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COULD THE MAGELLANIC CLOUDS BE TIDAL DWARFS EXPELLED FROM A PAST-MERGER EVENT OCCURRING IN ANDROMEDA?

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ABSTRACT

The Magellanic Clouds are often considered to be outliers in the satellite system of the Milky Way (MW) because they are irregular and gas-rich galaxies. From their large relative motion, they are likely in their first pass near the MW, 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 (LMC) could have been a tidal dwarf expelled during this event. Such a 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 place the LMC at 50 kpc from M31, 4.3–8 Gyr ago, depending on the adopted shape of the MW 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 MW halo, predicting a transverse motion of M31 of less than 107 km s^{-1} and down to values that are close to zero. We conclude that from present-day measurements, the Magellanic Clouds could well be tidal dwarfs expelled from a former merger events occurring in M31.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: interactions – galaxies: kinematics and dynamics – Local Group – Magellanic Clouds

Online-only material: color figures

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, 2006b). The total velocity of the Large Magellanic Cloud (LMC) in the Galactocentric coordinate is claimed to be 378 km s^{-1} (a transverse velocity of $v_{\rm tan}$ = 367 km s^{-1} and a radial velocity of $v_{\rm rad}$ = 89 km s^{-1}). Although the revised analysis by Piatek et al. (2008) decreases the transverse velocity to 346 km s^{-1}, both of the results from *HST* data are significantly higher than the previously adopted value, i.e., 281 km s^{-1} (van der Marel et al. 2002). At such a high speed, the 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 MW (see, e.g., Besla et al. 2007). The fact that their morphologies and gas content are at odds with other satellites also suggests that they recently fall to the MW 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 the LMC at a distance of 500–700 kpc about 5 Gyr ago. Although Besla et al. (2007) did not investigate the origin of the LMC with their models, one interesting orbit of the LMC is worth mentioning here. In their Figure 14, the orbit under the model of a prolate MW halo turns close to the direction of M31. The proposition that Magellanic Clouds may originate from M31 was first 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 a complete model of M31's 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 has angular momentum within small angles from the orbital angular momentum. The M31 disk is seen almost edge-on from the MW, suggesting that the MW 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, which could be tidal dwarfs, as massive and concentrated debris lying in a tidal tail ejected during a past event in M31, in the direction of the MW. 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 MW.

The goal of this Letter is to test whether the Magellanic Clouds could have been tidal dwarfs ejected during a past major merger occurring at the M31 location. The robust measurements of LMC proper motion provide a very strong constraint on its

Table 1
Basic Parameters

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

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

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 ± 150 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 Letter all the three-dimensional (3D) coordinate 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

Figure 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 (Section 2.1). This solution is similar to the results presented by Kallivayalil et al. (2009). Given that there are large uncertainties up to ± 150 km s^{-1} (see above) in the determination of the tangential motion of M31, one can expect that M31 could have a $v_x < 0$ at the 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 the 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 $V_0 = 220$ km s^{-1} for the circular velocity (Kerr & Lynden-Bell 1986) and the solar motion with respect to the local standard of rest which is corrected by taking $(U_\odot, V_\odot, W_\odot) = (10.0 \pm 0.4, 5.2 \pm 0.6, 7.2 \pm 0.4)$ km s^{-1} (Dehnen & Binney 1998). The basic data adopted for M31 are listed in Table 1, as well as the data for the LMC. In the following, we build a dynamical model of MW, M31, and LMC, then investigate the possible proper motions of M31 and its impact on the LMC origin.

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 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 Navarro–Frenk–White (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 of the three components (Hayashi et al. 2007; Shattow & Loeb 2009):

