A NORMAL STELLAR DISK IN THE GALAXY MALIN 1

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ABSTRACT

Since its discovery, Malin 1 has been considered the prototype and most extreme example of the class of giant low surface brightness disk galaxies. Examination of an archival Hubble Space Telescope I-band image reveals that Malin 1 contains a normal stellar disk that was not previously recognized, having a central I-band surface brightness of $\mu_i = 20.1$ mag arcsec$^{-2}$ and a scale length of 4.8 kpc. Out to a radius of $\sim 10$ kpc, the structure of Malin 1 is that of a typical SB0/a galaxy. The remarkably extended, faint outer structure detected out to $r \approx 100$ kpc appears to be a photometrically distinct component and not a simple extension of the inner disk. In terms of its disk scale length and central surface brightness, Malin 1 was originally found to be a very remote outlier relative to all other known disk galaxies. The presence of a disk of normal size and surface brightness in Malin 1 suggests that such extreme outliers in disk properties probably do not exist, but underscores the importance of the extended outer disk regions for a full understanding of the structure and formation of spiral galaxies.

Key words: galaxies: individual (Malin 1) — galaxies: spiral — galaxies: structure

1. INTRODUCTION

The galaxy Malin 1 has remained a singularly unusual and puzzling object for nearly two decades. As described in the discovery paper by Bothun et al. (1987) and in later work by Impey & Bothun (1989), it has the largest radial extent of any known spiral galaxy, with low surface brightness emission extending out to $\sim 100$ kpc, and its disk was found to have an extrapolated central surface brightness of only $\mu_0(V) \approx 25.5$ mag arcsec$^{-2}$, far fainter than any galaxy previously known. The exponential scale length of this disk was determined to be $\sim 70$ kpc. Despite the faint surface brightness of its disk, Malin 1 is a massive galaxy with a total optical luminosity of $M_V = -22.9$ mag (Pickering et al. 1997). Based on these properties, it has been considered the prototypical giant low surface brightness (LSB) galaxy. Even in comparison with other giant LSB galaxies discovered subsequently (Bothun et al. 1990; Sprayberry et al. 1993, 1995; Beijersbergen et al. 1999), the properties of Malin 1 are unusual; no other galaxy disk has been found with a surface brightness and scale length that approach these extreme values. Furthermore, it is one of the most gas-rich galaxies known, with an H I mass of $\sim 5 \times 10^{10} M_\odot$ (Pickering et al. 1997; Matthews et al. 2001). The H rotation curve measured by Pickering et al. (1997) reaches an asymptotic value of $v_c = 190$ km s$^{-1}$ and extends to radii as large as 110 kpc from the galaxy center, implying a dynamical mass of order $10^{12} M_\odot$, although the disk inclination is uncertain and the velocity structure shows some warping and noncircular motions.

The implications of this object for understanding the overall population of disk galaxies are significant. As emphasized by Bothun et al. (1997), galaxies like Malin 1 would likely be underrepresented in magnitude-limited galaxy surveys because of surface brightness selection effects. Even if such extreme giant LSB galaxies are rare, which appears to be the case (e.g., Minchin et al. 2004), the properties of Malin 1 pose interesting challenges to theories of galaxy formation. Models of disk formation in cold dark matter halos are not easily able to reproduce the properties of such enormously extended disks, although scenarios have been proposed that might account for the formation of Malin 1–type galaxies as rare density peaks in voids (Hoffman et al. 1992) or by secular evolution and radial mixing in ordinary disk galaxies (Noguchi 2001). As the most diffuse and gas-rich giant LSB galaxy known, Malin 1 is also a particularly interesting laboratory for understanding issues of disk stability and thresholds for the onset of star formation (Impey & Bothun 1989).

This paper presents a reexamination of an archival Hubble Space Telescope (HST) image of Malin 1, which reveals that the galaxy’s optical morphology is rather different from what had previously been determined based on ground-based imaging. It is shown that Malin 1 actually contains a fairly normal stellar disk typical of an early-type barred spiral, and that based on the presence of this disk Malin 1 does not satisfy the standard criteria for being classified as an LSB galaxy despite its having the most extended LSB outer regions of any known disk galaxy. This is not merely a semantic distinction, as this new observation significantly truncates the range of parameter space (in terms of central surface brightness and scale length) populated by real galaxy disks by removing an extremely aberrant data point from the observed galaxy population. A new optical spectrum of the galaxy is also used to derive its bulge velocity dispersion and to reexamine the classification of its active nucleus.

