Local Group Proper Motion Science from Wide Field Surveys

Roeland van der Marel
(STScI)
Stellar Dynamics

- Many reasons to understand the dynamics of stars, clusters, and galaxies in the nearby Universe

- **Formation:** The dynamics contains an imprint of initial conditions

- **Evolution:** The dynamics reflects subsequent (secular) evolution

- **Structure:** dynamics and structure are connected

- **Mass:** Tied to the dynamics through gravity
  - critical for studies of dark matter, galaxy masses and mass profiles
Line-of-Sight (LOS) Velocities

- Almost all observational knowledge of stellar dynamics derives from LOS velocities (spectroscopy)

- Yields only 1 component of motion
  - Limited insight from 1D information
  - 3D velocities needed for mass modeling

- Many assumptions/unknowns/degeneracies in LOS velocity modeling
Proper Motions (PMs)

- PMs provide much added information, either by themselves (2D) or combined with LOS data (3D)

- **Characteristic velocity accuracy necessary**
  - 1 km/s at 7 kpc (internal globular cluster dynamics)
  - 10 km/s at 70 kpc (Milky Way halo/satellite dynamics)
  - 100 km/s at 700 kpc (Local Group dynamics)

- **Corresponding PM accuracy**
  - 30 μ as / yr (~ speed of human hair growth at Moon distance)
Current Observational Approaches

- **VLBI, radio, water masers** [highest PM accuracy]
  - Only a few galaxies with suitable water masers

- **Ground-based, optical-IR** [low-medium PM accuracy]
  - Use old photographic 1\textsuperscript{st}-epoch data w/ long time baselines
  - Combine modern data and surveys (e.g., SDSS, USNO, 2MASS, ...)

- **HST, optical-IR** [high PM accuracy]
  - High spatial resolution, low background, stable, long time baselines
  - $30 \, \mu\text{as / yr} \sim 0.006$ HST ACS/WFC pixels in 10 yr
  - Many sources per field ($N = 10^2 \sim 10^6$, $\Delta \sim 1/\sqrt{N}$)
Emerging Observational Prospects

- **GAIA**
  - Spectacular PM Dynamics of Milky Way
    - Accuracy at V~15 will be ~10 μ as / yr
  - Some PM Dynamics for MW Satellites and Local Group
    - Accuracy at V~20 will be ~400 μ as / yr
  - HST will continue to be unique for faint targets and crowded areas
    - Accuracy at V~25 of ~100 μ as / yr already “routine”
Future Observational Prospects

- **ASTRO2010 Decadal Survey**: Astrometry - 1 of 5 Discovery Areas

- **Ground**: LSST, 30-m class telescopes, ...

- **Space**: JWST, EUCLID, WFIRST-AFTA, ATLAST (8-16m),....

- **Advantages**:
  - **Wide areas**: more sources, wider-scale phenomena
  - **Big mirrors**: fainter sources, lower random errors
  - **Longer time baselines**: when compared to existing high-resolution data (e.g. HST)

- **Prospects**
  - New studies *inside* the Local Group
  - First studies *outside* the Local Group (e.g., internal PM dynamics of the Virgo cluster)
Example: WFIRST-AFTA

- Like HST, but ~100x the FOV
- Similar pixel scale as WFC3/IR
- ~2x the pixel scale of ACS and WFC3/UVIS
- Use background galaxies as stationary references
HSTPROMO: The Hubble Space Telescope Proper Motion Collaboration
(http://www.stsci.edu/~marel/hstpromo.html)

- Set of many different HST investigations, with detailed theory components
  - Lead coordinators: van der Marel & Anderson
  - Project/Paper Leads: Sohn, Kallivayalil, Besla, Bellini
  - Many Other Members

- Status/Achievements
  - 10+ years of work
  - 33 HST projects (many ongoing)
  - 25 refereed papers (many more in preparation)
Collision Scenario for Milky Way and Andromeda Galaxy Encounter

[Sohn et al. 2012; vdMarel et al 2012a,b]
PM and Orbit of Magellanic Clouds

- **Traditional view**
  - Clouds have orbited Milky Way many times
  - Logarithmic Milky Way halo implies ~2 Gyr period

- **HST PM measurements**
  - Reflex motion of QSO wrt LMC/SMC stars over 7 years
  - Clouds move faster than traditionally believed → wider, longer-period orbit

[Image: LMC Field 1 of 22; 3 epochs 1x1 pixel box]

[Graph: [Kallivayalil et al. 2006,2013]]

[Image: Besla et al. 2007]

[Graph: Milky Way
LMC
 Previous, elliptical orbit
 Current, parabolic orbit
500,000 light-years]
LMC: First ever PM rotation field measurement (1 turn in 250 Myr)

[van der Marel & Kallivayalil 2014]
Internal Dynamics of Globular Clusters

- For example, 75,000 M15 stars (Bellini et al. 2014)

- Allows detailed studies of (lack of) internal equipartition (Trenti & van der Marel 2013)

- Similar data available for ~25 globular clusters
Expected Progress with wider-area Space Facilities: WFIRST-AFTA

- High-Latitude Survey (gravitational lensing) and Bulge Survey (microlensing)
  - will provide many PMs at magnitudes fainter than GAIA
- Targeted GO observations, or combination with already existing space data (HST, JWST)
  - can further improve accuracy for smaller areas
- Science Topics
  - Stellar streams
  - Bulge/Halo kinematics
  - Hypervelocity stars
  - Dwarf galaxies
Conclusions

- Proper Motions yield new insights into Local Group Galaxy Dynamics and Masses
  - Can be reliably measured with various techniques, HST being especially powerful

- Great prospects for future advances
  - Dedicated missions (GAIA)
  - Wider areas (LSST, EUCLID, WFIRST-AFTA)
  - Bigger mirrors (JWST, 30m-ground, ....)

- Key for progress in Galactic Archeology
  - Understand galaxy formation and evolution through resolved studies of nearby galaxies

- Movies: will run while you ask me questions
Large Magellanic Cloud Sky View Showing Rotation next 14 Myr

[vdMarel & Kallivayalil 2014; visualization: Greg Bacon and Ann Feild]
Zoom-in to M31 Spheroid Field with 30,000 years of projected motion

[Sohn et al. 2012; visualization: Zolt Levay, Greg Bacon, and Jay Anderson]
Zoom-in to Omega Cen with 10,000 years of projected motion

[Anderson & vdMarel 2010; vdMarel & Anderson 2010; visualization: Greg Bacon]
MW-M31-M33 N-body simulation
(one of several scenarios consistent with PMs)