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THE MILKY WAY, AN EXCEPTIONALLY QUIET GALAXY: IMPLICATIONS FOR THE FORMATION OF SPIRAL GALAXIES

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ABSTRACT

We compare both the Milky Way and M31 galaxies to local external disk galaxies within the same mass range, using their locations in the planes drawn by $V_{\rm flat}$ versus M_K (the Tully-Fisher relation), $j_{\rm disk}$ (angular momentum), and the average Fe abundance, [Fe/H], of stars in the galaxy outskirts. We find, for all relationships, that the Milky Way is systematically offset by $\sim 1\ \sigma$, showing a significant deficiency in stellar mass, angular momentum, disk radius, and [Fe/H] in the stars in its outskirts at a given $V_{\rm flat}$. On the basis of their location in the (M_K, $V_{\rm flat}$, and R_d) volume, the fraction of spirals like the Milky Way is 7% ± 1%, while M31 appears to be a "typical" spiral. Our galaxy appears to have escaped any significant merger over the last ∼10 Gyr, which may explain why it is deficient by a factor of 2–3 in stellar mass, angular momentum, and outskirt metallicity, thus unrepresentative of the typical spiral. As with M31, most local spirals show evidence of a history shaped mainly by relatively recent merging. We conclude that the standard scenario of secular evolution driven by the accretion of gas and disk instabilities is generally unable to reproduce the properties of most (if not all) spiral galaxies. However, the so-called spiral-rebuilding scenario proposed two years ago by Hammer et al. is consistent with the properties of both distant galaxies and of their descendants, the local spirals.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — galaxies: kinematics and dynamics — Galaxy: formation

Online material: color figures

1. INTRODUCTION

Disk galaxies constitute the majority of the galaxy population observed in the local universe. They represent 70% of intermediate-mass galaxies (stellar masses ranging from 3×10^{10} to $3 \times 10^{11}\ M_\odot$), which themselves include at least two-thirds of the present-day stellar mass (e.g., Hammer et al. 2005). Early studies of the Milky Way (MW) have led to a general description of the formation of a disk galaxy embedded in a halo (Eggen et al. 1962). Fall & Efstathiou (1980) set out a model of galaxy formation assuming that disks form from gas cooling and condensing in dark halos. Protogalactic disks are assumed to be made of gas containing a substantial amount of angular momentum, which condenses into stars to form thin disks (Larson 1976). These disks then evolve only through secular processes. This so-called standard model successfully reproduces the flat rotation curves and the size of spiral galaxies (e.g., Mo et al. 1998 and references therein). Such a model is (still) particularly adept at reproducing the properties of the Milky Way (e.g., Naab & Ostriker 2006 and references therein).

However, there are several outstanding difficulties with this standard scenario. One such difficulty is the so-called angular momentum problem. That is, simulated galaxies cannot reproduce the large angular momentum observed in nearby spiral galaxies (e.g., Steinmetz & Navarro 1999). Another is the assumed absence of collisions during and after the gas condensation process. Indeed, the hierarchical nature of the ΛCDM cosmology predicts that galaxies have assembled a significant fraction of their masses through collisions with other galaxies. It is likely that such collisions would easily destroy galactic disks (e.g., Toth & Ostriker 1992). Although the accretion of satellites may preserve the disk, it is also true that major collisions would certainly affect it dramatically. The key questions are then: Do major collisions always destroy disks? Can major collisions lead to the formation of new disks? Do these rebuilt or altered disks have properties consistent with those of local galaxies?

Observations of the merger rate evolution have now reached sufficient maturity to provide useful constraints on the theory of galaxy evolution. For example, considering only galaxies with masses larger than $3 \times 10^{10}\ M_\odot$, the pair fraction of galaxies over the relative mass range of 1:1 to 1:3 at $z = 0.6$ is ∼5% ± 1% (see Bell et al. 2007 and references therein). There is remarkable agreement between different methods of estimating the pair fraction. All recent estimates, no matter what the technique, for example, two-point correlation techniques (Bell et al. 2007), pair counts (Le Fèvre et al. 2000), or morphological classifiers (CAS: Conselice et al. 2003; GINI: Lotz et al. 2006), give consistent results. However, constraining the cosmological evolution of the merger rate requires us to assume a characteristic time for a real pair to actually merge. Using arguments based on either dynamical friction (Binney & Tremaine 1987) or a simple orbital timescale (e.g., Bell et al. 2007), this timescale has been estimated to be about 0.35 Gyr. Combining the pair fraction and characteristic timescale estimates suggests that for a present-day galaxy with a stellar mass larger than $3 \times 10^{10}\ M_\odot$, the chance that it has experienced a major merger since $z = 1$ is 50% ± 17%, 75% ± 25%, and 70%, according to Lotz et al. (2006), Hammer et al. (2005), and Bell et al. (2007), respectively.[1] Although less certain, integrating the merger rate to higher redshift implies that a typical bright galaxy may have experienced up to four or five major merging events since $z = 3$ (Conselice et al. 2003).

The high frequency of major mergers may be a real problem for the standard theory of disk formation. Assuming that protogalactic disks lie in the distant universe, how can this be reconciled with an absence of major collisions? How can we explain the large fraction of local disks if major mergers (with mass ratio ranging from 1:1 to 1:3) inevitably lead to the formation of

[1] The differences, although small, are probably related to disagreements about the slope of the pair fraction redshift evolution, possibly due to different approaches in correcting for the effects of evolution or not.

an elliptical galaxy? Even at $z \leq 1$ the observations are challenging for the standard scenario. At least one-third of intermediate-mass galaxies at $z = 0.4-1$ have morphologies very discrepant from that of E/S0/Sp galaxies (Brinchmann et al. 1998; van den Bergh et al. 2001; Zheng et al. 2005). A similar fraction of distant galaxies possess complex velocity fields (26%, Flores et al. 2006; Puech et al. 2006). Peculiar morphology, and even more so, complex kinematics, are almost certainly a result of ongoing or recent mergers (Puech et al. 2006; Puech et al. 2007). If those galaxies were the progenitors of present-day ellipticals, this would lead to a much larger fraction of ellipticals than is observed. Less than 10% of local intermediate-mass galaxies are ellipticals (7% of galaxies brighter than $M_B < -20$; Conselice 2006), and they formed the bulk of their stellar mass earlier, likely before $z = 1$ (see Jimenez et al. 2006; Bernardi et al. 2006).

In summary, observations of distant galaxies pose a challenge to the standard secular scenario of spiral formation and evolution. The past history of the Milky Way certainly lacks any major (and maybe even significant minor) interaction over at least the last 10 Gyr. The validity of the standard scenario is highly dependent on whether or not the Milky Way is representative of the general population of spiral galaxies. In the following, we consider several probes of the past history of galaxies and compare the properties of the Milky Way and M31 to those of other spirals selected from a complete sample of nearby galaxies. For such a purpose, we cannot use optical spectral energy distribution or colors, which can be seriously affected by instantaneous star formation and extinction. To derive unambiguously the age and the metallicity requires studies of individual stars. Such analyses are therefore limited to only two massive galaxies, the Milky Way and M31.

Galaxy dynamics (disk velocity and angular momentum) is certainly an interesting avenue for testing the history of galactic disks. The relationship between flat rotation velocity and stellar mass is very tight (e.g., Verheijen 2001) and reveals the way the stellar mass has been assembled into galactic halos (see McGaugh 2005). The disk angular momentum (as the product of the disk radius and the rotational velocity) is a relic of events (or absence of events) that have been experienced by a galaxy. It is noteworthy that the standard scenario of disk formation shows some difficulties in reproducing both relationships (Tully-Fisher and $j_{\rm disk}$-$V_{\rm flat}$). On the basis of three dynamically related parameters (i.e., $V_{\rm flat}$, M_K, used as a proxy of the stellar mass, and R_d), one may determine whether the Milky Way (and M31) is representative or not of the general population of spiral galaxies.

Few studies have brought the question of the representativeness of the Milky Way to the attention of the astrophysical community. Flynn et al. (2006) showed that the Milky Way lies at 1 σ from the Tully-Fisher relations of Verheijen (2001) and Pizagno et al. (2005). This conclusion needs to be firmly established, first because the two relations taken as references show different slopes and zero points and second because *I*-band luminosity may not be accurate enough to robustly estimate the stellar mass. More surprising is the fact that the stellar content of the outskirts of the Galaxy[2] is apparently different (in its stellar chemical abundances and colors) from other spiral galaxies (Mouhcine et al. 2006; Zibetti et al. 2004). In the following, we attempt to establish a Tully-Fisher relation for local spirals that is consistent for all data sets, discuss the representativeness of M31 and the MW compared to local spiral galaxies, and, as a result of these discussions, try to understand which scenario may apply to the entire ensemble of spiral galaxies.

The paper is organized as follows. In § 2, we describe the properties of the Milky Way and M31 as if they were observed at larger distances; in § 3, we concentrate on establishing a homogenized Tully-Fisher relation in (M_K-$V_{\rm flat}$) that reconciles results from the SDSS (Pizagno et al. 2006) with those from Courteau (1997) and Verheijen (2001); in § 4, we estimate on the basis of their positions in the (M_K, $V_{\rm flat}$, and R_d) volume how the Milky Way and M31 are representative of local spiral galaxies; in § 5, we discuss the general evidence that the Milky Way has had a "quiet" merging history; and finally, in § 6, we compare the relative merits of the two disk formation scenarios (the standard scenario, in which disk evolution is driven mainly by secular processes, and another, in which disk evolution is mainly driven by mergers of galaxies) in reproducing the characteristics of spiral galaxies. In this paper we adopt the Concordance cosmological parameters of $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. MILKY WAY AND M31 PROPERTIES FOR COMPARISON TO THOSE OF OTHER FIELD SPIRALS

2.1. *Disk Scale Length R_d and Angular Momentum*

Measurements of the Galactic disk scale length have lead to heterogeneous results since the early 1990s. The difficulty in making such estimates probably results from the fact that the Earth lies within the Galactic disk. Studies of the local stellar kinematics by *Hipparcos* and determinations of the dust and stellar mass distributions from all-sky surveys (especially at IR wavelengths; see, e.g., Drimmel & Spergel 2001 and references therein) have greatly improved the estimates of the Galactic disk scale length. Sackett (1997) convincingly showed that for most studies, the determination of R_0/R_d (where R_0 is the distance to the Galactic center) is more secure observationally than that of R_d. Table 1 summarizes the results for 15 estimates made since 1990, assuming the most accurate and direct estimate of R_0 (i.e., $R_0 = 7.62 \pm 0.32$ kpc; Eisenhauer et al. 2005; see also the Appendix). As Table 1 shows, very different approaches in estimating R_d produce a remarkably narrow range of values. Thus, it now appears reasonable to derive a value for the Galactic disk scale length with an accuracy roughly similar to those derived for external galaxies. One study has, however, produced a very discrepant result. In this study, Mendez & van Altena (1998) have used low-latitude star counts from the Guide Star Catalog to derive a value of R_d that is roughly twice that of other studies. While it is beyond the scope of this paper to argue for or against the robustness of any of these results, we note that it is quite surprising that shallow IR sky surveys such as *COBE*, DIRBE, 2MASS, or DENIS (see Table 1) would find systematically low values of R_d in comparison. Given this and the relatively large quoted uncertainty in the study of Mendez & van Altena, we choose to consider the other 14 studies of Table 1 for our analysis. Even if we did include this study and take a weighted average of the ensemble of values, we note that it would make very little difference in the resulting value. In order to compare the value of R_d for the MW with measurements made in the optical (generally, *R* or *I* band) for external galaxies, we adopt $R_d = 2.3 \pm 0.6$ kpc for the Milky Way. This value is within the 1 σ uncertainty of 14 of the 15 estimates presented in Table 1. Because of possible systematic errors, we have adopted an uncertainty in the value of R_d that is twice the dispersion in the 14 estimates listed in Table 1. Because Reylé & Robin (2001) determined a similar value for the exponential scale length of the thick disk (2.5 kpc), our adopted value applies for all the components with a disk geometry in the Milky

[2] We use content of the *outskirts* to mean the stellar component that partially fills the dark halo from 5 to 30 kpc from the galaxy center (see Brown et al. 2006 and the discussion in § 5).

