Could the Magellanic Clouds be tidal dwarves expelled from a past-merger event occurring in Andromeda?

Y. Yang[1,2]

and

F. Hammer[2]

ABSTRACT

The Magellanic Clouds are often considered as outliers in the satellite system of the Milky Way because they are irregular and gas-rich galaxies. From their large relative motion, they are likely from their first pass near the Milky Way, possibly originating from another region of the Local Group or its outskirts. M31 could have been in a merger stage in its past and we investigate whether or not the Large Magellanic Cloud could have been a tidal dwarf expelled during this event. Such an hypothesis is tested in the frame of present-day measurements and uncertainties of the relative motions of LMC and M31. Our method is to trace back the LMC trajectory using several thousands of different configurations that sample the corresponding parameter space.

We find several configurations that let LMC at 50 kpc from M31, 4.3 to 8 Gyrs ago , depending on the adopted shape of the Milky Way halo. For all configurations, the LMC velocity at such a location is invariably slightly larger than the escape velocity at such a radius. The preferred solutions correspond to a spherical to prolate Milky Way halo, predicting a transversal motion of M31 of less than 107 $\mathrm{km\,s^{-1}}$and down to values that are close to zero. We conclude that from present-day measurements, Magellanic Clouds could well be tidal dwarves expelled from a former merger events occurring in M31.

Subject headings: Galaxies: Local Group - Galaxies: Magellanic Clouds - Galaxies: evolution - Galaxies: dwarf - Galaxies: kinematics and dynamics - Galaxies: interactions

---

[1]Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

[2]GEPI, Observatoire de Paris, CNRS, Université Paris Diderot; 5 Place Jules Janssen, Meudon, France

1. INTRODUCTION

The origin of the Magellanic Clouds, as well as the nearby satellite galaxies of the Milky Way (MW), is still a matter of debate (Besla et al. 2007; Peebles 2009; Kallivayalil et al. 2009; Metz et al. 2008, 2009). The discussion is motivated by the accurate determination of the Clouds' proper motions that were carried out from the Hubble Space Telescope (HST) observations by Kallivayalil et al. (2006a,b). The total velocity of the Large Magellanic Cloud (LMC) in the Galactocentic coordinate is claimed be 378 $\mathrm{km\,s^{-1}}$ (a transverse velocity of $v_{\rm tan}$ = 367 $\mathrm{km\,s^{-1}}$ and a radial velocity of $v_{\rm rad}$ = 89 $\mathrm{km\,s^{-1}}$). Although the revised analysis by Piatek et al. (2008) decreases the transverse velocity to 346 $\mathrm{km\,s^{-1}}$, both of the results from HST data are significantly higher than the previously adopted value, i.e., 281 $\mathrm{km\,s^{-1}}$ (van der Marel et al. 2002). At such a high speed, LMC may approach the escape velocity at its distance to the MW and the orbital angular momenta is comparable and nearly perpendicular to the angular momentum of the MW disk (Kallivayalil et al. 2009). This may argue for a first passage of the Magellanic Clouds near the Milky Way (see e.g., Besla et al. 2007). The fact that their morphologies and gas content is at odd with other satellites also suggest that they recently falls to the Milky Way from the outskirts of the Local Group (van den Bergh 2006).

Kallivayalil et al. (2009) construct a model for the Local Group, including Andromeda (M31), the MW and the LMC. By solving the equations of motion, they find that M31 may have affected the orbit of LMC at a distance of 500 - 700 kpc about 5 Gyrs ago. Although Besla et al. (2007) did not investigate the origin of LMC by their models, one interesting orbit of LMC is worth to mention here. In their Fig. 14, the orbit under the model of prolate MW halo turns close to the direction of M31. The proposition that Magellanic Clouds may originate from M31 was firstly made by Raychaudhury & Lynden-Bell (1989), Byrd et al. (1994) and Shuter (1992).