Malin 1 has a redshift of 0.0825 (Pickering et al. 1997), corresponding to a luminosity distance of $D_L = 370$ Mpc and a projected angular scale of 1.53 kpc arcsec$^{-1}$ for a cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$. For consistency, observed quantities taken from the literature and listed in this paper have been rescaled to this cosmology.

2. ARCHIVAL DATA AND OBSERVATIONS

Images of Malin 1 were obtained with the WFPC2 as part of the HST program GO-5946 (principal investigator: C. D. Impey) on 1996 March 10. The galaxy was observed for one orbit each in the F330W (U band) and F814W (I band) filters, with the galaxy placed on the WF3 CCD near the center of the full WFPC2 field of view. Each orbit was split into four individual exposures for removal of cosmic-ray hits. The F330W exposures were read out with $2 \times 2$ pixel binning on the CCD, while the F814W images

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1 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the Data Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
were read out in the standard unbinned mode. Total exposure times were 2100 s in each filter. This data set was previously analyzed by O’Neil et al. (2000), who studied the properties of faint galaxies in the same WFPC2 field as Malin 1, but they did not discuss the structure of Malin 1 itself.

The images were retrieved from the HST data archive, and individual exposures were combined using standard tasks in IRAF STSDAS. Figure 1 shows a portion of the F814W WFPC2 mosaic centered on Malin 1. An image of the entire WFPC2 mosaic is shown by O’Neil et al. (2000). If the full HST image is viewed with extremely high contrast, some of the very low surface brightness outer spiral structure can just barely be seen at radii of up to 100 kpc from the galaxy center, and the faint spiral features match the structures visible in Figure 2 of Bothun et al. (1987). However, the signal-to-noise ratio (S/N) in the WFPC2 image at these large radii is too low to perform useful measurements of the surface brightness of the outer disk. The F300W image also has very low S/N and is not discussed further in this paper.

A new optical spectrum of Malin 1 was obtained at the Keck II telescope on 2005 May 16 UT with the ESI spectrograph (Sheinis et al. 2002). The exposure time was 1800 s with a 0.75” wide slit, yielding a spectrum with \( R \approx 6000 \) over the range 3800–10000 Å and S/N \( \approx 20 \) pixel\(^{-1}\) in the continuum at 5100 Å. The slit was oriented at the parallactic angle for the midpoint of the observation. Spectral extraction was done using a 1” width, and the extracted echelle orders were wavelength-calibrated using observations of HgNe, Xe, and CuAr lamps and flux-calibrated using an observation of the standard star BD +28 4211. The 10 individual echelle orders were combined into a single spectrum, weighted by the S/N in the overlap regions between orders. Several K-giant stars were also observed on the same night during twilight for use as velocity templates.

3. MEASUREMENTS AND RESULTS

3.1. Imaging

The WFPC2 image clearly reveals the morphology of Malin 1 at small angular scales where previous ground-based images were unable to discern the details of its structure. The galaxy is seen to have a compact bulge dominating the light profile out to \( r \approx 1” \), a bar of length \( \sim 6” \), and a nearly face-on disk with a hint of spiral structure that can be traced out to \( \sim 6”–7” \). The disk morphology appears smooth, and there are no obvious dust lanes, knots, or star-forming complexes. Apart from the remarkable but nearly invisible outer LSB structure, Malin 1 has the morphology of an SB0/a galaxy.

To decompose the galaxy’s structure into its subcomponents, model fits to the WFPC2 image were performed using the two-dimensional fitting package GALFIT (Peng et al. 2002). The components used in the model fit included an exponential disk, a Sérsic-law bulge, and a bar. Since GALFIT does not include bar models such as a Freeman (1966) bar or a flat bar (Prieto et al. 1997), the bar component was modeled using a Sérsic profile with the index \( n \) constrained to be \( \leq 0.5 \) to approximate a bar with a flat core, and with this constraint the bar has \( n = 0.5 \) in the best-fitting model. In addition, a central point-source component was added to allow for the possibility of unresolved emission from the active nucleus. The point-spread function for the F814W filter was generated using the TinyTim software package (Krist 1993).

