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Local Group Proper Motion Dynamics

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Abstract. Our knowledge of the dynamics and masses of galaxies in the Local Group has long been limited by the fact that only line-of-sight velocities were observationally accessible. This introduces significant degeneracies in dynamical models, which can only be resolved by measuring also the velocity components perpendicular to the line of sight. However, beyond the solar neighborhood, the corresponding proper motions have generally been too small to measure. This has changed dramatically over the past decade, especially due to the angular resolution and stability available on the Hubble Space Telescope. Proper motions can now be reliably measured throughout the Local Group, as illustrated by, e.g., the work of the HSTPROMO collaboration. In this review, I summarize the importance of proper motions for Local Group science, and I describe the current and future observational approaches and facilities available to measure proper motions. I highlight recent results on various Milky Way populations (globular clusters, the bulge, the metal-poor halo, hypervelocity stars, and tidal streams), dwarf satellite galaxies, the Magellanic Clouds and the Andromeda System.

1. Introduction: Local Group Dynamics and the Importance of Proper Motions

Structures in the Universe cluster on various scales. Our Milky Way Galaxy (MW) belongs to a small group, called the Local Group (LG). The two dominant galaxies in the LG are spiral galaxies: the MW and the Andromeda Galaxy (M31). Each of these galaxies has a significant companion that is roughly one-tenth of its mass: the MW has the Magellanic Clouds, i.e. the pair of the Large and Small Magellanic Clouds (LMC and SMC), and M31 has the Triangulum Galaxy (M33). The MW and M31 also each have their own system of dwarf satellite galaxies, which have much lower mass.

The Universe evolves hierarchically, with small structures merging and falling in to form bigger structures. Owing to its proximity, the LG is the best place to study some of these processes in detail. The last decade has seen a wealth of new discoveries in this area. For example, the ongoing disruption of the Sagittarius dwarf spheroidal (Sgr dSph) galaxy has produced a giant stream of stars around the Milky Way. The SDSS survey has revealed many other such streams, and there is also a giant stellar stream around M31. For these reasons, the LG and its two dominant spirals have become the benchmark for testing many aspects of galaxy formation and cosmological theories.

To understand the LG, it is necessary to study the dynamics of its stars and galaxies. The dynamics contain an imprint of the initial conditions, and also reflect subsequent evolution. Moreover, dynamical measurements are necessary to constrain the amount of (dark) mass, since the dynamics, structure, and mass of galaxies are tied through the laws of gravity and dynamical equilibrium.

Almost everything that is known about the dynamics of the LG, and of galaxies in the Universe in general, is based on observations of line-of-sight (LOS) velocities. Such observations constrain only one component of motion, and interpretation therefore generally requires that various assumptions be made. This limits the amount of insight that can be gained, e.g., through the well-known degeneracy between mass and velocity dispersion anisotropy (Binney & Mamon 1987).

An important step forward is to determine fully three-dimensional velocities, by also measuring proper motions (PMs) in the plane of the sky. This is possible with several techniques, as discussed in Section 2. PM measurements over the past decade have started to revolutionize our understanding of the LG, as reviewed (roughly in order of increasing distance) in Sections 3–6. Concluding remarks are presented in Section 7.

2. Observational Approaches and Future Prospects

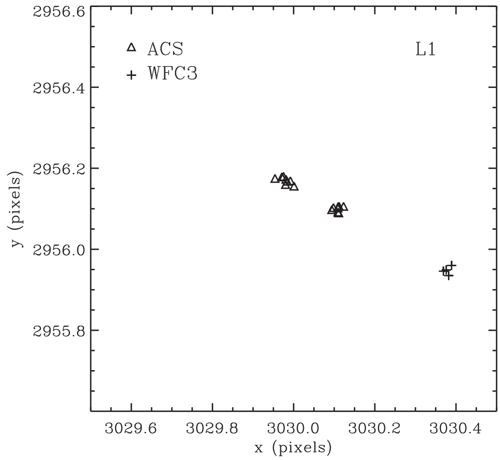
High PM accuracy is required to meaningfully address most dynamical topics in the LG. For reference, Δ PM $= 50\,\mu$as/yr corresponds to a velocity accuracy $\Delta v \approx (D/4)$ km/s at distance D kpc. Therefore, this is the accuracy required to study, e.g., MW halo objects at 40 kpc with 10 km s^{-1} accuracy, or to study dwarf satellite galaxies at 200 kpc with 50 km s^{-1} accuracy. To properly grasp the challenge that this poses, it is worth noting that $50\,\mu$as/yr corresponds roughly to the angular velocity with which one would observe the hair grow of a human placed at the distance of the moon.