This *Letter* revisits this proposition in the frame of the recent discoveries of large scale structures surrounding M31 suggesting a very tumultuous past history for this galaxy (Ibata et al. 2001, 2004; Brown et al. 2008). We are still lacking of a complete model of M31 outskirts although many of its properties are consistent with a past major merger (Hammer et al. 2007; Bekki 2010). If true, such a merger should have been gaseous rich enough to allow the reformation of the significant M31 disk (Hammer et al. 2005, 2009). During such events gas-rich dwarf galaxies may be formed from material liberated by the collision (Okazaki & Taniguchi 2000, and references therein). It is natural to wonder whether or not some tidal dwarf galaxies may have been ejected close to the orbital plane of the hypothetic merger, which is indeed defined by the actual M31 disk. A significant part of the ejected material have angular momentum within small angles from the orbital angular momentum. The M31 disk is seen almost edge-on from the Milky Way, suggesting that the Milky Way is located close to the orbital plane of the debris ejected from a major merger of M31. This may lead to a fully new interpretation of the Magellanic Clouds, that could be tidal dwarves, as massive and concentrated debris lying in a tidal tail ejected during a past event in M31, in the direction of the Milky Way. In fact, Hammer et al. (2010) propose a major model for the formation of M31 which reproduces most of its properties including those of its haunted halo; for *some* solutions, a significant amount of matter is predicted to be ejected from the merger in the direction of the Milky Way.

The goal of this *Letter* is to test whether the Magellanic Clouds could have been tidal dwarves ejected during a past major merger occurring at the M31 location. The robust measurements of LMC proper motion give a very strong constrain on its origin by inverting its past trajectory (e.g., Kallivayalil et al. 2009). On the other hand, there is a large uncertainty in the determination of the tangential motion of M31, up to $\pm150\,\mathrm{km\,s^{-1}}$, (see Peebles et al. 2001; Loeb et al. 2005; van der Marel & Guhathakurta 2008). Taking into account all uncertainties, we investigate the possible trajectories of the LMC and whether or not it could have approached M31 down to 50 kpc. We solve the equations of motion in a dynamical model including MW, M31 and LMC, and throughout the paper, all the 3D coordinates, velocities are quoted in the Galactocentric frame that is centered on the MW (van der Marel et al. 2002). We adopt the concordance cosmological parameters of $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$.

2. Analysis

Fig. 1 shows the 3D positions of the MW, M31 and LMC. A possible unbound trajectory of LMC in the past is also shown by assuming a zero transverse velocity of M31 for our model described below (Sect. 2.1). This solution is similar to the results presented by Kallivayalil et al. (2009). Given the fact of large uncertainties in the determination of tangential motion of M31, up to $\pm150\,\mathrm{km\,s^{-1}}$ (see above text), one can expect that M31 could have a $v_x < 0$ at present time, meaning that M31 was closer to the past trajectory of LMC. The 3D velocity of M31 can be linked to its proper motion on sky by following the work by van der Marel et al. (2002). We adopt the standard IAU values, i.e., $R_0 = 8.5$ kpc and $V_0 = 220\ \ \mathrm{km\,s^{-1}}$ for the circular velocity (Kerr & Lynden-Bell 1986), and the solar motion with respect to the local standard of rest is corrected by taking $(U_\odot, V_\odot, W_\odot) = (10.0 \pm 0.4, 5.2 \pm 0.6, 7.2 \pm 0.4)$ $\mathrm{km\,s^{-1}}$ (Dehnen & Binney 1998). The basic data adopted for M31 are listed in Table 1, as well as the data for LMC. In the following, we build a dynamical model of MW, M31 and LMC, then investigate the possible proper

