GALAXIES WITH SPIRAL STRUCTURE UP TO $z \approx 0.87$: LIMITS ON $M/L$ AND THE STELLAR VELOCITY DISPERSION

A. C. Quillen and V. L. Sarajedini

Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721;
aquillen@as.arizona.edu, vicki@as.arizona.edu

Received 1997 June 4; revised 1997 December 30

ABSTRACT

We consider seven distant galaxies with clearly evident spiral structure from Hubble Space Telescope images. We place upper limits on their mass-to-light ratios ($M/L$) by computing $M/L_\text{B}$ for a maximal disk. We find that these galaxies have maximal-disk mass-to-light ratios $M/L_\text{B} = 1.5-3.5$ ($M/L_\text{B}$) at the low end, but within the range seen in nearby galaxies. The mass-to-light ratios are low enough to suggest that the galaxies contain a young, rapidly formed stellar population. By using a Toomre stability criterion for formation of spiral structure, we place constraints on the ratio of $M/L$ to the stellar velocity dispersion. If these galaxies have maximal disks, they would have to be nearly unstable so as to have small enough velocity dispersions that their disks are not unrealistically thick. This suggests that either a fraction of the light originates from a component of stars in a thick disk or bulge not strongly affected by the spiral structure, or there is a substantial amount of dark matter present in the luminous regions of the galaxy.

Key words: galaxies: evolution — galaxies: kinematics and dynamics — galaxies: spiral

1. INTRODUCTION

The Hubble Space Telescope (HST) has observed distant galaxies with sufficient angular resolution to reveal morphologies of galaxies on kiloparsec scales. Some galaxies at moderate redshift (up to $z \sim 1$) show spiral structure similar to nearby galaxies. Recent spectroscopic studies such as those of Rix et al. (1997) and Vogt et al. (1996, 1997) have measured disk rotational velocities for these galaxies, allowing initial comparisons of the velocity-luminosity relations (Tully-Fisher) between distant and local galaxies. In this paper, we use the existence of spiral structure evident from the HST images, coupled with values estimated for their disk rotational velocities, to constrain the properties of their disks. Optical or UV rest-frame images are ideally suited for study of spiral structure at high redshift because spiral structure is expected to be more prominent in the bluer bands.

If we assume that the spiral structure that we observe is due to spiral density waves, then the disk must be sufficiently responsive or unstable to form these waves. In other words, the Toomre Q-parameter (see Binney & Tremaine 1987), which depends both on the disk mass-to-light ratio ($M/L$) and the velocity dispersion of the disk, is expected to be confined to the fairly narrow range $1 < Q < 2$. A disk with $Q < 1$ is violently unstable, and a disk with $Q > 2$ has such a high velocity dispersion that spiral density waves should not be observed. Stellar velocity dispersion measurements of nearby galaxies are consistent with these stellar disks being close to this instability range (Bottema 1993). With the above inequality for $Q$, we place limits on the ratio $M/L$ and the stellar velocity dispersion for the distant galaxies where HST reveals spiral structure. We compare this product with the mass-to-light ratio required for a "maximal disk." This ratio determines the most massive disk that could be present within the constraint set by the rotation curve. We assume that the disk in these galaxies has a mass-to-light ratio that does not vary with radius.

2. GALAXIES CHOSEN

We consider five galaxies from Sarajedini et al. (1997, hereafter SGGR; also studied in Sarajedini et al. 1996) observed in the Medium Deep Survey (Griffiths et al. 1994; Ratnatunga, Griffiths, & Ostrander 1997). These galaxies were chosen because of their clearly evident, prominent, nearly bisymmetric spiral structure seen in the HST Wide Field Planetary Camera 2 images observed in the F814W ($I_{814}$) filter and displayed in Figure 1. For these galaxies, the bulk of the light is from an exponential disk with contributions of less than a few percent from a bright unresolved nuclear component (SGGR).

