Local Group Galaxies from an External Perspective

S. S. McGaugh

Case Western Reserve University, 10900 Euclid Ave., Cleveland, OH, USA
email: stacy.mcgaugh@case.edu

Abstract. I discuss Local Group galaxies from the perspective of external galaxies that define benchmark scaling relations. Making use of this information leads to a model for the Milky Way that includes bumps and wiggles due to spiral arms. This model reconciles the terminal velocities observed in the interstellar medium with the rotation curve derived from stars, correctly predicts the gradual decline of the outer rotation curve, and extrapolates well out to 50 kpc. Rotationally supported Local Group galaxies are in excellent agreement with the baryonic Tully-Fisher relation. Pressure supported dwarfs that are the most likely to be in dynamical equilibrium also align with this relation. Local Group galaxies thus appear to be normal members of the low redshift galaxy population. There is, however, a serious tension between the dynamical masses of the Milky Way and M31 and those expected from the stellar masshalo mass relation of abundance matching.

Keywords. Local Group (929), Milky Way Galaxy (1054), Dwarf galaxies (416), Galaxy masses (607)

---

1. Introduction

Local Group galaxies are accessible to detailed study with large samples of individual stars. This information is complemented by information from external galaxies, which obey strong kinematic scaling relations (McGaugh et al. 2020; Lelli 2022). These include the Baryonic Tully-Fisher Relation (BTFR: Schombert et al. 2020), the Central Density Relation (Lelli et al. 2016), and the Radial Acceleration Relation (RAR: McGaugh et al. 2016; Lelli et al. 2017). Local Group galaxies prove to be completely normal members of the general galaxy population by these standards.

2. The Milky Way

The Milky Way is of obvious interest as our home galaxy, yet our place within it is a source of constant frustration: we cannot see it from 'above' as we do external spirals. We nevertheless infer that it is a barred spiral thanks to decades of work employing a broad spectrum of methods (Bland-Hawthorn & Gerhard 2016). In external galaxies, spiral features cause bumps and wiggles in the light profile that correspond to features in the rotation curve (Sancisi 2004). This correspondence is quantified by the RAR.

The RAR can be applied to the Milky Way to build a mass model for the stellar disk (McGaugh 2016). The terminal velocities observed by McClure-Griffiths & Dickey (2007) and McClure-Griffiths & Dickey (2016) were fit in detail between $3 < R < 8$ kpc. The resulting model is shown in Fig. 1, updated to the distance scale (McGaugh 2018) indicated by the GRAVITY Collaboration (2018).

Fig. 2 shows the surface density corresponding to the rotation curve seen in Fig. 1. The model has bumps and wiggles in the profile that are reminiscent of those seen in
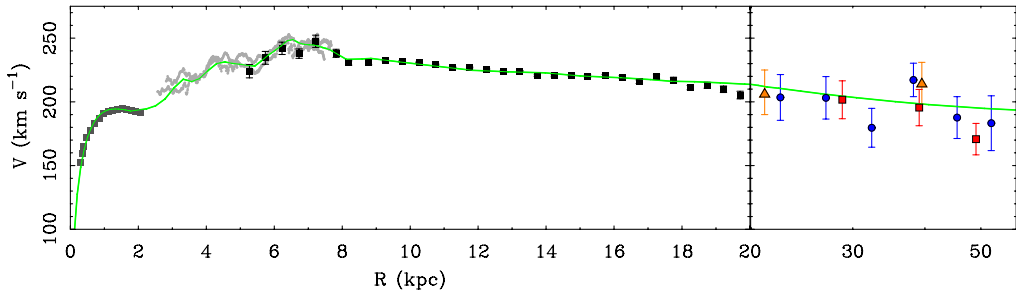
Figure 1. The rotation curve of the Milky Way. Light gray points are the terminal velocity data (McClure-Griffiths & Dickey 2007, 2016) to which the model was fit (McGaugh 2018, green line). The model was not fit to the data of Portail et al. (2017) (dark gray squares at $R < 2.2$ kpc) or Eilers et al. (2019) (black squares), but is nicely consistent with them (McGaugh 2019). It also extrapolates well out to 50 kpc as traced by K giants (red squares) and BHB stars (blue circles) (Bird et al. 2022) and by globular clusters (Watkins et al. 2019, orange triangles).
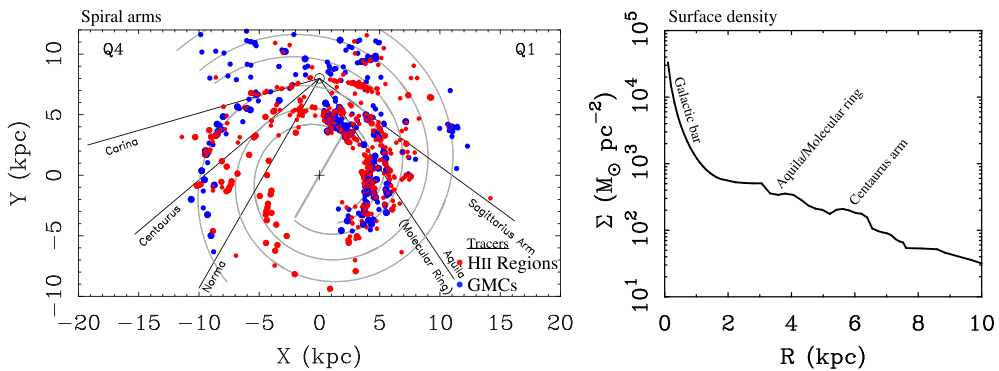

