Galactic Dynamics in the Era of Large Surveys
Proceedings IAU Symposium No. 353, 2019
M. Valluri & J. A. Sellwood, eds.

doi:10.1017/S1743921319008494

The LMC vs. the Milky Way

Gurtina Besla and Nicolás Garavito-Camargo

Steward Observatory, University of Arizona, 933 North Cherry
Avenue, Tucson, AZ 85721, USA
email: gbesla@email.arizona.edu

Abstract. Recent advancements in astrometry and in cosmological models of dark matter halo growth have significantly changed our understanding of the dynamics of the Local Group. The most dramatic changes owe to a new picture of the structure and dynamics of the Milky Way's most massive satellite galaxy, the Large Magellanic Cloud (LMC), which is most likely on its first passage about the Milky Way and ten times larger in mass than previously assumed. The LMC's orbit through the Milky Way's dark matter and stellar halo will leave characteristic signatures in both density and kinematics. Furthermore, the gravitational perturbations produced by both direct tidal forcing from the LMC and the response of the halo to its passage will together cause significant perturbations to the orbits of tracers of the Milky Way's dark matter distribution. We advocate for the use of basis field expansion methods to fully capture and quantify these effects.

Keywords. (galaxies:) Magellanic Clouds, Galaxy: halo,Galaxy: kinematics and dynamics, methods: numerical, (cosmology:) dark matter

1. Introduction

Recent advances in the field of astrometry and new data from space-based observatories such as the Hubble Space Telescope (HST) and Gaia satellite have enabled precision measurements of the 3D velocity vectors of extragalactic tracers of the Milky Way's dark matter halo. The HSTPROMO collaboration has utilized both these observatories to precisely measure 3D velocity vectors and compute orbits of halo tracers (satellite galaxies, stellar streams and globular clusters; e.g., Kallivayalil *et al.* 2013; Sohn *et al.* 2018, 2016; Fritz *et al.* 2018; Zivick *et al.* 2018, 2019), reaching distances as far as Andromeda (770 kpc away; van der Marel *et al.* 2019). High-precision astrometric measurements of extragalactic targets are not achievable by ground-based efforts without water masers or > 40-year baselines. Astronomy has thus only recently entered an era of precision kinematics, launching a new era for Local Group dynamics.

The promise of precision kinematics is the ability to utilize the constrained motions of halo tracers to reconstruct the dark matter distribution of the Milky Way. This solution can then be tested against cosmological predictions for the growth of Milky Way-like halos under different assumptions about the nature of the dark matter particle, e.g., CDM, FDM, SIDM. Changing the properties of the dark matter particle can impact the concentration of the halo (cores vs. cusps; e.g. Vogelsberger *et al.* 2012), the amount of substructure within the halo (e.g. Colin *et al.* 2000), and how the halo will respond to the motions of massive satellites (Furlanetto & Loeb 2002). Appropriate template models of the expected dark matter distribution and gravitational potential of the Milky Way's halo are required to interpret the astrometric measurements of halo tracers. However, existing templates in all these dark matter models have ignored the existence of the Milky Way's most massive satellite, the LMC.

The LMC is cosmologically expected to contribute $\sim 2 \times 10^{11}$ $M_{\odot}$ of dark matter to the Milky Way's halo (Besla *et al.* 2010, 2015). This is ∼20% of the total expected mass of the Milky Way (Boylan-Kolchin *et al.* 2011), meaning that the LMC is not a small galaxy. Indeed, the LMC's stellar disk has a radius that is almost half its current distance from the Milky Way (∼18.5 kpc; Mackey *et al.* 2016; Besla *et al.* 2016; Fig. 1)! As such, the LMC cannot be treated as a point mass tracer of the halo potential. Rather, such a massive satellite will contribute to the dark matter distribution of the Milky Way and change the shape of the gravitational potential in a non-symmetrical, time-evolving manner.