The highest PM accuracies, Δ PM $\lesssim 10\,\mu$as/yr, are generally obtained using interferometric telescope arrays at radio wavelengths. However, the number of sources in the LG that can be studied in this way is small. Water masers are the main targets, and these exist only in the few LG galaxies with high star formation rates. PM measurements have been reported for M33 and IC10, both satellites of M31 (Brunthaler *et al.* 2005, 2007). In the future, such measurements may become possible also for, e.g., M31 (Darling 2011) and the Magellanic Clouds.

Ground-based optical PM measurements have traditionally been based on comparison of photographic plate data taken at widely separated epochs (decades apart; e.g., Carlin *et al.* 2012). A variant of this is to compare historical photographic plate data with recent targeted CCD data (e.g., Casetti-Dinescu *et al.* 2007). Another approach is to compare homogeneous data from large surveys (e.g., SDSS) using shorter time baselines (e.g., Koposov *et al.* 2013). The accuracies thus reached are comparable to what is obtained from near-IR measurements for stars near the Galactic Center (e.g., Ghez *et al.* 2008). However, those stars move unusually fast around the MW's supermassive black hole, and they are relatively nearby. The ground-based techniques do not generally reach PM accuracies *on a per-star basis* that are sufficient for studies of Local Group dynamics. However, by calculating the average PM of large numbers of N stars, it is possible to reach the required accuracies (since random errors scale as $N^{-0.5}$).

The highest-quality optical/near-IR PM measurements are obtained from space, and specifically with the Hubble Space Telescope (HST). HST's location above the earth atmosphere yields several advantages, including high spatial resolution, low sky background, and exquisite telescope stability. Moreover, there is a large data archive of observations spanning 24 years (or 12 years when restricted to the highest quality cameras ACS and WFC3), thus making possible comparisons over large time baselines. While the field of view of HST is small compared to what is available from the ground, HST's ability to observe very faint sources yields more PM measurements per fixed area. The number of measurable stars in an HST field can range from $N \approx 10^{1-2}$ for a sparse halo pointing (Deason *et al.* 2012; Sohn *et al.* 2014) to $N \approx 10^{5-6}$ for the center of a globular cluster (e.g., Anderson & van der Marel 2010).

Due to HST's unparalleled astrometric capabilities, it can achieve the PM accuracy needed for LG science *for individual stars* (50 μas/yr corresponds to a motion of ~ 0.01 HST CCD pixels over 10 years). So it is possible not only to measure very accurate



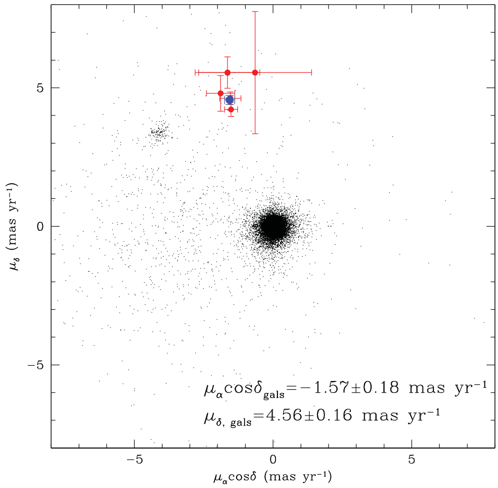


Figure 1. (left) HST measurements of the position of a background quasar relative to the stars in an LMC field (from Kallivayalil *et al.* 2013). The box is the size of a single CCD pixel. Measurements are shown with different instruments, at three epochs spread over a 7 year period. The average absolute PM of the LMC stars can be accurately measured from such data.

Figure 2 (right) PMs of all compact sources in an HST pointing centered on the bulge globular cluster M70 (from Massari *et al.* 2013), measured relative to the cluster PM. Point sources (black) are stars in either M70 (middle clump), the Sagittarius dSph galaxy in the background (top left clump), or the MW disk and bulge (extended distribution left of center). Red points with errorbars, and their weighted average in blue, are distant background galaxies which define the absolute PM zeropoint. Such data allow the measurement of both absolute bulk and relative internal motions of globular clusters and dwarf galaxies.

average PMs, but also to study internal PM kinematics of stellar systems. This includes studies of the velocity dispersion of globular clusters (not discussed in this review, but see, e.g.: McNamara *et al.* 2003, 2012; McLaughlin *et al.* 2006; van der Marel & Anderson 2010; Bellini *et al.* 2013), the rotation of galaxies (van der Marel & Kallivayalil 2014), or different kinematical populations in tidal streams (Sohn *et al.* 2014). These possibilities have led several groups over the past decade to focus on the use of HST for LG PM studies. Specifically, many of the results discussed in the following sections were obtained in the context of our HSTPROMO (Hubble Space Telescope Proper Motion) collaboration, a set of several dozen HST investigations with both observational and theoretical components (see the review in van der Marel 2014, or the HSTPROMO web page†).