Figure 2. Spiral structure (left) and surface density profile (right) of the Milky Way. The bumps and wiggles inferred kinematically correspond well to the features known from tracers like HII regions (red points) and Giant Molecular Clouds (blue points) (McGaugh 2016).

external spirals. Indeed, these kinematically inferred features correspond well to spiral arms that are known from traditional tracers (Fig. 2).

The model (McGaugh 2018) correctly predicted the slope $dV/dR = -1.7\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ of the outer rotation curve subsequently found by Eilers et al. (2019). It extrapolates well to data for globular clusters (Watkins et al. 2019) and halo stars (Bird et al. 2022) at still larger radii, and is nicely consistent with the inner mass distribution inferred by Portail et al. (2017) without that region having been specifically fit. This is a testament to how tightly the mass distribution is coupled to that of the light: the latter is predictive of the former (McGaugh 2020).

The stellar rotation curve derived by Eilers et al. (2019) is formally discrepant from the terminal velocities (McClure-Griffiths & Dickey 2007) at high significance. The model reconciles the two through numerical evaluation of the tracer term $\partial \ln \nu / \partial \ln r$ in the Jeans equation (McGaugh 2019). The apparent discrepancy is an artifact of the usual assumption of an exponential disk, which does not account for the bumps and wiggles in $\nu(r)$. Galactic data have reached a level of precision that these can no longer be neglected.

We can query the model for the halo mass it implies (Table 1). To be specific, I quote M_{200} for the standardization it provides, and the estimate I obtain is consistent with the range found by others (Wang et al. 2020). However, we should bear in mind that this mass is a rather notional quantity that involves an extrapolation to a radius that

Table 1. Mass Estimates.

Object	Model	M_* $10^{10}\,\mathrm{M_\odot}$	M_{200} $10^{10}\,\mathrm{M_\odot}$	c	V_{200} $\mathrm{km\,s^{-1}}$	Ref.
Milky Way	NFW from RAR	6.2	139	8.1	162	McGaugh (2018)
M31	NFW+SSP	13.5	160	10.1	169	Chemin et al. (2009)
M31+MW	Straight sum	19.7	299	. . .	. . .	McGaugh & van Dokkum (2021)

is not directly constrained by data using a model (Navarro et al. 1997) that persistently provides a poor depiction of observational reality.

A more robust quantity is the enclosed mass $M(R < 50\,\mathrm{kpc}) = 44 \times 10^{10}\,\mathrm{M_\odot}$. This agrees well with halo star (Bird et al. 2022) and globular cluster (Watkins et al. 2019) data. Going farther out is complicated by the perturbing influence of the LMC. Indeed, if we take seriously the downturn in the Gaia-derived rotation curve at $R \approx 19\,\mathrm{kpc}$ (Wang et al. 2023), a much lower mass is obtained (Sylos Labini et al. 2023). It is difficult to envision a model that is consistent with both this downturn and the data for halo stars.

Even in the absence of these considerations, the total mass of the Milky Way remains a fraught issue. Weak lensing observations of external galaxies (Brouwer et al. 2021) indicate that rotation curves persist in being approximately flat to hundreds of kpc, reaching beyond the expected virial radii of bright spirals. This is not consistent with an NFW profile, but it is consistent with the RAR, which is what works well above. These are not the same.

