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Constraining the Formation and Mass of the Milky Way Halo using Globular Cluster Orbits from HST Proper Motions

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Abstract. The globular cluster (GC) system of the Milky Way (MW) provides important information on the MW's present structure and past evolution. Full 3d motions, accessed through proper motions (PMs), are required to calculate accurate orbits of GCs in the MW halo. We present our HST program to create a PM database for 20 halo GCs. We demonstrate how the observed PMs of individual GCs can be used to study their origins, and we also describe how the PM measurements of our entire targets can be used to constrain the anisotropy profile. Finally, we describe how our PM results can be used for Gaia as an external check, and discuss prospects of PM measurements with HST and Gaia in the coming years.

Keywords. astrometry, Galaxy: globular clusters: general, Galaxy: halo

1. Introduction

The orbital timescales of halo GCs are very long compared to the age of the MW, so their phase-space structure is intimately linked to the accretion history of the MW halo. These properties make halo GCs excellent tracers for the gravitational potential of the MW halo. Full 3d motions are required to calculate orbits of GCs. While more than 90% of the known GCs in the MW halo have line-of-sight velocity ($V_{\rm LOS}$) measurements, accurate proper motion (PM) measurements have only been available for a few nearby halo GCs. Our HST program GO-14235 (PI: S. T. Sohn) is designed to remedy this situation by creating a high-quality PM database for a meaningful sample of distant GCs in the MW halo. The main scientific goals of this program are: to study the formation and assembly history of the MW halo through GC orbits; and to constrain the MW mass profile by directly calculating the anisotropy parameter (β). In this contribution, we summarize the data and analysis, present preliminary results, and discuss the future prospects of PM measurements using HST and Gaia.

2. Target Clusters and Proper Motions

Table 1 lists our 20 target GCs along with their distances, metallicities, and GC "classes" that are primarily based on Marín-Franch *et al.* (2009). Our target clusters are located in the Galactocetric distance range of $10 \lesssim R_{\rm GC} \lesssim 90$. We selected clusters with a wide range of properties (e.g., metallicities) to represent the halo GC population.

Table 1. Target globular clusters and their properties

Cluster	$R_{\rm GC}$ (kpc)	$R_\odot$ (kpc)	[Fe/H]	Class	Cluster	$R_{\rm GC}$ (kpc)	$R_\odot$ (kpc)	[Fe/H]	Class
NGC 6101	11.1	15.3	−1.98	Old	NGC 5024	18.3	17.8	−2.10	Old
NGC 6934	12.8	15.7	−1.47	Young	Rup 106	18.5	21.2	−1.68	Young
NGC 6426	14.6	20.7	−2.15	Old	Terzan 8	19.1	26.0	−2.16	Sgr
IC 4499	15.7	18.9	−1.53	Young	NGC 4147	21.3	19.3	−1.80	Young
NGC 2298	15.7	10.7	−1.92	Old	Arp 2	21.4	28.6	−1.75	Sgr
Pal 12	15.9	19.1	−0.85	Sgr	Pal 13	26.7	25.8	−1.88	Old
Terzan 7	16.0	23.2	−0.32	Sgr	Pal 15	37.9	44.6	−2.07	Old
NGC 5466	16.2	15.9	−1.98	Old	NGC 7006	38.8	41.5	−1.52	Young
NGC 5053	16.9	16.4	−2.27	Sgr?	Pyxis	41.7	39.7	−1.20	Young
NGC 1261	18.2	16.4	−1.27	Young	NGC 2419	91.5	84.2	−2.15	Old

To measure PMs of the GCs, we used multi-epoch HST ACS/WFC and WFC3/UVIS data. First-epoch data for most of the targets were obtained through the two survey programs by Sarajedini *et al.* (2007) and Dotter *et al.* (2011). We obtained second-epoch data for all target clusters through our HST program using the same detectors, telescope pointings and orientations as in the first-epoch observations. The PM measurements were carried out following the same methodology we used for measuring PMs of M31 (Sohn *et al.* 2012) and Leo I (Sohn *et al.* 2013). In short, we measured the bulk motions of stars in our target GCs with respect to the background galaxies found in the same HST field of each cluster. The final one-dimensional PM uncertainties are in the range 3–20 $\rm km\,s^{-1}$ at the distances of targets, with a median uncertainty of 6 $\rm km\,s^{-1}$.

3. Testing Associations with Halo Substructures

The observed kinematical properties of halo GCs can provide important information on their origins. For example, GCs associated with a satellite galaxy will show motions that are generally consistent with the motions of their host. Our targets include clusters thought to be associated with the Sagittarius (Sgr) dwarf spheroidal galaxy (dSph), so we are able test their associations using PM measurements along with other observed parameters. To do this, we adopt the N-body models of Law & Majewski (2010a) which successfully reproduces most of the observed properties of the Sgr stream in the distance range $R_\odot < 60$ kpc including PMs (see e.g., Sohn *et al.* 2015, 2016).

