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Local Group and Star Cluster Dynamics from HSTPROMO (The Hubble Space Telescope Proper Motion Collaboration)

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Abstract. The Hubble Space Telescope (HST) has proven to be uniquely suited for the measurement of proper motions (PMs) of stars and galaxies in the nearby Universe. Here we summarize the main results and ongoing studies of the HSTPROMO collaboration, which over the past decade has executed some two dozen observational and theoretical HST projects on this topic. This is continuing to revolutionize our dynamical understanding of many objects, including: globular clusters; young star clusters; stars and stellar streams in the Milky Way halo; Local Group galaxies, including dwarf satellite galaxies, the Magellanic Clouds, and the Andromeda galaxy; and AGN Black Hole Jets.

1. Introduction: Proper Motion Studies with HST

The dynamics of stars, clusters, and galaxies provide important information on the formation, evolution, structure, and mass of stellar systems. Most of what is known 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. To determine fully three-dimensional velocities, it is necessary to also determine PMs. If a PM accuracy $\Delta \text{PM} \approx 50 \mu\text{as/yr}$ is achieved, then many dynamical topics in the Local Group can be meaningfully addressed. This corresponds to a velocity accuracy $\Delta v \approx (D/4) \text{ km/s}$ at distance $D \text{ kpc}$.

Such PM accuracies are not generally accessible from the ground. VLBA can reach them, but only for a small number of maser sources. Gaia should reach them for many stars, but this will take several more years. For HST, $50 \mu\text{as/yr}$ corresponds to a motion of ~ 0.01 CCD pixel over 10 years. Since HST has many advantages for astrometry (high spatial resolution, long-term stability, and more than 20 years of Archival data), such accuracies have already been routinely achievable for years. This is true even for faint sources in crowded fields (unlike Gaia), thus allowing PM measurements for $N = 10^2$ – 10^6 sources per field, depending on the specific target.

The random errors for measurements of bulk motions and velocity dispersions scale as $N^{-0.5}$. Thus, systematic errors are often the limiting factor. These can be controlled by careful calibrations of PSF shapes, geometric distortions, charge-transfer efficiency, color effects, etc. (Anderson & King 2000). Relative PM measurements suffice for measurements of velocity dispersions, while absolute PM measurements are required for bulk motion measurements. The latter requires use of distant (i.e., stationary) background quasars or galaxies as reference sources (Mahmud & Anderson 2008).

Several other groups have used HST for PM studies of globular clusters (e.g., McNamara et al. 2003, 2012; McLaughlin et al. 2006), the Milky Way (e.g., Kuijken & Rich 2002; Brown et al. 2010), or the Local Group (e.g., Piatek & Pryor 2008; Lépine et al. 2011). Here instead we report on results and ongoing work of our HSTPROMO collaboration, the work of which has included some two dozen observational and theoretical HST projects over the past decade.¹

2. HSTPROMO Results and Projects

The following provides a sampling of our results on PM dynamics in the nearby Universe, roughly in order of increasing distance.

Globular Clusters (GCs). Anderson & van der Marel (2010) presented a PM catalog for 170,000 stars in the GC omega Centauri. Detailed dynamical models by van der Marel & Anderson (2010) placed an upper limit of $1.2 \times 10^4 M_\odot$ on the mass of any possible intermediate mass black hole (IMBH) at the center of this GC. Comparison of the PM dispersion of stars of different mass along the main sequence (MS) shows that Omega Cen is not in equipartition. Trenti & van der Marel (2013) performed N -body simulations to model this, and found that despite popular belief to the contrary, GCs are not generally expected to ever get close to equipartition. Massari et al. (2013) presented measurements of the absolute PM of the GC NGC 6681 (M70). Bellini et al. (2013) are

¹See details on the HSTPROMO web page: <http://www.stsci.edu/~marel/hstpromo.html>

extending these studies to a sample of two dozen GCs. The resulting datasets can be interpreted with dynamical modeling tools such as those presented by Chanamé et al. (2008), and will provide many new insights into the structure, dynamics, multiple populations and possible IMBHs of GCs.