Figure 2 shows the results of the GALFIT modeling. The structure of the galaxy is reproduced well overall, although there are systematic residuals around the bulge and inner bar region. These residuals could be reduced somewhat if the constraint on the...
Sérsic index of the bar were relaxed, at the expense of having an unrealistic bar profile with a very centrally peaked structure. However, whether the bar profile is constrained or not in the fit has almost no effect on the central surface brightness or scale length of the disk component, since the disk parameters are mainly determined from the region around $r = 4'' - 6''$, where it dominates the galaxy profile.

Figure 3 shows the galaxy’s radial profile as measured from the WFPC2 image and from the GALFIT model. The radial profiles were measured using the IRAF task ellipse, which fits elliptical isophotes to the image at a series of fixed semimajor axis lengths, following the methods described by Jedrzejewski (1987). Conversion from HST F814W filter magnitudes to standard Cousins I-band Vega-based magnitudes was done using the SYNPHOT package in IRAF, assuming an S0-type spectrum from the spectral atlas of Kinney et al. (1996). The brightness profiles include a correction for Galactic extinction ($A_I = 0.067$ mag; Schlegel et al. 1998), a $K$-correction of 0.08 mag for the I band, determined using the Kinney et al. (1996) S0 template spectrum, and a correction for cosmological surface brightness dimming of 0.34 mag. Brightness profiles derived from 0.2'' wide slices along the major and minor axes of the bar are shown in Figure 4. Aside from small deviations in the disk due to the spiral arms, the major and minor axis brightness profiles are very symmetric about the nucleus.

Another issue to consider is the effect of inclination on the disk surface brightness. One simple method that is commonly used to correct for inclination is to apply the relation $\mu_{\text{corr}} = \mu_{\text{obs}} - 2.5C \log (a/b)$, where $a$ and $b$ are the major and minor axis lengths of the disk and $C$ is a parameter whose value ranges from 0 for an optically thick disk to 1 for the optically thin case (de Jong 1996; Seigar & James 1998). From the GALFIT decomposition, the disk axis ratio $b/a$ is 0.858, consistent with the mean ellipticity of $\varepsilon = 1 - (b/a) = 0.14$ measured by the ellipse routine over the disk-dominated region from $r = 4''$ to $6''$. This corresponds to a surface brightness correction of $-0.17$ mag in the optically thin case. Given the approximate nature of this method and the small magnitude of the correction, we choose not to apply this correction to the measured quantities, but we consider it a minor effect that would tend to increase the central surface brightness by a small amount.

The structural parameters derived from the GALFIT modeling are listed in Table 1. While the formal fitting uncertainties from GALFIT are negligibly small, the actual uncertainties on the derived model parameters are predominantly systematic due to real deviations of the galaxy components from the simple fitting functions used by GALFIT and are therefore difficult to estimate. Trial GALFIT runs with slightly different fitting models (i.e., without constraints on the bar Sérsic index $n$ or without including a point-source component) yielded magnitude differences of order $\sim 0.2$ mag for the bulge and bar components relative to the best-fit model listed in Table 1, which gives some indication of the likely systematic uncertainties in the decomposition.

**TABLE 1**

**Structural Properties of Malin 1**

| Parameter               | Value       |
|-------------------------|-------------|
| Bulge $r_e$             | 0.6 kpc     |
| Bulge Sérsic index $n$  | 1.24        |
| Bulge $I$ magnitude     | 17.0 mag    |
| Bar $I$ magnitude       | 17.6 mag    |
| Point source $I$ magnitude | 20.6 mag |
| Disk $\mu_0(I)$         | 20.1 mag arcsec$^{-2}$ |
| Disk scale length $h$   | 4.8 kpc     |
| Bulge velocity dispersion | 196 $\pm$ 15 km s$^{-1}$ |

**Notes.**—The properties listed here are determined from the GALFIT decomposition of the WFPC2 image and from the Keck spectrum. The magnitudes listed above include a correction for Galactic extinction of 0.067 mag. In addition, a $K$-correction of 0.08 mag and a correction for cosmological surface brightness dimming have been applied to the value of the disk central surface brightness $\mu_0(I)$. 