Observationally determined PMs can be of two kinds: relative PMs or absolute PMs. Relative PMs are easier to obtain, and suffice e.g. if the goal is to measure the *internal* kinematics of a stellar system. But for LG science it is generally necessary to obtain absolute PMs, by measuring the motion of foreground stars with respect to distant (stationary) background objects. Most early studies (e.g., Piatek *et al.* 2002; Kallivayalil *et al.* 2006a) focused on fields centered on a single background quasar (see, e.g., Fig. 1). A quasar has the advantage of being a point source, so that its position can be measured with the same techniques as the foreground stars (Anderson & King 2000). However, this limits the applicability to the small fraction of fields that contain a known quasar. It also limits the accuracy per field to the accuracy with which a single source can be centroided.

† http://www.stsci.edu/∼marel/hstpromo.html

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It is possible to achieve higher absolute PM accuracies by using compact background galaxies as stationary reference sources (see, e.g., Fig. 2). While their individual positional accuracy is somewhat poorer that for a point source, their much larger number provides an overwhelming $\sqrt{N}$ advantage in averaging (a typical 1 hour HST pointing will contain of order 10^2 background galaxies sufficiently bright and compact for astrometry). Also, background galaxies sample the whole detector, which reduces systematic errors upon averaging. Measuring positions of background galaxies is more complicated than for point sources, but sophisticated techniques for this now do exist (e.g., Mahmud & Anderson 2008; Sohn *et al.* 2012,2013,2014).

Systematic errors are often the limiting factor in PM studies. Thus it is necessary to perform careful calibrations of PSF shapes, geometric distortions, charge-transfer efficiency, color effects, time variability in calibrations, etc. (e.g., Anderson & King 2000; Sohn *et al.* 2012). When this is done, the systematics can be controlled to levels below the typical random errors. This has been confirmed for several studies by the good agreements between HST PM measurements and independent estimates from combinations of theoretical models and LOS velocity measurements (e.g., van der Marel *et al.* 2012a; van der Marel & Kallivayalil 2014; Sohn *et al.* 2014).

The results from GAIA, a full-sky astrometric satellite launched in 2013, will further revolutionize our understanding of PM dynamics. However, the best results will likely be limited to the MW and its satellites. This is because GAIA is not optimized for faint targets or crowded fields. For example, the predicted end-of-mission accuracy at magnitude $V \sim 20$ is Δ PM $\sim 430\,\mu$as/yr (this includes the contributions from scattered light discovered post-launch). By comparison, HST already reaches Δ PM $\sim 100\,\mu$as/yr at $V \sim 25$ (e.g., Sohn *et al.* 2014). Therefore, HST will continue to be a unique and complementary resource in the GAIA era. Looking further into the 2020s, the EUCLID and WFIRST-AFTA space missions will enable HST-quality PM measurements over much wider fields of view, thus opening the door for even more ambitious scientific investigations of the LG.

3. Milky Way Populations

Studies of the dynamics of the MW disk through PM measurements of stars in the solar neighborhood date back more than a century. The Hipparcos mission has produced the most important catalog in this field (e.g., Dehnen & Binney 1998), and the GAIA mission will further improve our knowledge. I will not review the local MW disk dynamics here, but will focus instead on more distant MW components and tracers.

Globular Clusters The absolute PMs of many globular clusters have been measured from ground-based observations in a series of papers by Casetti-Dinescu *et al.* (e.g., 2007, 2010, 2013). A catalog with the PMs of ~ 60 clusters is available online†. The PMs have been used, e.g., to assess the three-dimensional orbits of clusters, the equilibrium dynamics of the cluster population as a whole, the dynamical differences between disk and halo clusters, the possible external origin of some clusters, or potential associations of specific clusters with tidal streams. However, the available ground-based PM uncertainties are such that for $D \gtrsim 10\,$kpc, the corresponding velocity uncertainties are generally too large to strongly constrain these questions. More accurate HST PM measurements of globular clusters are now starting to become available as well (e.g., Massari *et al.* 2013; Sohn *et al.* 2014; see Fig. 2). These have the potential to probe the cluster dynamics to much larger distances.