This effect has not been accounted for in existing models of the Milky Way; yet, it has the potential to perturb the kinematics of all tracers of the halo potential. The lack of template halo models that include both the precise location and orbital history of the LMC will inhibit all future efforts to constrain the properties of dark matter using next generation kinematic and photometric surveys of the Milky Way's stellar halo (e.g., Gaia, DESI, 4MOST, LSST, JWST).

2. The Impact of the LMC on the Halo of the Milky Way

We have recently created a suite of eight high-resolution controlled N-body simulations designed to quantify the LMC's impact on the Milky Way's dark matter halo and the corresponding observational signatures in the stellar halo (Garavito-Camargo *et al.* 2019; hereafter G19). These are some of the highest resolution N-body simulations of the LMC+Milky Way system to date (10^8 dark matter particles), varying both the infall mass of the LMC ($0.8 - 2.5 \times 10^{11}$ $M_{\odot}$) and the kinematics of the Milky Way's dark matter halo (isotropic and radially-biased beta profiles). In all cases the Milky Way was initially modeled using a spherical Hernquist profile and a virial mass of 1.2 $\times 10^{12}$ $M_{\odot}$, and the current 3D position and velocity vectors of the LMC were matched within 2 sigma of the observed values.

In G19, we used the resulting eight simulations to make the first detailed predictions of observable perturbations to the density, radial velocities, and tangential velocities of stars in the Milky Way's stellar halo owing to the dark matter wake induced by the orbit of the LMC. In particular we find that the LMC induces resonances that produce over- and underdensities in the Milky Way's dark matter halo. These structures consequently affect the kinematics of the dark matter halo and may leave observable imprints in the stellar halo (Figure 1).

The LMC passed through its first pericentric approach to our Galaxy ∼50 Myr ago, which will result in dramatic changes in the dark matter distribution of the halo on timescale less than the dynamical time (∼1 Gyr) of the stellar halo (Fig. 2). This will necessarily affect the orbits of all halo tracers.

Specifically, the presence of the LMC will change the orbital barycenter of the LMC+Milky Way system by tens of kpc (Gómez *et al.* 2015). The orbital plane of the Sagittarius dwarf spheroidal (the progenitor of the Sagittarius Stellar Stream) can tilt owing to this effect (Vera-Ciro & Helmi 2013; Gómez *et al.* 2015). Triaxial halos, however, can produce a similar effect (Law & Majewski 2010). As such, neglecting the LMC when modeling the orbits of satellites and streams will force artificial shifts in the gravitational potential, which can be misinterpreted as intrinsic properties of the Milky Way's halo.

3. Quantifying the Shape of the Milky Way's Dark Matter Halo in the Presence of the LMC

The shapes of dark matter halos in cosmological simulations are typically estimated by fitting ellipsoids to the dark matter particle distribution (Vera-Ciro *et al.* 2011; Allgood *et al.* 2006). However, this approach is insufficient to describe the complex halo response

https://doi.org/10.1017/S1743921319008494 Published online by Cambridge University Press

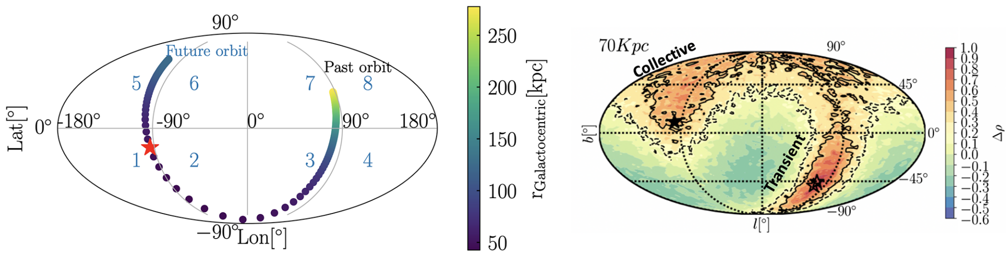

Figure 1. Visual representations of the stellar counterpart to the dark matter wake structure using Mollweide all-sky maps. Left: The past (2 Gyr) and future (1 Gyr) orbital path of the LMC, color coded by Galactocentric distance and plotted in Galactic coordinates. The current location of the LMC is marked with the red star. Right: The color bar indicates local changes in stellar density relative to the average density of K-giants (Xue *et al.* 2015) in a spherical shell, 5 kpc in thickness at 70 kpc. Contours mark stellar overdensities of $\Delta\rho = 0.1$ (dashed) and $\Delta\rho = 0.2$(solid) relative to the mean. The Transient Response traces the past orbit of the LMC, marked by the stars and is similar to the classical Chandrasekhar wake. The Collective Response is seen in the North. Predictions for the radial and tangential velocities of halo stars are made in G19.

