HST Proper Motion of the SMC: Is the SMC bound to the LMC?

(Kallivayalil et al. 2006, ApJ, 652, 1213)

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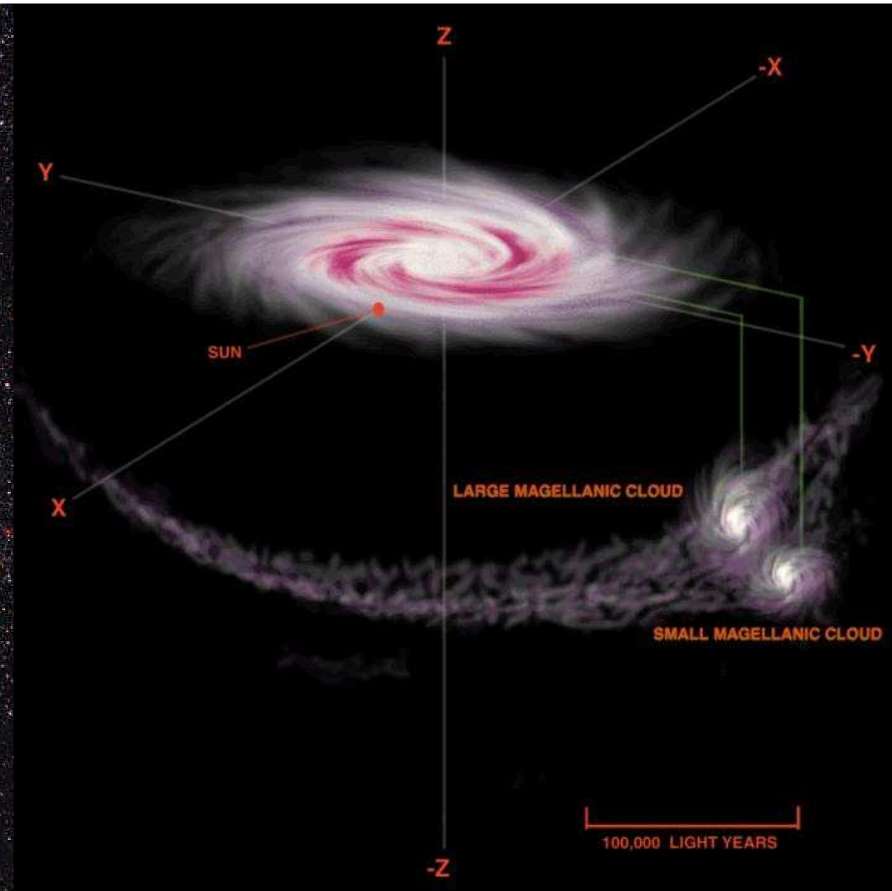


- Dwarf irregulars (LMC : Irr/SB(s)m)
- Satellites of the Milky Way
- Gas-rich and more metal-poor than the MW
- Long stellar formation histories from very young to very old

Introduction

- Interaction between the Clouds and the Milky Way
  - Dynamic evolution of the MW's outer parts & MW warp
- MW: major influence on the Clouds' development
  - Star formation history & structural and chemical evolution and kinematics
- Magellanic Stream
  - HI gas trail of the Clouds in their orbit around the MW & Inter- Cloud bridge
  - Origin of some current dwarf galaxies and globular clusters
  - Provide a "fossil record" of the history of the buildup of MW mass
- To interpret the fossil record
  - Require detailed modeling of the internal evolution of the satellites
  - Sensitive observations to falsify theoretical predictions
- Major uncertainty is the orbital motion of the Clouds

Models of the Clouds' orbits

- Tidal models
  - MW exerts the tidal force on the Clouds
  - Stream is a product of the tidal disruption of the SMC (1-2 Gyr ago)
  - Inter-Cloud is the result of a close encounter between the Clouds
  - Gravitationally bound to the MW and will become separated in the next 1-2 Gyr
  - Lack of detailed gas dynamic properties & lack of stars in the Stream is still poorly understood
- Ram pressure stripping models
  - Encounter between the Clouds produce the inter-Cloud region
  - Stream is produced from collisions between the inter-Cloud region gas and high-vel. clouds or an extended halo of diffuse ionized gas
  - Difficulty in producing the leading arm of the Stream
  - Number density of high-vel. clouds is uncertain
  - Didn't include the SMC in the analysis