† http://www.astro.yale.edu/dana/gc.html

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Galactic Bulge Moving on to individual stars outside the solar neighborhood, several groups have studied the dynamics of the MW Bulge. Early ground-based PM measurements (Spaenhauer *et al.* 1992) found the velocity dispersions to be near-isotropic. Subsequent HST studies have revealed more complex kinematical signatures, such as rotation, and radial (depth) variations within the bulge (Kuijken & Rich 2002; Clarkson *et al.* 2008; Soto *et al.* 2014). These have been used to improve our understanding of the bulge's structure and its connection to the central bar (Rattenbury *et al.* 2007; Poleski *et al.* 2013).

Metal-Poor Halo The PMs of distant stars in the metal-poor halo can also be measured with HST. Deason *et al.* (2013) showed that it is possible to uniquely identify main-sequence halo stars in random, multiply-imaged HST fields, by combining PM and color-magnitude diagram (CMD) information. They measured the PMs of 13 stars at 24 ± 6 kpc toward the Andromeda-Triangulum halo overdensity, which imply a halo velocity ellipsoid that is roughly isotropic. This is more tangential than the velocity ellipsoid of halo stars near the Sun, which is measured from ground-based PMs to be highly radially anisotropic (e.g., Bond *et al.* 2010). These results are consistent with the hypothesis that the Andromeda-Triangulum overdensity may be a shell in the halo, possibly resulting from an ancient accretion event. Work is ongoing to use data for many more fields in the HST Archive to measure PMs for ~ 1000 distant stars throughout the halo (Sohn *et al.*, in prep.). This will help constrain halo formation mechanisms (through the implied velocity dispersion anisotropy of halo stars, and the amount of substructure in velocity space), and it will improve our knowledge of the radial MW mass profile by resolving the mass vs. velocity dispersion anisotropy degeneracy.

Hypervelocity Stars Dynamical interactions near the Milky Way's central supermassive black hole can eject stars at high velocities. Such stars are observed as hypervelocity stars in the MW halo (Brown *et al.* 2005). Given their distances, only HST has so far been able to measure their PMs. An accurate PM can confirm the origin near the Galactic Center (Brown *et al.* 2010), while the implied deviation from purely radial motion can in principle constrain the shape of the MW's dark halo (Gnedin *et al.* 2005).

Tidal Streams The MW halo contains many stellar streams, composed of the tidally stripped material from globular clusters or dwarf satellites. These streams hold great promise to constrain the shape and density profile of the MW's dark matter halo, especially when PMs are available in addition to sky positions, distances, and LOS velocities. Koposov *et al.* (2010) used ground-based USNO-B astrometry to study the PMs of the GD1 Stream. However, since this stream is at $D \approx 10$ kpc, it provides only limited information on the MW's dark matter halo. The Sagittarius Stream, composed of material stripped from the Sgr dSph, is a more useful tracer in this regard, since it reaches distances up to ~ 100kpc (Belokurov *et al.* 2014). For the Sgr dSph itself, both ground-based (Dinescu *et al.* 2005) and HST-based PMs (Pryor *et al.* 2010; Massari *et al.* 2013; Sohn *et al.* 2014; see Fig. 2) are available. For the Sgr Stream, Carlin *et al.* (2012) and Koposov *et al.* (2013) obtained ground-based PMs along the trailing arm, while Sohn *et al.* (2014) obtained higher accuracy HST PMs along both arms. The latter study was even able to kinematically separate trailing-arm from leading-arm stars *within the same field*, based on their PMs. The average stream PMs are close to the predictions of the best-fitting Stream model previously constructed by Law & Majewski (2010). In this model, the MW dark halo is near-oblate and oriented orthogonal to the MW disk. Further measurements and models will likely be required to either validate or refute this model (see also, Deg & Widrow 2013; Ibata *et al.* 2013; Vera-Ciro & Helmi 2013). The PMs of other streams, including the Orphan stream, are also being studied with HST (van der Marel *et al.*, in prep.).

4. Dwarf Satellite Galaxies

The PMs of almost all of the MWs classical dSph satellites have been measured using HST (Piatek *et al.* 2003, 2005, 2006, 2007; Lepine *et al.* 2011; Pryor *et al.* 2014), and these are generally the most accurate measurements available. Knowledge of the PMs has been used to determine the dSph orbits. These can be used to investigate the origin of these galaxies, the cause of structural of star formation history features, and/or their connection with other satellites. For example, there has long been evidence that some MW satellites lie in a plane (e.g., Lynden-Bell & Lynden-Bell 1995). By measuring PMs it is possible to verify that the orbital angular momentum vectors are roughly perpendicular to this plane (e.g., Pawlowski & Kroupa 2013), as expected for a long-lived configuration. Also, the satellite orbits can be modeled as an ensemble under the assumption of hydrostatic equilibrium, to constrain the MW mass profile (e.g., Watkins *et al.* 2010).

