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Implications of recent measurements of the Milky Way rotation for the orbit of the Large Magellanic Cloud

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1 INTRODUCTION

Recently, Kallivayalil et al. (2006, hereafter K06) measured the proper motion of the Large Magellanic Cloud (LMC), and pioneered a first assessment of its 3D velocity vector. Based on this measurement, Besla et al. (2007, hereafter B07) concluded that the LMC was unlikely to have passed near the Milky Way (MW) before and was most likely formed outside of the boundaries of the Galaxy, in contrast to traditional scenarios (see references in van der Marel et al. 2002, hereafter vdM02). This new conclusion is intriguing given that there are no other examples of massive gas-rich galaxies like the LMC within the much bigger volume that separates the MW from its neighbouring galaxy, Andromeda (M31). Other recent studies have also found the B07 results difficult to accept and propose alternate strategies of binding the LMC and MW either through Modified Newtonian Dynamics (MOND) gravity (Wu et al. 2008) or by giving the LMC and its smaller counterpart, the Small Magellanic Cloud, a common halo (Bekki 2008).

A couple of years after K06 published their findings, Piatek, Pryor & Olszewski (2008; hereafter P08) confirmed independently their results to within one standard deviation, although at the lower end of the inferred range of values. Also, within the past five years, the circular velocity of the MW and the distance between the Sun and the Galactic Centre have been updated by Reid & Brunthaler (2004; hereafter RB04) and Gillensen, Genzel & Eisenhouer (private communication; hereafter GGE08), respectively. These increased the likely circular velocity of the MW from the IAU standard of $V_{\text{circ}} = 220 \pm 15$ km s$^{-1}$. A value of 220 km s$^{-1}$ now corresponds to a reduction of the best-fitting value by two standard deviations (and equivalent to moving the Sun a total of 1 kpc closer to the centre of the Galaxy). Uemura et al. (2000) used parallax measurements from Hipparcos and SKYMAP to obtain a similar value of $V_{\text{circ}} = 255 \pm 8$ km s$^{-1}$.

The rotation speed of the MW affects the analysis of the past LMC orbit in two ways. First, because the proper motion of the LMC is measured relative to the Solar system which orbits the Galaxy, it is necessary to know the rotational velocity of the Sun in order to transform to the Galactocentric frame (see e.g. vdM02). Secondly, the depth of the gravitational potential well of the MW (involving its estimated mass and scale radius) depends on the normalization of its rotation curve. B07 adopted the IAU standard in their analysis instead of the modified values for the MW’s rotation. In this Letter, we examine the implications of the change in the MW parameters for the LMC orbit (also with the updated P08 value). In the particular geometry of the LMC orbit, both of the above mentioned effects make the LMC more gravitationally bound to the MW owing to an increase in $V_{\text{esc}}$. Despite the small fractional magnitude of the correction in circular velocity ($\sim 14 \pm 6$ per cent), we find that the qualitative nature of the LMC orbit changes. Instead of the LMC being possibly unbound as suggested by B07, the $\sim 10$ per cent decrease in the LMC velocity and the $\sim 50$ per cent increase in the MW mass lead us to conclude that the LMC’s past trajectory was probably confined within the virial radius of the MW. The apogalacticon distance of the orbit is comparable to the MW virial radius, as expected for a satellite that had formed at the outer edge of the Galactic halo.

Traditional studies of the LMC’s orbit around the MW (e.g. Murai & Fujimoto 1980; Lin & Lynden-Bell 1982; Gardiner, Sawa & Fujimoto 1994; Lin, Jones & Klemola 1995; Gardiner & Nuguchi 1996; vdM02; Bekki & Chiba 2005; Mastropietro et al. 2005; Connors, Kawata & Gibson 2006) considered the MW as an isolated galaxy. While this might have been acceptable for studies where the LMC’s orbit was confined well within the MW halo, the high LMC velocity measured by K06 and P08 implies (B07) that the apogalacticon could extend beyond the edge of the MW’s

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halo – where the gravitational influence of M31 is non-negligible (see table 1 in B07). Thus, we also include the tidal effect of M31 in our calculations.

In Section 2, we describe our adopted model for the mass distribution of the MW halo. We then calculate the past LMC orbit (Section 3) and the effect of M31 on it (Section 4). Finally, we discuss the implications of our results in Section 5.