3. The Local Group

The Milky Way falls on the BTFR defined by external galaxies (Fig. 3). Indeed, all of the rotationally supported Local Group galaxies do so, within the uncertainties: there is no indication that they are abnormal in this regard. This provides both a constraint— nothing particularly peculiar is permitted—and an opportunity: if we can calibrate the dynamical masses of Local Group galaxies, we can infer those of more distant galaxies.

3.1. *Dwarf Spheroidal Galaxies and Tully-Fisher*

The BTFR may further serve as a method to unite the mass scales of pressure supported early type dwarf galaxies with their rotationally supported late type brethren. Typically we measure only a single, bulk velocity dispersion σ_* for dwarf spheroidals. The dwarf spheroidals of the Local Group fall into two populations in the BTFR plane (McGaugh & Wolf 2010): the L-σ_* data for classical dwarfs parallels the BTFR, while for the ultrafaint dwarfs σ_* is uncorrelated with L, seeming to hit a floor. As a consequence of their relatively high velocity dispersions, the latter appear to be very dense and hence safe from tidal influences (Pace et al. 2022). This may be an illusion of the assumption of dynamical equilibrium, as it seems unlikely that these tiny dwarfs can survive unmolested deep in the potential well of the Milky Way while the Milky Way itself is being strongly perturbed by the LMC. Excepting the (primarily ultrafaint) dwarfs that may be subject to tidal influence by the criterion of Bellazzini et al. (1996), the remaining dwarfs of the Local Group fall nicely on the BTFR defined by rotating galaxies given a simple transformation $M_* = \Upsilon_* L_V$ and $V_f = \beta_c \sigma_*$ with $\log \beta_c = 0.25 \log \Upsilon_* + 0.226$ (McGaugh et al. 2021). This works out to $\beta_c = 2$ for $\Upsilon_* = 2\,\mathrm{M_\odot/L_\odot}$. This quantifies the circular velocity
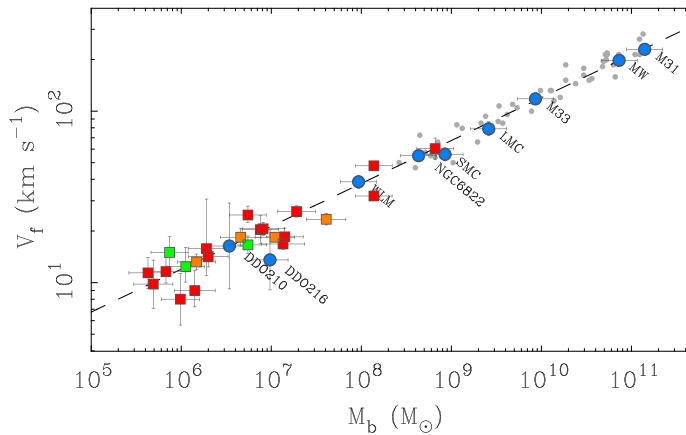
Figure 3. The baryonic TullyFisher relation of Local Group galaxies (blue circles) follows that defined by external galaxies (grey points Schombert et al. 2020). This extrapolates to pressure supported dwarfs (squares) when $V_f = 2\sigma_*$ (McGaugh et al. 2021). Red squares are satellites of M31, orange squares are satellites of the Milky Way; green squares are unaffiliated (McConnachie et al. 2021).

that is equivalent to the line of sight velocity dispersion in an average sense. The strong regularity seen in Fig. 3 is surely teaching us something about the dynamical masses of galaxies.

3.2. *Kinematic Masses and Abundance Matching*

A common method for relating the observed stellar masses of galaxies with their host dark matter halos is Abundance Matching (AM: Behroozi et al. 2013; Moster et al. 2013; Kravtsov et al. 2018; Mowla et al. 2019). Indeed, this has become an essential ingredient for understanding galaxies in ΛCDM. The Local Group provides an ideal opportunity to test these relations with independent kinematic data.