TABLE 1

Recent Estimates of the Milky Way Exponential Disk Scale Length

Reference	Data Set[a]	R_0/R_d	$\Delta(R_0/R_d)$	R_d[b] (kpc)	$\Delta(R_d)$[c] (kpc)
Kent et al. (1991)	2.4 μm	2.7	...	2.8	0.5
Robin et al. (1992)	0.45–0.55 μm	3.4	...	2.23	0.3
Fux & Martinet (1994)	Kinematics	3.1	0.4	2.5	0.8
Ojha et al. (1996)	0.36–0.65 μm	3.5	...	2.17	0.6
Ortiz & Lepine (1993)	*IRAS*+NIR	3	...	2.5	...
Ruphy et al. (1996)	DENIS	3.7	...	2.05	0.1
Porcel et al. (1998)	2MASS	4.0	...	1.9	0.3
Spergel et al. (1996)	DIRBE	2.86	...	2.66	...
Dehnen & Binney (1998)	Kinematics	3.22	0.2	2.36	0.1
Bienaymé (1999)	Kinematics	4.54	0.5	1.67	0.2
Gould et al. (1997)	M dwarfs	2.8	...	2.7	0.4
Mendez & van Altena (1998)	Guide Stars	1.42	0.4	5.36	2
Ng et al. (1997)	Visual	3.2	...	2.38	0.5
Chen et al. (1999)	*COBE*/*IRAS*	3.55	...	2.14	0.1
Drimmel & Spergel (2001)	*COBE*/DIRBE	3.57	...	2.13	0.1

[a] The data sets used to derive the values of R_d. If the data are from optical or near-IR imaging, we list the central wavelengths used for the determination.

[b] All values are derived using a solar radius $R_\odot = 7.62 \pm 0.32$ kpc (Eisenhauer et al. 2005).

[c] The quoted uncertainties are the maximum of the error quoted in the reference and of the error associated with the relation $R_d = R_0(R_0/R_d)^{-1}$. Note that for two studies, 5 and 8, uncertainties are not available.

Way and is probably close to what would be derived by an observer located outside the Milky Way.

For M31, we find that $R_d = 5.9 \pm 0.3$ kpc in *R* band (or 6.5 ± 0.3 kpc in *B* band), after correcting the original value in Walterbos & Kennicutt (1987) to a distance of 785 kpc (see McConnachie et al. 2005). Geehan et al. (2006) derive $R_d = 5.4$ kpc using *R*-band data from Walterbos & Kennicutt (1987) and using the same supplemental data from Kent (1983). Using *Spitzer* observations, Barmby et al. (2006) find $R_d = 6.08 \pm 0.09$ kpc. These values are unlikely to be affected by the outer, star-forming ring of M31, which is weak at red wavelengths. Moreover, Barmby et al. carefully estimated the disk scale length, excluding areas containing the outer ring and the most distant regions of the galaxy that are likely to be relatively more contaminated by emission from the sky background. Furthermore, the *Spitzer* data reach much lower relative surface brightness levels and thus extend much farther out in the galaxy light profile compared to the 2MASS data (Seigar et al. 2006). It is also likely that the latter may be affected by sky subtraction (see Barmby et al. 2006; Seigar et al. 2006). Given this situation, we adopt $R_d = 5.8 \pm 0.4$ kpc, where the adopted uncertainty accounts for the range of all the above estimates.

We adopt $V_{\rm flat} = 220$ km s^{-1} for the Milky Way (the current IAU standard; Kerr & Lynden-Bell 1986) and 226 km s^{-1} for M31 (Carignan et al. 2006), adopting a conservative uncertainty of ± 10 km s^{-1} in each value (see a detailed discussion in the Appendix). With these values, the angular momentum of M31 is 2.5 times higher than that of the Milky Way. The Milky Way has indeed a small disk scale length; at $V_{\rm flat} = 220$ km s^{-1}, galaxies in the SDSS show an average disk scale length of 4.75 kpc (Pizagno et al. 2006; see their Fig. 20), twice the Milky Way value. M31 has a disk scale length rather similar to the average value for SDSS galaxies. These comparisons are based on what are presently the best estimates of the disk scale length and velocity for both the Milky Way and M31.

We are, however, cognizant of the fact that because these estimates have shown some variations in the past, future experiments (such as *Gaia*) will provide us with much more accurate, and perhaps even discrepant, values. However, given the concordance of previously determined values, this seems unlikely. Perhaps more problematic therefore is the fact that the disk scale length for the Milky Way has been estimated using methodologies different from that used for external galaxies, including M31. Some systematic uncertainty might affect these estimates when comparing them with external galaxies such as M31. To make a definite conclusion about the robustness of these estimates certainly requires a careful analysis of the complexity of both the Milky Way and M31, which is unfortunately beyond the scope of this paper. But we note that both the Milky Way and M31 have been fully imaged by *COBE*, DIRBE, 2MASS, and DENIS for the former, and including *Spitzer* for the latter. Thus, any possible systematic effects related to the extinction are unlikely to be a significant source of bias affecting the estimates of the ratio of the disk scale lengths of MW and M31. The robustness of the estimates for the Milky Way are also supported by the excellent agreement between IR measurements and models constrained by the detailed kinematics of various galactic components (see Table 1). Critically, both types of methods provide estimates that should be representative of the underlying stellar mass distribution. The *Spitzer* observations are also the best representation of the stellar mass distribution of M31 (Barmby et al. 2006). Little doubt should therefore be left that the M31 disk has a significantly larger scale length than that of the Milky Way after comparing the Barmby et al. value for M31 ($R_d = 6.08 \pm 0.09$ kpc) to that of all-sky surveys in IR for the Milky Way ($R_d = 2.31 \pm 0.36$ kpc; see Table 1). We then assume in the following that the disk scale length of M31 is 2.5 ± 0.8 times that of the Milky Way. We note that the quoted uncertainty of 0.8 also takes into account possible systematic uncertainties in the disk scale lengths of the MW and M31.

2.2. *Total Absolute Luminosity in the K Band and Total Stellar Mass*

Motivated by a strong desire to remove the imprint of the strong Milky Way signal from the very faint cosmic microwave background (CMB) fluctuations, the *COBE* experiment has provided an accurate value for the near-IR luminosity of the Milky Way. Drimmel & Spergel (2001) derived an extinction-corrected value for the *K*-band absolute magnitude of $M_K = -24.02$. This

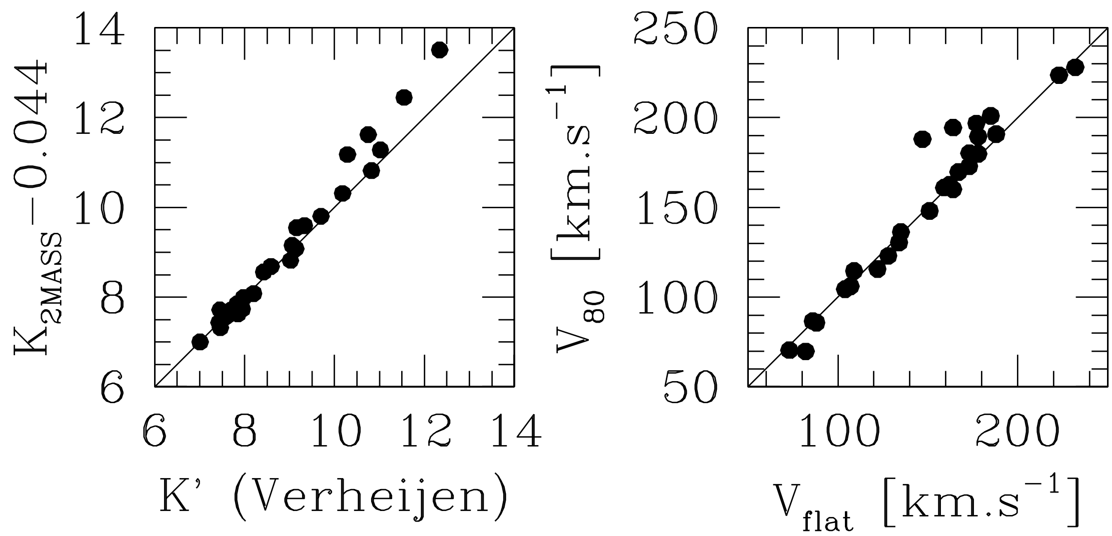

Fig. 1.—*Left*: Comparison between *K*-band magnitudes from 2MASS (corrected by 0.044 mag; see Bessel 2005) to the K' value adopted by Verheijen (2001). Although they show very good agreement for bright galaxies, the depth of the early measurements by Tully et al. (1996) overestimates the luminosity of faint objects by approximately 1 mag. *Right*: Comparison of V_{80} (rotational velocity at 80% of the total *I*-band luminosity) from Pizagno et al. (2006) with $V_{\rm flat}$ from Verheijen (2001). Values are very similar for all objects, except for five that are highly discrepant. The most discrepant object is NGC 4138, which is a Sa galaxy with $V_{80} = 187$ km s^{-1} and $V_{\rm flat} = 147$ km s^{-1}. NGC 4138 has a large bulge, and so it is likely that V_{80} is closer to $V_{\rm max}$ than is $V_{\rm flat}$. Other similarly discrepant objects show large inclinations in excess of 80°.

estimate is close to the value $M_K = -24.12$ found by Kent et al. (1991). Observations by *Spitzer* of M31 give $m(3.6\ \mu{\rm m}) = -0.34$ after sky subtraction and integrating the light profile to large distances (Barmby et al. 2006). Barmby et al. (2006) assume $K - m(3.6\ \mu{\rm m}) = 0.3$, which implies $M_K = -24.51$. This value has not been corrected for extinction; the correction is -0.188 mag after applying the formalism of Tully et al. (1998). The values of the *K*-band absolute magnitude for both the Milky Way and M31 are robust, and we adopt a conservative ± 0.1 mag for the uncertainty in each estimate.

One is able to derive the stellar mass from M_K, using an empirical estimate of the color-dependent $M_{\rm star}/L_K$ ratios (Bell et al. 2003). Using $B - V = 0.79$ (Boissier 2000) and $B - R = 1.5$ (Walterbos & Kennicutt 1987) for the Milky Way and M31, respectively, we derive $M_{\rm star} = 5 \times 10^{10}\ M_\odot$ for the Milky Way and $10.3 \times 10^{10}\ M_\odot$ for M31. We have assumed $M_{K_\odot} = 3.3$ (Bell et al. 2003) and a Kroupa initial mass function (IMF). For the Milky Way, our estimate is remarkably consistent with that of Flynn et al. (2006). For M31, our estimate is very close to the sum of the disk ($7.2 \times 10^{10}\ M_\odot$) and of the bulge ($3.2 \times 10^{10}\ M_\odot$) found by Geehan et al. (2006) and consistent with that of Barmby et al. (2006; P. Barmby 2006, private communication). Because stellar mass estimates are subject to systematic uncertainties related to the choice of the IMF and the star formation history through the adopted value of M/L_K, in the following we choose to use M_K values as the basis for making the comparison between the Milky Way, M31, and other local spirals. M_K is used as a surrogate for the total stellar mass.