We also consider three galaxies displayed and studied in Vogt et al. (1996, hereafter VFP), observed as part of the Deep Extragalactic Evolutionary Probe (DEEP) project (Koo et al. 1995). These galaxies were also chosen because of their clearly evident, prominent, nearly bisymmetric spiral structure seen in the HST images. Their rotational velocities were measured spectroscopically by these same authors. We did not choose galaxies from the sub-$L^*$ sample of Vogt et al. (1997) because none of these galaxies had obvious spiral structure. All galaxies chosen are brighter than $I^*$ ($M_B \sim -20.4$). One galaxy (denoted as 0309-00115 in VFP) is found in both samples (=uem00-4 in SGGR). We list this galaxy twice in all our tables so as to maintain consistency between the measured quantities.

Observed galaxy and disk parameters for these galaxies are listed in Table 1. The surface brightness profile assumed by VFP and SGGR was that of an exponential disk, with exponential scale length denoted here by $h$. Derived rest-frame properties are listed in Table 2. Rest-wavelength $B$-band central surface brightnesses, $S_B(r = 0)$, and absolute magnitudes were computed using $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.50$ and 0.05, a cosmological constant of zero, and an internal extinction correction based on the galaxy inclination from Rubin et al. (1985). Rest-frame magnitudes were computed with a code provided by C. Gronwall that fits...
redshifted model galaxy spectral energy distributions to the observed $V-I$ color. By computing rest-frame magnitudes in the $B$ band from the observed $V$- and $I$-band magnitudes, we have attempted to minimize errors in the $K$-correction for the highly redshifted galaxies. The central surface brightness is computed from the galaxy luminosity using $S(r = 0) = L/2\pi h^2$; this is accurate when the disk component dominates.

Values for the circular velocity, $v_{TF}$, predicted from the Tully-Fisher relation are listed in Table 3. We computed $v_{TF}$ from the $B$-band rest-frame absolute magnitudes with the local ($z = 0$) $B$-band Tully-Fisher relation of Pierce & Tully (1992). As found by Vogt et al. (1997), the differences between the circular velocities predicted from the local Tully-Fisher relation and those observed for high-redshift galaxies are not extremely large ($\lesssim 1$ mag), though these three galaxies have lower magnitudes than expected from the local Tully-Fisher relation.

The physical scale lengths of the galaxies are similar to that of the Milky Way ($h \sim 3$ kpc; see summary in Sackett 1997). Their rotational velocities (observed or predicted by the Tully-Fisher relation) range from Milky Way--sized ($\sim 200$ km s$^{-1}$) to, in one case, $\sim 350$ km s$^{-1}$. However, their absolute magnitudes are somewhat brighter than those of the Milky Way. For comparison, the Milky Way disk has a $B$-band luminosity of $M_B \sim -19.9$ and a disk central surface brightness of $S_B \sim 20.8$ mag arcsec$^{-2}$ (based on that estimated in the $V$ band from van der Kruit 1986 and Binney & Tremaine 1987, and colors typical of an Sc galaxy; de Jong 1996).

3. "MAXIMAL DISK" MASS-TO-LIGHT RATIO

If the galaxy disk contributes most of the mass in the central few scale lengths (meaning that the dark halo contribution is negligible), then we can say that the galaxy has a "maximal disk." Here we estimate the disk mass-to-light ratios of these galaxies assuming that they have "maximal disks." We assume here that the disk mass-to-light ratio is constant (does not vary with radius). An exponential disk has a maximum circular velocity at a radius $r = 2.2h$ of

$$v_{\text{max}} \approx 0.6 \sqrt{\frac{GM}{h}} = 0.6 \sqrt{\frac{GL(M/L)}{h}},$$

(1)

where $L$ is the total luminosity of the disk and $M/L$ is its mass-to-light ratio. If the disk is "maximal," then the rotation curve reaches a maximum near $r = 2.2h$ and has approximately the circular velocity given by the above equation. From a prediction or observation of the circular velocity, we can invert this equation to determine a "maximal disk" mass-to-light ratio given the disk scale length and absolute magnitude of the galaxy.

