The Magellanic Clouds and Stream: Probes of the Milky Way Halo

Roeland van der Marel

Proper motions: Nitya Kallivayalil
Orbit calculations: Gurtina Besla
**Recent Near-IR surveys**

- **2MASS**: Two Micron All Sky Survey \([J,H,K_s]\)
- **DENIS**: Deep Near-IR Southern Sky Survey \([I,J,K_s]\)
  - Insensitive to dust absorption
  - Superb Statistics (1-2 million stars)
  - CMDs allow separation of different stellar populations
AGB(C) AGB(O) Tip-RGB RGB

[Marigo et al. (Padua models)]

2MASS

CMD allows extraction of the intermediate age/old population:
AGB/RGB stars \(\Rightarrow\) tracer of underlying mass distribution

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LMC Morphology: Near-IR
Selected RGB & AGB Stars

vdM (2001):
Smooth morphology
(contrast to optical)

Surface Density Profile ~ Exponential

At large radii:

\[ PA_{\text{maj}} = 189 \pm 1 \, \text{deg} \]
\[ \varepsilon = 0.20 \pm 0.01 \]
LMC: Viewing Angles

- Viewing angles describe our vantage point w.r.t. LMC plane
  - $i$ = inclination angle
  - $\Theta$ = line of node pos. angle
- Geometrical determination
  - Magnitude variations from distance variations to an inclined plane:
    \[0.038\text{[mag]} \cdot r[\text{deg}] \cdot \tan i \cdot \sin (\text{PA} - \Theta)\]
- vdM & Cioni (2001): use positional dependence of well-defined features in the near-IR CMDs
  - RGB Tip
  - AGB Modal Magnitude

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Magnitude Variations along Rings

Polar grid on sky

Sinusoidal magnitude variations

i = 34.7 ± 6.2 deg

Θ= 122.5 ± 8.3 deg
The Deprojected (face-on) view of the LMC

\[ \Theta \neq PA_{maj} \Rightarrow \text{LMC disk is not circular (} \epsilon = 0.31 \) \]
LMC/SMC proper motion
Improved Measurements

☆ Use HST/ACS to image LMC/SMC star fields centered on background quasars
☆ Determine shifts in stellar positions w.r.t. quasars
LMC Proper Motion Results
(Kallivayalil, vdM, Alcock et al. 2006a,b)

☆ 21 LMC and 5 SMC QSO fields
☆ 2-year baseline
   (Cyc 16: 5yr w/ WFPC2)
☆ Random ORIENTs
☆ ~0.005 pix accuracy/field
☆ LMC:
   \[ \mu_W = -2.03 \pm 0.08 \text{ mas/yr} \]
   \[ \mu_N = 0.44 \pm 0.05 \text{ mas/yr} \]
☆ SMC:
   \[ \mu_W = -1.16 \pm 0.18 \text{ mas/yr} \]
   \[ \mu_N = -1.17 \pm 0.18 \text{ mas/yr} \]
Modeling the Line-of-Sight Velocity Field

\[ v_{\text{los}}(\rho,\text{PA}) = \]
\[ + fV(R)\sin i \cos (\text{PA} - \Theta) \]
\[ + v_{\text{sys}} \cos \rho \]
\[ + v_t \sin \rho \cos (\text{PA} - \Theta_t) \]
\[ + D_0 \left( \frac{\text{di}}{\text{dt}} \right) \sin \rho \sin (\text{PA} - \Theta) \]

Previous studies have not properly take the full complexity of this equation into account.
Fit to Carbon Star Data

vdM, Alves, Hardy, Suntzeff (2001)

1041 Carbon stars:
☆ Kunkel et al. (1997)
☆ Hardy et al. (2002)
The LMC Transverse Velocity

☆ The line-of-sight velocity field allows a determination of the LMC transverse velocity, if one assumes:
  ☆ $m-M = 18.50$
  ☆ $di/dt = 0$
☆ $\Rightarrow$ consistent with proper motion data
LMC: Thickness