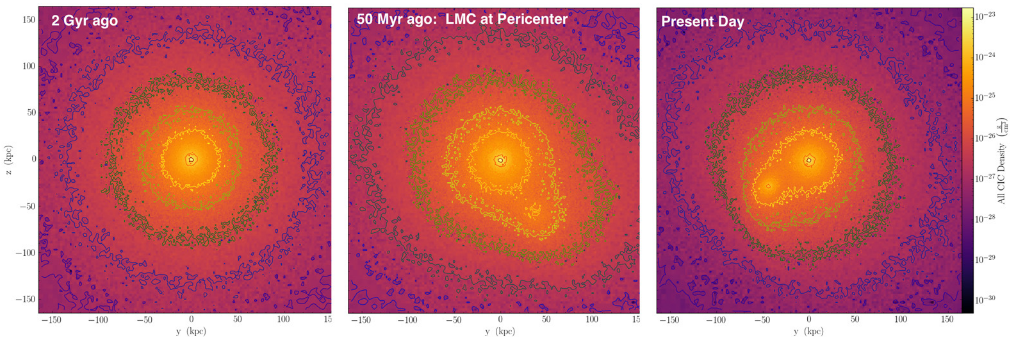

Figure 2. Isodensity contours depicting the evolution of the dark matter distribution of the Milky Way and LMC system over a period of 2 Gyr, starting with a spherical halo (left). The LMC passed through its pericentric approach to the Galaxy only 50 Myr ago (middle panel), resulting in a rapid change in the halo density and potential on timescales less than the dynamical time of all halo tracers. Such perturbations, including the Milky Way halo response, have neither been accounted for in orbit integration schemes for satellites nor in simulations of stellar streams. Image from Garavito-Camargo, Besla+in prep.

(Transient and Collective; Figs. 1 and 2) that arises from a massive satellite's motion. Instead, in Garavito-Camarago, Besla+in prep we apply the Self-Consistent Field (SCF) halo expansion technique (Hernquist & Ostriker 1992), which allows for analytic representations of non-idealized dark matter halos. Specifically, the potential and density of the dark matter halos are expanded in a bi-orthogonal series of spherical harmonics and radial functions. The SCF method has been applied to cosmological halos (Lowing *et al.* 2011), but to date has not been used to model the Milky Way system.

Figure 3 illustrates an example of the SCF reconstruction for the Milky Way dark matter density distribution after the infall of a 10^{11} $M_\odot$ LMC. Here, the LMC dark matter particles are not included in the reconstruction–what is seen is only the Milky Way halo's response. **Clearly the density perturbations induced by the LMC are complex - the Milky Way's dark matter halo shape is not accurately described as a spherical, oblate, prolate, or triaxial halo.**

https://doi.org/10.1017/S1743921319008494 Published online by Cambridge University Press