**Fig. 3.**—$I$-band surface brightness profile for the inner region of Malin 1 (crosses), measured with the IRAF ellipse task. Model components are the central point source (dot-dashed curve), bulge (dotted curve), bar (short-dashed curve), and disk (long-dashed curve), with the total galaxy model plotted as a solid line. The bottom panel displays the ellipticity profile for the galaxy and for the GALFIT model.

**Fig. 4.**—Surface brightness cuts along the major (top) and minor (bottom) axes of the bar. Crosses represent the measured surface brightness averaged over a 2 pixel wide extraction through the image. Model components are the central point source (dot-dashed curve), bulge (dotted curve), bar (short-dashed curve), and disk (long-dashed curve), with the total galaxy model plotted as a solid line.
Figure 5.—Best fit of a broadened K-giant template star, HD 92068 (K0 III), to the spectrum of Malin 1.

3.2. Spectroscopy

As previously shown by Impey & Bothun (1989), the bulge spectrum is consistent with a predominantly old stellar population. The stellar velocity dispersion of the bulge was measured from the Keck spectrum by direct fitting of broadened and diluted stellar spectra in the wavelength domain, following the methods described by Barth et al. (2002). The fit was performed over the rest wavelength range 5210–5480 Å, which contains Fe λ5270 and several other reasonably strong features. The Mg b lines were excluded from the fit since the galaxy spectrum has a lower Fe/α abundance ratio than typical nearby K-giant stars, as is generally found for high-dispersion galaxies. Weak [N II] λ5200 emission appears to be present as well. Fits were performed using nine template stars with spectral types between G8 III and K3 III. The best fit was found with a K0 star, giving σ = 196 ± 15 km s\(^{-1}\), where the final uncertainty is the sum in quadrature of the fitting uncertainty from the best-fitting template (10 km s\(^{-1}\)) and the standard deviation of the results from fitting all nine templates (11 km s\(^{-1}\)). Figure 5 shows the fit of the broadened KO star to the spectrum of Malin 1 over this region.

The velocity dispersion fitting code was also used to generate starlight-subtracted spectra in the regions surrounding the Hβ and Hα emission lines. Using the best-fitting K-type stellar template and allowing for a featureless continuum dilution yielded an adequate continuum subtraction over these regions, giving a pure emission-line spectrum (Fig. 6).

Reddening-corrected emission-line flux ratios measured from the nuclear spectrum are [O II] λ3727/O III λ5007 = 3.1, [O III] λ5007/Hβ = 1.9, [O I] λ6300/Hα = 0.3, and [N II] λ6584/Hα = 0.85. These measurements are consistent with a LINER classification (Heckman 1980; Ho et al. 1997a). Impey & Bothun (1989) had previously found [O III]/Hβ = 4.8 and classified Malin 1 as a high-excitation Seyfert galaxy; presumably this resulted from not having performed a starlight subtraction and therefore missing most of the Hβ flux. Approximately 30% of S0–Sa galaxies contain LINER nuclei (Ho et al. 1997b), so Malin 1 is not unusual in exhibiting this type of activity. There is at best weak evidence for a broad component to the Hα emission line. Model fits including three Gaussian components for the three narrow emission lines are somewhat improved by the addition of a broad component (having a best-fitting width of FWHM = 2010 ± 80 km s\(^{-1}\)), but the relatively low S/N of the spectrum precludes any definitive conclusions regarding the possible presence of a broad-line component.

4. DISCUSSION

The measurements described above indicate a very different structure for Malin 1 than that which has previously been found. Bothun et al. (1987) fitted the galaxy profile with a model consisting of an r\(^{1/4}\) law bulge and an exponential disk, and determined that the bulge had r\(_e\) = 2.9′′ ± 0.5′′, which corresponds to 4.4 kpc for the cosmology assumed in this paper. Pickering et al. (1997) found similar results from newer ground-based imaging data. The HST image shows that the bulge radius is smaller than this value by nearly an order of magnitude, and it seems likely that the bulge region described by Bothun et al. (1987) was actually the combined light from the bulge, bar, and normal disk of the galaxy. Since the surface brightness of the disk within several arcseconds of the nucleus is much fainter than the surface brightness of the bulge or bar, it is not surprising that it would be difficult to recognize the disk in ground-based imaging of average seeing. Interestingly, Bothun et al. (1987) note that the nucleus “appears to be surrounded by extended nebulosity of somewhat high surface brightness.” In retrospect, this “nebulosity” must have been starlight from the disk itself.