Sohn *et al.* (2013) measured the absolute PM of Leo I. This is one of the most unusual MW satellites, because of its large Galactocentric distance ($r = 261 \pm 13\,\mathrm{kpc}$) and the fact that it is rapidly receding away from the MW ($v_{\mathrm{rad}} = 168 \pm 3\,\mathrm{km\,s^{-1}}$). The measured PM implies a significant tangential velocity $v_{\mathrm{tan}} = 101 \pm 34\,\mathrm{km\,s^{-1}}$, indicating that it is not on a radial orbit due to a slingshot interaction with another satellite. Orbit integrations indicate instead that it likely entered the MW virial radius for the first time only $2.3 \pm 0.2\,\mathrm{Gyr}$ ago, and had its first pericenter passage $1.0 \pm 0.1\,\mathrm{Gyr}$ ago at $91 \pm 36\,\mathrm{kpc}$. Comparison of the properties of Leo I to the properties of subhalos in cosmological simulations yields important new constraints on the mass of the MW (Boylan-Kolchin *et al.* 2013). Assuming that Leo I is the least-bound classical MW satellite, the implied MW virial mass is $M_{\mathrm{vir}} \approx (1.6 \pm 0.3) \times 10^{12}\ M_{\odot}$; for lower MW masses it would be vanishingly unlikely to find a subhalo as distant and rapidly moving as Leo I. HST studies of the PMs of other distant dwarf galaxies are currently ongoing, including both distant MW satellites such as Leo T (Do *et al.*, in prep.), as well as distant LG satellites such Cetus, Tucana, Leo A, and the Sgr dwarf Irregular galaxy (Sohn *et al.*, in prep.).

Future studies, either with HST or future facilities, hold the promise to determine also the *internal* kinematics of dwarf galaxies. Such measurements have the potential to break the mass vs. velocity dispersion anisotropy degeneracy. This can help constrain the nature of dark matter, by determining whether dark halo mass profiles have central cores or cusps (Strigari *et al.* 2007).

5. The Magellanic Clouds

One of the first crude measurements of the PMs of the Magellanic Clouds was obtained by the Hipparcos satellite (Kroupa & Bastian 1997). With HST it has been possible to significantly refine the accuracy of these measurements. Kallivayalil *et al.* (2006a,b) presented PMs based on two epochs of HST data with a 2-year time baseline. These measurements were recently refined by Kallivayalil *et al.* (2013) using a third-epoch of HST data that extends the time baseline to 7 years (see Fig. 1). The key finding from this work has been that the Magellanic Clouds move faster about the Milky Way than was previously believed based on models of the Magellanic Stream. In these models, the Clouds were assumed to have been long-term MW satellites moving on near-circular orbits in a logarithmic potential (e.g., Gardiner & Noguchi 1996). By contrast, orbit calculations based on the HST PMs in a cosmologically motivated MW halo potential

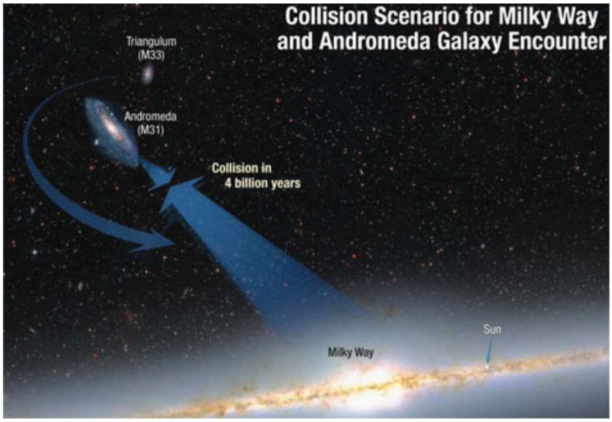

Figure 3. (left) Deep ground-based LMC image (courtesy Y. Beletsky, vertical scale $\sim 14°$), with HST measurements of the LMC PM rotation overlaid (red arrows; from van der Marel & Kallivayalil 2014). The LMC makes one revolution every few-hundred million years. The PM data can measure this rotation accurately, which (when combined with LOS data) provides a fully three-dimensional probe of the internal disk kinematics.