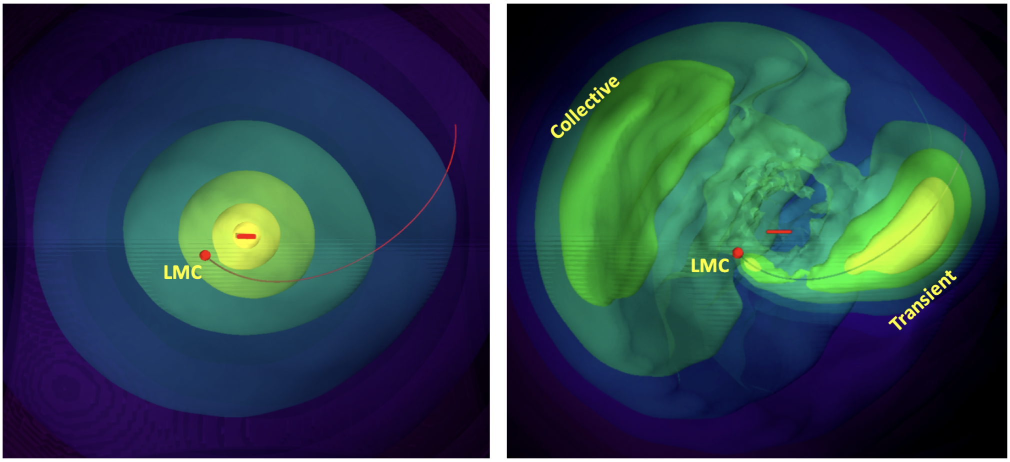

Figure 3. *Left:* The SCF analytic reconstruction of the present-day dark matter distribution of the Milky Way, as modified by the passage of the LMC (red dot; LMC orbit over past 1 billion years is tracked by the red line). LMC particles are *not* included in this reconstruction - depicted is only the halo response. The Milky Way stellar disk is indicated by the red horizontal line, for scale. The dark matter density is skewed along the LMC's orbit. *Right:* The same as the left, but the spherical terms in the SCF reconstruction are removed, revealing the asymmetry induced by the passage of the LMC, including the Collective Response towards the left and the Transient Response that traces the orbit of the LMC. The Milky Way's dark matter halo is clearly not symmetric; perturbations track the LMC's orbit over the past billion years. Image from Garavito-Camargo, Besla+ in prep.

It was recently shown that perturbations from a massive ($\sim 10^{11}$) LMC are required to match proper motion data from Gaia in simulations of the Orphan stellar stream (Erkal *et al.* 2019; Shipp *et al.* 2019). However, missing in such stream models is the response of the Milky Way's halo to the presence of the LMC (halo wakes) and the distortions to the LMC's dark matter distribution caused by the tidal field of the Milky Way. Weinberg (1998, 2000) have illustrated that wakes generated in the dark matter halo of the host by orbiting satellites can greatly augment the perturbative effects of the satellite. Such effects cannot be captured analytically without the proposed SCF reconstruction.

4. Conclusions

The LMC is a massive satellite on first infall into the Milky Way's dark matter halo (Besla *et al.* 2007). In the Cold Dark Matter paradigm, this necessarily implies that the Milky Way's dark matter halo will respond to the LMC's passage, generating large scale perturbations that will cause the Milky Way halo to deform significantly as a function of time. The changing shape of the dark matter halo will impact orbit reconstruction for the majority of objects orbiting the Milky Way, including satellites, stellar streams, halo stars and globular clusters.

With the upcoming launch of the *James Webb Space Telescope* and start of survey missions like the *Large Synoptic Survey Telescope*, 6D phase space measurements are destined to accelerate, reaching unprecedented distances, including the outskirts of our Milky Way and the environs of our massive neighbor, the Andromeda Galaxy. Significantly, Andromeda also hosts a recently captured, massive satellite galaxy, M33 (Patel *et al.* 2017), which is similarly expected to perturb the kinematics of Andromeda's outer halo.

Future models of the dark matter halos of Milky Way type galaxies must include the perturbations of their most massive satellites. In particular, we advocate for basis field expansion methods, such as the SCF technique, to appropriately capture the halo response. Models such as those of G19 and Garavito-Camargo, Besla in prep are crucial to realize the full potential of upcoming observational datasets to constrain the motions of all objects in the Milky Way and the dark matter distributions traced by these motions.