LMC: \( \frac{V}{\sigma} = 3.5 \pm 0.9 \)

Compare:
- Milky Way thick disk: \( \frac{V}{\sigma} = 3.9 \)
- Milky Way thin disk: \( \frac{V}{\sigma} = 8.9 \)

LMC disk is thicker than previously believed
- Consistent with predictions of Milky Way tidal influence
- Microlensing predictions unaffected (depend on \( \sigma \) only)
- Self-lensing still cannot account for all observed lensing events (Mancini et al. 2004)
SMC Proper Motion

Bound LMC/SMC orbits exist with the 1-sigma error ellipse

LMC & SMC bound for >5 Gyr or 1-5 Gyr
Magellanic Clouds
Orbit Properties

☆ Previous work
☆ Assume logarithmic potential
☆ Estimate proper motion from Magellanic Stream models
☆ Gardiner & Noguchi (1996): \( v_{\text{tan}} = 287 \, \text{km/s} \)
☆ \( v_{\text{rad}} \ll v_{\text{tan}} \Rightarrow \) Magellanic Clouds just past pericenter

Period
\(~2 \, \text{Gyr}\)
⇒
multiple passages

☆ New insights
☆ Better cosmological understanding of dark halo profiles
☆ Clouds move significantly faster than previously argued
☆ HST: \( v_{\text{tan}} = 367 \pm 18 \, \text{km/s} \)
New Exploration of Orbits
Besla et al. (2007)

- Fixed Milky Way Potential
  - Disk + Bulge + Hot Halo + Dark Halo (Lambda CMD motivated NFW, adiabatically contracted)
- Simple Point-Mass orbits
  - Integrated backwards in time
  - From current conditions (+Monte-Carlo realizations of errors)
  - Includes dynamical friction prescription
Dependence on Milky Way Potential

Logarithmic Potential

10^{12} M_\odot ACMD Halo

- New Proper Motion
  - Larger period
  - Larger apocenter

- Escape Velocity
  - Parabolic orbit, First Passage
  - or: More Massive \sim 2 \times 10^{12} M_\odot DH

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Likelihood of a First Passage Scenario

van den Bergh 2006

MW Satellites

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Local Group Demographics

All Irr galaxies (satellites with high gas fractions) are located at large Galactocentric radii, except for the Magellanic Clouds.

Theory

Bullock et al. (2007, in prep.): 70% of halos have accreted an LMC-type galaxy in the past 5 Gyr.

accreted = first falls within a ~300 kpc virial radius.
Magellanic Stream: Models

☆ Many plausible models constructed over the years
  ☆ Multiple passages almost always assumed

☆ Little agreement on dominant physical process
  ☆ Tidal stripping
    recent example: Connors et al. (2005)
    ☆ Stream formed ~1.5 Gyr ago from SMC gas during the last close LMC-SMC encounter
  ☆ Ram-pressure stripping
    recent example: Mastropietro et al. (2005)
    ☆ Stream formed from LMC gas due to ram pressure stripping by a low-density ionized halo (SMC not modeled!)
Magellanic Stream: Tidal Model
Magellanic Stream: Ram-Pressure Model
Comparison of Orbit to Magellanic Stream Location

- Newly calculated orbits are not co-located in the sky with the Magellanic Stream

  - Independent of
    - Dark Halo profile
    - Dark Halo axial ratio
    - PM West-component

- Driven by PM North-component
  - HST result identical to average of ground-based data
  - many-sigma different from Gardiner & Naguchi (1996)
HI velocity gradient comparison

- $V_{\text{LSR}}$ gradient along orbit not the same as HI gradient along Stream
- The extent to which this is expected depends on the physical processes that form the Stream
Conclusions

☆ Our understanding of the **Magellanic Clouds**, their structure, and their interaction with the **Milky Way** is improving continuously

☆ **Proper Motions & Orbit Calculations**
  - Magellanic Clouds may be on their first passage about the Milky Way and/or
  - Milky Way may be more massive than typically believed

☆ **Strong motivation to revisit existing Magellanic Stream models**