Figure 4 (right) Illustration of the predicted future evolution of the LG, based on the observed M31 PM from HST (Sohn *et al.* 2012) and the observed M33 PM from water maser observations (Brunthaler *et al.* 2005). The MW and M31 will collide in ~ 4 Gyr, and they will fully merge in ~ 6 Gyr. M33 will swing around M31 and take part in the collision as well (from van der Marel *et al.* 2012b).

imply either a much longer-period more-elliptical orbit, or that the Clouds are on their first infall into the MW (Besla *et al.* 2007). Given the individual LMC and SMC PM measurements, the first-infall models are the only ones in which the LMC and SMC form a bound pair (Kallivayalil *et al.* 2013), consistent with their structures and star formation histories. The plausibility of a first-infall scenario is further supported by both cosmological simulations (Boylan-Kolchin *et al.* 2011) and the gas-rich nature of the Clouds (van den Bergh 2006). In a first-infall scenario, the Magellanic Stream may have formed purely from interaction between the Clouds, without assistance from MW tidal or ram pressure forces (Besla *et al.* 2010; Peebles & Tully 2013). These results have not just refined our understanding of the Magellanic Clouds, but also of the formation of Magellanic Irregular galaxies in general (Besla *et al.* 2012).

Almost all of our knowledge of the rotation of galaxies is based on LOS velocity measurements. However, PM measurements can also probe this rotation. By mapping variations in the HST PM measurements across the face of the LMC (Kallivayalil *et al.* 2006a; Piatek *et al.* 2008), it has been possible to measure PM rotation for the first time for any galaxy. van der Marel & Kallivayalil (2014; see Fig. 3) measured both the PM rotation field and rotation curve of the LMC in detail, and demonstrated that the results are consistent with knowledge from LOS velocity measurements for individual stars. They used the three-dimensional dynamical information obtained from combination of the different techniques to obtain new insights into the geometry, structure, and distance of the LMC. HST studies of the internal PM dynamics of the SMC (Kallivayalil *et al.*, in prep.) and the Magellanic Bridge (van der Marel *et al.*, in prep.) are currently ongoing.

6. The Andromeda System

M31 was the first galaxy for which a LOS velocity was measured, and it has been known for about a century that it is moving towards the MW (Slipher 1913). However, to understand the future orbit and evolution of the M31-MW system, and hence the LG, it is necessary to also know the PM of M31. Sohn *et al.* (2012) used HST to obtain the first-ever PM measurement for M31, using data with 5–7 year time baselines for three different fields studied with multiple HST cameras. The result agrees with indirect estimates based on the LOS kinematics of M31 and LG satellites (van der Marel & Guhathakurta 2008). The combined results imply that the M31 velocity vector is statistically consistent with a radial (head-on collision) orbit towards the Milky Way ($V_{\rm tan,M31} \leqslant 34.3\,{\rm km\,s^{-1}}$ at 1σ confidence; van der Marel *et al.* 2012a).

The M31 and MW protogalaxies started moving away from each other after the Big-Bang, but their mutual gravity caused the turn-around that led to their current approach. Their combined mass implied by this "LG timing argument", including corrections for cosmic bias and scatter, is $M_{\rm LG} = M_{\rm MW,vir} + M_{\rm M31,vir} = (4.93 \pm 1.63) \times 10^{12}\,M_\odot$. Bayesian combination with other mass estimates for the individual MW and M31 galaxies yields the more accurate estimate $M_{\rm LG} = (3.17 \pm 0.57) \times 10^{12}\,M_\odot$ (van der Marel *et al.* 2012a).

N-body and Monte-Carlo simulations can be used to predict the future evolution of the MW-M31 system (van der Marel *et al.* 2012b; see Fig. 4). The galaxies will merge $t = 5.86^{+1.61}_{-0.72}$ Gyr from now. The first pericenter occurs at $t = 3.87^{+0.42}_{-0.32}$ Gyr, at a pericenter distance $r = 31.0^{+38.0}_{-19.8}$ kpc. In 41% of Monte-Carlo orbits M31 makes a direct hit with the MW, defined here as a first-pericenter distance less than 25 kpc. The PM of the Triangulum galaxy, M33, is known from water maser observations (Brunthaler *et al.* 2005), so its orbit can be calculated as well. The most likely outcome is for the MW and M31 to merge first, with M33 settling onto an orbit around them that may decay towards a merger later. However, there is a 9% probability that M33 makes a direct hit with the MW at its first pericenter, *before* M31 gets to or collides with the MW. Also, there is a 7% probability that M33 gets ejected from the Local Group, temporarily or permanently. The radial mass profile of the MW-M31 merger remnant is significantly more extended than the original profiles of either the MW or M31, and suggests that the merger remnant will resemble an elliptical galaxy. The Sun will most likely ($\sim 85\%$ probability) end up at larger radius from the center of the MW-M31 merger remnant than its current distance from the MW center, possibly further than 50 kpc ($\sim 10\%$ probability). There is a $\sim 20\%$ probability that the Sun will at some time in the next 10 Gyr find itself moving through M33 (within 10 kpc), but while dynamically still bound to the MW-M31 merger remnant.