3. TOWARD A HOMOGENIZED TULLY-FISHER RELATION FOR LOCAL SPIRALS

Our goal is to derive a Tully-Fisher relation for a representative sample of local galaxies. Measurements of a sample of SDSS galaxies (Hα emission line) have been recently presented by Pizagno et al. (2006), hereafter called the SDSS sample. Although more needs to be done on this type of sample, the current sample includes all types of spirals from S0 to Sd, and the only morphological preselection requirement is that the galaxies be roughly edge-on ($b/a < 0.6$). The present data are apparently representative of the local galaxy luminosity function for $M_r < -20.5$ galaxies, and the completeness of this sample as it relates to our analysis is addressed later in this section (see Fig. 1 of Pizagno et al. 2006).

Among the best-studied Tully-Fisher relation is the study made by Verheijen (2001) based on a sample of Ursa Major cluster galaxies. Verheijen (2001) was able to calculate $V_{\rm flat}$ for 28 galaxies (hereafter called the Ursa Major sample) among 38 cluster members with H I data. Verheijen mentioned that $V_{\rm flat}$ can be estimated for all galaxies except those with rising velocity curves. Interestingly, such sources are flagged "3" in the Pizagno et al. (2006) study, and so for further comparison between the two samples, we only keep flag 1 and 2 galaxies in the Pizagno et al. sample.[3] Indeed $V_{\rm flat}$ has generally been preferred to $V_{\rm max}$, because, conversely to the latter, it is not affected by the influence of the bulge on the dynamics. Verheijen (2001) found a very tight correlation between M_K and $V_{\rm flat}$ and concluded that $V_{\rm flat}$ is the best proxy for the total galaxy mass.

Using different samples often leads to different slopes and zero points in the Tully-Fisher relation. This is illustrated by Figure 16 of Flynn et al. (2006), in which the individual Tully-Fisher relations from Bell & de Jong (2001) and Pizagno et al. (2005) are compared. Note, however, that the Bell & de Jong sample was originally the Verheijen (2001) sample of galaxies for which stellar masses have also been estimated. Because SDSS and Ursa Major studies have applied the same procedure to estimate extinction corrections (the "mass-dependent extinction" method; see Tully et al. 1998), we have been motivated to understand what the causes of this difference are.

In the left panel of Figure 1, we compare the K' magnitudes from Tully et al. (1996) and 2MASS for galaxies in Ursa Major. It shows an excellent agreement between the measurements, except for objects with $K' > 10$ for which K' data overestimate the *K*-band luminosity by approximately 1 mag. Indeed, this problem was already noticed by Tully et al. (1996), who write,

[3] Pizagno et al. (2006) classify galaxies into several distinct categories based on their rotation curves. Galaxies categorized as flag-1 are those with extended flat portions in velocity with increasing radius; flag-2 are those with rotation curves just reaching the turnover region, flag-3 have rotation curves still rising at the outermost measurement, while galaxies categorized as flag-4 have velocity curves that are not characterizable as rotation curves.

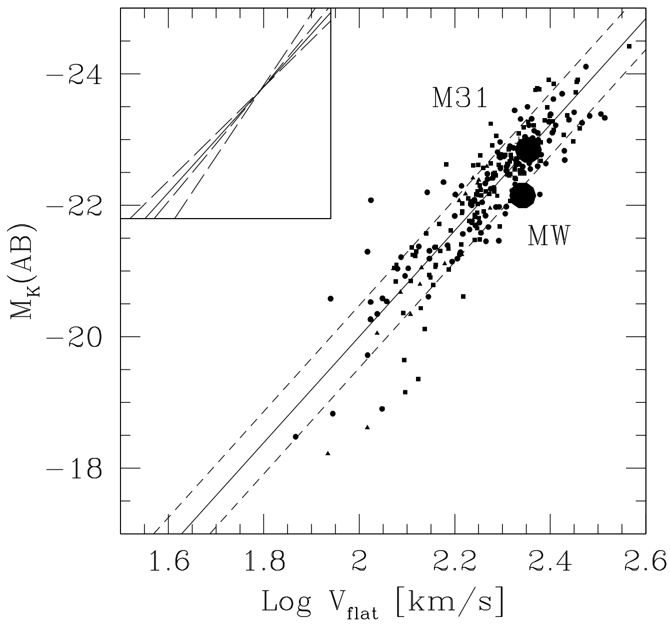

FIG. 2.—*K*-band Tully-Fisher relation for three local galaxy samples: triangles (22 points; Verheijen 2001), dots (105 points; Pizagno et al. 2006), and squares (124 points; Courteau 1997). After revising *K*-band magnitudes for the Verheijen sample (see Fig. 1), the three samples define remarkably consistent relationships. The solid line is the fit of the three samples, and the dashed lines represent the $\pm1\ \sigma$ deviation about the best-fit line (0.47 mag). This result is very close to what has been derived from the single Pizagno et al. sample. The location of the Milky Way and M31 are marked as large green dots. *Insert*: Best fit of the relation for each of the three samples: dashed line, Ursa Major; dashed line, UGC; and dashed line, SDSS, illustrating the larger slope for the Ursa Major sample (see text and Table 2). [*See the electronic edition of the Journal for a color version of this figure.*]

"From inspection of the luminosity profiles, it is seen that there is a good agreement between the various pass-bands, except that the K' material is truncated about 2 magnitudes shallower than the *B*, *R*, *I* material. It would require long exposures to reach surface brightness at K' comparable to those at optical bands." Because in the 2MASS database magnitude errors from 0.02 to 0.08 are given, we have decided to adopt *K* magnitudes from 2MASS and then compare the SDSS and Verheijen (2001) Tully-Fisher relations again.

To do so also requires a common method for estimating the rotation velocity of galaxies within the two samples. For this, we adopt the definition of $V_{\rm flat}$ as a good proxy for the total mass for the following reasons.

1. The remarkably tight baryonic Tully-Fisher relation over five decades in baryonic mass ($\sim V_{\rm flat}^4$; see McGaugh 2005). Such a tight relation must indicate that it is fundamentally a correlation between the maximum rotational velocity of the dark matter ($V_{\rm flat}$) and the total baryonic mass inside that halo (e.g., Verheijen 2001);

2. It is derived at large galactocentric radii and is thus not affected by possible nonaxisymmetric gas motions due to the presence of a bulge or a bar, as is often the case for the definition of $V_{\rm max}$.

3. The Milky Way and M31 have similar total masses[4] (see Ibata et al. 2005 and references therein) and similar $V_{\rm flat}$, but different $V_{\rm max}$. Please keep in mind, however, that the methods used to derive the total masses for both objects are different.

The right panel of Figure 1 shows that estimates of V_{80} provide a good estimate for $V_{\rm flat}$, at least for objects without large bulges that are not purely edge-on. Indeed, the estimates of V_{80} have been adopted by Pizagno et al. (2006) to derive the Tully-Fisher relation, as it generally samples the rotational velocity at the optical radius and is approximately equivalent to 3 times the disk scale length.

Figure 2 shows the Tully-Fisher relation for the two samples (Verheijen 2001; assuming the *K* magnitudes from 2MASS) and Pizagno et al. (2006) using only flag 1 and 2 galaxies. We have also superimposed the data from Courteau (1997), hereafter called the UGC sample, which includes 169 Sb–Sc UGC galaxies for which 2MASS photometry is available. For consistency, we consider only those galaxies having rotational velocities rising with radius by less than 10% of the adopted $V_{\rm flat}$, which has been assumed to be the rotational velocity at 3 times the disk scale length (e.g., similar to the V_{80} of Pizagno et al. 2006; see Fig. 1). For all galaxies, to determine the absolute *K*-band magnitude, M_K(AB) [where $M_K({\rm AB}) = M_K({\rm Vega}) + 1.87$], we adopt the *K*-band magnitude from 2MASS and a single scheme for estimating the extinction (using the mass-dependent extinction method; Tully et al. 1998). In addition, all *K*-band absolute magnitudes have been *k*-corrected by $-2.1z$ (Bell et al. 2003). The results are given in Table 2 for each of the three samples.

After our homogenization of data for the three samples, we find very good agreement between UGC and SDSS data, while the Ursa Major sample still shows a discrepant Tully-Fisher relation (Fig. 2 and Table 2). Even if the latter sample is much smaller than the other ones, this might present a significant problem for our purpose here. Figure 3 shows the distribution of M_K(AB) and log $V_{\rm flat}$ for the three samples. Examination of Figure 3 (and of Fig. 2) is illuminating: the Ursa Major sample includes fainter and

[4] With $M = 7.5^{+2.5}_{-1.3} \times 10^{11}\ M_\odot$ for M31 (on the basis of the giant stream kinematics: Ibata et al. 2004; Geehan et al. 2006; on the basis of the satellite motions: Evans & et al. 2000), and $M = (5–9) \times 10^{11}\ M_\odot$ (Battaglia et al. 2006), for the dark matter halo of the Milky Way, assuming either a Navarro, Frenk, and White or a truncated flat model, respectively.

TABLE 2

SLOPES, ZERO POINTS, AND RESIDUAL STANDARD DEVIATIONS (IN MAGNITUDE) OF THE TULLY-FISHER RELATIONS FOR THE URSA MAJOR, SDSS, AND UGC SAMPLES

Sample (1)	$N_{\rm points}$ (2)	Zero Point $\pm1\ \sigma$ Error (3)	Slope $\pm1\ \sigma$ (4)	$\sigma_{\rm res}$ (5)	$N_{\rm points}$ (6)	Zero Point $\pm1\ \sigma$ Error (7)	Slope $\pm1\ \sigma$ (8)	$\sigma_{\rm res}$ (9)
Ursa Major	22	2.37 ± 2.17	−10.86 ± 0.99	0.48	14	−13.86 ± 4.47	−3.68 ± 1.99	0.35
SDSS	105	−5.90 ± 0.78	−7.16 ± 0.34	0.47	79	−6.55 ± 1.33	−6.88 ± 0.57	0.38
UGC	124	−2.29 ± 0.93	−8.77 ± 0.41	0.44	97	−4.29 ± 1.23	−7.92 ± 0.53	0.36
All	251	−3.86 ± 0.58	−8.07 ± 0.26	0.47	190	−5.96 ± 0.87	−7.17 ± 0.37	0.38
SDSS/UGC	229	−4.50 ± 0.60	−7.79 ± 0.26	0.47	176	−5.60 ± 0.91	−7.32 ± 0.39	0.38

NOTES.—Cols. (1)–(5) give the best fit for all galaxies for which the rotation curve allows calculating $V_{\rm flat}$. Cols. (6)–(9) give the same numbers after considering only galaxies with log $V_{\rm flat} > 2.2$. Note that the SDSS and UGC samples show very similar values and that limiting the sample to the fast-rotating systems does not alter the Tully-Fisher relation for these two samples.