For the VFP galaxies, we use the observed rotational velocities to compute "maximal disk" values for the mass-to-light ratio. These values are listed in Table 3 along with maximum disk masses derived from them. However, rotational velocities have not been observed for the SGGK galaxies. To compute the maximal-disk $M/L$ we can use rotational velocities predicted from the Tully-Fisher relation; however, we must do this cautiously since there is some uncertainty in the offset of the Tully-Fisher relation at high redshift.

We estimate errors in the "maximal disk" mass-to-light ratio by considering the uncertainty in the Tully-Fisher
### Table 1: Galaxy Parameters

| Galaxy (1)          | z    | h (arcsec) | m_I (mag) | V_f - I (mag) | i (deg) | v_{obs} (km s^{-1}) |
|---------------------|------|------------|-----------|---------------|---------|---------------------|
| ua400-8             | 0.431 | 0.56       | 19.89     | 0.83          | 56      | ...                 |
| uem00-4             | 0.477 | 0.97       | 18.61     | 1.18          | 44      | ...                 |
| ukg00-1             | 1.05  | 1.05       | 18.12     | 0.76          | 60      | ...                 |
| uko01-25            | 0.593 | 0.62       | 20.29     | 0.62          | 36      | ...                 |
| uui00-3             | 0.222 | 0.64       | 18.40     | 0.81          | 31      | ...                 |
| 074 − 2237          | 0.1535 | 1.33   | 17.93     | 0.77         | 80      | 200 \pm 15^15       |
| 0305 − 00115        | 0.4761 | 0.97   | 19.10     | 1.18         | 46      | 215 \pm 40^15       |
| 064 − 4442          | 0.8770 | 0.46    | 22.07     | 0.99         | 60      | 200 \pm 40^15       |

Notes.—The top five galaxies are from SGGG (see also Ratnatunga et al. 1997), the bottom three from VFP. Note that 0305 − 00115 and uem00-4 are the same galaxy. Columns: (1) galaxy identification number; (2) redshift; (3) disk exponential scale length (for the SGGG galaxies this was estimated from the half-light radius); (4) I_d, I_c-band observed magnitude (error \~0.1 after correction for Galactic extinction); (5) observed V − I color (error \~0.15 mag) — here V is the HST F606W filter (mean 5939.6 Å and equivalent width 1500.0 Å) and I is the F814W filter (mean 7877.5 Å and equivalent width 1459.0 Å); (6) galaxy inclination from the I_d, I_c images, cos i = b/a (error \~10'); (7) spectroscopically observed circular velocity from VFP.

### Table 2: Derived Properties

| Galaxy (1) | h (kpc) | A^I (mag) | M_d (mag) | S_{I}(r = 0_d) | (B − V)_0 | (V − I)_0 |
|------------|---------|-----------|-----------|----------------|-----------|-----------|
| ua400-8    | 2.76    | 2.50      | 0.48      | -20.93         | -20.74    | 19.83     | 0.41      | 0.86      |
| uem00-4    | 5.03    | 4.52      | 0.37      | -22.07         | 21.84     | 20.00     | 0.65      | 1.11      |
| ukg00-1    | 3.90    | 3.67      | 0.56      | -21.50         | 21.36     | 20.02     | 0.47      | 0.92      |
| uko01-25   | 3.57    | 3.13      | 0.17      | -21.12         | -21.83    | 20.21     | 0.17      | 0.61      |
| uuu03-3    | 2.04    | 1.94      | 0.13      | -20.22         | -20.11    | 19.90     | 0.54      | 1.02      |
| 074 − 2237 | 3.19    | 3.08      | 1.00      | -20.75         | -20.67    | 20.34     | 0.51      | 0.99      |
| 0305 − 00115| 5.02  | 4.51      | 0.37      | -22.07         | -21.84    | 20.00     | 0.65      | 1.11      |
| 064 − 4442 | 3.11    | 2.57      | 0.53      | -20.77         | -20.35    | 20.26     | 0.17      | 0.61      |

