observed inner rotation velocities for UGC 6973 and NGC 3949, the two HSB examples. There was no attempt to make a bulge-disk decomposition. For the LSB NGC 3917, the same choice of \( M/L \) fails by a wide margin to explain the
observed rotation. The disk contribution could be raised with an increased $M/L_e$ but not sufficiently for it to become dominant. If anything, it might be expected that $M/L$ values are lower for LSB systems compared with HSB types, not higher. The idea that there is a dynamical difference between HSB and LSB types is revisited in the next section. The photometric gap appears to have a dynamical correspondence.

7. DISCUSSION

A discreteness between "normal" and "dwarf" galaxies was suggested by Dekel & Silk (1986) based on a theoretical idea, although the idea was motivated by observations. They argued for a potential well threshold: small galaxies lose much of their gas when an early burst of star formation leads to supernova-driven winds that exceed the escape velocity, while large galaxies retain the gas.

The concept could explain the distinction between LSB and HSB conditions and the apparent augmentation in $M/L$ with LSB types. It may be a problem for the theory that there are examples of the LSB class within our small sample that have rotation velocities as high as $V_{\text{obs}} \sim 150$ km s$^{-1}$, since Dekel and Silk predict that there is substantial mass-loss only if virial velocities are $\lesssim 100$ km s$^{-1}$. Perhaps that stretch can be accommodated. However, we have a more fundamental concern.

It is not evident how the Dekel-Silk model fits with the observation that HSB and LSB systems of a given maximum rotation value have the same luminosity. Their "dwarfs" lose a large fraction of the gas that could create stars and luminosity. Alternatively, these observations could be satisfied if two conditions are met: (1) the maximum velocity of a galaxy is set by the dark halo; (2) there is a fixed initial fraction of the protogalaxy in matter that can form stars, and this matter is largely conserved. This latter condition is quite at odds with the Dekel-Silk proposition, although remember that we need only be concerned with the domain $-19 < M_B < -17$, where HSB and LSB types overlap. The Dekel-Silk mechanism could kick in at a fainter magnitude.

If our two rules are met, then the observations of Figures 10 and 11 can be explained since a predictable number of stars are formed in a given halo, although the concentration may vary. We need a different mechanism from that proposed by Dekel and Silk, one that creates the discrete HSB and LSB classes while preserving the dissipational mass content.

Mestel (1963) pointed out that self-gravitating disks would find their ways to specific radial configurations since there are radial forces in disks that are not experienced if there is spherical symmetry. Mestel anticipated that one stable radial gradient results in a flat rotation curve. Gunn
FIG. 12.—$I$-band inclination-adjusted surface brightness vs. radius for the three HSB-LSB pairs of galaxies identified in Figs. 10 and 11. The $B$ images of the pairs are shown in the inset at common scales. Pair 1, NGC 4085/NGC 4010; pair 2, NGC 3985/UGC 6917; and pair 3, NGC 4218/UGC 6446.

(1982) has shown that a flat rotation curve due to a dynamically important disk embedded in an isothermal halo implies an exponential mass distribution for the disk. Ryden & Gunn (1987) get flat rotation curves with galaxy formation in a cold dark matter scenario, but the halos are dominant. Ryden (1988) could find an inner regime where the dissipational material is dynamically dominant in cases with large initial fluctuation amplitudes, which become large galaxies. These models do not entertain possible transfer of angular momentum between successive collapsing shells during formation.

Our proposition is that the HSB and LSB modes correspond to two alternative radially stable configurations. To understand the two possibilities, let us consider the large and small extremes, then the intermediate cases. The small extreme may be the simplest. Suppose that the dissipational component has sufficient angular momentum that it reaches rotational equilibrium at densities that still leave the halo dominant. If small galaxies that have avoided merging are the progeny of small-amplitude ($\Delta \sigma_p$) initial fluctuations, then it is reasonable that they formed late, hence with relatively high specific angular momentum & Jones (1979).

One of Mestel’s (1963) stable configurations involves self-gravitating diffuse disks, but there is evidence from disk-halo decompositions that the diffuse LSB disks are not self-gravitating (Fig. 13, NGC 3917; see also de Blok & McGaugh 1996). The dark matter halos contribute substantially at all radii. If this quasi-spherical system collapsed conserving angular momentum in radial shells, then it ends up in the stable configuration described by Ryden and Gunn.