Recent work by Aguerri et al. (2005) on the I-band photometric properties of SB0 galaxies provides an ideal comparison sample to examine the structure of Malin 1 in the context of galaxies of similar Hubble type. Based on a sample of 14 nearby galaxies, they found that SB0 galaxies generally have nearly exponential bulge profiles with n = 1.48 ± 0.16 and r\(_e\) in the range 0.3–1.0 kpc, with a mean of 0.6 kpc, so Malin 1’s bulge properties are typical for its Hubble type. With a bulge absolute magnitude of M\(_I\) = −20.9 mag and σ = 196 km s\(^{-1}\), Malin 1 also
falls within the normal range of SB0 galaxies in the Faber-Jackson relation (see Fig. 5 of Aguerri et al. 2005).

The disk of Malin 1 also has properties similar to the SB0 sample. Figure 7 plots the central $I$-band surface brightness against disk scale length. While Malin 1 falls toward the lower end of the sample in terms of its surface brightness, it is still consistent with the normal range for this Hubble type. The only aspect of Malin 1’s structure that appears different from the SB0 sample is the ratio of bulge to disk radius. Aguerri et al. (2005) find a surprisingly tight coupling with $r_e/h = 0.20 \pm 0.01$ for their sample, while Malin 1 has $r_e/h = 0.13$. A portion of this difference could be the result of the different bar model adopted for the GALFIT analysis, however, since Aguerri et al. (2005) used Freeman bar or flat bar models in their one-dimensional radial profile fits, and different assumptions for the bar profile will directly affect the flux inferred to arise from the outer part of the bulge. In any case, a bulge-to-disk scale length ratio of 0.13 is well within the normal range for low or high surface brightness spiral galaxies of a range of Hubble types (de Jong 1996; Seigar & James 1998; Beijersbergen et al. 1999). Overall, these results indicate that out to $r \approx 10$ kpc, the optical structure of Malin 1 does not deviate very significantly from the general population of early-type barred galaxies.

The LSB structure at large radii appears to be a photometrically distinct component of the galaxy’s structure rather than a smooth extension of the normal inner disk. For a disk scale length of 4.8 kpc, the extrapolated surface brightness of the inner disk at $r = 50''$ (equivalent to $\sim 75$ kpc) would be undetectably faint: 36.1 mag arcsec$^{-2}$ in the $B$ band, which is far fainter than the actual outer disk brightness of $\mu_B \approx 27$ mag arcsec$^{-2}$ at this radius (Bothun et al. 1987). There may be a break in the exponential light profile of the disk at radii greater than $\sim 7''$, but deeper images would be needed to trace the surface brightness profile in the transition region between the inner disk and the extended outer disk.

Given the presence of this newly identified disk in Malin 1, should it still be considered an LSB galaxy? LSB galaxies are generally classified as such based on the extrapolated central surface brightness of their disk components. A crucial point is that the LSB classification applies only to the disk component. Giant LSB disk galaxies have high surface brightness bulges that dominate the light of the central regions (e.g., Sprayberry et al. 1995). Thus, the total light profiles of giant LSB galaxies apparently always have high surface brightness central regions, and a radial profile decomposition is required in order to determine whether a galaxy should be classified as having a giant LSB disk or not. Clearly, to perform such classifications in a meaningful way, observations with sufficient spatial resolution to decompose the bulge and inner disk components accurately are required.