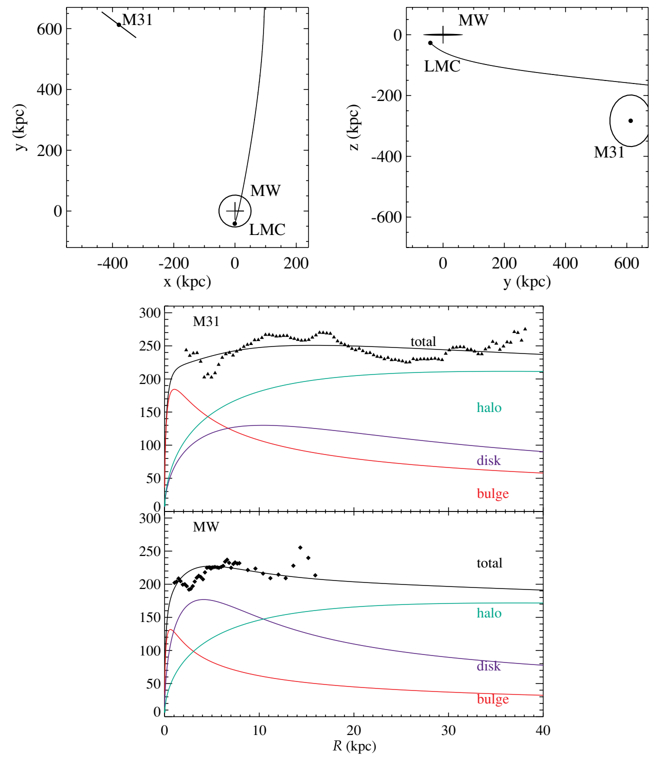

Figure 1. Upper panels: 3D positions of the MW, M31, and LMC. The left panel shows the projection in the x–y plane while the right panel in the y–z plane. The solid lines indicate a possible unbound trajectory of the LMC in the past. Middle panel: the rotation curves of M31. The triangles are the measured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

(A color version of this figure is available in the online journal.)

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

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

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

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

where the subscripts b, d, and h denote the bulge, disk, and halo, respectively, a_{b} is the scale length of the Hernquist profile, R_d is the scale length of the disk, and c and r_{s} denote 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 Figure 1.

The equation of motion for each object can be written as

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

Then the trajectories of each object can be solved numerically using the standard method for an N-body simulation in the barycentric frame. Choosing a small time step for the integration

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]	...

Notes.
[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.

Table 3
Possible Solutions

q[a]	$\mu_{\rm W}$	$\mu_{\rm N}$	$v_{\rm rad}$[b]	$v_{\rm tan}$[b,c]	$T_{\rm travel}$	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

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

provides us with an accuracy down to 0.1% over 10 Gyr, which is precise enough for our discussions.

As mentioned in the Introduction, the non-spherical halo of the MW may have impacted the trajectory of the LMC as seen in Besla et al. (2007). The case of a 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 are adopted and 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 for $q < 1$ refers to an oblate halo.

2.2. Results

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

$$\mu_{\rm W} = -62 \pm 18\ \mu\text{as yr}^{-1}, \tag{6}$$

$$\mu_{\rm N} = -25 \pm 13\ \mu\text{as yr}^{-1},$$

where the error bar accounts for the error of the LMC proper motions, and $\mu_{\rm W}$ and $\mu_{\rm N}$ are quoted in the equatorial system as usually used. It corresponds to $v_{\rm rad} = -128$ km s^{-1} and $v_{\rm tan} = 102$ km s^{-1} for M31 relative to the MW. The averaged time since the LMC was ejected from M31 is 5.5 ± 1.4 Gyr ago. Table 3 summarizes the results after assuming different values for the axis ratio of the MW potential. In this Table $v_{\rm tan}$, $T_{\rm travel}$, and v_{50} are averaged values for all of the trajectories that put the LMC at 50 kpc from M31 at look-back 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 km s^{-1} consistent 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 MW and M31.

In Figure 2, we show the trajectories of M31 and the LMC for the mean solution ($q = 1$). In the right panel of Figure 2, we show the solutions of M31 proper motion varying with q that corresponds to the average of all successful solutions. We have scanned a region of $q = [0.5, 1.5]$ with a 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 extreme for both prolate and oblate ones.

3. DISCUSSION AND CONCLUSION

Could the Magellanic Clouds be ejected tidal dwarfs from a previous major merger occurring at the M31 location? In this Letter, we simply demonstrate that this could be the case