2 METHOD

Following B07, we adopt a Navarro, Frenk & White (1996; hereafter NFW) mass profile for the dark matter distribution in the MW halo, and include dynamical friction (Chandrasekhar 1943; Hashimoto, Funato & Makino 2003) in calculating the LMC motion through the MW halo. We also add the gravitational potential of M31 in the form of another NFW profile at a present-day Galactocentric distance of 780 kpc (McConnachie et al. 2005; Cox & Loeb 2008, and references therein). The full gravitational potential \( \Phi_{\text{tot}} \) as a function of radius \( r \) in each galaxy (either MW or M31) includes contributions from a disc \( \Phi_{\text{disc}} \), a bulge \( \Phi_{\text{bulge}} \) and a dark matter halo \( \Phi_{\text{NFW}} \):

\[
\Phi_{\text{tot}}(r) = \Phi_{\text{disc}}(r) + \Phi_{\text{bulge}}(r) + \Phi_{\text{NFW}}(r),
\]

where (Xue et al. 2008)

\[
\Phi_{\text{disc}}(r) = -\frac{GM_{\text{disc}}(1 - e^{-r/r^\text{vir}})}{r},
\]

\[
\Phi_{\text{bulge}}(r) = -\frac{GM_{\text{bulge}}}{r + c_0},
\]

\[
\Phi_{\text{NFW}}(r) = -\frac{4\pi G \rho_s r_\text{vir}^2}{c^3 r} \ln \left(1 + \frac{c r}{r_\text{vir}}\right)
\]

with

\[
\rho_s = \frac{\rho_c \Omega_m \delta_n}{3 \ln(1 + c) - c/(1 + c)}.
\]

We adopt the standard \( \Lambda \) cold dark matter cosmological parameters \( \Omega_m = 0.3, H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Komatsu et al. 2008), and an overdensity of \( \delta_n = 340 \) (Wechsler et al. 2002; Klypin, Zhao & Somerville 2002), with

\[
M_{\text{vir}} = \frac{4\pi}{3} \frac{\rho_c \Omega_m \delta_n r_\text{vir}^3}{c} \propto V_{\text{circ}}^3
\]

and

\[
\rho_c = 8\pi G M_{\odot}/3H_0^2.
\]

Some of our initial conditions (\( M_{\text{vir}} \) and \( r_{\text{vir}} \)) depends on the distance of the Sun from the centre of the MW Galaxy, as will be discussed in Section 3, but we consistently adopt \( M_{\text{disc}} = 4 \times 10^{10} M_\odot, M_{\text{bulge}} = 0.8 \times 10^{10} M_\odot, \) a disc scalelength \( b = 3.5 \) kpc, a disc scaleheight \( c_0 = 0.7 \) kpc and a halo concentration \( c = 12 \) for the MW; and \( M_{\text{disc}} = 7 \times 10^{10} M_\odot, M_{\text{bulge}} = 1.9 \times 10^{10} M_\odot, M_{\text{vir}} = 1.6 \times 10^{12} M_\odot, b = 5.7 \) kpc, \( c_0 = 1.14 \) kpc, \( r_{\text{vir}} = 300 \) kpc and \( c = 12 \) for M31, as suggested by Klypin et al. (2002). Aside from the revised normalization of \( M_{\text{vir}} \) and \( r_{\text{vir}} \) based on the modified value of \( V_{\text{circ}} \), we have used the same mass profile as B07.

3 CONSTRAINTS ON THE ORBITAL HISTORY

Previous calculations of the history of the LMC have adopted the IAU standard values of \( d_\odot = 8.5 \) kpc and \( V_{\text{circ}} = 220 \) km s\(^{-1}\), as derived by Kerr & Lynden-Bell (1986, hereafter KLB86). These values assume the angular velocity of circular rotation for the Sun to be \( \Theta_0/d_\odot = 25.9 \) km s\(^{-1}\) kpc\(^{-1}\). RB04 directly measured this value\(^1\) from the proper motion of Sgr A\(^*\) to be \( \Theta_0/d_\odot = 29.45 \pm 0.15 \) km s\(^{-1}\) kpc\(^{-1}\), which using \( d_\odot = 8 \pm 0.5 \) kpc (Reid 1993) implies \( V_{\text{circ}} = 236 \pm 15 \) km s\(^{-1}\). Based on the observed orbits of individual stars around Sgr A\(^*\), Ghez et al. (2008) and GGE08 measured the distance of the Sun from the MW centre to be \( d_\odot = 8.4 \pm 0.4 \) kpc, assuming that Sgr A\(^*\) is at rest.\(^2\) These latest measurements are similar to the value inferred by KLB86, and bring the maximum \( V_{\text{circ}} \) (within 1\( \sigma \)) up to 265 km s\(^{-1}\), which is \( \approx 20 \) per cent higher than the 220 km s\(^{-1}\) on which all prior studies were based. Calculations based solely on KLB86 are therefore at the lower end (2\( \sigma \) below) of the allowed values for \( M_{\text{vir}}, V_{\text{circ}} \) and \( r_{\text{vir}} \). The new values are listed in Table 1. The inferred masses and radii assume the commonly accepted value of \( M_{\text{vir}} = 1 \times 10^{12} M_\odot \) for \( V_{\text{circ}} = 220 \) km s\(^{-1}\). The values of \( v_{X, Y, Z} \) (corresponding to Galactic coordinates \( X, Y, Z \)) were all calculated using the standard method of vdMG02, changing only the value of \( V_{\text{circ}} \).