Notes.—The top five galaxies are from SGGG, the bottom three from VFP. Note that 0305 − 00115 and uem00-4 are the same galaxy. Columns: (1) galaxy identification number; (2) exponential scale length for q_0 = 0.05 and 0.50, respectively; (3) internal brightness; (4) rest-frame I-band absolute magnitude predicted using C. Gronwall’s code and the observed V − I for q_0 = 0.05 and 0.50, respectively; (5) rest-frame B-band disk central surface brightness; (6) rest-frame B − V and V − I colors predicted by C. Gronwall’s code.

### Table 3: Dynamical Properties

| Galaxy (1) | v_{TF} (km s^{-1}) | M_{max}/L_d (M/L_d) | M_{disk} (10^{11} M_{☉}) | Q_{a} [(M/L_d) km s^{-1}] |
|------------|---------------------|---------------------|--------------------------|---------------------------|
| ua400-8    | 242                 | 228                 | 2.8                      | 2.7                       | 1.0 | 0.8                | 0.048 | 0.049 |
| uem00-4    | 343                 | 320                 | 3.6                      | 3.4                       | 3.8 | 3.0                | 0.043 | 0.045 |
| ukg00-1    | 288                 | 276                 | 3.3                      | 3.2                       | 2.1 | 1.8                | 0.048 | 0.049 |
| uko01-25   | 256                 | 234                 | 3.4                      | 3.2                       | 1.5 | 1.1                | 0.055 | 0.058 |
| uuu03-3    | 194                 | 188                 | 2.5                      | 2.5                       | 0.5 | 0.4                | 0.055 | 0.056 |
| 074 − 2237 | 229                 | 223                 | 2.6                      | 2.7                       | 0.8 | 0.8                | 0.054 | 0.056 |
| 0305 − 00115| 343              | 320                 | 1.4                      | 1.5                       | 1.5 | 1.3                | 0.027 | 0.030 |
| 064 − 4442 | 230                 | 202                 | 2.5                      | 3.0                       | 0.8 | 0.7                | 0.052 | 0.063 |

Notes.—The top five galaxies are from SGGG, the bottom three from VFP. Note that 0305 − 00115 and uem00-4 are the same galaxy. Columns: (1) galaxy identification number; (2) circular velocity predicted using the B-band Tully-Fisher relation (Pierce & Tully 1992) and the absolute magnitudes listed in Table 2, for q_0 = 0.05 and 0.50, respectively; (4, 5) B-band mass-to-light ratio for a maximal disk computed using eq. (1), for q_0 = 0.05 and 0.50, respectively (disk parameters used are listed in Table 2); (6, 7) maximum disk masses using M_d listed in Table 2 and M/L_d for a maximal disk, for q_0 = 0.05 and 0.50, respectively; (8, 9) Q_{a} = Q(M/L_d)/σ computed using disk parameters listed in Table 2, at a radius of r = 2.2h (see eq. [3]), for q_0 = 0.05 and 0.50, respectively. Maximal-disk mass-to-light ratios (cols. [4], [5]) and Q_{a} (cols. [8], [9]) were computed for the five galaxies from SGGG using the circular velocity predicted from the local Tully-Fisher relation. For the three VFP galaxies, the spectroscopically measured circular velocity (see Table 1) was used. For the SGGG galaxies an offset of 1 mag in the Tully-Fisher relation results in a decrease in the value for v_{TF} and Q_{a} by a factor of 0.77 and a maximal-disk mass-to-light ratio that is 0.58 times that shown here.
relation for distant galaxies. Recent comparisons of the Tully-Fisher relation between local and distant galaxies find mean offsets of less than 0.4 mag (Vogt et al. 1997) and 1.5 mag (Rix et al. 1997) (at B band), such that distant galaxies of a given magnitude have lower velocities than nearby ones (z = 0). Vogt et al. (1997) also see a typical scatter of ~ 1 mag for observed galaxies about the local Tully-Fisher relation. We compute that an offset of 1 mag in the Tully-Fisher relation results in a decrease in our value for $v_T(r)$ by a factor of 0.77 and a resulting maximal-disk mass-to-light ratio that is 0.58 times that computed from the local Tully-Fisher relation (shown in Table 3). The maximal-disk $M/L$ depends on the square of the rotational velocity. Another comparison can be made by computing the maximal-disk $M/L$ for the VFP galaxies by using velocities predicted from the Tully-Fisher relation (using Pierce & Tully 1992) instead of those observed. We compute $M/L_B = 3.4, 3.6$, and 3.3 for 074–2237, 0305–00115, and 064–4442, respectively, using $v_{TF}$ derived from the local Tully-Fisher relation and $q_0 = 0.05$. These ratios are somewhat higher than those computed from the observed velocities. If the Tully-Fisher relation for distant galaxies is indeed offset from the local (z = 0) relation, then the maximal-disk mass-to-light ratios computed using the offset relation would be lower than those listed in Table 3 for the SGGR galaxies. This would make the SGGR mass-to-light ratios more consistent with the mean of the VFP galaxies.