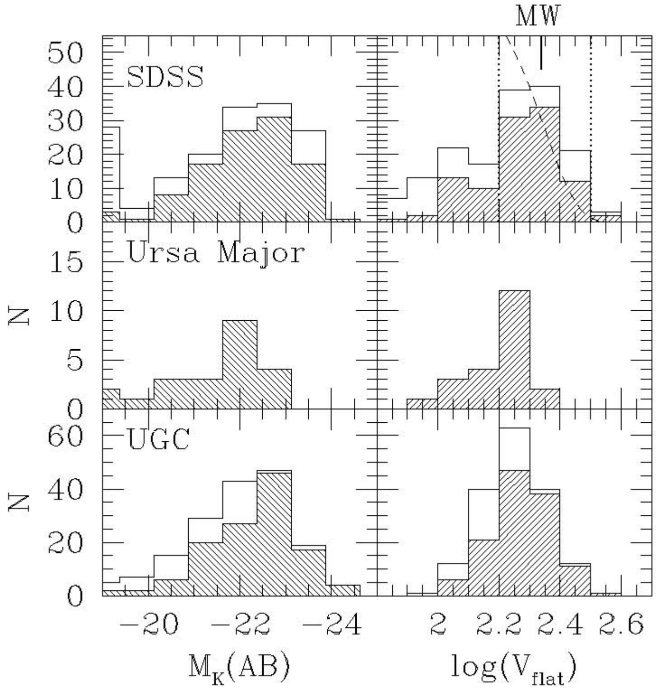

FIG. 3.—Histograms of M_K(AB) (*left*) and log V_{flat} (*right*) for the three samples, SDSS, Ursa Major, and UGC. The shaded histogram is for galaxies for which V_{80} appears to be an appropriate proxy for V_{flat}, i.e., flagged 1 and 2 galaxies (SDSS), as well as flat rotational curves for UGC galaxies (see text for details). *Top left*, Very similar to Fig. 1 of Pizagno et al., showing a deficiency of faint, slowly rotating galaxies with $M_r > -21$, $M_K(AB) > -22$, and log $V_{80} < 2.2$. This is illustrated by the dashed line (*top right*) showing the local log V number distribution function derived from the local K-band luminosity function [Cole et al. 2001; with $M_K^\star$(AB) $= -22.4$ and a slope of -1] after assuming log $V^\star = 2.35$ from the Tully-Fisher relation and $L_K \sim V^4$, following McGaugh (2005). Within $2.2 <$ log $V_{flat} < 2.5$ (*vertical dotted lines*), the SDSS sample provides a robust representation of the spiral galaxy distribution for comparison with the Milky Way. [*See the electronic edition of the Journal for a color version of this figure.*]

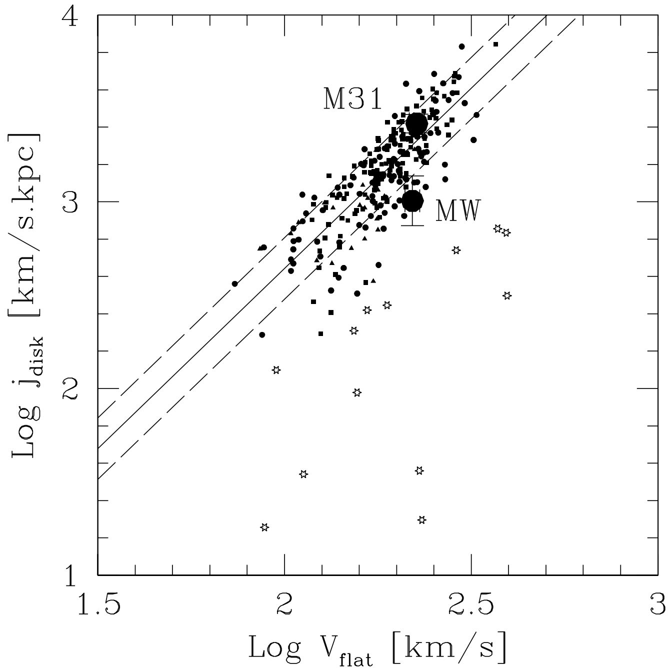

FIG. 4.—The j_{disk} vs. V_{flat} relation for galaxies in the three local samples (same symbols as in Fig. 2). Open stars represent the results from simulations of (Steinmetz & Navarro 1999), illustrating the difficulty of reproducing the angular momentum of spiral galaxies when using the standard model for disk formation. [*See the electronic edition of the Journal for a color version of this figure.*]

slower rotating galaxies than the other samples, and these galaxies tend to lie off the relation defined by the brighter galaxies. This is probably due to low-mass galaxies having large gas fractions (e.g., McGaugh 2005). This effect explains in a simple way the higher slope of the relation for Ursa Major. It is also illustrative to compare the K-band luminosity function of the Tully-Fisher samples to that of the population of local galaxies. The SDSS sample is indeed lacking small galaxies (see Fig. 3), especially below log $V_{80} = 2.2$ [or equivalently, with $M_K(\mathrm{AB}) > -22$]. Given the selection procedure adopted by Pizagno et al. (2006), as well as the large and statistically robust sample of the SDSS itself, we believe that it provides the best way to test the representativeness of the Milky Way among galaxies having parameters in the same range. The Milky Way has log $V_{flat} = 2.34$, and Figure 3 shows that the SDSS sample is limited to log $V_{flat} = 2.5$, because very few spirals have rotational velocities in excess of 320 km s^{-1}. Within the range $2.2 <$ log $V_{flat} < 2.5$, the distribution of velocities in the SDSS sample matches reasonably well what one would expect from a Schechter function. In the following, we have chosen this interval to characterize the representativeness of the Milky Way and M31 compared to the ensemble of local spiral galaxies.

4. REPRESENTATIVENESS OF THE MILKY WAY AND OF M31 IN THE (M_K, V_{flat}, and R_d) VOLUME

We confirm the results of Flynn et al. (2006) and find that the Milky Way lies at $\sim 1\ \sigma$ from the Tully-Fisher relation derived from the three local samples (Fig. 2). Such a discrepancy for the Milky Way is found in both the I- and K-band Tully-Fisher relations, so it is unlikely that it could be affected by an error in the magnitude or extinction estimate. Flynn et al. (2006) have extensively discussed the possible source of systematic errors associated with such estimates and found none convincing (see also the Appendix). The K-band measurement by *COBE* (Drimmel & Spergel 2001) is certainly as accurate as K-band measurements of external galaxies and accounts for extinction, as well as for spiral arms on the opposite side of the galaxy from the Sun. The Milky Way K-band luminosity is half the average value for local spirals with similar V_{flat}. This can be translated into a similar factor in stellar mass. The difference ($\sim$0.7 mag) is much larger than the uncertainty in the total K-band luminosity estimate of the Milky Way. Besides this, M31 lies on the average relation delineated by other local spirals.

We also compute the specific angular momentum of the disk, estimating it using $j_{disk} = 2R_d V_{flat}$, appropriate for a thin disk (see Mo et al. 1998). The only difference adopted here is the use of V_{flat} instead of V_{max}, as we believe it is a better proxy for the halo velocity (see § 3). Disk scale lengths are estimated in I band for the SDSS sample, in K band for the Ursa major sample, and in r band for the UGC sample. We choose not to apply an inclination correction to R_d values, such as Dutton et al. (2007) have done, simply because we do not find any correlation between R_d and disk inclination. Figure 4 shows that the three samples show a similar distribution in the j_{disk}-V_{flat} plane and that observed galaxies show a larger angular momentum than expected based on the simulations of Steinmetz & Navarro (1999). It also illustrates that, due to its small disk radius, the Milky Way is deficient in angular momentum by a factor of 2 compared to average local spirals with the same velocity. Conversely, M31 lies marginally above, but still well in, the mean relation of local spirals.

Assuming that the SDSS sample is a good representation of local galaxies with $2.2 <$ log $V_{flat} < 2.5$, one can estimate how

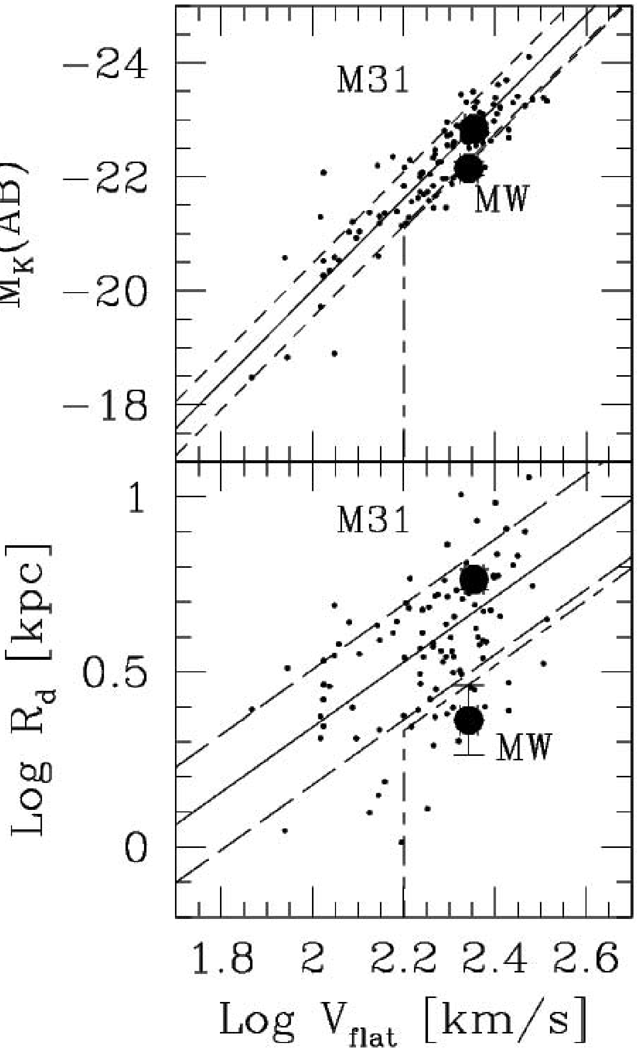

FIG. 5.—M_K (*top*) and R_d (*bottom*) vs. V_{flat} for SDSS galaxies (*points*). Large dots represent the position of the Milky Way, and the 1 σ uncertainty of both relations is shown as dashed lines. Long- and short-dashed lines show how we select Milky Way–like galaxies, which are discrepant in both L_K and disk length scale. Because of the large scatter in the R_d-V_{flat} relation, we also consider as an alternative all objects within $V_{flat} = 2.2$–2.5 having $R_d \leq 2.3 + 0.6$ kpc in gauging the representativeness of the Milky Way (see text for details). [*See the electronic edition of the Journal for a color version of this figure.*]

representative the Milky Way and M31 are in the (M_K, V_{flat}, and R_d) volume. Figure 5 illustrates how we identified those galaxies having a deficiency in L_K and R_d like the Milky Way does. We find that the fraction of Milky Way–like spirals is 7% ± 1% in this volume. M31 falls just on the Tully-Fisher relation delineated by the SDSS sample (as well as by the UGC sample). However, its radius (5.8 kpc) is slightly larger than the average (4.7 kpc) at $V_{flat} = 226$ km s^{-1}. Using the same method as we use to determine the Milky Way's representativeness, we find that 30% ± 3% of the SDSS galaxies have a disk radius larger than or equal to 5.8–0.4 kpc, i.e., the M31-like galaxies. Because the R_d-V_{flat} distribution is not as tight as the Tully-Fisher relation (see Fig. 5), we adopt two different schemes for estimating the fraction of MW-like (and M31-like) galaxies in the corresponding plane. One assumes that the R_d-V_{flat} correlation is real; the other considers only galaxies with disk radii smaller than 2.3 + 0.6 kpc (for Milky Way–like galaxies) and larger than 5.8–0.4 kpc (for M31-like galaxies). Both alternatives produce similar numbers, and the difference is attributed to the uncertainties discussed previously.

In summary, we find that very few galaxies have properties M_K, V_{flat}, and R_d similar to those of the Milky Way, while M31 is far more representative. The above calculation is affected by the fact that we have assumed a much larger relative error bar ($\Delta R_d/R_d$) for the Milky Way than for M31. Applying similar relative errors for both objects (i.e., considering $\Delta R_d/R_d = 0.26$) would lead to a much higher fraction of M31-like galaxies. This is consistent with the location of the two galaxies relative to the 1 σ error of the two relations shown in Figure 5. If the distributions were Gaussian and independent, the location of the Milky Way outside the 1 σ error is consistent with few percent of Milky Way–like galaxies, while M31 is a typical spiral.