7. Concluding Remarks

The ability to measure the PMs of stars and galaxies in the nearby Universe with HST and other facilities has led to a revolution in our understanding of the dynamics of the LG and its galaxies. The LG continues to evolve, with Leo I, and probably also the Magellanic Clouds, just now falling into the MW for the first time. In a few billion years, M31 will arrive as well, which will cause the Local Group to be drastically reshaped. With the continuing improvements in observational facilities, and the prospect of GAIA and other future space telescopes, it is likely that PM measurements will continue to improve our understanding of our dynamic LG environment. In turn, this will be a key ingredient for understanding the formation and evolution of galaxies and galaxy groups in general.

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References

Anderson, J. & King, I. R. 2000, *PASP*, 112, 1360

Anderson, J. & van der Marel, R. P. 2010, *ApJ*, 710, 1032

Bellini, A., van der Marel, R. P., & Anderson, J. 2013, *Memorie della Societa Astronomica Italiana*, 84, 140

Belokurov, V., *et al.* 2014, *MNRAS*, 437, 116

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

Besla, G., Kallivayalil, N., Hernquist, L., van der Marel, R. P., Cox, T. J., & Kereš, D. 2010, *ApJL*, 721, L97

Besla, G., Kallivayalil, N., Hernquist, L., van der Marel, R. P., Cox, T. J., & Kereš, D. 2012, *MNRAS*, 421, 2109

Binney, J. & Mamon, G. A. 1982, *MNRAS*, 200, 361

Bond, N. A., *et al.* 2010, *ApJ*, 716, 1

Boylan-Kolchin, M., Besla, G., & Hernquist, L. 2011, *MNRAS*, 414, 1560

Boylan-Kolchin, M., Bullock, J. S., Sohn, S. T., Besla, G., & van der Marel, R. P. 2013, *ApJ*, 768, 140

Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2005, *ApJ*, 622, L33

Brown, W. R., Anderson, J., Gnedin, O. Y., Bond, H. E., Geller, M. J., Kenyon, S. J., & Livio, M. 2010, *ApJ*, 719, L23

Brunthaler, A., Reid, M. J., Falcke, H., Greenhill, L. J., & Henkel, C. 2005, *Science*, 307, 1440

Brunthaler, A., Reid, M. J., Falcke, H., Henkel, C., & Menten, K. M. 2007, *A&A*, 462, 101

Carlin, J. L., Majewski, S. R., Casetti-Dinescu, D. I., Law, D. R., Girard, T. M., & Patterson, R. J. 2012, *ApJ*, 744, 25

Casetti-Dinescu, D. I., Girard, T. M., Herrera, D., van Altena, W. F., Lopez, C. E., & Castillo, D. J. 2007, *AJ*, 134, 195

Casetti-Dinescu, D. I., Girard, T. M., Korchagin, V. I., van Altena, W. F., & Lopez, C. E. 2010, *AJ*, 140, 1282

Casetti-Dinescu, D. I., Girard, T. M., Jilkova, L., van Altena, W. F., Podesta, F., & Lopez, C. E. 2013, *AJ*, 146, 33

Clarkson, W., *et al.* 2008, *ApJ*, 684, 1110

Darling, J. 2011, *ApJ*, 732, L2

Deason, A. J., Van der Marel, R. P., Guhathakurta, P., Sohn, S. T., & Brown, T. M. 2013, *ApJ*, 766, 24

Deg, N. & Widrow, L. 2013, *MNRAS*, 428, 912

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

Dinescu, D. I., Girard, T. M., van Altena, W. F., & Lopez, C. E. 2005, *ApJ*, 618, L25

Gardiner, L. T. & Noguchi, M. 1996, *MNRAS*, 278, 191

Ghez, A. M., *et al.* 2008, *ApJ*, 689, 1044

Gnedin, O. Y., Gould, A., Miralda-Escude, J., & Zentner, A. R. 2005, *ApJ*, 622, L33

Ibata, R., Lewis, G. F., Martin, N. F., Bellazzini, M., & Correnti, M. 2013, *ApJ*, 765, L15

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

Kallivayalil, N., van der Marel, R., Besla, G., Anderson, J., & Alcock, C. 2013, *ApJ*, 764, 161