References

Allgood, B., Flores, R. A., Primack, J. R., Kravtsov, A. V., Wechsler, R. H., Faltenbacher, A., & Bullock, J. S. 2006, *MNRAS*, 367, 1718

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., & Keres, D., 2010 *ApJL*, 721, L97

Besla, G. 2015 Lessons from the Local Group: A Conference in honour of David Block and Bruce Elmegreen, ISBN 978-3-319-10613-7. Springer International Publishing Switzerland, p. 311

Besla, G., Martinez-Delgado, D., van der Marel, R. P., Beletsky, Y., Seibert, M., Schafly, E. F., Grebel, E. K., & Neyer, F. 2016 *ApJ*, 825, 20

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

Colin, P., Avila-Reese, V., & Valenzuela, O. 2000, *ApJ*, 542, 622

Erkal, D., + 15 co-authors. 2019, *MNRAS*, 487, 2, 2685

Fritz, T. K., Battaglia, G., Pawlowski, M. S., Kallivayalil, N., van der Marel, R., Sohn, T. S., Brook, C., & Besla, G. 2018, *A&A*, 619, 103

Furlanetto, S. R. & Loeb, A. 2002, *ApJ*, 565, 854

Garavito-Camargo, N., Besla, G., Laporte, C. F. P., Johnson, K. V., Gomez, F. A., & Watkins, L. L. 2019, arXiv:1902.05089. [**G19**], *ApJ*, 884, 51

Gómez, F. A., Besla, G., Carpintero, D. D., Villalovolo, A., O'Shea, B. W., & Bell, E. F. 2015, *ApJ*, 802, 128

Hernquist, L. & Ostriker, J. P. 1992, *ApJ*, 386, 375

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

Law, D. R. & Majewski, S. R. 2010, *ApJ*, 714, 229

Lowing, B., Jenkins, A., Eke, V., & Frenk, C. 2011, *MNRAS*, 416, 2697

Mackey, A. D., Koposov, S. E., Erkal, D., Belokurov, V., Da Costa, G. S., & Gómez, F. A. 2016, *MNRAS*, 459, 239

Patel, E., Besla, G., & Sohn, S. T. 2017, *MNRAS*, 464, 382

Shipp, N., Li, T. S., Pace, A. B., Erkal, D., Drlica-Wagner, A., Yanny, B., Belokurov, V., Wester, W., Koposov, S. E., Lewis, G. F., Simpson, J. D., Wan, Z., Zucker, D. B., Martell, S. L., & Wang, M. Y. 2019, arXiv:1907.09488

Sohn, S., Watkins, L., Fardal, M., van der Marel, R., Deason, A., Besla, G., & Bellini, A. 2018, *ApJ*, 862, 52

Sohn, S. T., van der Marel, R. P., Kallivayalil, N., Majewski, S. R., Besla, G., Carlin, J. L., Law, D. R., Siegel, M. H., & Anderson, J. 2016, *ApJ*, 833, 235

van der Marel, R. P., Fardal, M. A., Sohn, S. T., Patel, E., Besla, G., del Pino-Molina, A., Sahlmann, J., & Watkins, L. L. 2019, *ApJ* ,872, 24

Vera-Ciro, C. A., Sales, L., Helmi, A., Frenk, C. S., Navarro, J. F., Springel, V., Vogelsberger, M., & White, S. D. M. 2011, *MNRAS*, 416, 1377

Vera-Ciro, C. & Helmi, A. 2013, *ApJ*, 773, 4

Vogelsberger, M., Zavala, J., & Loeb, A. 2012, *MNRAS*, 423, 4, 3740

Weinberg, M. D. 1998, *MNRAS*, 299, 499

Weinberg, M. D. 2000, *ApJ*, 532, 922

Xue, X.-X., Rix, H.-W., Ma, Z., *et al.* 2015, *ApJ*, 809, 144

Zivick, P., Kallivayalil, N., van der Marel, R. P., Besla, G., Linden, S. T., Kozlowski, S., Fritz, T. K., Kochanek, C. S., Anderson, J., Sohn, S. T., Geha, M. C., & Alcock, C. R. 2018, *ApJ*, 864, 55

Zivick, P., Kallivayalil, N., Besla, G., Sangmo T. S., van der Marel, R. P., del Pino, A., Linden, S. T., Fritz, T. K., & Anderson, J. 2019, *ApJ*, 874, 78