5. THE ALMOST UNTOUCHED OUTSKIRTS OF THE MILKY WAY

We have shown that dynamical properties of the Milky Way may be quite exceptional compared to local spiral galaxies with similar rotation speeds. Let us investigate whether previous kinematic events have left some imprint on the outskirts of the Galaxy's stellar populations, since those populations are most likely to show the most obvious residual effects of the merging history (dynamical relaxation times are long, and so mixing of the stellar populations in terms of both chemistry and dynamics is likely to be significantly less than in the disk or inner regions of the galaxy, e.g., Font et al. 2006; Renda et al. 2005). The definition of the stellar halo by Renda et al. (2005; see also Chapman et al. 2006) is intended to include all stars within the outskirts of a galaxy (they used limiting radii ranging from 4 to 30 kpc). This definition is comparable to the "spheroid" of M31 that is used by Brown et al. (2006) to be 5–30 kpc from the disk minor axis. The spheroid of M31 is well described by a de Vaucouleurs law (Pritchett & van den Bergh 1994; Irwin et al. 2005) up to 30 kpc (Durrell et al. 2004). Given this, we have adopted the word "outskirts" to encompass the various, perhaps ill-defined, definitions of what constitutes stars beyond the relatively high surface brightness disks of these spiral galaxies.

One of the most spectacular events currently under investigation in the outskirts of the Milky Way is the Sagittarius stream (Ibata et al. 1994; Majewski et al. 2003). While it is interesting to study the Sagittarius stream to understand the evolution of the halo of the MW, its stellar content is very small ($2 \times 10^7\ L_\odot$ in V band; see Majewski et al. 2003). The Sagittarius stream represents only a very tiny fraction of the stellar content of the Milky Way stellar halo ($2 \times 10^9\ M_\odot$; see Carney et al. 1990). The stellar content of the outskirts of the Milky Way is essentially made of old stars with low metal abundance ($\langle$[Fe/H]$\rangle = -1.6$; Beers & Sommer-Larsen 1995; Morrison et al. 2003; see also the review by Prantzos 2006). Conversely, the outskirts of M31 are dominated by metal-rich stars ($\langle$[Fe/H]$\rangle$ from -1 to -0.8; Mould & Kristian 1986; Rich et al. 1996; Durrell et al. 2004, and references therein). It has been argued by Kalirai et al. (2006) that stars within 30 kpc of the center of M31 are indeed part of an extended spheroid (or bulge). By itself, this property illustrates the profound difference between M31 and the Milky Way. For the Milky Way, such a chemically enriched extended spheroid, which dominates the star counts up to 30 kpc, does not exist. In the following, we review briefly how the properties of the Milky Way outskirts (defined as a region from 5 to 30 kpc from the center) compare with those of external spirals.

Comparing with the properties of the outskirts of Milky Way and M31, however, requires some care. First, most abundance studies in the Milky Way are based on high-resolution spectroscopy, while color-magnitude diagrams are most commonly used for stars in external galaxies. We note, however, that the study of,

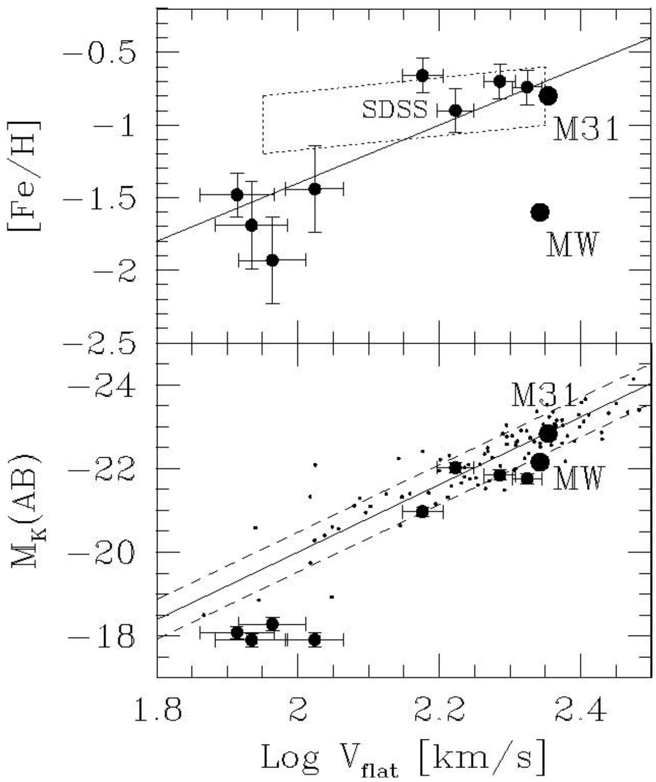

FIG. 6.—*Top*: Iron abundances estimated for the outskirts of eight spiral galaxies from Mouhcine et al. (2006) plotted against log $V_{\rm flat}$ (*small points*). Large points represent the values for the Milky Way and M31. The solid line assumes $M_{\rm star} \sim V^4$ (McGaugh 2005) and $M_{\rm star} \sim Z^2$, following the prescription of Dekel & Silk (1986). Dashed lines represent the range of Zibetti et al. (2004), after stacking 1047 edge-on SDSS galaxies and assuming that their colors are dominated by red giant stars. *Bottom*: Tully-Fisher relation for the same galaxies (very small dots represent the sample of Pizagno et al. 2006). [*See the electronic edition of the Journal for a color version of this figure.*]

e.g., Morrison et al. (2003), shows that the agreement between abundances estimated from spectroscopic and photometric measurements is excellent. Second, the areas surveyed to derive stellar abundances are small, they may be unrepresentative of the dominate populations, and this may lead to biases in all estimates. For example, an external observer of the Milky Way might have unluckily observed the region where the bulk of the stars belonging to Sagittarius lie and would likely conclude that the outskirts of the Milky Way are indeed enriched. However, this conclusion becomes more and more unrealistic, given the reasonable number and variety of locations of surveyed areas in the outskirts of M31 and the insignificant fraction of the total mass within Sagittarius.

Mouhcine et al. (2006) have compared the abundances in the outskirts of several spiral galaxies. Mouhcine et al. selected red giant stars that lie 2–10 kpc along the projected minor axis of eight nearby spirals in areas that are part of galactic outskirts, although they might also be contaminated by bulge or thick-disk stars. Figure 6 (*top*) shows the $\langle[{\rm Fe/H}]\rangle$ of red giant stars against $V_{\rm flat}$: all galaxies, except the Milky Way, show a trend of increasing metal abundance with rotation velocity of the disk. This trend, found by Mouhcine et al., is likely explained through an examination of Figure 6 (*bottom*): while massive galaxies have transformed most of their gas into stars and metals, smaller galaxies have been much less efficient in doing so and still include a large gas fraction, as indicated by their location in the Tully-Fisher relation (e.g., McGaugh 2005). Interestingly, such a relation, if confirmed, requires a certain mixing of stars with different enrichment patterns in the outskirts of the galaxy, such as might be provided by a merger. The Galaxy's outskirts are underabundant relative to the trend line formed by external galaxies by about 1 dex, implying that it has been far less enriched than those of other galaxies of the same total mass. On the other hand, M31 has a location similar to other large spirals in Figure 6. This strengthens our hypothesis that the properties of M31 are rather typical of large spiral galaxies, while the Milky Way appears to be exceptional.

Similarly, and perhaps more generally, the results of Zibetti et al. (2004) add more credence to our hypothesis. They found, by stacking 1047 images of SDSS edge-on spirals, that the average color of stars at $\geq$5 times the disk scale length, beyond the disk minor axis, is redder by $\Delta(r - i) = 0.3$–0.4 than Milky Way globular clusters (or Galactic halo stars), or, after converting SDSS photometry (Jordi et al. 2006), by $\Delta(V - I) = 0.45 \pm 0.1$. This discrepancy is especially large for the brightest galaxies of the Zibetti et al. sample, i.e., those with absolute magnitudes similar to the Milky Way. The brightest galaxies show the reddest stellar halo colors, accentuating this difference with the Milky Way. Zibetti et al. show convincingly that their measurements are not significantly affected by dust. If these measurements are dominated by red giant stars, such a large shift in $V - I$ colors is unlikely related to an age difference between SDSS galaxies and the Milky Way, but more likely due to different metallicities (see, e.g., Lee et al. 1993). The Galactic globular clusters and halo stars are indeed very old, and a 0.45 mag shift in $V - I$ to the red is likely due to a shift of 0.8 ± 0.2 dex in [Fe/H] (Lee et al. 1993). Comparing the $V - I$ colors from Zibetti et al. to that of nearby galaxies studied by Mouhcine et al. allows us to place this ensemble of galaxies in Figure 6. It is apparent that the SDSS galaxies lie within the range defined by the intermediate-mass spirals, including M31. The bulk of the Zibetti et al. (2004) sample is composed of galaxies with M_i (where i refers to the i band of the SDSS) ranging from -19.5 to -22.5 (for $H_0 = 70$ km s^{-1} Mpc^{-1}). This corresponds to log $V_{\rm flat}$ ranging from 1.95 to 2.35, or galaxies with rotation velocities similar to or less than that of M31 and the MW (Pizagno et al. 2005).

Taken together, the above results strongly suggest that stars in the outskirts of the Milky Way have an average chemical abundance 3 times lower than those of most spirals within a similar mass range. Simulations show that the very low metal abundance of the outskirts of our galaxy may require the absence of any previous merger of satellites with mass larger than or equal to $10^9\,M_\odot$ (Font et al. 2006).

6. TOWARD A FORMATION SCHEME FOR SPIRAL GALAXIES WITHIN THE CONTEXT OF DIFFERENCES BETWEEN THE MILKY WAY AND M31

In the previous sections of this paper, we have shown that perhaps the properties of the Milky Way are not representative of those of a typical local spiral galaxy. In this context, we have used M31 as a foil to the Milky Way in trying to demonstrate that it is a typical representative of the spiral galaxy population (at least for those that have rotation speeds similar to the Milky Way). Since we find a compelling case for the differing relative natures of the Milky Way and M31, we wish now to discuss and conjecture about what these differences may be telling us about galaxy formation. Unlike previous discussions of the relative characteristics of the Milky Way and M31, we wish to embed this within the context of what we know about the properties of distant galaxies.

6.1. *A Quiet Formation History Compared to a Merger-driven Formation History: The MW versus M31*

Historically, the Milky Way and M31 were thought to be quite similar. They have the same Hubble type and similar total masses.

At a given V_{flat}, we find that M31 has a stellar mass and angular momentum close to that of the average of local spiral galaxies. In contrast with this, the Milky Way has a stellar mass and angular momentum that are 2 to 3 times lower than average. Its outskirts could be even more peculiar, with stellar abundances 3 times lower than those of other spirals with approximately the same absolute magnitude and rotation velocity.

What renders the Milky Way so exceptional? Its peculiarities seem to be tightly linked to its quiet history of formation. It is interesting to compare its formation history with those of other local spiral galaxies. M31 has properties that are much closer to those of an average spiral. Let us investigate how M31, when compared to the Milky Way, may have acquired 2 times more stellar mass and 2.5 times more angular momentum.

Detailed studies of the bulge, disk, and outskirts of M31 have been (mainly recently) made. Recent discoveries about M31 are numerous (giant stream, large faint clumpy disk, age-metallicity relation of stars in the disk, characterization of the metallicities and ages of the globular cluster system, detailed measurements of the chemical abundances and ages of bulge and halo stars, etc.). Reviewing these discoveries alone would by itself require a very long manuscript. Such a detailed review is obviously beyond the scope of this paper. Let us just summarize some of the widely accepted implications of these new discoveries. Both the stream (Ibata et al. 2001) and the extended clumpy thick disk (Ibata et al. 2005) plead for an active merger history for M31. Ibata et al. (2005) suggested that either a succession of minor mergers or possibly a major merger, either having occurred within the last 8 Gyr, could explain these properties of M31.