While there is perhaps no universal agreement on the surface brightness threshold for a galaxy disk to be considered an LSB disk, a common criterion is a central surface brightness fainter than $\mu_B = 23.0$ mag arcsec$^{-2}$ (Impey & Bothun 1997). As noted by Bothun et al. (1997), a galaxy with a central surface brightness fainter than this level would represent a $>4\sigma$ deviation from the distribution of surface brightness found by Freeman (1970) and would therefore be a very unusual outlier if the actual distribution of disk surface brightnesses were described by Freeman’s law. To compare the disk properties of Malin 1 with this criterion, the $B$ magnitude of the Malin 1 disk was estimated by performing synthetic photometry on the $S0$ template spectrum from Kinney et al. (1996). The $(B - I)$ color index for this spectrum is 2.2 mag. Assuming this $(B - I)$ color for the disk of Malin 1, it has an estimated $\mu_B(B) = 22.3$ mag arcsec$^{-2}$, which would not qualify it as an LSB disk. In the classification system of McGaugh (1996) Malin 1 would have an “intermediate surface brightness” disk.

Another related criterion that has been applied to distinguish low and high surface brightness galaxies is a “diffuseness index” for the disk, which combines central surface brightness and scale length into a single parameter. The diffuseness index criterion given by Sprayberry et al. (1995) is $\mu_B(0) + 5 \log(h) > 27.0$ for a galaxy to be classified as a giant LSB disk. Based on the GALFIT results and the assumed $(B - I)$ color index of 2.2 mag, the disk in Malin 1 has $\mu_B(0) + 5 \log(h) = 25.0$, which lies well inside the high surface brightness range for this parameter. Thus, based on either central surface brightness or diffuseness, the disk of Malin 1 out to $r \approx 10$ kpc should not be considered an LSB disk according to conventional criteria.

Malin 1 still might be considered an LSB galaxy based on the average surface brightness over its entire disk area, however. According to Pickering et al. (1997) the galaxy’s total luminosity is $M_V = -22.9 \pm 0.4$ mag. The $HST$ measurements yield $M_V = -22.4$ mag for the combined bulge, bar, and normal disk components. Assuming $(V - I) = 1.3$ mag for an $S0$ galaxy as determined from SYNPHOT, this corresponds to $M_V = -21.1$ mag. Thus, the comparison between the $HST$ and ground-based measurements indicates that the majority of the galaxy’s total optical luminosity lies in the extended disk region beyond the normal disk. It would be useful to confirm this result with new ground-based imaging data and a single-profile decomposition over the entire radial range of the galaxy; the $HST$ image could be used to exclude background galaxies and improve the measurement accuracy for the outer disk brightness profile.

In comparison with all other known disk galaxies, Malin 1 has always appeared as a unique and distant outlier in plots of central surface brightness against disk scale length (see, e.g., Bothun et al. 1987, 1997; Sprayberry et al. 1995; Dalcanton et al. 1997; van den Bosch 1998). The previously measured disk scale length and central

\[\text{Fig. 7.—}I\text{-band central surface brightness vs. scale length for disk components in SB0 galaxies. Open squares are from Aguerri et al. (2005). Malin 1 is represented by a cross.}\]
surface brightness \[ h \approx 70 \text{kpc}; \mu_0(V) = 25.5 \text{mag arcsec}^{-2} \] from Bothun et al. (1987) are far outside the ranges found for normal spirals or even for other giant LSB galaxies. In the giant LSB sample of Sprayberry et al. (1995), for example, the disk scale lengths range from 5 to 13 kpc, and the faintest disk has \[ \mu_0(0) = 24.2 \text{mag arcsec}^{-2} \]. Clearly, however, when the normal disk of Malin 1 is compared with the disk properties of other galaxies in these diagrams, it is no longer an outlier. It might be argued that the extended outer structure in Malin 1 still has the form of a disk with a very low extrapolated central surface brightness and large scale length, and that this extended disk remains an outlier relative to all other known galaxies. However, it seems more reasonable and consistent to compare the normal, central disk of Malin 1 with those of other galaxies, and to consider its extended outer disk in the context of the extreme outer disks of other nearby spiral galaxies, which sometimes display structures similar to (albeit less extended than) that of Malin 1.