We find that for the galaxies considered here “maximal disk” mass-to-light ratios are low; for the SGGR galaxies $M/L_B = 2.5–3.6$ ($M/L_B$) (solar units) using the local Tully-Fisher relation and $M/L_B = 1.4–2.1$ using a Tully-Fisher relation offset by 1 mag. The ratios for the VFP galaxies are similar, with $M/L_B = 1.4–3.0$. These mass-to-light ratios represent maximum values for the disk $M/L$, since if it is higher than this, the circular velocity would be higher than either that observed (for the VFP galaxies) or that predicted from the Tully-Fisher relation (for the SGGR galaxies).

Maximal-disk mass-to-light ratios for nearby galaxies lie in the range 1 ($M/L_0$) $\lesssim M/L_0 \lesssim 7$ ($M/L_0$) (Sackett 1997; Begeman 1987; Broeils & Courteau 1997; Kent 1986, 1987). Using colors typical of Sc galaxies (de Jong 1996), this range is equivalent to 2 ($M/L_b$) $\lesssim M/L_b \lesssim 15$ ($M/L_b$). Therefore, the distant galaxies studied here have mass-to-light ratios that lie at the low end of the range of “maximal disk” values estimated for the Milky Way and for nearby galaxies. The ratios of these distant galaxies are low enough as to be typical of stellar systems that have undergone a rapid episode of star formation (see, e.g., Kennicutt, Tamlyn, & Congdon 1984). The maximum disk masses (computed from the maximal-disk $M/L$‘s and listed in Table 3) are not significantly different from that estimated for the Milky Way (~ 6 x 10$^{10}$ $M_\odot$; Sackett 1997), which has a similar rotational velocity.

Since our galaxies cover a range of inclinations (see Table 1) yet have remarkably similar “maximal disk” mass-to-light ratios, it is unlikely that large errors are caused by the correction for internal extinction (listed in Table 2).

4. DISK STABILITY

The Toomre parameter describing local disk stability is given by

$$Q \equiv \frac{\kappa \sigma}{3.36 \Sigma}$$

where $\kappa$ is the epicyclic frequency, $\sigma$ is the stellar velocity dispersion, and $\Sigma$ is the disk mass surface density, $\Sigma = S(M/L)$ for $S$ the disk surface brightness.

Using the approximation $\kappa \sim v_c \sqrt{2/r}$ for the circular velocity $v_c$, which is exact in the case of a flat rotation curve, and an exponential disk described by a central surface brightness $S_c$ and a scale length $h$ ($S(r) = S_c \exp(-r/h)$), we can compute the quantity we denote $Q_a$ (an adjusted $Q$):

$$Q_a = \frac{Q M/L}{\sigma} = \frac{v_c \sqrt{2}}{3.36 \Sigma h S_c \exp(-r/h)}$$

where we have grouped the unknowns on the left-hand side (here we assume that $v_c$ is either observed or well estimated).