Young Star Clusters. The phenomenon of runaway O/B stars from young clusters has been known for a long time. To better understand the dynamical origin of these stars, we are determining PMs of stars in the 30 Dor star-forming region in the Large Magellanic Cloud (LMC; Sabbi et al. 2013, Platais et al., in prep.), and in regions near young clusters in the Galactic Center (Lennon et al., in prep.). An important advantage of such measurements is that the direction of the PM vectors can help identify the probable places of origin of any runaway stars.

Milky Way (MW) Halo Stars and Streams. By combining PM and color-magnitude diagram information it is possible to uniquely identify distant MS halo stars. The PMs of 13 stars at 24 ± 6 kpc toward the Andromeda-Triangulum halo overdensity imply a halo velocity ellipsoid that is more tangentially anisotropic than near the Sun. This suggests the presence of a shell in the halo, probably resulting from an ancient accretion event (Deason et al. 2013). We will extend this work to a sample of ~ 1000 stars spread over the sky. We are also in the process of determining the PMs for stars along the Sagittarius and Orphan Streams (Sohn et al., van der Marel et al., in prep.), which will constrain the shape of the MW dark matter halo.

Magellanic Clouds. Kallivayalil et al. (2006a,b) were the first to obtain high-accuracy PMs of the Magellanic Clouds, which were recently refined by Kallivayalil et al. (2013). The results imply that the Clouds are moving faster than previously believed, and are likely just past their *first* MW pericenter (Besla et al. 2007). This has led to revisions in our understanding of both the Magellanic Stream (Besla et al. 2010), and the formation of Magellanic Irregular galaxies in general (Besla et al. 2012). By mapping the variations in PM across the face of the LMC, it has been possible to measure its PM rotation field and rotation curve (van der Marel & Kallivayalil 2013), the first time this has been possible for any galaxy.

Local Group (LG) Dwarf Satellite Galaxies. Sohn et al. (2013) measured the absolute PM of the rapidly-moving distant MW satellite Leo I, which indicates it likely had its *first* pericenter passage 1.0 ± 0.1 Gyr ago at 91 ± 36 kpc. Cosmological simulations show that subhalos are almost always bound to their host. Assuming that Leo I is the least-bound classical MW satellite, the implied MW virial mass is $M_{\text{vir}} \approx (1.6 \pm 0.3) \times 10^{12} M_{\odot}$ (Boylan-Kolchin et al. 2013). We are also studying other LG dwarfs, to determine both internal PM kinematics (Sohn et al., in prep.: Draco, Sculptor) and absolute PMs (Massari et al. 2013, for the Sgr dSph; van der Marel et al., in prep: Cetus, Tucana, Leo A, Sgr dIrr; Do et al., in prep.: Leo T.)

The Andromeda Galaxy (M31). Sohn et al. (2012) obtained the first-ever PM measurement for M31. The result agrees with indirect estimates based on the LOS kinematics of its satellites (van der Marel & Guhathakurta 2008). The LG timing argument combined with other mass estimates implies a total LG virial mass $M_{\text{MW}} + M_{\text{M31}} = (3.2 \pm 0.6) \times 10^{12} M_{\odot}$ (van der Marel et al. 2012b). The PM is consistent with a head-on collision orbit for M31 toward the MW. *N*-body simulations show that the first passage will occur in 4 Gyr, followed by a complete merger after 6 Gyr (van der Marel et al. 2012a). The remnant will resemble an elliptical galaxy. There is a 10% probability that the Triangulum galaxy, M33, will hit the MW before M31 does.

AGN Black Hole Jets. Meyer et al. (2013) measured the PMs of features in the optical jet of M87, and found evidence for helical motion. Similar measurements for 3C264, 3C273, and 3C346 are in progress.

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