While all of the recalculated masses are consistent with various recent measurements, the circular velocity of 251 km s\(^{-1}\), corresponding to \( M_{\text{vir}} = 1.485 \times 10^{12} M_\odot \), gives the minimum value of the virial mass that is consistent with the timing argument, which puts the total mass of the Local Group (LG) between 3.2 \( \times 10^{12} \) and 5.5 \( \times 10^{12} M_\odot \) (Binney & Tremaine 1987, hereafter BT87; van der Marel & Guhathakurta 2008, hereafter vdMG08; Li & White 2008). The MW and M31 galaxies dominate the LG and are of comparable masses; a combined mass of 3–4 \( \times 10^{12} M_\odot \) is on the lower end of the timing argument estimate. Li & White (2008), using the Millennium Simulation and data on Leo I, find the most likely mass for MW halo to be \( M_{\text{MW}} = 2.34 \times 10^{12} M_\odot \) with a lower limit of 0.8 \( \times 10^{12} M_\odot \), giving a more than adequate range to accommodate our inferred masses. Additional mass estimates of the MW halo are found in Table 3 and discussed further in Section 5.

The P08 (251 km s\(^{-1}\)) entry (with this notation denoting the proper motion from P08 and a circular velocity of 251 km s\(^{-1}\)) in Table 2 for the LMC velocity of 339 km s\(^{-1}\) is significantly lower (by more than 2\( \sigma \)) than the K06 (220 km s\(^{-1}\)) value of 378 \( \pm 18 \) km s\(^{-1}\), although it is higher than the vdMG02 (220 km s\(^{-1}\)) weighted average of previous studies, 293 \( \pm 39 \) km s\(^{-1}\). Comparing the corresponding LMC velocities for \( V_{\text{circ}} = 251 \) km s\(^{-1}\), the K06 and P08 values are much closer (in agreement with their initial transverse velocities being within one standard deviation of each other). P08, K06 and

\( ^1 \) The supermassive black hole, Sgr A\(^*\), is expected to lie nearly motionless at the dynamical centre of the MW since its mass far exceeds that of the surrounding stars. Hence, the apparent motion of Sgr A\(^*\) on the sky represents the reflex of the Sun’s orbit around the Galactic Centre, including both the mean Galactic rotation and the small peculiar motion of the Sun relative to the local standard of rest (RB04).

\( ^2 \) Since the surrounding stars are lighter by six orders of magnitude than Sgr A\(^*\), and since there is currently no evidence for a second (intermediate-mass) black hole, the assumption that Sgr A\(^*\) is at rest at the dynamical centre of the MW appear most natural.

Table 1. Modified values for \( V_{\text{circ}}, M_{\text{vir}} \) and \( r_{\text{vir}} \) of the MW.

| \( d_\odot \) (kpc) | \( V_{\text{circ}} \) (km s\(^{-1}\)) | \( M_{\text{vir}} \) (10\(^{12} M_\odot\)) | \( r_{\text{vir}} \) (kpc) | Colour |
|-----------------|-----------------|-----------------|-----------------|--------|
| 7.5             | 220             | 1,000           | 258             | Yellow |
| 8.0             | 236             | 1,234           | 277             | Green  |
| 8.5             | 251             | 1,485           | 295             | Blue   |
| 9.0             | 265             | 1,748           | 310             | Purple |

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Table 2. Calculated velocities for the LMC.