Studies of color-magnitude diagrams of disk, bulge, and halo stars provide a complementary view of the star formation history of M31. The ages for globular clusters derived from Lick indices are sensitive to the template model used for the analysis (see, e.g., Beasley et al. 2004). For example, using Thomas et al. (2003) or Bruzual & Charlot (2003) templates changes the ages of the intermediate ages of globular clusters discovered by Beasley et al. (2004) from $\sim$3 to $\sim$6 Gyr. Nevertheless, it is widely accepted that the globular cluster system of M31 resembles that of the Milky Way, on which is superposed a population of globular clusters with intermediate ages (from less than 1 Gyr to about 8 Gyr). Interestingly, such globular clusters with intermediate ages can be formed during advanced, but still relatively obvious, mergers (e.g., Schweizer 2006). In M31 this additional population represents $\sim$42% of the whole globular cluster system and reflects a relatively recent enrichment of the outskirts of M31 by infall of another galaxy (Beasley et al. 2004). This is confirmed by the large age variance found for the properties of the stars in the outskirts (or "spheroid"; see Brown et al. 2006) of M31, which contrasts with the single, old stellar population in the stars of our own galaxy's outskirts. The stream star ages show a peak at $\sim$8–9 Gyr (Brown et al. 2006), while the (outer) disk stars show a peak at 5–7 Gyr, about 2 Gyr younger.

The differences between the Milky Way and M31 are likely due to the quiescent formation in the former case and to the merger-dominated history for the latter. It is still not definite whether M31 has experienced a major merger or a succession of several minor mergers. Both merger scenarios can explain the significant fraction of stars with intermediate age and metallicity in the outskirts, as well as the fact that M31 has assembled twice the stellar mass of the Milky Way. For either alternative, successive minor mergers (or many episodes of intense minor merging) or a few major mergers over the lifetime of a galaxy, simulations reproducing all the above observations are, however, not yet available. Besides this, the large angular momentum of M31 compared to the Milky Way (greater by a factor of 2.5) suggests a major encounter. Successive and numerous minor mergers are likely to be less efficient in producing large angular momentum.[5] Another argument, given by Brown et al. (2006) is, "if the Andromeda spheroid is the result of many smaller mergers that did not occur in the Milky Way, one must ask why there is such a statistically significant distinction between the merger histories of two similarly-sized spirals in the same galaxy group." Ibata et al. (2005) also favored a major encounter to interpret the homogeneous chemical properties of the "extended clumpy disk."

How credible is the hypothesis that M31 experienced a major merger in the past? If the M31 stream is a relic of such an event, it might have occurred $\sim$8 Gyr ago, as was suggested by Brown et al. (2003). Simulations of the stream have focused on a very recent (0.5 Gyr old) merging of a $10^9\,M_\odot$ dwarf (Font et al. 2006). Brown et al. (2006) suggested it would be useful to test whether the stream could actually be due to an earlier event in the history of M31, as well as whether such a giant stream would still be evident after 8 Gyr. Indeed, such a major merger can explain the similarities between the stream and the populations of the outskirts (Brown et al. 2006), since both will be polluted in a similar way during the merging process. This is in contrast with expectations from a scenario involving multiple minor mergers for which the age-metallicity signature should be far less uniform that what is observed. Eight Gyr ago, the progenitor of M31 was undoubtedly a much smaller galaxy than it is today: as noticed by Ibata et al. (2005), an event involving a galaxy of the size of M33 would have been a major merger event. Is such an ancient major merger event realistic, knowing that M31 possesses a large thin disk (Morrison et al. 2004)? On the basis of the properties of the old disk globular clusters, Morrison et al. (2004) have argued that the thin disk is indeed old. However, their arguments have been contradicted by much lower age estimates of the same objects (Beasley et al. 2004). The ages of disk stars, 5–7 Gyr, are consistent with a disk built predominately during $\leq$2 Gyr after a major merger event: simulations predict a rapid formation of the new disk after a major gas-rich merger event (but also including the effects of substantial feedback Governato et al. 2007; Robertson et al. 2006).

The large (specific) angular momentum of M31 (compared to that of the Milky Way), the similarity of halo and stream stellar populations, and the difficulty of having a succession of many minor encounters in M31 and very few or none for the Milky Way all favor a relatively recent, $\sim$8 Gyr ago, major merger having a substantial impact on the final characteristics of M31. Interestingly, a similar conclusion was reached by Durrell et al. (2004). They noticed that a major merger scenario naturally explains the relative metallicity distribution functions of the stars in both the outskirts and globular clusters. They also suggest similarities between the M31 spheroid and the outer part of giant ellipticals. As a matter of interest, M31 falls precisely on the same relation between black hole and bulge mass as for elliptical galaxies (e.g., Tremaine et al. 2002). This suggests that, even on much smaller scales than that of the outskirts, a major merger might have had a substantial impact on the properties of M31. Note specifically that the black hole–bulge relationship has been explained in the context of major mergers, intimately connecting a quasar phase of galaxies (Hopkins et al. 2006a, 2006b) to the overall evolution of galaxies (Springel & Hernquist 2005), with active galactic nucleus

[5] Note that this argument also applies if one considers the spin parameter, because the total masses of M31 and the Milky Way are so similar that their ratio of spin parameters scales with that of their angular momentum.

(AGN) feedback being a necessary and crucial process responsible for this interplay.

In summary, one can explain the differences between the Milky Way and M31 by the absence of significant merger events over the last 10–11 Gyr for the former. M31 has a stellar mass and a chemical enrichment in the stars in its outskirts typical of local spiral galaxies. Its angular momentum is 1.25 times that of an average SDSS galaxy at the same $V_{\rm flat}$. Besides this, the Milky Way has a deficiency of a factor of 2 in both stellar mass and angular momentum when compared to a similar average. Accounting for this, galaxies as or more exceptional than the Milky Way represent only 7% of all local spirals. Because of the remarkable properties of the relatively unpolluted Galactic outskirts, the fraction of Milky Way–like galaxies may be even lower. It is then probable that most local spirals, like M31, have experienced more and perhaps later mergers than the Milky Way. In such a case, the differences in the formation histories of the Milky Way and M31 are simply reflected in the differences between the properties of the Milky Way and those of the bulk of local spirals.

6.2. *Does the Exceptionally Quiet Merger History of the MW Imply It Grew through Secular Processes?*

Advocating a new scenario of spiral formation means we have to break some taboos—the main one being the fact that Milky Way may be an exception rather than the rule. The widely accepted assumption that a major merger would inevitably lead to an elliptical galaxy is perhaps no longer tenable: accounting for the large number of major mergers that have apparently occurred since $z = 3$ would imply that all present-day galaxies should be ellipticals. This is obviously not the case. So it is likely that disks either can survive or are "rebuilt" after a major merger, through whatever mechanism, as yet perhaps unknown in detail (see, for example, Robertson et al. 2006).

Many simulations implicitly assume that most of the star formation in intermediate-mass galaxies occurred well before $z = 1$. This is, however, not correct: nearly half of their present-day stellar masses was formed since that epoch, as shown by Hammer et al. (2005) or Bell et al. (2005). But more than this, to reproduce the zero point of the local Tully-Fisher relation within the framework of the standard gas accretion model requires spin parameters (λ from 0.06 to 0.08) larger than those expected for dark matter halos ($\lambda = 0.042$ on average; see Pizagno et al. 2005; Dutton et al. 2007). This discrepancy has led Dutton et al. (2007) to relax the adiabatic contraction hypothesis of the standard scenario. They assume instead that the halo expands during a major merger and must lead to a new disk being formed (or perhaps a preexisting disk preserved in some way), with a clear reference to the simulations of Robertson et al. (2006). It seems more and more evident that the formation of disk galaxies requires a larger influence of mergers than hypothesized in the standard scenario.

The Milky Way being an exceptionally quiet galaxy alters the validity of the standard scenario of spiral formation, which has been mostly based on our Galaxy's properties. This being the case, the situation is in reality worse for the general validity of this scenario. Indeed, giant stars of the Galactic bulge show a large α/Fe ratio, indicating a fast ($\sim$1 Gyr) formation of the bulge (Zoccali et al. 2006; Lecureur et al. 2007). If confirmed, it seems that the Milky Way's bulge formed at very early epochs through the merger of large clumps (or progenitor galaxies), with the disk being built (or rebuilt) later on. This is in stark contrast with a primordial condensation of gas into a disk that then forms stars, the main assumption in the standard scenario.

More interesting perhaps is to consider the Milky Way as an archetype of a galaxy having experienced no merging event in the last 10–11 Gyr. We assume here that very small encounters, such as the present disruption of Sagittarius (with a mass of less than 1% of that of the Milky Way), are not sufficient to significantly enrich the stellar halo in mass or substantially alter its average metallicity. Font et al. (2006) indeed argue that the very low metal abundance of the Galactic stellar halo requires the absence of any previous merger of satellites with mass larger than or equal to $10^9\ M_\odot$. If correct, this implies that the Galactic disk may have mostly grown by an approximately smooth gas accretion, or, in other words, by secular evolution (see also Croton et al. [2006], who suggest that such infall may be sufficient to build the Milky Way disk). In the following, we consider that secular evolution includes either smooth gas accretion or accretion of small satellites. Let us consider that the Galactic disk was formed by secular evolution and that the Galactic bulge (in which $\sim$25% of the stellar mass is locked; see Flynn et al. 2006) was formed by an early merger. If the fractions of the mass of the Milky Way and M31 that grew through secular evolution—accretion of gas and small satellites—were similar, since they inhabit the same group, we can use the difference in stellar masses to estimate the likely contribution of smooth gas accretion in general. The difference between the M31 and Milky Way stellar masses can be accounted for if $\sim$36% (estimated with the ratio $M_{\rm star}^{\rm MWdisk}/M_{\rm star}^{\rm M31}$) of the mass assembly of M31 is due to secular evolution, while 64% may be directly linked with mergers. Since M31 has a typical stellar mass among local spirals of the same total mass (also including the dark matter component, which influences their dynamics), this balance may apply to most spirals or at least those inhabiting environments of density similar to the Local Group.

6.3. *The Spiral-rebuilding Hypothesis: Formation of Spiral Galaxies after Major Mergers?*

The mass assembly of typical spirals, including M31, has probably been driven predominantly by mergers, and their assembly history might not be best represented in the characteristics of the Milky Way. Galaxies with approximately the same rotation speeds as the MW also show larger angular momentum. Those can be produced by a single major merger, while it is difficult to reconcile them with a succession of minor mergers. Here we investigate how a scenario with major mergers can be reconciled with observations.

The spiral-rebuilding scenario was proposed by Hammer et al. (2005) to explain the observations of the distant galaxies. Specifically, this hypothesis was used to explain for distant galaxies the simultaneous evolution of the global stellar mass, luminosity-metallicity relationship, pair statistics, evolution of the IR light density, colors of spiral cores (bulges?), evolution in the number density of spheroids and spiral galaxies, and evolution in the fraction of peculiar galaxies (mergers and compact). It is consistent with all these evolutionary trends, while a scenario in which the stellar mass formation is dominated by minor encounters ("collisional starbursts"; Somerville et al. 2001) has difficulties in reproducing in particular the evolution of the IR light density, number density of peculiar galaxies, and spiral core colors. In such a framework, the question of the representativeness of the Milky Way may simply be linked with the small fraction of galaxies that have escaped a major merger since $z \sim 3$.

Galaxies like the MW with a quiet merger history are expected to have, on average, a lower stellar mass, a lower angular momentum, and a less enriched stellar halo for their rotation speed. However, they still could be the product of a very early major merger. Conversely, the representativeness of M31 compared to the 50%–75% fraction of galaxies of similar masses may be a result of the ubiquity of major mergers since $z = 1$ (see § 1) and their significant influence in determining the properties of spirals at the current epoch. The differences between the MW and M31 may be simply due to the epoch of the last equal- or nearly equal-mass merger. In the case of the MW, perhaps it occurred well before $z = 1$; for M31, it is likely that it occurred around or after $z = 1$.