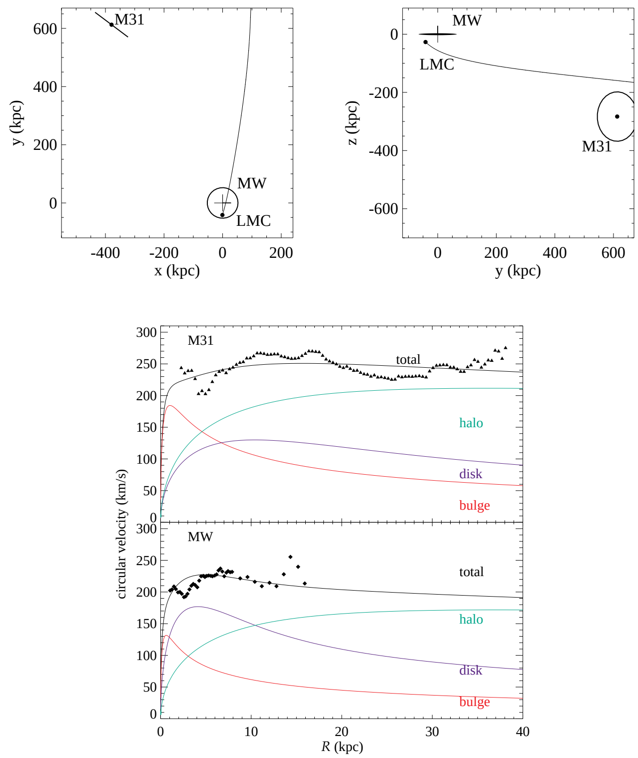

Fig. 1.— *Upper panels*: 3D positions of the MW, M31, LMC. The left panel shows the projection in x-y plane while the right panel in y-z plane. The solid lines indicate a possible unbound trajectory of LMC in the past. *Middle panel*: the rotation curves of M31. The triangles are the measured rotation curve from HI observation (Chemin et al. 2009). The red, blue, green and black are the rotation curve of bulge, disk, halo the total of them, respectively (Sect. 2.1). *Lower panel*: the rotation curves of MW. The diamonds are from HI observation by Knapp et al. (1985).

Table 1: Basic parameters

Parameter	M31	LMC
(l, b)	$(121.174, -21.573)$[a]	$(280.531, -32.523)$[b]
$(\mu_{\rm W}, \mu_{\rm N})$ ($\rm mas\,yr^{-1}$)	to be investigated	$(-2.03 \pm 0.08, 0.44 \pm 0.05)$[c]
$v_{\rm sys}$ ($\rm km\,s^{-1}$)	-301[d]	262.2[b]
D_0 (kpc)	770[e]	50.1[f]

[a] NED. [b] van der Marel et al. (2002). [c] Kallivayalil et al. (2006a). [d] Courteau & van den Bergh (1999). [e] van der Marel & Guhathakurta (2008). [f] Kallivayalil et al. (2009).

motions of M31 and its impact on the LMC origin.

Table 2: Model parameters

Parameter	MW	M31	LMC
$M_{\rm virial}$ ($10^{12}M_{\odot}$)	1.0[a]	1.6[a]	—
$R_{\rm virial}$ (kpc)	258[b]	300[b]	—
c[c]	15	18	—
$M_{\rm baryon}$ ($10^{10}M_{\odot}$)	5.6[d]	10.9[d]	2.0
B/T[e]	0.15	0.3	—
$a_{\rm b}$ (kpc)	0.62	1.0	—
$r_{\rm d}$ (kpc)	2.3[d]	5.8[d]	—

[a] Data are from Besla et al. (2007). [b] Data are from Klypin et al. (2002). [c] The concentration of the NFW profile. [d] Data are from Hammer et al. (2007). [e] B/T is defined as the mass ratio of bulge to the total baryon mass.