The luminous galaxies find their way to become disk dominated at their centers. Somehow we end up with the disk-halo “conspiracy” of flat rotation (van Albada & Sancisi 1986). There have been a lot of experiments with $N$-body simulations in the framework of the cold dark matter model, and there is general agreement with the observed rotation properties of galaxies (see Blumenthal et al. 1986; Navarro, Frenk, & White 1996). There are systematics that make the “conspiracy” less than perfect, with some initial decline with radius in concentrated, luminous systems (Casertano & van Gorkom 1991). The central densities of the disks remarkably conform to Freeman’s law. Galaxies know the law. If there is too much dissipational material in the cores to abide the law, then a bulge is formed. The “conspiracy” co-ops this third component.

Our qualitative interpretation of events is that the galaxies have settled into a mandated stable radial configuration, in the spirit of the Mestel argument, but with the revision required because of the lurking dark halo. The formation process presumably involved a considerable transfer of angular momentum outward to the halo. Such a process would seem to be a natural consequence of hierarchical merging, where blobs come together in nonaxisymmetric ways, and is seen in $N$-body simulations & Efstathiou and collision simulations with gas (Barnes & Hernquist 1991). The differences in the surface brightness distributions for galaxies with and without close neighbors, seen in Figure 5, provides strong evidence that interactions can reorganize the luminous matter in galaxies. Even without such jostling, the Ryden (1988) models show that more massive systems (with parts that form earlier with less angular momentum) have more significant dissipationally
IG. 13.—Rotation curve decompositions. Examples of the three distinct classes of disk galaxies are presented in each of the vertical groups. On the left is UGC 6973, a system with an HSB exponential disk and a central bulge. In the middle is NGC 3949, a system with an HSB disk but no appreciable bulge. On the right is NGC 3917, a system with an LSB disk and no bulge. In each case, the horizontal axes are the position in kiloparsecs. In the top and bottom panels the origin with respect to the nucleus is at the left axis, while in the middle panels the origin with respect to the nucleus is at the center of the plots. Surface brightnesses at $I$, corrected for inclination, are shown in the top panels. Images at $B$ are shown in the second row. The major axes are indicated, as well as the FWHM beam of the $\text{H}\ I$ observations. The velocity-position decomposition of the $\text{H}\ I$ observations is seen in the panels of the third row. Velocities averaged over annuli are given as dots. The rotation curve decompositions are provided in the bottom panels. The solid lines with error bars illustrate the observed rotation curves. Dot-dashed curves illustrate the amplitude of rotation expected from the observed distributions of light and $M/L_0.4$ at $K$. The dotted curves illustrate the contribution expected from the gas component. The dashed curves demonstrate the residual contribution attributed to a dark matter halo. Isothermal spheres are used in this modeling.

dominant cores. The dissipational collapse of disks was discussed by Fall & Efstathiou (1980), and we can mention the contribution by Shaya & Tully (1984).

Two stable radial configurations have been identified. In massive systems with a significant component of low angular momentum material, the dissipational matter will collapse to form a dynamically important disk that rotates with a velocity tied to the requirements of the dark halo. In dwarf systems the dissipational material does not collapse enough to dominate the dark halo even near the center. Now consider the intermediate regime. The evidence from the Ursa Major Cluster sample is that galaxies opt for one of the two aforementioned stable configurations rather than find some state in between. There is a 2–3 mag domain between giants and dwarfs where the galaxies have a choice. It is seen from Figure 9 that, proceeding from bright galaxies to faint, the number of HSBs drops and the number of LSBs picks up. The evolutionary path followed by a specific intermediate-size galaxy must depend either on the amount of angular momentum it acquired as a protocloud or on the degree of trauma of its birth and during its lifetime. Systems that retain lots of angular momentum hang up as LSB gal-
axles. Systems that never had much angular momentum or, probably more relevant, those that transfer angular momentum outward collapse to the HSB state.