Major advances in simulations have provided a theoretical framework for the disk-rebuilding scenario. Cox et al. (2006) have shown that the remains of dissipational mergers have significant rotation and angular momentum compared to dissipationless mergers. Even without efficient feedback, ellipticals, when formed after a merger, possess a seed for the subsequent formation of a rotation-supported disk. Robertson et al. (2006) have shown that gas-dominated mergers (gas fraction larger than 50%) can produce remnants with disks of sufficiently high angular momentum (unlike simulations that do not include gas-rich major mergers to explain the large angular momentum of disks; e.g., Steinmetz & Navarro 1999). The importance of high gas fraction has been already been suggested by Hammer et al. (2005), since it is the gas expelled through the impact of strong feedback that subsequently feeds the newly formed disk and provides the necessary rotational support and sufficient specific angular momentum (e.g., Robertson et al. 2006). Since the stellar mass density of galaxies has nearly doubled since $z = 1$, the condition that galaxies have large gas fractions must be the case on average. Evolution of the gas content in galaxies is also observed, although indirectly, from the observed evolution of the gas-phase metal abundance in distant galaxies. Liang et al. (2006) have estimated that the gas content in intermediate-mass galaxies at $z \sim 0.6$ was 2 times larger than in galaxies at the current epoch. Erb et al. (2006) have found, at $z \sim 2$, gas fractions ranging from 0.2 to 0.8.

Although the consequences of adopting this scenario need to be more accurately evaluated, the disk-rebuilding scenario is becoming more and more viable. Regardless, observations show that there is sufficient gas at redshifts less than 1 from which disks could be rebuilt. The rebuilt disks and bulges after a major merger should be compared to observations of present-day galaxies in a realistic way, i.e., after accounting for further gas accretion (or secular evolution), which may essentially feed the disk (see also Croton et al. 2006). Thus, the disk-rebuilding scenario may only require some tuning of the simulation assumptions. In essence, this scenario implicitly solves both problems of the standard scenario (e.g., disk stability to further collisions and angular momentum), because subsequent collisions help generate a large angular momentum as it is observed in local spirals. Late-epoch merging generally results in disks with higher angular momentum than disks that had their last major merger earlier in the history of the universe, as perhaps did the Milky Way. Besides explaining the difference in angular momentum, it may also explain why the average metallicity of stars in our halo is less than that of typical spirals at the same rotation speed and other characteristics of the Milky Way's halo.

However, this alternative to the standard scenario has not been carefully considered in the literature or through simulations, possibly because it appears too exotic or too disturbing. A possible caveat could be the significant fraction of LIRGs (galaxies with high IR luminosities of $\gtrsim 10^{11}\,L_\odot$) at high redshift showing spiral morphologies (Melbourne et al. 2005; Bell et al. 2005). However, the disk-rebuilding phase corresponds to a phase of strong gas infall (from gas left over from the merger and by a gradual cooling of the hot halo gas), during which the galaxy may well have the appearance of a LIRG with spiral morphology.

Is there observational evidence for a subsequent disk-rebuilding phase occurring later, after the merging? At least an interesting clue can be derived from recent observations of the evolution of the Tully-Fisher relation. One can compare the pair fraction ($5\% \pm 1\%$ of $z = 0.6$ galaxies; see § 1) to the higher fraction (26%; Flores et al. 2006) of $z = 0.6$ galaxies having complex velocity fields, later being probably associated with merger remnants from comparison to numerical simulations (Puech et al. 2007). Assuming 0.35 Gyr to be the characteristic time for a real pair to actually merge (see § 1) implies a remnant phase from 1.5 to 2 Gyr, in relatively good agreement with expected times needed to rebuild a significant disk after an efficient feedback phase (Robertson et al. 2006; Governato et al. 2007). A more quiescent history of cold and clumpy gas flow has also been been investigated for disk formation (Dekel & Birnboim 2006). Such a scenario, however, needs to show how it succeeds in reproducing the strong evolution of violent star formation with epoch (i.e., the strong number density evolution in galaxies with substantial IR luminosities, $L_{\rm IR} \gtrsim 10^{11}\,L_\odot$) and in solving the angular momentum problem. Assuming collisions of large enough gas clumps might succeed in explaining the above, although it would become closer and closer to a scenario based on the observed large fraction of major mergers at intermediate redshifts.

7. CONCLUSION

Compared to local spiral galaxies with similar rotation velocities, the Milky Way has a significant deficiency of stellar mass, angular momentum, and chemical abundances in stars in its outskirts. Such differences are interpreted as being due to the exceptionally quiet formation history of the Milky Way compared to other spirals at comparable rotation velocities. After the rapid building of its bulge, more than 10 Gyr ago, the disk of the Milky Way formed inside-out, mostly through smooth gas accretion, in a secular mode. In the same dynamical mass range, the bulk of spiral galaxies, including M31, have accreted most of their mass and angular momentum through a more recent and active merger history. In other words, other galaxies may have populations of stars in their outskirts similar to the Milky Way, but for which a significant component would have been accreted later through further episodes of mergers. Combining results from observations of distant galaxies (merger rate and evolution of LIRGs) with those of local galaxies (Tully-Fisher and angular momentum), we have hypothesized that most spiral galaxy disks have been "rebuilt." The timing of this rebuilding and how many episodes of rebuilding are also crucial parameters within this hypothesis. In such a scenario, to reproduce the properties of the Milky Way, the disk of the Milky Way was built (or rebuilt, if it had a preexisting disk) at a much earlier epoch ($\sim$10 Gyr ago) than the general population of local spiral galaxies. Thus, the standard scenario of disk formation may not even apply to the Milky Way.

The major advantages of the disk-rebuilding scenario are that it may solve various problems simultaneously, such as the so-called angular momentum problem (major merger are very efficient in producing angular momentum), the large fraction of stellar mass produced in LIRGs since $z = 1$ (major mergers are an efficient way to produce episodic strong star formation), and the chemical abundances of stars in the outskirts of spiral galaxies (by efficient mixing). However, the most important point of this paper is that it may also naturally explain why the Milky Way is so exceptional in its properties when compared to other spirals. Specifically, we think that adopting the spiral-rebuilding scenario for understanding the evolution of spiral galaxies has a number of significant consequences. These are the following:

1. M31 appears to be a typical spiral, emphasizing the need to further investigate its precise formation history in order to understand how the majority of spiral galaxies may have formed.

What differences in the final characteristics result from the exact time at which the rebuilding occurs?

2. The Milky Way had an exceptionally quiet formation history, having escaped any major merger (and possibly a significant number of minor mergers) during the last 10–11 Gyr; Milky Way–like galaxies correspond to only 7% of local spirals, and possibly much less.

3. Modeling the formation history of spirals needs to use a superposition of a "quiet" history like that of the Milky Way with an active history of merging, which could be responsible for almost 2/3 of the stellar mass.

4. The failure of the standard scenario for spiral formation to reproduce the properties of spiral galaxies, including their stellar mass–Tully-Fisher relation, their high angular momentum, and the chemical abundances of stars in their outskirts, is explained.

5. The spiral-rebuilding scenario has a reasonable chance of reproducing most of the observed local spiral properties, as well as those of their progenitors at large distances.

Galaxy simulations are certainly needed to investigate the past history of spiral galaxies. The above evidence for a scenario where the evolution of disk galaxies is driven predominantly by mergers, rather than by other secular processes, lets us suggest that the key question now is to gauge the relative impact of minor and major mergers in shaping spiral galaxies as we see them today. Observationally, M31 is certainly the best target for a robust investigation to determine the past history of a typical spiral galaxy. In addition, follow-up of the pioneering modeling work of Robertson et al. (2006) and Governato et al. (2007) would also be very valuable in understanding the role of mergers (both major and minor) in disk galaxy evolution. Major mergers with a variety of mass ratios and angular momentum vectors should be investigated to see whether they can reproduce the characteristics of spiral galaxies in detail. Such simulations must include realistic amounts of gas for the progenitors within the redshift range $z = 0.5$–3, and more observational effort should be expended to determine this parameter. Subsequently, such models could be scaled to the observed fraction of mergers (and merger remnants) and observationally determined distributions of mass ratios and angular momentum vectors. Assuming a realistic rate of "smooth" gas accretion after the last major merger would let one investigate whether the reshaped disks and bulges are consistent or not with the observed properties of the ensemble of bulges and disks in present-day galaxies.

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APPENDIX

ON THE ROTATIONAL VELOCITY OF THE MILKY WAY

As noted by Flynn et al. (2006), the Tully-Fisher relation is so steep that with a value of $V_{\rm flat} = 185$ km s^{-1}, the Milky Way would fall nicely along and within the scatter of the Tully-Fisher relation of external galaxies (see Fig. 2). Indeed, for estimates of the local circular rotation, Θ_0, values down to 185 km s^{-1} (Olling & Merrifield 1998) and up to 235 km s^{-1} (Reid & Brunthaler 2004) or even 255 km s^{-1} (Uemura et al. 2000) have been reported. These estimates are highly degenerate, as they depend on the value of R_0, the distance to the Galactic center. This is well illustrated in Figure 1 of Olling & Merrifield (1998). Here we consider together the combinations of (Θ_0, R_0) values adopted by the different studies. They are (185, 7.1), (235, 8.0), and (255, 8.5) for Olling & Merrifield (1998), Reid & Brunthaler (2004), and Uemura et al. (2000), respectively. The most accurate and direct estimate of R_0(7.94 ± 0.42 kpc) has been determined by Eisenhauer et al. (2003) on the basis of proper motions around the Galactic black hole, a value that has been further refined by Eisenhauer et al. (2005) to $R_0 = 7.62 \pm 0.32$ kpc. Note that these values agree with the best overall estimate made by Reid (1993) on the basis of a combination of previous estimates. Using the Eisenhauer et al. (2005) value of R_0, Brunthaler et al. (2006) derive $\Theta_0 = 225 \pm 10$ km s^{-1}, the uncertainty depending mostly on the uncertainty in the values of R_0.

A robust measurement of the relative rotational velocity of the Sun to the halo has been made by Sirko et al. (2004), who find 222.1 ± 7.7 km s^{-1}. This measurement was based on an analysis of the kinematics of 1170 blue horizontal branch stars in the Galactic halo. Solar velocities significantly lower than the IAU standard would correspond to a halo with significant counterrotation (Sirko et al. 2004). Conversely, the rotation velocity of the Galactic halo is found to be in the same sense as the disk rotation and marginally consistent with an absence of rotation (Sirko et al. 2004 and references therein). Extreme values for the local circular velocity are also excluded by open cluster velocities in the Milky Way (Frinchaboy & Majewski 2006). The evidence seems to favor a value of the rotation velocity of the Milky Way that is close to the IAU standard, and we see no need to adopt a different value.

To compare the Milky Way to external galaxies requires us to determine what an external observer would estimate for $V_{\rm flat}$. Indeed, within the range of reasonable (Θ_0, R_0) values (Brunthaler et al. 2006; Eisenhauer et al. 2005), the fit of the Milky Way rotation curves (see Fig. 1 of Olling & Merrifield 1998) shows a flat or a slightly rising curve. To some extent, this contrasts with the rotation curve of M31, which smoothly decreases from 259 km s^{-1} at 10 kpc to 226 km s^{-1} at large radii (Carignan et al. 2006). Such a decline is likely due to the effect of the prominent bulge of M31. A further comparison between the Milky Way and M31 is also very instructive. It has been argued by Evans et al. (2000) that, contrary to earlier ideas, the halo mass of the Milky Way could be equal to, or even higher than, that of M31. Because $V_{\rm flat}$ is intimately linked with the total mass of a galaxy (see § 3), it is reasonable to adopt for the Milky Way a value (220 km s^{-1}) that is close to that of M31 (226 km s^{-1}). In summary, the deficiency of the stellar mass of the Milky Way compared to M31, and hence to external galaxies, appears to be particularly robust.