Previous work on the SMC PM

- *Hipparcos* measurements of 11 stars
  - μ_W = -1.23 $\pm$ 0.84 mas yr^{-1} & μ_N = -1.21 $\pm$ 0.75 mas yr^{-1}
- AAT and CTIO with a baseline of 15-20 yr
  - μ_W = -0.92 $\pm$ 0.2 mas yr^{-1} & μ_N = -0.69 $\pm$ 0.2 mas yr^{-1}
- Freire et al. (2003) combined with the absolute PM of 47 Tuc
  - μ_W = -0.6 $\pm$ 0.6 mas yr^{-1} & μ_N = -1.9 $\pm$ 0.6 mas yr^{-1}

- Unweighted average of three independent measurements
  - $\langle\mu_W\rangle$ = -0.91 $\pm$ 0.19 mas yr^{-1} & $\langle\mu_N\rangle$ = -1.28 $\pm$ 0.36 mas yr^{-1}
  - Consistent with the current understanding of the Magellanic Stream and the Cloud-MW system
  - But, the errors are not accurate enough to constrain its dynamics

Sampling and Observation

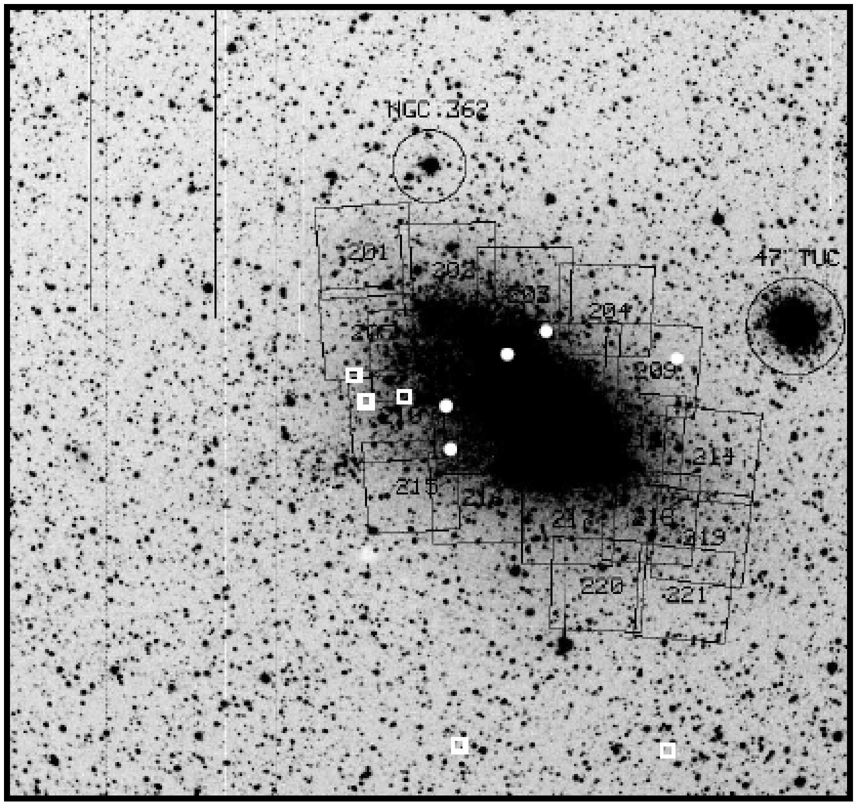


FIG. 1.—*R*-band image of the SMC (4° × 4°). The MACHO photometric coverage is indicated (*black boxes*). White circles indicate reference QSOs for which we obtained two epochs of ACS HRC imaging, and white squares indicate QSOs for which we did propose but did not get two epochs of imaging in our snapshot program.

- Imaged five out of 10 QSOs identified in the MACHO database
- Two epochs with the High Resolution Camera (HRC) on the Advanced Camera for Surveys (ACS) on *HST*
- Average baseline achieved is ~2 yr

Analysis

- Procedure to obtain a PM
  - Master list of sources for each QSO field by cross-referencing all 18 frames with the 1st frame as a reference
  - Foreground stars with large PM were not used
  - Reflex motion of the QSO (the difference between its average position in two epochs) was measured w.r.t. the star field (i.e. -1 times the PM of the SMC)
- Consistency Checks
  - From its CMD, QSOs are not systematically the brightest sources, nor do they all have the same color (fig. 2)
  - Final errors are dominated by the centroiding errors of QSOs and aligning the star field shows smaller errors (fig. 3)
  - PM and σPM show the expected random errors
  - No obvious trend with position on the CCD chip
  - NO systematic errors larger than ~0.005 pixels