| Author   | $V_{\text{circ}}$ (km s$^{-1}$) | $v_x$, $v_y$, $v_z$ (km s$^{-1}$) | $|v|$ (km s$^{-1}$) | Colour  |
|----------|---------------------------------|----------------------------------|-------------------|---------|
| vdM02    | 220                             | $-56$, $-220$, 186               | 293               | Grey    |
| vdM02    | 251                             | $-56$, $-189$, 186               | 271               | Grey    |
| K06      | 220                             | $-86$, $-268$, 252              | 377               | Black   |
| K06      | 251                             | $-86$, $-237$, 252              | 356               | Black   |
| P08      | 220                             | $-83$, $-258$, 238              | 360               | Yellow  |
| P08      | 236                             | $-83$, $-243$, 238              | 350               | Green   |
| P08      | 251                             | $-83$, $-227$, 238              | 339               | Blue    |
| P08      | 265                             | $-83$, $-213$, 238              | 330               | Purple  |

vdM02 with $V_{\text{circ}} = 251$ km s$^{-1}$ are all compared in Fig. 1. Fig. 2 compares the P08 proper motion at various values of $V_{\text{circ}}$.

4 TIDAL EFFECT OF M31

In our simplified analysis of the dynamics of M31, we ignore its transverse motion and consider only the perturbative influence of M31 as its radial distance changes relative to the MW (BT87). While the transverse component of M31’s velocity might be non-negligible (Loeb et al. 2005), recent analysis suggests that it is lower than the radial component (vdM08) and its inclusion would only have a weak effect on the results reported here. We also ignore any diffuse intergalactic mass in between the MW and M31, although future modelling might take the related uncertainty into consideration (Cox & Loeb 2008). To account for the changing separation between the two galaxies, we used the standard radial dynamics model (BT87).

We find that M31 has a small but non-negligible effect on the trajectory of the LMC. Based on the current position of the LMC (see Figs 3 and 4), the addition of M31 pulls the LMC away from the Galactic Centre and towards the LG centre of mass. Fig. 5 compares the distance of the LMC from the Galactic (MW) Centre with (blue line) and without (light blue line) the gravitational influence of M31, assuming $V_{\text{circ}} = 251$ km s$^{-1}$ for the MW. Our figures keep the MW at the centre of the coordinate system (corresponding to an accelerated frame of reference). Without M31, the LMC is more tightly bound to the MW; in the P08 (251 km s$^{-1}$) case, the orbital period of the LMC is 5 Gyr, about 1.5 Gyr shorter than if M31 is included.

5 DISCUSSION

We have found that the $\sim 14 \pm 6$ per cent increase in the MW circular velocity, relative to the IAU standard of 220 km s$^{-1}$, allows the LMC to be gravitationally bound to the MW. Despite its relatively high proper motion (K06, P08), the orbit of the LMC remains confined within the virial radius of the MW.
Since the MW and M31 galaxies account for most of the mass in the LG, the LG itself is not much more spatially extended than the two are individually, having an estimated zero energy surface at a radius of $\sim 0.9$ Mpc (Karachentsev et al. 2008). If the LMC had followed the path dictated by the P08 (220 km s$^{-1}$) parameters in Table 2, it would have originated from a distance of $\gtrsim 1.5$ Mpc away from the MW centre (see Fig. 3). In comparison, if we admit the P08 (251 km s$^{-1}$) parameters, then the LMC originated roughly at the virial radius of the MW halo and well within the boundaries of the LG. The path suggested by P08 (236 km s$^{-1}$) puts the LMC origin outside the LG but closer than the P08 (220 km s$^{-1}$) case. If the P08 (265 km s$^{-1}$) model is to be believed, the LMC is on its third pass by the MW centre and also originated on the edge of the MW halo. The Galactocentric distance on which this result is based ($d_\odot = 9.0$ kpc) is $1\sigma$ above the most recent estimate (8.4 $\pm$ 0.5 kpc; see GGE08), so it is not excluded.

We note that during the long time-scale between perigee passes ($\sim 6$ Gyr, see Fig. 2), the MW halo mass could evolve by tens of percent (Diemand, Kuhlen & Madau 2007). Future studies might use cosmological simulations to incorporate the evolution of both the host (MW like) galaxy and its most massive (LMC-like) satellite to get a statistical understanding of their likely past interaction. Our most likely model has the LMC forming at roughly the MW virial radius, as expected from a hierarchical formation of the MW halo (Springel et al. 2008, figs 11 and 12). Also, all our quoted uncertainty for the LMC orbit stem from the uncertainty in $d_\odot$ (and therefore $V_{\text{circ}}$). Errors in the proper motion were not taken into account.