REFERENCES

Barmby, P., et al. 2006, ApJ, 650, L45
Battaglia, G., et al. 2006, MNRAS, 370, 1055
Beasley, M. A., Brodie, J. P., Strader, J., Forbes, D. A., Proctor, R. N., Barmby, P., & Huchra, J. P. 2004, AJ, 128, 1623
Beers, T. C., & Sommer-Larsen, J. 1995, ApJS, 96, 175
Bell, E. F., & de Jong, R. S. 2001, ApJ, 550, 212
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Bell, E. F., Phleps, S., Somerville, R. S., Wolf, C., Borch, A., & Meisenheimer, K. 2007, ApJ, 652, 270
Bell, E. F., et al. 2005, ApJ, 625, 23

Bernardi, M., Nichol, R. C., Sheth, R. K., Miller, C. J., & Brinkmann, J. 2006, AJ, 131, 1288
Bessel, M. S. 2005, ARA&A, 43, 293
Bienaymé, O. 1999, A&A, 341, 86
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Boissier, S. 2000, Ph.D. thesis, Institut d'Astrophysique Paris
Brinchmann, J., et al. 1998, ApJ, 499, 112
Brown, T. M., Ferguson, H. C., Smith, E., Kimble, R. A., Sweigart, A. V., Renzini, A., Rich, R. M., & VandenBerg, D. A. 2003, ApJ, 592, L17
Brown, T. M., Smith, E., Ferguson, H. C., Rich, R. M., Guhathakurta, P., Renzini, A., Sweigart, A. V., & Kimble, R. A. 2006, ApJ, 652, 323
Brunthaler, A., Reid, M. J., Falcke, H., Henkel, C., & Menten, K. M. 2006, preprint (astro-ph/0611208)
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Carignan, C., Chemin, L., Huchtmeier, W. K., & Lockman, F. J. 2006, ApJ, 641, L109
Carney, B., Latham, D., & Laird, J. 1990, AJ, 99, 572
Chapman, S. C., Ibata, R., Lewis, G. F., Ferguson, A. M. N., Irwin, M., McConnachie, A., & Tanvir, N. 2006, ApJ, 653, 255
Chen, B., Figueras, F., Torra, J., Jordi, C., Luri, X., & Galadi-Enriquez, D. 1999, A&A, 352, 459
Cole, S., et al. 2001, MNRAS, 326, 255
Conselice, C. J. 2006, MNRAS, 373, 1389
Conselice, C. J., Gallagher, J. S., III, & Wyse, R. F. G. 2003, AJ, 125, 66
Courteau, S. 1997, AJ, 114, 2402
Cox, T. J., Jonsson, P., Primack, J. R., & Somerville, R. S. 2006, MNRAS, 373, 1013
Croton, D. J., Springel, V., White, S. M., et al. 2006, MNRAS, 365, 11
Dehnen, W., & Binney, J. 1998, MNRAS, 294, 429
Dekel, A., & Birnboim, Y. 2006, MNRAS, 368, 2
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Drimmel, R., & Spergel, D. N. 2001, ApJ, 556, 181
Durrell, P. R., Harris, W. E., & Pritchet, C. J. 2004, AJ, 128, 260
Dutton, A. A., van den Bosch, F. C., Dekel, A., & Courteau, S. 2007, ApJ, 654, 27
Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748
Eisenhauer, F., Schödel, R., Genzel, R., Ott, T., Tecza, M., Abuter, R., Eckart, A., & Alexander, T. 2003, ApJ, 597, L121
Eisenhauer, F., et al. 2005, ApJ, 628, 246
Erb, D. K., Shapley, A. E., Pettini, M., Steidel, C. C., Reddy, N. A., & Adelberg, K. L. 2006, ApJ, 644, 813
Evans, N. W., Wilkinson, M. I., Guhathakurta, P., Grebel, E. K., & Vogt, S. S. 2000, ApJ, 540, L9
Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189
Flores, H., Hammer, F., Puech, M., Amram, P., & Balkowski, C. 2006, A&A, 455, 107
Flynn, C., Holmberg, J., Portinari, L., Fuchs, B., & Jahreiß, H. 2006, MNRAS, 372, 1149
Font, A. S., Johnston, K. V., Guhathakurta, P., Majewski, S. R., & Rich, R. M. 2006, AJ, 131, 1436
Frinchaboy, P. M., & Majewski, S. R. 2006, BAAS, 209, 165.01
Fux, R., & Martinet, L. 1994, A&A, 287, L21
Geehan, J. J., Fardal, M. A., Babul, A., & Guhathakurta, P. 2006, MNRAS, 366, 996
Gould, A., Bahcall, J. N., & Flynn, C. 1997, ApJ, 482, 913
Governato, F., Willman, B., Mayer, L., Brooks, A., Stinson, G., Valenzuela, O., Wadsley, J., & Quinn, T. 2007, MNRAS, 374, 1479
Hammer, F., Flores, H., Elbaz, D., Zheng, X. Z., Liang, Y. C., & Cesarsky, C. 2005, A&A, 430, 115
Hopkins, P. F., Hernquist, L., Cox, T. J., Robertson, B., & Springel, V. 2006a, ApJS, 163, 50
Hopkins, P. F., Narayan, R., & Hernquist, L. 2006b, ApJ, 643, 641
Ibata, R., Chapman, S., Ferguson, A. M. N., Irwin, M., Lewis, G., & McConnachie, A. 2004, MNRAS, 351, 117
Ibata, R., Chapman, S., Ferguson, A. M. N., Lewis, G., Irwin, M., & Tanvir, N. 2005, ApJ, 634, 287
Ibata, R., Gilmore, G., & Irwin, M. 1994, Nature, 370, 194
Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001, Nature, 412, 49
Irwin, M. J., Ferguson, A. M. N., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2005, ApJ, 628, L105
Jimenez, R., Bernardi, M., Haiman, Z., Panter, B., & Heavens, A. F. 2006, ApJ, submitted (astro-ph/0610724)
Jordi, K., Grebel, E. K., & Ammon, K. 2006, A&A, 460, 339
Kalirai, J. S., et al. 2006, ApJ, 648, 389
Kent, S. 1983, ApJ, 266, 562
Kent, S. M., Dame, T. M., & Fazio, G. 1991, ApJ, 378, 131
Kerr, F. J., & Lynden-Bell, D. 1986, MNRAS, 221, 1023
Larson, R. B. 1976, MNRAS, 176, 31
Le Fèvre, O., et al. 2000, MNRAS, 311, 565
Lecureur, A., Hill, V., Zoccali, M., Barbuy, B., Gomez, A., Minniti, D., Ortolani, S., & Renzini, A. 2007, A&A, 465, 799
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, ApJ, 417, 553
Liang, Y. C., Hammer, F., & Flores, H. 2006, A&A, 447, 113
Lotz, J. M., Madau, P., Giavalisco, M., Primack, J., & Ferguson, H. C. 2006, ApJ, 636, 592
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. 2003, ApJ, 599, 1082
McConnachie, A. W., Irwin, M. J., Ferguson, A. M. N., Ibata, R. A., Lewis, G. F., & Tanvir, N. 2005, MNRAS, 356, 979
McGaugh, S. S. 2005, ApJ, 632, 859
Melbourne, J., Koo, D. C., & Le Floc'h, E. 2005, ApJ, 632, L65
Mendez, R., & van Altena, W. 1998, A&A, 330, 910
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319
Morrison, H. L., Harding, P., Hurley-Keller, D., & Jacoby, G. 2003, ApJ, 596, L183
Morrison, H., Harding, P., Perrett, K., & Hurley-Keller, D. 2004, ApJ, 603, 87
Mouhcine, M., Bamford, S. P., Aragón-Salamanca, A., Nakamura, O., & Milvang-Jensen, B. 2006, MNRAS, 369, 891
Mould, J., & Kristian, M. 1986, ApJ, 305, 591
Naab, T., & Ostriker, J. P. 2006, MNRAS, 366, 899
Ng, Y. K., Bertelli, G., Chiosi, C., & Bressan, A. 1997, A&A, 324, 65
Ojha, D. K., Bienaymé, O., Robin, A. C., Creze, M., & Mohan, V. 1996, A&A, 311, 456
Olling, R., & Merrifield, M. 1998, MNRAS, 297, 943
Ortiz, R., & Lepine, J. 1993, A&A, 279, 90
Pizagno, J., et al. 2005, ApJ, 633, 844
———. 2006, AJ, submitted (astro-ph/0608472)
Porcel, C., Garzon, F., Jimenez-Vicente, J., & Battaner, E. 1998, A&A, 330, 136
Prantzos, N. 2006, preprint (astro-ph/0611476)
Pritchett, C., & van den Bergh, S. 1994, AJ, 107, 1730
Puech, M., Hammer, F., Flores, H., Östlin, G., & Marquart, T. 2006, A&A, 455, 119
Puech, M., Hammer, F., Lehnert, M., & Flores, H. 2007, A&A, 466, 83
Reid, M. 1993, ARA&A, 31, 345
Reid, M., & Brunthaler, A. 2004, ApJ, 616, 872
Renda, A., Gibson, B. K., Mouhcine, M., Ibata, R., Kawata, D., Flynn, C., & Brook, C. B. 2005, MNRAS, 363, L16
Reylé, C., & Robin, A. 2001, A&A, 373, 886
Rich, R. M., Mighell, K. J., & Neil, J. D. 1996, in ASP Conf. Ser. 92, Formation of the Galactic Halo . . . Inside and Out, ed. H. Morrison & A. Sarajedini (San Francisco: ASP), 544
Robertson, B., Bullock, J. S., Cox, T. J., Di Matteo, T., Hernquist, L., Springel, V., & Yoshida, N. 2006, ApJ, 645, 986
Robin, A. C., Creze, M., & Mohan, V. 1992, A&A, 265, 32
Ruphy, S., Robin, A. C., Epchtein, N., Copet, E., Bertin, E., Fouqué, P., & Gugliemo, F. 1996, A&A, 313, L21
Sackett, P. D. 1997, ApJ, 483, 103
Schweizer, F. 2006, in Globular Clusters: Guides to Galaxies, ed. T. Richtler & S. Larsen (New York: Springer), in press (astro-ph/0606036)
Seigar, M. S., Barth, A. J., & Bullock, J. S. 2006, ApJ, submitted (astro-ph/0612228)
Sirko, E., et al. 2004, AJ, 127, 914
Somerville, R. S., Primack, J. R., & Faber, S. M. 2001, MNRAS, 320, 504
Spergel, D. N., Malhotra, S., & Blitz, L. 1996, Spiral Galaxies in the Near-IR, ed. D. Minniti & H.-W. Rix (Garching: ESO)
Springel, V., & Hernquist, L. 2005, ApJ, 622, L9
Steinmetz, M., & Navarro, J. 1999, ApJ, 513, 555
Thomas, D., Maraston, C., & Bender, R. 2003, MNRAS, 339, 897
Toth, G., & Ostriker, J. P. 1992, ApJ, 389, 5
Tremaine, S., et al. 2002, ApJ, 574, 740
Tully, R. B., Pierce, M. J., Huang, J.-S., Saunders, W., Verheijen, M. A. W., & Witchalls, P. L. 1998, AJ, 115, 2264
Tully, R. B., Verheijen, M. A. W., Pierce, M. J., Huang, J.-S., & Wainscoat, R. J. 1996, AJ, 112, 2471
Uemura, M., Ohashi, H., Hayakawa, T., Ishida, E., Kato, T., & Hirata, R. 2000, PASJ, 52, 143
van den Bergh, S., Cohen, J. G., & Crabbe, C. 2001, AJ, 122, 611
Verheijen, M. A. W. 2001, ApJ, 563, 694
Walterbos, R. A. M., & Kennicutt, R. C., Jr. 1987, A&AS, 69, 311
Zheng, X. Z., Hammer, F., Flores, H., Assémat, F., & Rawat, A. 2005, A&A, 435, 507
Zibetti, S., White, S. D. M., & Brinkmann, J. 2004, MNRAS, 347, 556
Zoccali, M., et al. 2006, A&A, 457, L1