In the images (see Fig. 1 and VFP), we observe that the spiral structure extends a few scale lengths for all galaxies. We therefore compute $Q_a$ at $r = 2.2h$, where the rotation curve is expected to reach a maximum and be nearly flat. This radius is also roughly equivalent to that of the solar neighborhood with respect to the Milky Way’s scale length (Sackett 1997), and so we can compare the solar neighborhood’s stellar velocity dispersion with that predicted using the above inequality, given $M/L$ for the galaxies considered here. In Table 3, we list values computed for $Q_a$ using the observed circular velocities for the VFP galaxies and the circular velocities predicted from the local Tully-Fisher relation for the SGGR galaxies. We compute $Q_a$ using $M/L_B$ in solar units. Once again, we must consider the possible offset in the Tully-Fisher relation for distant galaxies. $Q_a \propto v_c$, so an offset of 1 mag in the Tully-Fisher relation results in a decrease in $v_T$, and a resulting decrease in $Q_a$ by a factor of 0.77 for the SGGR galaxies.

Since $Q$ should lie in the range $1 < Q < 2$, we can construct the inequality

$$\frac{1}{Q_a} < \frac{\sigma}{M/L} < \frac{2}{Q_a}$$

Using this inequality, we ask what value of $M/L$ results in a range for $\sigma$ similar to that observed in the solar neighborhood. For the SGGR galaxies and 0074–2237 and 064–4442, with $Q_a(r = 2.2h) \sim 0.05$ ($M/L_b$) km$^{-1}$ s$^{-1}$, a value of $M/L_b \sim 1.0$ (0.8) ($M/L_b$) is required for the local Tully-Fisher relation (and that offset by 1 mag, respectively) applied to the SGGR galaxies for 20 km s$^{-1}$ $< \sigma < 40$ km s$^{-1}$, which would be consistent with the stellar velocity dispersion in the solar neighborhood. The radial velocity dispersion at the solar neighborhood in the Galactic plane is $\sim 30$ km s$^{-1}$ (Wielen 1977). For 0305–00115, which has $Q_a(r = 2.2h) \sim 0.027$ ($M/L_b$) km$^{-1}$ s$^{-1}$, a somewhat lower $M/L_b = 0.5$ ($M/L_b$) is required to yield the same range for the velocity dispersion.

For comparison, using values for the Milky Way from the range discussed in Sackett (1997), $v_c = 200$ km s$^{-1}$, $M_B = -19.9$ mag, and $h = 2.7$ kpc, we find $M/L_B$ (maximal disk) = 4.8 ($M/L_b$) and $Q_a(r = 2.2h) = 0.10$ ($M/L_b$) km$^{-1}$ s$^{-1}$. The galaxies considered here have maximal-disk mass-to-light ratios and $Q_a$ substantially lower than those of the Milky Way. A lower $M/L$ and lower dispersion than the Milky Way such as might be expected from a young, recently formed disk would be consistent with the above inequalities.
If the mass-to-light ratio is that of the maximal-disk values, ~3 (MLb)⊙, then the stellar velocity dispersions would be quite high, 60 km s⁻¹ < σ < 120 km s⁻¹ (45 km s⁻¹ < σ < 90 km s⁻¹ for the offset Tully-Fisher relation), for the SGGR galaxies, 0074–2237 and 064–4442. For 0305–00115, a maximal-disk M/L also yields a similar range for the velocity dispersion. If these disks have a vertical-to-radial velocity dispersion ratio similar to that of the Milky Way (σ/σr ~ 0.5; Mihalas & Binney 1981), then they must be nearly unstable (Q ≈ 1) so that their vertical velocity dispersions are not so high that they would be too thick to show fine features such as narrow spiral arms (hydrostatic equilibrium requires σ/σr ~ h/r for h the disk thickness). One possibility is that these galaxies are "submaximal" or fall short of having "maximal disks." This would suggest that a substantial amount of dark matter is present in the luminous regions of the galaxy. Another possibility is that a fraction of the disk light originates from a thick disk stellar component that is not strongly affected by the spiral structure. In this case Qa would be an estimate for only the thin disk component showing the spiral structure, and a maximal-disk M/L could be allowed (with mass contributed from both thin and thick components). This could also be true for the Milky Way since, as emphasized by Sackett (1997), the Milky Way could have a "maximal disk."