2.1. Dynamical model

Following Besla et al. (2007) and Kallivayalil et al. (2009), we constructed a model of the MW, M31 and of the LMC, the latter being considered as a point mass with a total mass of $2 \times 10^{10} M_{\odot}$. For both the MW and M31 we adopt a model consisting of a NFW halo (Navarro et al. 1997), a Hernquist bulge (Hernquist 1990) and an exponential disk. Then the total gravitational potential of the galaxy model is the sum-up of the three components (Hayashi et al. 2007; Shattow & Loeb 2009):

$$\phi(r) = \phi_{\rm b}(r) + \phi_{\rm d}(r) + \phi_{\rm h}(r), \tag{1}$$

$$\phi_{\rm b}(r) = -\frac{GM_{\rm b}}{r + a_{\rm b}}, \tag{2}$$

$$\phi_{\rm d}(r) = -\frac{GM_{\rm d}(1 - e^{-\frac{r}{R_d}})}{r}, \tag{3}$$

$$\phi_{\rm h}(r) = -\frac{GM_{\rm vir}/r_{\rm s}}{\ln(1+c) - c/(1+c)} \frac{\ln(1 + r/r_{\rm s})}{r/r_{\rm s}}, \tag{4}$$

where the subscript b, d, and h denote bulge, disk and halo, respectively; $a_{\rm b}$ the scale length of Hernquist profile; R_d the scale length of disk; c and $r_{\rm s}$ the concentration and scale length of the NFW profile. The parameters of the model are summarized in Table 2. The models are required to match the rotation curves of the MW and M31, respectively, see Fig. 1.

The equation of motion for each object can be written as:

$$\frac{d^2}{dt^2}\vec{r}_i = \frac{\partial}{\partial \vec{r}_i} \sum_{j \neq i} \phi_j[\mid \vec{r}_i - \vec{r}_j \mid]. \tag{5}$$

Then the trajectories of each object can be solved numerically using the standard method for

N-body simulation in barycentric frame. By choosing a small time step for the integration, it provides us an accuracy down to 0.1% over 10 Gyr, which is precise enough for our discussions.

As mentioned in the introduction, nonspherical halo of MW may have impacted to the trajectory of LMC as seen in (Besla et al. 2007). The cases of non-spherical MW halo can be studied by replacing r in $\phi_{\rm h}(r)$ by $r = \sqrt{R + z^2/q^2}$, where the cylindrical polar coordinates is adopted, q characterizes the axis ratio of halo potential (Hayashi et al. 2007; Besla et al. 2007). For $q > 1$ we refer to a prolate halo while $q < 1$ to an oblate halo.

2.2. Results

We uniformly sampled ∼2000 possible M31 proper motions with the amplitude of [0,0.12] $\rm mas\,yr^{-1}$ and the orientation [0,360] degrees on the sky. We define a reasonable solution by searching when the minimal distance between LMC and M31 can be less than 50 kpc, enough close to be consistent with material ejected from an ancient merger, during the last 10 Gyrs. We do find a group of solution by using the LMC proper motion from Kallivayalil et al. (2006a). The solution of M31 proper motion for a spherical MW halo is:

$$\begin{aligned} \mu_{\rm W} &= -62 \pm 18\,\mu{\rm as\,yr^{-1}}, \\ \mu_{\rm N} &= -25 \pm 13\,\mu{\rm as\,yr^{-1}}, \end{aligned} \tag{6}$$

where the error bar accounts for the error of LMC proper motions, and $\mu_{\rm W}$, $\mu_{\rm N}$ are quoted in the equatorial system as usually used. It corresponds to $v_{\rm rad}$=−128$\rm km\,s^{-1}$ and $v_{\rm tan}$=102$\rm km\,s^{-1}$ for M31 relative to the MW. The averaged time since LMC was ejected from M31 is 5.5 ± 1.4 Gyrs ago. Table 3 summarises the results after assuming different values for the axis ratio of the Milky Way potential. In this Table $v_{\rm tan}$, $T_{\rm travel}$ and v_{50} are averaged values for all the trajectories that put the LMC at 50 kpc from M31 at lookback times indicated by $T_{\rm travel}$. At such a distance from M31 and for all solutions, the relative velocity of LMC to M31 was slightly higher than the escape velocity which is 408 $\rm km\,s^{-1}$, consistently with expectations for material ejected from M31. Note that we define the escape velocity when an object arrives to the intergalactic space, i.e., 600 kpc from M31, between the Milky Way and M31.