The K06 measurements, for example, are slightly over $1\sigma$ off from the P08 measurements of the LMC proper motion. The difference between these two cases (as seen in Fig. 1) is drastic – in one case, the LMC is clearly bound to the MW (P08), and in the other it is not (K06). A $1\sigma$ shift in the other direction, however, would alter the path of the LMC into an even tighter orbit, similar to the P08 (265 km s$^{-1}$) model.

With the value of the distance between the Sun and the Galactic Centre at its IAU value (GGE08, KLB06), $\sim 8.5 \pm 0.5$ kpc, the total mass of the MW Galaxy increases by a factor of 1.23–1.75 relative to the values inferred for the lower distance of 8 $\pm 0.5$ kpc (Reid 1993). B07 correctly rules out a larger mass for the MW but only considers the low-mass ($1 \times 10^{12} M_\odot$) and the high-mass ($2 \times 10^{12} M_\odot$) models of Klypin et al. (2002) which bracket our preferred range. Xue et al. (2008) describe the uncertainties of the prior assumption that the galactic $V_{\text{circ}}$ is 220 km s$^{-1}$. Table 3 provides the corresponding range of masses for the MW halo, all calculated from observational data, fit either to a flat rotation curve or an NFW profile, such as the one we have adopted in this work.

The $\sim 50$ per cent increase in mass (from $1 \times 10^{12}$ to $1.485 \times 10^{12} M_\odot$) and the $\sim 6$ per cent decrease in the velocity of the LMC [P08 (220 km s$^{-1}$) to P08 (251 km s$^{-1}$)] have a comparable influence on making LMC orbit bound to the MW. The combined effect of these changes is not equivalent to a change in the MW mass, as considered by B07. The K06 (251 km s$^{-1}$) and P08 (220 km s$^{-1}$) lines in Figs 1 and 2 correspond to roughly the same LMC velocity (as derived from the IAU standard with the P08 proper motion) but a different MW mass. The higher mass of the MW contributes about half of the overall difference between these cases. This parallels the comparison made in B07 between the K06 (220 km s$^{-1}$) and the K06 (220 km s$^{-1}$) $+4\sigma$ numbers in their Fiducial and High-Mass Models, except that our findings do not require a $4\sigma$ deviation from the measured LMC velocity or a $2\sigma$ deviation from the mass of the MW in order to make the LMC orbit bound to the MW.

The previous suggestion (B07) of possibly disqualifying the LMC and SMC as MW satellites has undesirable implications for the satellites in the MW halo. M31 has 18 satellites, five of which are gas rich, whereas the MW, if the LMC and SMC are no longer bound to it, has only 12 bound satellites, two of which are gas rich (Karachentsev 2005, vdMG08). M31’s satellites range in mass from 0.58 to $500 \times 10^8 M_\odot$, whereas the remaining MW satellites are in the range of 0.1–$1 \times 10^8 M_\odot$ (Mateo 1998). Excluding the LMC and SMC as satellites of the MW appears unnatural, as

| Author                        | Mass ($10^{12} M_\odot$) | Model   |
|-------------------------------|---------------------------|---------|
| Wilkinson & Evans (1999)      | 1.9$^{+1.6}_{-1.7}$       | FRC$^1$ |
| Sakamoto, Chiba & Beers (2003)| 2.5$^{+0.5}_{-1.0}$       | FRC     |
| Sakamoto, Chiba & Beers (w/o Leo I) | 1.8$^{+0.04}_{-0.07}$ | FRC     |
| Smith et al. (2007)           | 1.42$^{+1.14}_{-0.54}$    | NFW     |
| Xue et al. (2008)             | 0.79 $\pm$ 0.15 –        | NFW     |
|                               | 1.18 $\pm$ 0.28          |         |
| Li & White (2008)             | 2.43                      | N-body$^2$ |

$^1$FRC denotes a flat rotation curve, as in an isothermal sphere. These mass calculations have cut-offs of $\sim 50$ kpc.

$^2$For example, the Millennium Simulation. Here, the limiting radius is the virial radius, similar to the NFW calculation.

Table 3. MW halo mass in recent studies.
there is no reason for the two comparably sized galaxies to have a large disparity in the abundance of massive satellites. Moreover, the chance of finding massive galaxies like the LMC and the SMC so close to the MW centre requires a special coincidence if they are unbound to the MW, since they would have spent most of their orbital time far away from the MW in that case. Yet, no similar galaxies are known to exist in the much larger volume between M31 and the MW. Although these statistical arguments are not definitive, they support indirectly the higher updated values of \( V_{\text{circ}} \) (RB04) and \( d_\odot \) (GGE08) for the MW.