Here we consider the role of gas in the galaxy disk. We follow Jog & Solomon (1984), who considered stability to spiral structure formation in a two-component (gas and stars) model. When the gas mass fraction is between a few percent and 10%, then, as found by Jog & Solomon (1984), the combined stellar and gas system can be unstable to spiral structure even when the more massive stellar component alone would be stable. However, this situation only arises when the stellar component is nearly unstable or has a Toomre Q-value that is within the inequality we assumed above (Q < 2).

If, on the other hand, the gas disk is a significant percentage of the disk mass, then the stability would be determined by the properties of the gas disk alone, since the gas velocity dispersion is expected to be lower than the stellar one. Then equation (4) depends on the gas mass fraction f_g ≡ Σ_g/Σ_*, (where Σ_g is the gas surface density and Σ_* is the stellar surface density) and becomes

\[ \frac{1}{Q_a} < \frac{\sigma_g}{(M/L) f_g} < \frac{2}{Q_a}, \]

where σ_g is the gas velocity dispersion. Using this relation, our value of Q_a = 0.05 (MLb)_⊙ km⁻¹ s⁻¹ for most of the galaxies, and a typical gas velocity dispersion of 10 km s⁻¹ yields 0.5 (MLb)_⊙ > f_g (MLb) > 0.25 (MLb)_⊙, requiring both low gas densities and rather low mass-to-light ratios. This appears to contradict our assumption (in this paragraph) that the gas disk is a significant percentage of the disk mass.

5. SUMMARY AND DISCUSSION

In this paper we concentrate on seven distant galaxies with evidence of spiral structure in their HST images. We compute maximal-disk mass-to-light ratios based on observed rotational velocities for the three VFP galaxies and based on those predicted from the Tully Fisher for the five galaxies from SGGR. Maximal-disk mass-to-light ratios are low [MLb ~ 1.5–3.5 (MLb)_⊙] but within the range found for nearby galaxies [2 (MLb)_⊙ ≤ MLb ≤ 15 (MLb)_⊙], taking into account uncertainties in the offset of the Tully-Fisher relation for the SGGR galaxies without measured rotational velocities. The maximal-disk mass-to-light ratios are so low as to suggest that the galaxies contain a young, rapidly formed stellar population. The disk masses computed from the maximal-disk M/L's are similar to that of the Milky Way.

Based on the observed spiral structure, we compute a quantity Q_a derived from the Toomre stability parameter Q, which depends on the ratio of M/L to the stellar velocity dispersion. Q_a can be constrained since a disk showing spiral structure should have 1 < Q < 2. For the galaxies considered here, the ratio of M/L to the velocity dispersion is lower than that observed in the Milky Way. For a value of MLb ~ 1, the velocity dispersions are similar to that observed in the solar neighborhood. However, for the maximal-disk M/L the velocity dispersions would be higher than that of the Milky Way, and unless the disk is nearly unstable (Q ~ 1), the disk would be so thick that spiral structure should not present as observed. This suggests that either a fraction of the light originates from material (such as a thick disk) not strongly affected by the spiral structure or that there is a substantial amount of dark matter present in the luminous regions of the galaxy.