In Fig. 2 we show the trajectories of M31 and LMC for the mean solution ($q = 1$). In the right panel of Fig. 2 we show the solutions of M31 proper motion varying with q that correspond to the average of all successful solutions. We have scanned a region of $q = [0.5, 1.5]$ with span of 0.2, i.e., from oblate to prolate (see also Table 3). Note that q is used in potential space, therefore the halo shape in density space would be even more

Table 3: Possible Solutions

q[a]	μ_W	μ_N	v_{rad}[b]	v_{tan}[b,c]	T_{travel}	v_{50}[d]
	(μas yr^{-1})		(km s^{-1})	(km s^{-1})	(Gyr)	(km s^{-1})
0.5	-83 ± 10	01 ± 08	-127	194 ± 44	-4.3 ± 0.5	432
0.7	-77 ± 14	-10 ± 10	-128	160 ± 56	-4.5 ± 0.6	428
0.9	-68 ± 16	-21 ± 14	-128	124 ± 53	-5.1 ± 1.1	423
1.0	-62 ± 18	-25 ± 13	-128	106 ± 63	-5.5 ± 1.4	421
1.1	-56 ± 20	-28 ± 11	-129	89 ± 68	-6.2 ± 1.9	418
1.3	-56 ± 16	-30 ± 09	-129	89 ± 48	-7.8 ± 2.2	417
1.5	-52 ± 15	-32 ± 09	-129	80 ± 46	-7.2 ± 2.3	417

[a] The shape parameter of MW halo. [b] The velocities are given relative to the Milky Way. [c] The error bars actually delineate the solutions regions. [d] The velocity of LMC at 50 kpc to the M31 center.

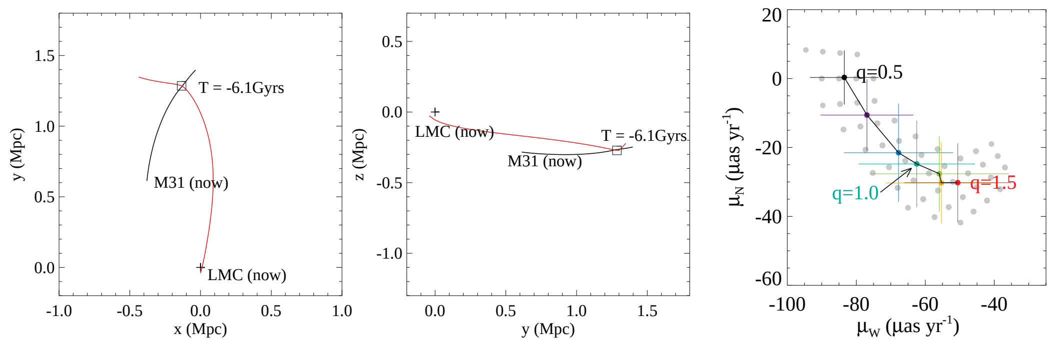

Fig. 2.— *Left and Middle panels*: Trajectories of LMC (red) and M31(black) for the mean solution of a spherical MW halo (Eq. 6). The open boxes indicate the time when LMC is closest to M31. *Right panel*: Possible M31 proper motions that satisfy our hypothesis. The gray dots are all the possible solutions, including by varying of MW shape, i.e., q, and accounting for the measurement errors of the LMC proper motion. The color dots connected by a line indicate the mean value for different q. The bars attached to each point indicate the solution region for each q.

extreme for both prolate and oblate ones.