Figure 1 shows the comparison of the positional and kinematical properties between the observations of five GCs (Pal 12, Terzan 7, Arp 2, Terzan 8, and NGC 5053) and the N-body model particles from Law & Majewski (2010a). Terzan 7, Arp 2 and Terzan 8 are close to the main body of Sgr dSph (at $\Lambda_\odot = 0$), and hence have been long known as highly probably members. This is indeed confirmed from the left panels of Figure 1, where all observed parameters indicate that these three clusters are consistent with the Sgr trailing arm. Pal 12 has also been claimed as a probable member of Sgr, but there have been questions on whether it belongs to the trailing arm or the leading arm (Law & Majewski 2010b). The top three panels of Figure 1 (left) show that Pal 12 is consistent with either the trailing- (blue) or leading-arm particles (red), but adding the PM information as illustrated in the lower two panels clearly show that this cluster is associated with the trailing arm of the Sgr stream. NGC 5053 is another interesting case. Based on its position, distance, and radial velocity (top-right three panels of Figure 1), this cluster has been claimed as a candidate Sgr cluster. However, our PMs clearly indicate

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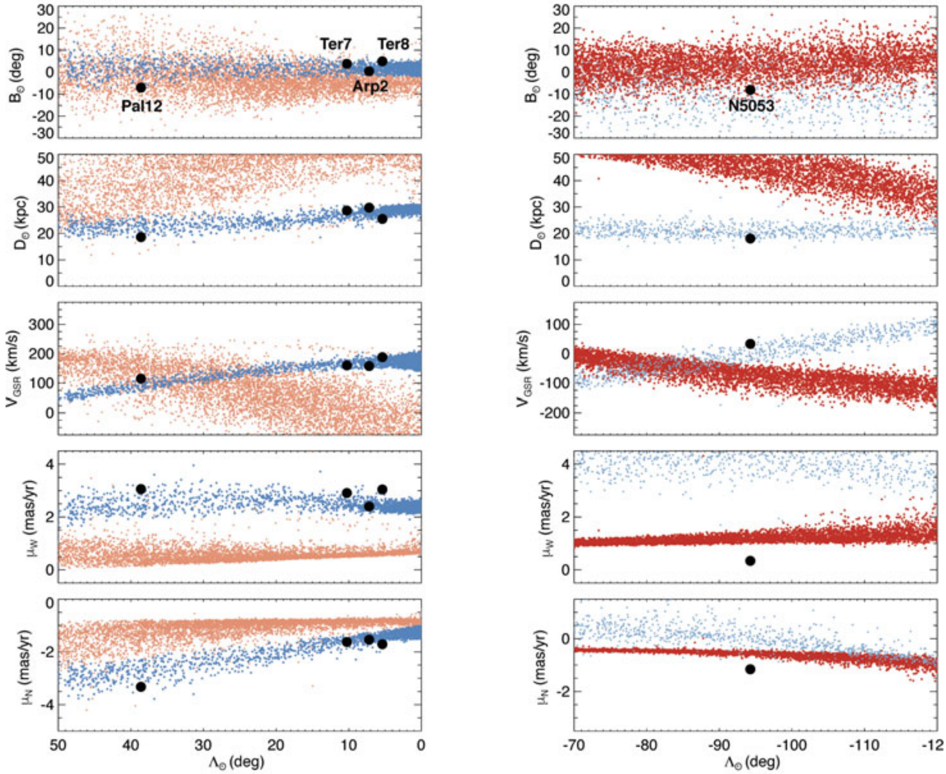

Figure 1. Sgr latitudes, distances, radial velocities, and PMs as a function of Sgr longitude for Law & Majewski (2010a) N-body model particles (small dots) and GC observations (big dots) of Pal 12, Terzan 7, Arp 2 and Terzan 8 (left panels), and NGC 5053 (right panels). Sgr latitude and longitude are coordinate systems that run across and along the Sgr stellar stream, respectively, as defined by Majewski *et al.* (2003). Blue and red dots are model particles for the Sgr trailing and leading arms, respectively. For each tidal arm, dark-colored model particles represent the first half of the 180 deg wrap, while the light-colored ones are for the other half. Uncertainty for each observed data point are typically smaller than the size of the dot.

that NGC 5053 is *not* associated with the Sgr stream at all. This is consistent with the findings of the contribution by B. Tang *et al.*in this proceedings based on orbital analysis using our HST PM.