The focus has been on the distinction between LSB and HSB families. There is the second transition between systems that are exponential disks to their cores and systems with central bulges. Both varieties have disks that obey Freeman’s law. Densities do not want to exceed the mandated threshold in a rotating disk. If there is low angular momentum material that would cause an excess, then it finds its way into a bulge.

What we have been presenting at first blush seems to contradict the “universal rotation curve” idea of Persic, Salucci, & Stel (1996). How can our three discrete states be reconciled with their continuum of rotation properties as a function of total luminosity? The apparent contradiction at the state transition between bulge/no-bulge can be disregarded because Persic et al. make the disclaimer that their “universal rotation curve” may not apply at small radii in cases of bulges. As for the state transition between HSB and LSB, it depends on how one looks at the data. In Figure 13 it is seen that HSB and LSB systems have very distinct metric radial distributions because the LSB types are much more extended. However, the rotation curves are only different in a subtle way if the radial scale is normalized by either exponential scale length or optical radius as Persic et al. do. The exponential HSB NGC 3949 reaches $V_\text{disk}^{\text{max}}$ at $\sim 2.1 r_d$, located by the little arrow in the bottom panel of Figure 13. The LSB NGC 3917 reaches $V_\text{obs}^{\text{max}}$ somewhat farther out than this photometric scale length located by the arrow. It will take a large sample of high-quality velocity fields to confirm if the rotation curves are continuing to rise at $\sim 2.1 r_d$ in LSB types while they tend to have peaked by this radius in HSB systems of the corresponding luminosity. Since the HSB and LSB types overlap in luminosity, it can be understood how the very small differences in normalized curves get averaged and result in a smoothly continuous “universal rotation curve.”

It is important to recall the point made by Zwaan et al. (1995), however. The masses and $M/L$ measures are functions of the metric radii. Hence, although the scale length-normalized rotation curves of an HSB-LSB pair of a given luminosity might be almost indistinguishable, $(M/L)_{\text{HSB}} > (M/L)_{\text{LSB}}$ within the optical domains. In the case of the HSB galaxies, it was seen in Figure 13 that model velocities $V_\text{disk}^{\text{max}}$ approaching $V_\text{obs}^{\text{max}}$ can be associated with the light and $M/L$ values characteristic of star ensembles. By contrast, for LSB systems the velocities $V_\text{disk}^{\text{max}}$ associated with stars and gas fall far short of $V_\text{max}$ (see also de Blok & McGaugh 1996, 1997). Qualitatively, $V_\text{max}$ is given by the following relationship:

$$\left(\frac{V_\text{disk}}{L}\right)^2 \sim \frac{(M/L)}{r_d}.$$  (8)

In an HSB system, $r_d$ for a given $L$ is small, and the required $M/L$ to give $V_\text{disk}^{\text{max}} \approx V_\text{obs}^{\text{max}}$ is reasonable. In an LSB system with the same $L$ and $V_\text{obs}^{\text{max}} r_d$ there is a larger $r_d$ and the required $M/L$ ratio to give $V_\text{disk}^{\text{max}} \approx V_\text{max}$ is unreasonably large for a stellar system. If anything, the blue LSBs can be expected to have lower stellar $M/L$ values than redder HSBs.

Note that Persic et al. (1996) are arguing as we do that low-luminosity galaxies have much more important dark halo contributions within the optical domain than is the case with high-luminosity galaxies. The difference is that

they see the transformation with luminosity as a continuum, while we think there is a discrete transition involved. Our point of view receives some support from information in the literature. As in Figure 13, disk-bulge decompositions of well-established rotation curves lead to models in which either the disk component substantially dominates the halo interior to $\sim 2 r_d$ or the disk component is at best comparable to the halo at the center. We are unaware of a well-established case in which the disk is only modestly dominant at the center.