3. Discussion and Conclusion

Could the Magellanic Clouds be ejected tidal dwarves from a previous major merger occurring at the M31 location? In this letter we simply demonstrate that it could be the case, within a reasonable range of parameters for both the Milky Way and M31. In our study we did not consider the effect of the Small Magellanic Cloud (SMC) to LMC as the former has a much smaller mass than the latter, and as such, our study of the LMC motion can realistically apply to the motion of both Magellanic Clouds together. We have also considered the possible impact of the gravitational potential of both the Virgo cluster and the Great Attractor (see e.g., Lynden-Bell et al. 1988), which are modelled by giant halos of NFW profile and find that they affect very marginally the LMC trajectories. The model presented here is possibly static assuming that only the M31 mass could have increase during the last 8 Gyr, through a major merger, thus neglecting some possible mass accretion of minor mergers. Assuming a smaller mass of M31 in the past (2 times less massive) would generate a larger travel time for the LMC (8 Gyr instead of 5.5 Gyr for our $q = 0$ model).

Besides this, we show that such an hypothesis is possible, although it does not demonstrate that it is indeed the case. To go beyond requires an estimate of several quantities, especially the tangential velocity of M31 and the axis ratio of the Milky Way potential. van der Marel & Guhathakurta (2008) have estimated tangential velocity of M31 to be $\mu_{\rm W} = -22 \pm 12\ \mu{\rm as\,yr^{-1}}$ and $\mu_{\rm N} = -11 \pm 10\ \mu{\rm as\,yr^{-1}}$, i.e. in the same direction than assumed in Eq. 6), but with smaller amplitude. These estimates were based on the assumption that M31 satellites follow the motion of M31 through space. We have tested a null hypothesis for the tangential velocity of M31 and find that it implies a very prolate Milky Way halo with $q = 1.7$. However the van der Marel & Guhathakurta (2008) assumption may not hold in the case of an major merger in the past history of M31 because the orbital motions of its satellite system could be much more chaotic than expected by van der Marel & Guhathakurta (2008). On the other hand, assuming a spherical halo for the Milky Way leads to values for the M31 proper motion which are larger than what is typically quoted, often on the basis of the timing argument. Possibly, the timing argument has to be re-formulated in a scheme for which there were more than 2 bodies with a mass similar to the Milky Way, 6 Gyr ago (see e.g., Hammer et al. 2010).

It is wiser to test our hypothesis by considering observable parameters that are not assuming a specific history for the Local Group satellite system. The result is somewhat troubling. First, by tracing back the LMC motion to M31, it is found that its relative velocity to M31 at 50 kpc is slightly above the escape velocity which is quite expected for tidal material ejected from a merger. Second, the travel time to reach the Milky Way is ranging from 4 to 8 Gyrs, depending on the axis ratio of the Milky Way potential (see Table

3). Hammer et al. (2007) estimated that if M31 have experienced a gaseous rich major merger, it should have occurred 5-8 Gyrs ago on the basis of the age of the M31 disk stars. Indeed in such an event most stars in the rebuilt disk should have ages slightly smaller than the merger look-back time.

The origin of the Magellanic Clouds is still an enigma as they are the only blue, gas rich irregular in the immediate outskirts of the Milky Way. Our proposition has the advantage of explaining them in a consistent way, as being originating from the most massive body in the Local Group that show evidences for a very rich merger history. Future measurements of the M31 transverse velocity (possibly with GAIA) may confirm or infirm its validity. Further modeling of both LMC and SMC could be done to verify whether their internal structures (e.g. the LMC bar) and their star formation history (see e.g., Harris & Zaritsky 2009) can be reproduced. Important tests of our hypothesis may come from better estimates of the dark matter content of the LMC (could it be a tidal dwarf if it has a total mass as adopted by Peebles (2010)?) and from verifying whether it is consistent with the numerous features found in the outskirts of the Milky Way.

We would like to thank the referee for the helpful comments. This work has been supported by the China-France International Associated Laboratory "Origins" and by National Basic Research Program of China (973 Program), No. 2010CB833000. We warmly thank Jim Peebles for enlightening discussions about the motion and mass of the LMC. We would like to thank Mathieu Puech for helpful discussions.

.