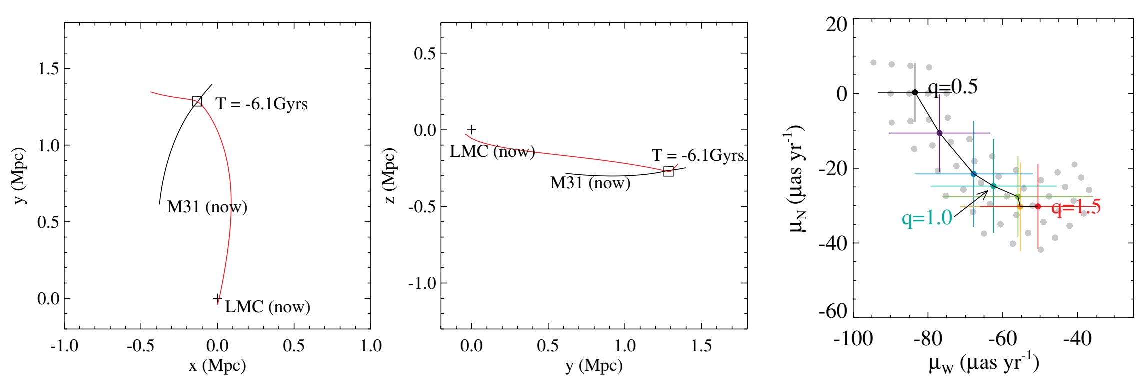

Figure 2. Left and middle panels: trajectories of LMC (red) and M31 (black) for the mean solution of a spherical MW halo (Equation (6)). The open boxes indicate the time when the LMC is closest to M31. Right panel: possible M31 proper motions that satisfy our hypothesis. The gray dots are all the possible solutions, including varying the 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.

(A color version of this figure is available in the online journal.)

within a reasonable range of parameters for both the MW and M31. In our study we did not consider the effect of the Small Magellanic Cloud (SMC) on the 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 modeled by giant halos of the NFW profile and find that they affect the LMC trajectories very marginally. The model presented here is possibly static assuming that only the M31 mass could have increased 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 (two 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 a 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 MW potential. van der Marel & Guhathakurta (2008) have estimated the 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 that is assumed in Equation (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 MW halo with $q = 1.7$. However, the van der Marel & Guhathakurta (2008) assumption may not hold in the case of a 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 MW 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 two bodies with a mass similar to the MW, 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 MW is ranging from 4 to 8 Gyr, depending on the axis ratio of the MW 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 Gyr 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 irregulars in the immediate outskirts of the MW. Our proposition has the advantage of explaining them in a consistent way, as originating from the most massive body in the Local Group that shows evidence for a very rich merger history. Future measurements of the M31 transverse velocity (possibly with *GAIA*) may confirm or negate its validity. Further modeling of both the 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 MW.

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REFERENCES

Bekki, K. 2010, MNRAS, 401, L58
Besla, G., Kallivayalil, N., Hernquist, L., Robertson, B., Cox, T. J., van der Marel, R. P., & Alcock, C. 2007, ApJ, 668, 949
Brown, T. M., et al. 2008, ApJ, 685, L121
Byrd, G., Valtonen, M., McCall, M., & Innanen, K. 1994, AJ, 107, 2055
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
Hammer, F., Flores, H., Elbaz, D., Zheng, X. Z., Liang, Y. C., & Cesarsky, C. 2005, A&A, 430, 115
Hammer, F., Flores, H., Puech, M., Yang, Y. B., Athanassoula, E., Rodrigues, M., & Delgado, R. 2009, A&A, 507, 1313
Hammer, F., Puech, M., Chemin, L., Flores, H., & Lehnert, M. D. 2007, ApJ, 662, 322
Hammer, F., Yang, Y. B., Wang, J. L., Puech, M., Flores, H., & Fouquet, S. 2010, ApJ, in press, arXiv:1010.0679v2
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., Chapman, S., Ferguson, A. M. N., Irwin, M., Lewis, G., & McConnachie, A. 2004, MNRAS, 351, 117
Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001, Nature, 412, 49
Kallivayalil, N., Besla, G., Sanderson, R., & Alcock, C. 2009, ApJ, 700, 924
Kallivayalil, N., van der Marel, R. P., & Alcock, C. 2006a, ApJ, 652, 1213
Kallivayalil, N., van der Marel, R. P., Alcock, C., Axelrod, T., Cook, K. H., Drake, A. J., & Geha, M. 2006b, ApJ, 638, 772
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
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
Okazaki, T., & Taniguchi, Y. 2000, ApJ, 543, 149
Peebles, P. J. E. 2009, arXiv:0907.5207v1
Peebles, P. J. E. 2010, arXiv:1009.0496v1
Peebles, P. J. E., Phelps, S. D., Shaya, E. J., & Tully, R. B. 2001, ApJ, 554, 104
Piatek, S., Pryor, C., & Olszewski, E. W. 2008, AJ, 135, 1024
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., & Guhathakurta, P. 2008, ApJ, 678, 187