8. LINKAGE BETWEEN PHOTOMETRIC AND KINEMATIC PROPERTIES

A direct linkage can be established between the surface brightness bimodality and a dynamical bimodality. The luminosity–line width fits given by the lines in Figure 10 translate to relationships between rotation velocities, surface brightnesses, and scale lengths given equation (3) and our assumed distance to the sample of 15.5 Mpc. At $K'$ band,

$$\log W_k/2 = 3.555 - 0.112 \mu K^{-1/4} + 0.561 \log r_d.$$  (9)

Here, $W_k/2$ approximates $V_\text{obs}^{\text{max}}$ and, to be precise, this relation is based on the double regression to the data in Figure 10 rather than the single regression with errors in $W_k$ that we use for distance measurements. At the same time, the peak rotation velocity that arises out of an exponential disk is given by

$$V_\text{max} = 8.60 \times 10^4 \sqrt{10^{-0.4 \mu K^{-1/4} r_d} M/L K'},$$  (10)

or in the logarithmic form,

$$\log V_\text{max} = 4.934 - 0.2 \mu K^{-1/4} + 0.5 \log r_d + 0.5 \log M/L K',$$  (11)

where $V_\text{max}$ in km s$^{-1}$ is the peak rotation velocity at $2 r_d$ for an exponential disk, in the units of Figures 1, 3, and 11 at our assumed distance. The coefficient of equation (10) is $3.14 \times 10^3$ if the units of $r_d$ are kiloparsecs. Combining these equations,

$$\log (V_\text{max}/0.5 W_k) = 1.579 - 0.0878 \mu K^{-1/4} - 0.0610 \log r_d + 0.5 \log M/L K'.$$  (12)

Suppose that a fixed value of $M/L K'$ is assumed. The maximum disk fits illustrated in Figure 13 suggest $M/L K' = 0.4 M_\odot/L_\odot$. Then a choice of $V_\text{max}/0.5 W_k$ translates to an almost horizontal line in Figure 11. The solid line illustrates $V_\text{max}/0.5 W_k = \frac{1}{2}$ and the dashed line illustrates $V_\text{max}/0.5 W_k = \frac{1}{3}$. The lines would be exactly horizontal if the coefficient for the term in $\log r_d$ in equation (9) were 0.5, which would arise if $L K' \sim (W_k)^{0.5}$. Instead, the double regression of the $K'$ panel of Figure 10 gives $L K' \sim (W_k)^{0.4}$. These lines make graphic the point first discussed by Aaronson, Huchra, & Mould (1979): the relation $L \sim (W_k)^{0.4}$ is explained if $\mu_0$ and $M/L$ are constants for disk galaxies and $V_\text{obs}^{\text{max}} \sim V_\text{disk}^{\text{max}}$.

Equation (12) tells us that the bimodality in $\mu_0$ implies a bimodality in either $V_\text{max}/0.5 W_k$ or stellar $M/L$. A bimodality in $M/L$ is unlikely since it would require that, at all bands from $B$ to $K'$, the stellar $M/L$ is greater for LSB galaxies although these systems are known to have pro-
portionately younger populations than HSB galaxies. It is much more probable that the bimodality is in \( \frac{V_{\text{disk}}}{0.5 W_i} \).

Accepting the simplifying assumption that \( M/L = \) constant (specifically, 0.4 \( M_\odot/L_\odot \) at \( K \)), then any location in the \( \mu_0, r_d \) plane corresponds to a determinate value of \( \frac{V_{\text{disk}}}{0.5 W_i} \) from equation (12). Figure 14 is the histogram of all such values for the isolated fraction of our sample (those with no significant neighbors within 80 kpc in projection). Except for the weak dependence on \( r_d \) identified in equation (12), Figure 14 is essentially a rescaling of the middle \( K^\prime \) panel of Figure 5.

The rotation curve decompositions of Figure 13 help with the interpretation of this rescaling of the bimodality phenomenon. With the HSB cases, \( V_{\text{disk}} \) is a substantial fraction of \( \frac{V_{\text{obs}}}{V_{\text{max}}} \). Halo components contribute, but the disk components are dominant inside 2\( r_d \). For example, with NGC 3949 the decomposition gives \( \frac{V_{\text{disk}}}{V_{\text{obs}}} = 0.68 \). By contrast, in the LSB case, NGC 3917, \( \frac{V_{\text{disk}}}{V_{\text{obs}}} = 0.39 \). It can be seen in Figures 10 and 11 that NGC 3917 is one of the most luminous LSBs and at the HSB limit of the LSB family. Yet even in this case, the dark halo potential dominates the disk at all radii. Hence, the bimodal distribution in Figure 14 can be given a dynamical interpretation. The galaxies in the peak about \( \frac{V_{\text{max}}}{0.5 W_i} = 0.73 \) have self-gravitating disks with rotation in response to the luminous matter at \( r \leq 2r_d \). The galaxies in the peak about \( \frac{V_{\text{max}}}{0.5 W_i} = 0.42 \) have dynamically insignificant disks in dominant dark halos. These two dynamical classes have direct correspondences with the photometric HSB and LSB classes, respectively.