REFERENCES

Byrd, G., Valtonen, M., McCall, M., & Innanen, K. 1994, AJ, 107, 2055

Barnes, J. E., & Hernquist, L. 1992, Nature, 360, 715

Besla, G., Kallivayalil, N., Hernquist, L., Robertson, B., Cox, T. J., van der Marel, R. P., & Alcock, C. 2007, ApJ, 668, 949

Bekki, K. 2010, MNRAS, 401, L58

Brown, T. M., et al. 2008, ApJ, 685, L121

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

Courteau, S., & van den Bergh, S. 1999, AJ, 118, 337

Dehnen, W., & Binney, J. J. 1998, MNRAS, 298, 387

Diemand, J., Kuhlen, M., & Madau, P. 2007, ApJ, 667, 859

Hammer, F., Flores, H., Elbaz, D., Zheng, X. Z., Liang, Y. C., & Cesarsky, C. 2005, A&A, 430, 115

Hammer, F., Puech, M., Chemin, L., Flores, H., & Lehnert, M. D. 2007, ApJ, 662, 322

Hammer, F., Flores, H., Puech, M., Yang, Y. B., Athanassoula, E., Rodrigues, M., & Delgado, R. 2009, A&A, 507, 1313

Hammer, F., Yang, Y. B., Wang, J. L., Puech, M., Flores, H., & Fouquet, S., 2010, ApJ, accepted (arXiv:1010.0679v1)

Harris, J., & Zaritsky, D. 2009, AJ, 138, 1243

Hayashi, E., Navarro, J. F., & Springel, V. 2007, MNRAS, 377, 50 ; ref for halo potential

Hernquist, L. 1990, ApJ, 356, 359

Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001, Nature, 412, 49

Ibata, R., Chapman, S., Ferguson, A. M. N., Irwin, M., Lewis, G., & McConnachie, A. 2004, MNRAS, 351, 117

Ibata, R., Martin, N. F., Irwin, M., Chapman, S., Ferguson, A. M. N., Lewis, G. F., & McConnachie, A. W. 2007, ApJ, 671, 1591

Loeb, A., Reid, M. J., Brunthaler, A., & Falcke, H. 2005, ApJ, 633, 894

Lynden-Bell, D., Faber, S. M., Burstein, D., Davies, R. L., Dressler, A., Terlevich, R. J., & Wegner, G. 1988, ApJ, 326, 19

Metz, M., Kroupa, P., & Libeskind, N. I. 2008, ApJ, 680, 287

Metz, M., Kroupa, P., Theis, C., Hensler, G., & Jerjen, H. 2009, ApJ, 697, 269

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

Kallivayalil, N., van der Marel, R. P., Alcock, C., Axelrod, T., Cook, K. H., Drake, A. J., & Geha, M. 2006, ApJ, 638, 772

Kallivayalil, N., van der Marel, R. P., & Alcock, C. 2006, ApJ, 652, 1213

Kallivayalil, N., Besla, G., Sanderson, R., & Alcock, C. 2009, ApJ, 700, 924

Kerr, F. J., & Lynden-Bell, D. 1986, MNRAS, 221, 1023

Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, 573, 597

Knapp, G. R., Turner, E. L., & Cunniffe, P. E. 1985, AJ, 90, 454

Okazaki, T., & Taniguchi, Y. 2000, ApJ, 543, 149

Piatek, S., Pryor, C., & Olszewski, E. W. 2008, AJ, 135, 1024

Peebles, P. J. E., Phelps, S. D., Shaya, E. J., & Tully, R. B. 2001, ApJ, 554, 104

Peebles, P. J. E. 2009, arXiv:0907.5207

Peebles, P. J. E. 2010, arXiv:1009.0496

Raychaudhury, S., & Lynden-Bell, D. 1989, MNRAS, 240, 195

Shattow, G., & Loeb, A. 2009, MNRAS, 392, L21

Shuter, W. L. H. 1992, ApJ, 386, 101

van den Bergh, S. 2006, AJ, 132, 1571

van der Marel, R. P., Alves, D. R., Hardy, E., & Suntzeff, N. B. 2002, AJ, 124, 2639

van der Marel, R. P., & Guhathakurt a, P. 2008, ApJ, 678, 187

Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52