Koposov, S. E., Rix, H.-W., & Hogg, D. W. 2010, *ApJ*, 712, 260

Koposov, S. E., Belokurov, V., & Evans, W. N. 2013, *ApJ*, 766, 79

Kroupa, P. & Bastian, U. 1997, *New Astronomy*, 2, 77

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Kuijken, K. & Rich, R. M. 2002, *AJ*, 124, 2054
Law, D. R. & Majewski, S. R. 2010, *ApJ*, 714, 229
Lepine, S., Koch, A., Rich, R. M., & Kuijken, K. 2011, *ApJ*, 741, 100
Lynden-Bell, D. & Lynden-Bell, R. M. 1995, *MNRAS*, 275, 429
Mahmud, N. & Anderson, J. 2008, *PASP*, 120, 907
Massari, D., Bellini, A., Ferraro, F. R., van der Marel, R. P., Anderson, J., Dalessandro, E., & Lanzoni, B. 2013, *ApJ*, in press
McLaughlin, D. E., Anderson, J., Meylan, G., Gebhardt, K., Pryor, C., Minniti, D., & Phinney, S. 2006, *ApJS*, 166, 249
McNamara, B. J., Harrison, T. E., & Anderson, J. 2003, *ApJ*, 595, 187
McNamara, B. J., Harrison, T. E., Baumgardt, H., & Khalaj, P. 2012, *ApJ*, 745, 175
Pawlowski, M. S. & Kroupa, P. 2013, *MNRAS*, 435, 2116
Peebles, P. J. E. & Tully, R. B. 2013, *ApJ*, 778, 137
Piatek, S., *et al.* 2002, *AJ*, 124, 3198
Piatek, S., Pryor, C., Olszewski, E. W., Harris, H. C., Mateo, M., Minniti, D., & Tinney, C. G. 2003, *AJ*, 126, 2346
Piatek, S., Pryor, C., Bristow, P., Olszewski, E. W., Harris, H. C., Mateo, M., Minniti, D., & Tinney, C. G. 2005, *AJ*, 130, 95
Piatek, S., Pryor, C., Bristow, P., Olszewski, E. W., Harris, H. C., Mateo, M., Minniti, D., & Tinney, C. G. 2006, *AJ*, 131, 1445
Piatek, S., Pryor, C., Bristow, P., Olszewski, E. W., Harris, H. C., Mateo, M., Minniti, D., & Tinney, C. G. 2007, *AJ*, 133, 818
Piatek, S., Pryor, C., & Olszewski, E. W. 2008, *AJ*, 135, 1024
Poleski, R., *et al.* 2013, *ApJ*, 776, 76
Pryor, C., Piatek, S., & Olszewski, E. W. 2014, *AJ*, submitted [arXiv1407.3509]
Rattenbury, N. J., Mao, S., Debattista, V. P., Sumi, T., Gerhard, O., & de Lorenzi, F. 2007, *MNRAS*, 378, 1165
Slipher, V. M. 1913, *Lowell Observatory Bulletin*, vol. 1, 56
Sohn, S. T., Anderson, J., & van der Marel, R. P. 2012, *ApJ*, 753, 7
Sohn, S. T., Besla, G., van der Marel, R. P., Boylan-Kolchin, M., Majewski, S. R., & Bullock, J. S. 2013, *ApJ*, 768, 139
Sohn, S. T., van der Marel, R. P., Carlin, J. L., Majewski, S. R., Kallivayalil, N., Law, D. R., Anderson, J., & Siegel, M. H. 2014, *ApJ*, submitted [arXiv:1408.3408]
Soto, M., Zeballos, H., Kuijken, K., Rich, R. M., Kunder, A., & Astraatmadja, T. 2014, *A&A*, 562, 41
Spaenhauer, A., Jones, B. F., & Whitford, A. E. 1992, *AJ*, 103, 297
Strigari, L. E., Bullock, J. S., & Kaplinghat, M. 2007, *ApJ*, 657, L1
van den Bergh, S. 2006, *AJ*, 132, 1571
van der Marel, R. P. & Guhathakurta, P. 2008, *ApJ*, 678, 187
van der Marel, R. P. & Anderson, J. 2010, *ApJ*, 710, 1063
van der Marel, R. P., Fardal, M., Besla, G., Beaton, R. L., Sohn, S. T., Anderson, J., Brown, T., & Guhathakurta, P. 2012a, *ApJ*, 753, 8
van der Marel, R. P., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012b, *ApJ*, 753, 9
van der Marel, R. P. & Kallivayalil, N. 2014, *ApJ*, 781, 121
van der Marel, R. P., *et al.* 2014, in *Proc. of Structure and Dynamics of Disk Galaxies*, M. S. Seigar, & P. Treuthardt, eds., ASP Conference Series, Vol. 480 , 2014, p.43
Vera-Ciro, C. & Helmi, A. 2013, *ApJ*, 773, L4
Watkins, L. L., Evans, N. W., & An, J. H. 2010, *MNRAS*, 406, 264