Typical AM relations are well calibrated around the knee of the luminosity function, but not to the very low masses of dwarf spheroidals (Bullock & Boylan-Kolchin 2017). The agreement between kinematic mass estimates and AM masses is reasonably good for intermediate mass galaxies like M33. The two diverge dramatically for the brightest galaxies of the Local Group, M31 and the Milky Way (Table 1 and Fig. 4)

Dynamical studies typically suggest that the total mass of the Milky Way is in the range of 0.5—$2 \times 10^{12}\,M_\odot$ (Bland-Hawthorn & Gerhard 2016; Wang et al. 2020). A similar range holds for Andromeda (Chemin et al. 2009; Kafle et al. 2018). AM predicts considerably higher masses: $\sim 3 \times 10^{12}\,M_\odot$ for the Milky Way and $> 10^{13}\,M_\odot$ for M31. There is some room to hedge this for the Milky Way by adopting a stellar mass on the low end of the plausible range, but even then the halo mass is abnormally low. The result for Andromeda differs by an order of magnitude. There is of course some scatter in the stellar mass–halo mass relation from AM, but it is not sufficient to explain this stark discrepancy.

According to AM, a galaxy the mass of M31 should be the central object of a much larger group. Indeed, for its stellar mass, the Milky Way should be the central object of the Local Group. Andromeda should not be here. Despite its normalcy in other respects, the Local Group has far too many stars for its mass from the perspective of abundance matching.
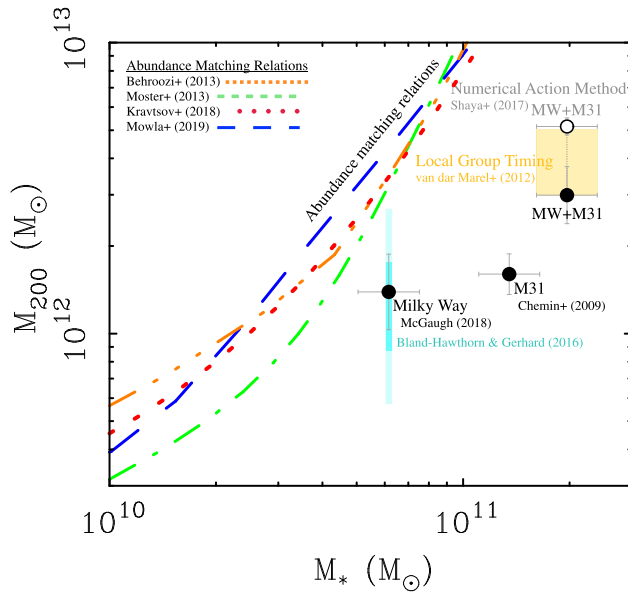
Figure 4. Stellar mass–halo mass relations in the context of the Local Group (McGaugh & van Dokkum 2021). Filled points are from rotation curve fits to the Milky Way (McGaugh 2018), M31 (Chemin et al. 2009), and their sum (Table 1). The open circle adopts for the summed total mass that estimated by Shaya et al. (2017). The blue band shows range of Milky Way mass estimates (Bland-Hawthorn & Gerhard 2016; Wang et al. 2020). Lines are the stellar masshalo mass relations from abundance matching Behroozi et al. (2013); Moster et al. (2013); Kravtsov et al. (2018); Mowla et al. (2019). The yellow box shows the timing mass of the Local Group (van der Marel et al. 2012). There is a pronounced discrepancy between dynamical and abundance matching estimates of the halo masses of the Local Group and its brightest members.

It is not clear what the resolution of this issue might be. There could be a morphological type dependence that is not accounted for in the AM relations considered here. There might be more mass at large radii than kinematic tracers have so far revealed, though this is limited by the timing argument (van der Marel et al. 2012; Peñarrubia et al. 2014; Shaya et al. 2017). The discrepancy appears to be real, and would hardly be the first indication of a problem with the dark matter paradigm in the dynamics of galaxies (Sanders & McGaugh 2002; Famaey & McGaugh 2012; McGaugh 2020; Banik & Zhao 2022).