In this paper we have computed some dynamical quantities for a very few galaxies. There are thousands of distant galaxies that have been observed at high spatial resolution with HST. With spectroscopic follow-up projects to measure the redshifts and rotational properties of these galaxies, it is possible to compute dynamical quantities for a well-defined galaxy sample. A substantial fraction of these galaxies also show evidence of spiral structure, so limits can also be placed on the stellar velocity dispersion (as introduced here). Detection of these galaxies in the near-infrared would shed light on the ages of these disks. For example, if these galaxies are very red, then their disks would most likely contain a larger fraction of old stars and have high mass-to-light ratios and thick disks. If high-quality spectra are observed of individual galaxies, the properties of their stellar populations, such as their mass-to-light ratios, could be constrained by population synthesis modeling and compared with values predicted from dynamical arguments. Near-infrared high angular resolution imaging (such as is possible with the HST Near-Infrared Camera and Multi-object Spectrometer) may constrain what percentage of light originates from an older thick disk.

Comparison of well-defined samples with these galaxies should constrain the process of galaxy evolution. If the galaxies studied here are similar to faint blue galaxies, then they could be more typical of later-type, more recently formed galaxies that are observed during a time of elevated star formation. However, the majority of galaxies seen in the Canada-France Redshift Survey (Hammer et al. 1997; Lilly et al. 1996) have red colors typical of star formation occurring slowly over an extended period. It would be informative to look at the morphology of galaxies selected with varying colors.

We thank the referees for many comments that have improved this paper. We thank C. Gronwall for providing us with her code that predicts rest-frame luminosities based on the observed V − I color. We acknowledge helpful discussions and correspondence with P. Sackett, C. Gronwall,
R. Kennicutt, H.-W. Rix, C. Liu, R. Green, G. Rieke, and J. Navarro. We also acknowledge support from NSF grant AST 95-29190 to M. and G. Rieke and NASA project NAG 5-3359. The Medium Deep Survey catalog is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. The Medium Deep Survey is funded by STScI grant GO-2684.

REFERENCES

Begeman, K. 1987, Ph.D. thesis, Univ. Groningen
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Bottema, R. 1993, A&A, 275, 16
Broeils, A. H., & Courteau, S. 1997, in ASP Conf. Ser. 117, Dark and Visible Matter in Galaxies, ed. M. Persic & P. Salucci (San Francisco: ASP), 74
de Jong, R. S. 1996, A&A, 313, 377
Griffiths, R. E., et al. 1994, ApJ, 437, 67
Hammer, F., et al. 1997, ApJ, 481, 49
Jog, C. H., & Solomon, P. M. 1984, ApJ, 276, 114
Kennicutt, R. C., Jr., Tamblyn, P., & Congdon, C. W. 1984, ApJ, 345, 22
Kent, S. M. 1986, AJ, 91, 1301
——— 1987, AJ, 93, 816
Koo, D. C., Vogt, N. P., Phillips, R. G., Wu, K. L., Faber, S. M., Gronwall, C., Forbes, D. A., & Illingworth, G. D. 1995, ApJ, 469, 535
Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1
Mihalas, D., & Binney, J. 1981, Galactic Astronomy (2d ed.; San Francisco: Freeman)
Pierce, M. J., & Tully, R. B. 1992, ApJ, 387, 47
Ratnatunga, K., Griffiths, R. E., & Östrender, E. J. 1997, in preparation
Rix, H.-W., Guhathakurta, P., Colless, M., & Ing, K. 1997, MNRAS, 285, 779
Rubin, V. C., Burstein, D., Ford, W. K., & Thonnard, N. 1985, ApJ, 289, 81
Sackett, P. D. 1997, ApJ, 483, 103
Sarajedini, V. L., Green, R. F., Griffiths, R. E., & Ratnatunga, K. 1996, ApJ, 471, L15
———. 1997, submitted
———. 1997, in preparation (SGGR)
von der Kruit, P. C. 1986, A&A, 157, 230
Vogt, N. P., Forbes, D. A., Phillips, A. C., Gronwall, C., Faber, S. M., Illingworth, G. D., & Koo, D. C. 1996, ApJ, 465, L15 (VFP)
Vogt, N. P., et al. 1997, ApJ, 479, L121
Wielen, R. 1977, A&A, 60, 263