A qualitative story has been presented. More detailed velocity field data are required to go further and, of course, more quantitative modeling. There is the usual disclaimer that we have assumed Newtonian gravity is valid in this regime, for if not, then the discussion of this section is built on a boguernz premise (Milgrom 1983; Sanders 1984; Mannheim 1993). Still, the bimodal surface brightness observations have to be explained.

9. SUMMARY

There is suggestive evidence that galaxies avoid a region of parameter space between high central surface brightness and low central surface brightness domains. The statistics provided by the present sample are insufficient to make the case compelling; however, it will be straightforward to check our claim with larger controlled data sets. Since we are predicting a minimum between two distributions, any experimental criteria that includes both the HSB and LSB regimes should properly sample the intermediate zone. The case for bimodality of surface brightnesses is strongest for galaxies without near (<80 kpc) neighbors.

We argue that the luminosity function for the HSB family cuts off at the faint end. Again, our results have some uncertainty because the cutoff is close to our completion boundary. It will be easy to design an experiment that goes 1 mag deeper and checks this claim.

There is the curiosity that galaxies of a given luminosity, whether of HSB or LSB, have little dispersion in the profile width. Yet the light of HSB and LSB galaxies is distributed so differently that it would be surprising if the rotation curves of these classes were not correspondingly different. Preliminary evidence is presented that suggests that the exponential HSB class have rotation curves that peak by about 2\( r_d \), as anticipated for dynamically important exponential disks, while there is evidence that the LSB class has rotation curves that continue to rise beyond this radius. In the LSB types it appears that reasonable stellar \( M/L \) values produce inner rotation velocities that rise closer to \( V_{\text{obs}} \) while for LSB types velocities associated with reasonable models of the disk components fall considerably short of \( V_{\text{obs}} \).

The dichotomy between HSB and LSB types implies to us that there are two basic control conditions: (1) maximum rotation is mandated by the dark halo, and (2) there is a fixed fraction of precollapse dissipational material that is preserved to give the observed luminosity. The latter point is at odds with the idea that the LSB class is the result of gas loss during an early starburst phase, but it is the obvious explanation of the tightness of luminosity–line width relations. The HSB and LSB types of a given luminosity would live in similar halos and have the same amount of dissipational material. However, the LSB types are in rotational equilibrium in potentials dominated by the dark halos at all radii, while the HSB types have either transferred angular momentum away from much of their gas or were born with low specific angular momentum and have secularly evolved to stable states with dynamically important disks. Although in our model HSB and LSB types of a given luminosity have the same total dissipational and dark halo masses, the HSB cases have lower measured \( M/L \) ratios because the light is more confined within the dark halo; i.e., a smaller fraction of the total halo is within the domain of the observed rotation curve.

While the emphasis has been on the distinction between HSB and LSB families, attention has been drawn to another transition between “exponential HSB” and “bulge HSB” families. Freeman’s law is obeyed in both cases. Evidently, disks are forbidden from rising in central density above this threshold. Low angular momentum matter that would broach this limit is shunted into a bulge. The bulges have a clear manifestation in the rotation curves. Velocities approach maximum values much closer to the centers than
the radius of about 2.1r_e characteristic of the peak for self-gravitating exponential disks. There could be said to be the maintenance of the flat rotation curve “conspiracy.”

It is pointless to go too far with speculation in the absence of much detailed rotation curve information, but the potential importance of these results should be given attention. Only discrete radial gradients of matter are stable for disk systems since, unlike in spherical systems, a particle in orbit at a given radius feels the net gravity of mass at larger radii. Galaxies must arrange themselves into one of these discrete states. Evidently, galaxies of intermediate mass have a choice.

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