4. Constraining the Milky Way Halo Mass Profile

The MW mass is a fundamental quantity for understanding the MW in cosmological context. Many methods have been used to estimate this mass, based on the ensemble of kinematics of tracer objects. Despite the various works, the mass remains poorly known: $0.5 \lesssim M_{\mathrm{MW,vir}}/(10^{12} M_\odot) \lesssim 3$. The is wide range of mass estimates is due in part to the profound lack of 3d kinematical information. Studies based entirely on LOS velocities suffer from a well-known mass-anisotropy degeneracy. Traditionally, studies have used the predictions of numerical simulations to estimate the unknown β of kinematical tracers. However, since we have the full component of velocities for our target clusters, we are able to directly calculate β which is defined as $\beta = 1-(\sigma_{\mathrm{tan}}/\sigma_{\mathrm{rad}})^2$, where σ_{tan} and σ_{rad} are the velocity dispersions measured in tangential and radial directions, respectively. Figure 2 shows the result compared to those from other studies for various ranges of R_{GC}. For this β calculation, we excluded NGC 2419 due to its large separation in distance from

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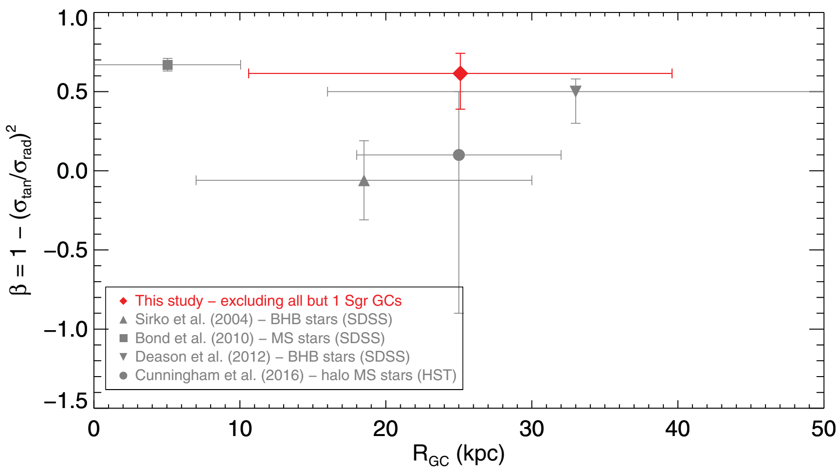

Figure 2. Anisotropy (β) profile of the MW halo from various tracer objects. The (red) diamond indicates the β computed using our PM results combined with existing line-of-sight velocities.

the other clusters in our sample. We also included only one Sgr cluster, Arp 2, to match the ratio between Sgr and non-Sgr clusters, which is approximately 1:20. Estimating the MW mass using this β is currently under progress, and we expect to report the results in a refereed journal.

5. Prospects of Proper Motions with HST and Gaia

With the end-of-mission data, Gaia will measure systemic PMs and parallaxes of GCs to 1% or better out to $\sim$ 15 kpc (Pancino *et al.* 2017). For classical dwarf spheroidal galaxies, Gaia will be able measure PMs using plenty of stars brighter than its detection limits out to $\sim$ 200 kpc. Therefore, for halo objects in the range $R_{\rm GC} \lesssim 200$ kpc, the current and upcoming PM results from HST will be used as important external checks for the Gaia results. Beyond $R_{\rm GC} = 200$ kpc, stars in satellite objects are too faint to be detected by Gaia, so HST will continue to be a unique platform for distant objects.

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References

Dotter, A., Sarajedini, A. & Anderson, J. 2011 *ApJ*, 738, 74
Law, D. R. & Majewski, S. R. 2010a *ApJ*, 714, 229
Law, D. R. & Majewski, S. R. 2010b *ApJ*, 718, 1128
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D. & Ostheimer, J. C. 2003 *ApJ*, 599, 1082
Marín-Franch, A., Aparicio, A., Piotto, G., *et al.* 2009 *ApJ*, 694, 1498
Pancino, E., Bellazzini, M., Giuffrida, G. & Marino, S. 2017 *MNRAS*, 467, 412
Sarajedini, A., Bedin, L. R., Chaboyer, B. *et al.* 2007 *AJ*, 133, 1658
Sohn, S. T., Anderson, J., & van der Marel, R. P. 2012, *ApJ*, 753, 7
Sohn, S. T., Besla, G., van der Marel, R. P. *et al.* 2013, *ApJ*, 768, 139
Sohn, S. T., van der Marel, R. P., Carlin, J. L. *et al.* 2015, *ApJ*, 803, 56
Sohn, S. T., van der Marel, Kallivayalil, N. *et al.* 2016, *ApJ*, 833, 235

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