*Astronomy and Astrophysics in the Gaia sky*
*Proceedings IAU Symposium No. 330, 2017*
*A. Recio-Blanco, P. de Laverny, A.G.A. Brown & T. Prusti, eds.*

doi:10.1017/S1743921317006056

# HST Proper Motions of Distant Globular Clusters: Constraining the Formation & Mass of the Milky Way

**S. Tony Sohn[1], Roeland P. van der Marel[1], Alis Deason[2], Andrea Bellini[1], Gurtina Besla[3] and Laura Watkins[1]**

[1]Space Telescope Science Institute,
3700 San Martin Drive, Baltimore 21218, USA
email:tsohn@stsci.edu

[2]Institute for Computational Cosmology,
Department of Physics, Durham University,
South Road, Durham DH1 3LE, UK

[3]Steward Observatory, University of Arizona,
933 North Cherry Avenue, Tucson, AZ 85721, USA

**Abstract.** Proper motions (PMs) are required to calculate accurate orbits of globular clusters (GCs) in the Milky Way (MW) halo. We present our HST program to create a PM database for 20 GCs at distances of $R_{\rm GC}$ = 10–100 kpc. Targets are discussed along with PM measurement methods. We also describe how our PM results can be used for Gaia as an external check, and discuss the synergy between HST and Gaia as astrometric instruments in the coming years.

**Keywords.** astrometry, Galaxy: evolution, Galaxy: formation, Galaxy: globular clusters: general, Galaxy: halo

## 1. Introduction

The globular cluster (GC) system of the Milky Way (MW) provides important information on the MW's present structure and past evolution. Clusters in the halo are particularly useful tracers; because of their long dynamical timescales, their orbits retain imprints of the origin and accretion history. Full 3d motions are required to calculate orbits of GCs. While most GCs in the MW halo have known line of sight velocities, accurate proper motion (PM) measurements have only been available for a few halo GCs. Our HST program GO-14235 is designed to remedy this situation by creating a high-quality PM database for several distant GCs in the MW halo. Orbit calculations based on our PMs will provide important clues to the origins of individual halo GCs. Our PMs will also yield the best handle yet on the velocity anisotropy profile of any tracer population in the halo, and subsequently provide an improved estimate of the MW mass.

## 2. Target Clusters and Proper Motions

Table 1 lists our 20 target GCs along with their distances, metallicities, and GC "class" based on Mackey & van den Bergh (2005). We included clusters with a wide range of properties to select a representative sample of the halo population. 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), except for Pal 13 and NGC 2419. We obtained second-epoch data for all target clusters through this program using the same detectors, telescope

**Table 1.** Target globular clusters and their properties

| Cluster | $R_{GC}$ (kpc) | $R_{\odot}$ (kpc) | [Fe/H] | Class | Cluster | $R_{GC}$ (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 | Young | 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 | Sgr |
| 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 | Young |
| 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 | Young | NGC 7006 | 38.8 | 41.5 | −1.52 | Young |
| NGC 5053 | 16.9 | 16.4 | −2.27 | Young | 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 |

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. We have carefully tested and verified our method to minimize possible systematic errors by correcting for local effects around each background galaxy. The final 1-D PM errors are in the range 3–20 $\mathrm{km\,s^{-1}}$ at the distances of targets, with a median uncertainty of 6 $\mathrm{km\,s^{-1}}$.

## 3. Prospects of Proper Motions with HST and Gaia

The average velocity dispersion of the MW halo is measured to be $\sim 100\,\mathrm{km\,s^{-1}}$ (e.g., Battaglia *et al.* 2005), and so a 1-D PM error lower than $\sim 50\,\mathrm{km\,s^{-1}}$ is required to get a meaningful dynamical measure of halo objects. Beyond 50 kpc, objects with required PM qualities are considerably lacking. Together with the Gaia PM results, our current and future HST programs will significantly increase the number of samples that will help better constrain the MW halo mass profile out to and beyond 100 kpc.

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 $R_{GC} \lesssim 200$ kpc, the current and upcoming PM results from HST will be used as important external checks for the Gaia results. Beyond $R_{GC} = 200$ 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. Meanwhile, it may be possible to use Gaia astrometry against HST or JWST for bright stars to measure PMs.

### References

Battaglia, G., Helmi, A., Morrison, H. *et al.* 2005 *MNRAS*, 364, 433
Dotter, A., Sarajedini, A. & Anderson, J. 2011 *ApJ*, 738, 74
Mackey, A. D. & van den Bergh, S. 2005, *MNRAS*, 360, 631
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