References

Banik, I. & Zhao, H. 2022, Symmetry, 14, 1331

Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, Astrophys. J., 762, L31

Bellazzini, M., Fusi Pecci, F., & Ferraro, F. R. 1996, Mon. Not. Royal Astron. Soc., 278, 947

Bird, S. A., Xue, X.-X., Liu, C., et al. 2022, Mon. Not. Royal Astron. Soc., 516, 731

Bland-Hawthorn, J. & Gerhard, O. 2016, Ann. Rev. Astron. & Astrophys., 54, 529

Brouwer, M. M., Oman, K. A., Valentijn, E. A., et al. 2021, A & A, 650, A113

Bullock, J. S. & Boylan-Kolchin, M. 2017, Ann. Rev. Astron. & Astrophys., 55, 343

Chemin, L., Carignan, C., & Foster, T. 2009, Astrophys. J., 705, 1395

Eilers, A.-C., Hogg, D. W., Rix, H.-W., et al. 2019, Astrophys. J., 871, 120

Famaey, B. & McGaugh, S. S. 2012, Living Reviews in Relativity, 15, 10

GRAVITY Collaboration, Abuter, R., Amorim, A., et al. 2018, A & A, 615, L15

Kafle, P. R., Sharma, S., Lewis, G. F., et al. 2018, Mon. Not. Royal Astron. Soc., 475, 4043

Kravtsov, A. V., Vikhlinin, A. A., & Meshcheryakov, A. V. 2018, Astronomy Letters, 44, 8

Lelli, F., McGaugh, S. S., Schombert, J. M., et al. 2016, Astrophys. J., 827, L19

Lelli, F., McGaugh, S. S., Schombert, J. M., et al. 2017, Astrophys. J., 836, 152

Lelli, F. 2022, Nature Astronomy, 6, 35

McClure-Griffiths, N. M. & Dickey, J. M. 2007, Astrophys. J., 671, 427

McClure-Griffiths, N. M. & Dickey, J. M. 2016, Astrophys. J., 831, 124

McConnachie, A. W., Higgs, C. R., Thomas, G. F., et al. 2021, Mon. Not. Royal Astron. Soc., 501, 2363

McGaugh, S. S. 2016, Astrophys. J., 816, 42

McGaugh, S. S. 2018, Research Notes of the American Astronomical Society, 2, 156

McGaugh, S. S. 2019, Astrophys. J., 885, 87

McGaugh, S. 2020, Galaxies, 8, 35

McGaugh, S., Lelli, F., Li, P., et al. 2020, Galactic Dynamics in the Era of Large Surveys, 353, 144

McGaugh, S. S., Lelli, F., & Schombert, J. M. 2016, Phys. Rev. Lett., 117, 201101

McGaugh, S. S., Lelli, F., Schombert, J. M., et al. 2021, Astron. J., 162, 202

McGaugh, S. S. & van Dokkum, P. 2021, Research Notes of the American Astronomical Society, 5, 23

McGaugh, S. S. & Wolf, J. 2010, Astrophys. J., 722, 248

Milgrom, M. 1983, Astrophys. J., 270, 371

Moster, B. P., Naab, T., & White, S. D. M. 2013, Mon. Not. Royal Astron. Soc., 428, 3121

Mowla, L., van der Wel, A., van Dokkum, P., et al. 2019, Astrophys. J., 872, L13

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, Astrophys. J., 490, 493

Pace, A. B., Erkal, D., & Li, T. S. 2022, Astrophys. J., 940, 136

Peñarrubia, J., Ma, Y.-Z., Walker, M. G., et al. 2014, Mon. Not. Royal Astron. Soc., 443, 2204

Portail, M., Gerhard, O., Wegg, C., et al. 2017, Mon. Not. Royal Astron. Soc., 465, 1621

Sancisi, R. 2004, Dark Matter in Galaxies, 220, 233

Sanders, R. H. & McGaugh, S. S. 2002, Ann. Rev. Astron. & Astrophys., 40, 263

Schombert, J., McGaugh, S., & Lelli, F. 2020, Astron. J., 160, 71

Shaya, E. J., Tully, R. B., Hoffman, Y., et al. 2017, Astrophys. J., 850, 207

Sylos Labini, F., Chrobáková, Ž., Capuzzo-Dolcetta, R., et al. 2023, Astrophys. J., 945, 3

van der Marel, R. P., Fardal, M., Besla, G., et al. 2012, Astrophys. J., 753, 8

Wang, W., Han, J., Cautun, M., et al. 2020, Science China Physics, Mechanics, and Astronomy, 63, 109801

Wang, H.-F., Chrobáková, Ž., López-Corredoira, M., et al. 2023, Astrophys. J., 942, 12

Watkins, L. L., van der Marel, R. P., Sohn, S. T., et al. 2019, Astrophys. J., 873, 118

Discussion

Müller: What is the reason for these strong regularities?

McGaugh: This behavior was predicted by MOND (Milgrom 1983).