No work on the Magellanic Clouds would be complete without a mention of the Magellanic Stream (MS). There is < 2 per cent change in the trajectory over the length of the MS (100°) between the P08 (220 km s\(^{-1}\)) and the P08 (251 km s\(^{-1}\)) models, both of which are well within the error margins in fig. 8 of B07. We reiterate the concerns presented in B07 that neither tidal stripping nor ram pressure can fully explain the orientation of the stream.

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REFERENCES

Bekki K., 2008, ApJL, 684, L87
Bekki K., Chiba M., 2005, MNRAS, 356, 680
Besla G. K. N., Hernquist L., Robertson B., Cox T. J., van der Marel R. P., Alcock C., 2007, ApJ, 668, 949 (B07)
Binney J., Tremaine S., 1987, in Ostriker J. P., ed., Galactic Dynamics. Princeton Univ. Press, Princeton, NJ, p. 605 (BT87)
Chandrasekhar S., 1943, ApJ, 97, 255
Connors T. W., Kawata D., Gibson B. K., 2006, MNRAS, 371, 108
Cox T. J., Loeb A., 2008, MNRAS, 386, 461
Diemand J., Kuhlen M., Madau P., 2007, ApJ, 667, 859
Gardiner L. T., Noguchi M., 1996, MNRAS, 278, 191
Gardiner L. T., Sawa T., Fujimoto M., 1994, MNRAS, 266, 567
Ghez A. M. et al., 2008, ApJ, accepted (arXiv:0808.2870)
Hashimoto Y., Funato Y., Makino J., 2003, ApJ, 582, 196
Kallivayalil N., van der Marel R. P., Alcock C., Axelrod T., Cook K. H., Drake A. J., Geha M., 2006, ApJ, 368, 772 (K06)
Karachentsev I. D., 2005, AJ, 129, 178 (K05)
Karachentsev I. G., Karachentsev V., Huchtmeier W., Makarov D., Kaisin S., Sharina M., 2008, Galaxies in the Local Volume. Springer, Berlin (K08)
Kerr F. J., Lynden-Bell D., 1986, MNRAS, 221, 1023 (KLB86)
Klypin A., Zhao H., Somerville R. S., 2002, ApJ, 573, 597 (KZS02)
Komatsu E. et al., 2008, preprint (astro-ph/0803.0547)
Li Y.-S., White S. D. M., 2008, MNRAS, 384, 1459
Lin D. N. C., Lynden-Bell D., 1982, MNRAS, 198, 707
Lin D. N. C., Jones B. F., Klemola A. R., 1995, ApJ, 439, 652
Loeb A., Reid M. J., Brunthaler A., Falcke H., 2005, ApJ, 633, 894
Mateo M. L., 1998, ARA&A, 36, 435
McConnachie A. W., Irwin M. J., Ferguson A. M. N., Ibata R. A., Lewis G. F., Tanvir N., 2005, MNRAS, 356, 979
Mastropietro C., Moore B., Mayer L., Wadsley J., Stadel J., 2005, MNRAS, 363, 509
Murai T., Fujimoto M., 1980, PASJ, 32, 581
Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563 (NFW)
Piatak S., Pryor C., Olszewski E., 2008, AJ, 135, 1024 (P08)
Reid M. J., 1993, ARA&A, 31, 345
Reid M. J., Brunthaler A., 2004, ApJ, 616, 872 (RB04)
Sakamoto T., Chiba M., Beers T. C., 2003, A&A, 397, 899
Smith M. et al., 2007, MNRAS, 379, 755
Springel V. et al., 2008, MNRAS, submitted (astro-ph/0809.0898)
Uemura M., Ohishi H., Hayakawa T., Ishida E., Kato T., Hirata R., 2000, PASJ, 52, 143
van der Marel R. P., Guhathakurta P., 2008, ApJ, 678, 187 (vdMG08)
von der Marel R. P., Alves D. R., Hardy E., Suntzeff N. B., 2002, AJ, 124, 2639 (vdM02)
Wechsler R. H., Bullock J. S., Primack J. R., Kravtsov A. V., Dekel A., 2002, ApJ, 568, 52
Wilkinson M. I., Evans N. W., 1999, MNRAS, 310, 645
Wu X., Famaey B., Gentile G., Perets H., Zhao H., 2008, 386, 2199
Xue X. et al., 2008, preprint (astro-ph/0801.1232)

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