Recent work has revealed a great deal of detail and a diversity of properties among the extreme outer disk regions of some nearby spiral galaxies. Deep narrowband observations of some late-type spirals have detected \([\text{H} \alpha]\) regions far beyond the galaxies’ optical radii (Ferguson et al. 1998b; Lelièvre & Roy 2000), and Galaxy Evolution Explorer observations of the nearby spiral M83 have detected UV-bright stars in the outer disk at distances of greater than 20 kpc from the galaxy center (Thilker et al. 2005). In these examples, the regions of recent star formation have filamentary, spiral-like structures with an appearance similar to the outer disk regions of Malin 1. Ferguson et al. (1998a) noted that the distant outer regions of spiral disks have physical properties (such as low column densities of gas and high gas-to-stellar mass ratios) that are very similar to the inferred properties of Malin 1. It is now apparent that this similarity is not merely a coincidence; the parameters previously found for Malin 1 were precisely those of its extreme outer disk region. Extended outer disk structure has recently been found out to \( r \approx 40 \text{kpc} \) in M31 as well (Ferguson et al. 2002; Ibata et al. 2005), but in the case of M31 the extended outer structure appears to be a smooth continuation of the exponential profile of the main disk, in contrast to the photometrically decoupled outer structure of Malin 1. The stellar disk of the late-type spiral NGC 300 also follows a single exponential profile from its inner regions to the outer disk at distances up to 10 scale lengths (Bland-Hawthorn et al. 2005).

New observations of early-type barred galaxies have revealed surprising outer disk structures as well. Erwin et al. (2005) have found that at least 25\% of SB0–SBB galaxies have photometric profiles characterized by an outer exponential disk component with a larger scale length than the inner, main disk component. The transition from the inner to outer disk occurs at three to six scale lengths of the inner disk and at surface brightnesses of \( 22.6 \)–25.6 mag arcsec\(^{-2}\), and spiral structure is often seen in the outer disk region. Erwin et al. call such structures “antitruncated” disks. Malin 1 appears to fit within this category, although deeper images would be needed to determine the structure of the transition region between the inner and outer disks.

Simulations by Peñarrubia et al. (2006) have explored one possible mechanism that could form such highly extended outer disks, by the tidal shredding of dwarf galaxies in the outskirts of an M31-sized galaxy. With an initial apocenter of \( r = 75 \text{kpc} \), the dwarf satellites were tidally distorted into extended disks having spiral-like filamentary structure, extending to over 100 kpc from the center of the larger galaxy. The tidal debris tends to evolve into a nearly exponential profile, with scale lengths of up to 50 kpc, depending on the compactness of the original stellar distribution in the dwarf galaxy.

Could other giant LSB galaxies possess inner, high surface brightness disks that have gone undetected? Several of the other known giant LSB galaxies lie at distances comparable to that of Malin 1 (e.g., Sprayberry et al. 1995), and inadequate spatial resolution could cause a normal disk to be missed in a bulge-disk decomposition. This would be a natural pitfall of fitting a simple two-component model to a galaxy with a bright central region (including a bulge and disk) and a very diffuse and extended outer disk that was brighter than a simple extension of the inner disk profile at large radii. The outer disk would dominate the fit at large radii and therefore determine the scale length and central surface brightness of the exponential disk component in the fit, and the inner, high surface brightness disk, if present, would be subsumed in the outer part of the bulge profile. Deep, high-resolution imaging of a representative sample of giant LSB galaxies would be useful to clarify the nature of these objects.

5. CONCLUSIONS

The stellar disk of Malin 1 has long been thought to be an extreme and distant outlier compared to the disk properties of all other known spiral galaxies. The archival HST data demonstrate that the central structure of Malin 1 is that of a normal early-type barred spiral galaxy, and the central surface brightness of its disk is \( \sim 4 \text{mag brighter than the value originally found by Bothun et al. (1987). Thus, it seems reasonable to consider Malin 1 not as an LSB galaxy but rather as a galaxy with the normal structural components of an early-type barred spiral, which is embedded in a remarkably extended, optically faint, and gas-rich outer structure beyond its normal disk.}

Bothun et al. (1997) remark that giant LSB galaxies such as Malin 1 are “truly enigmatic in that ‘normal’ formation processes were at work to create the bulge component but no conspicuous stellar disk ever formed around this bulge.” Malin 1 is perhaps a somewhat less enigmatic galaxy once its normal disk has been recognized.

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