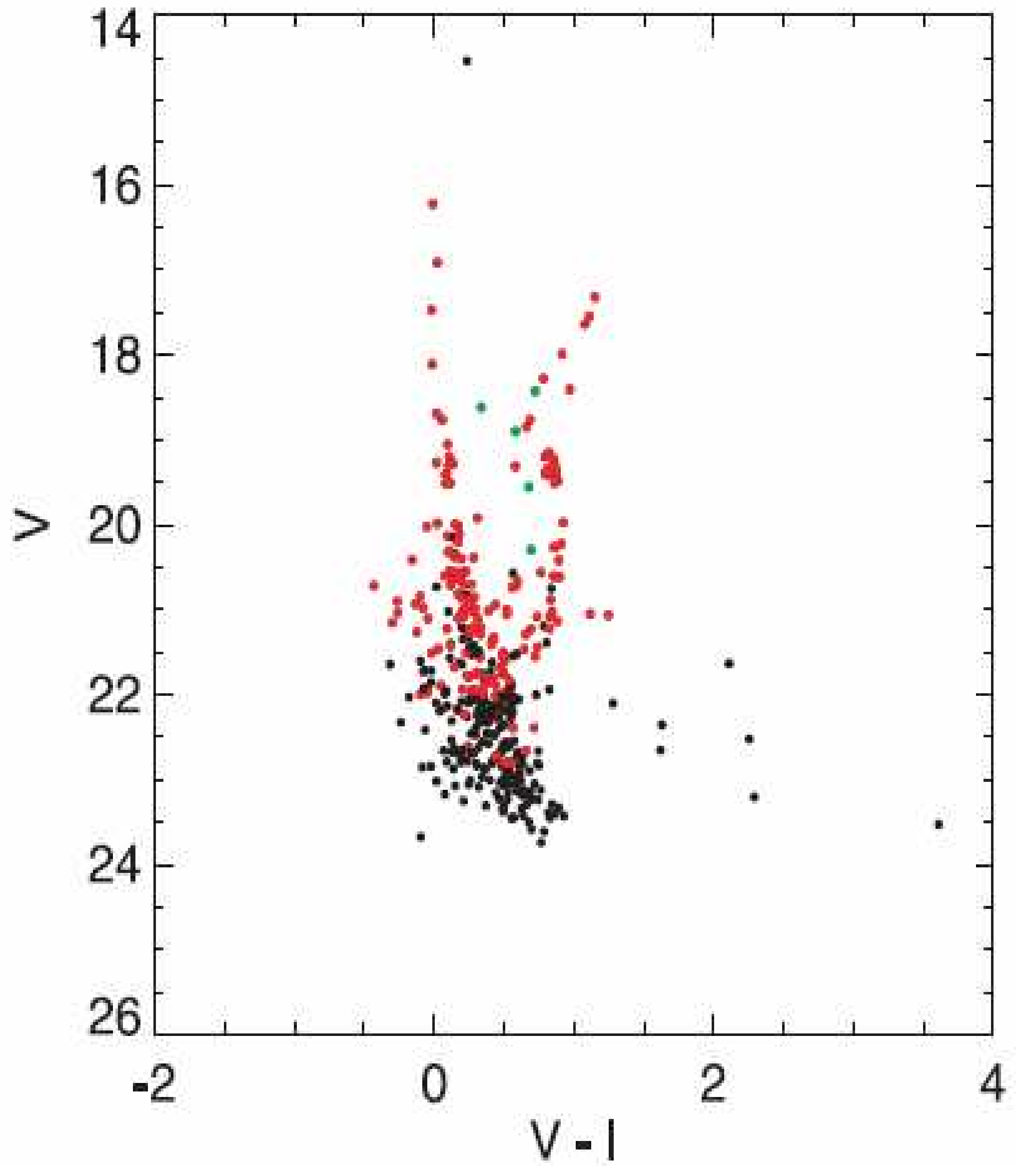


Fig. 2.—$(V-I, V)$ color-magnitude diagram for the SMC. QSOs are marked in green, stars in the master list with PM $<$ 0.1 pixels and δPM $<$ 0.1 pixels are marked in red, and the rest are shown in black.

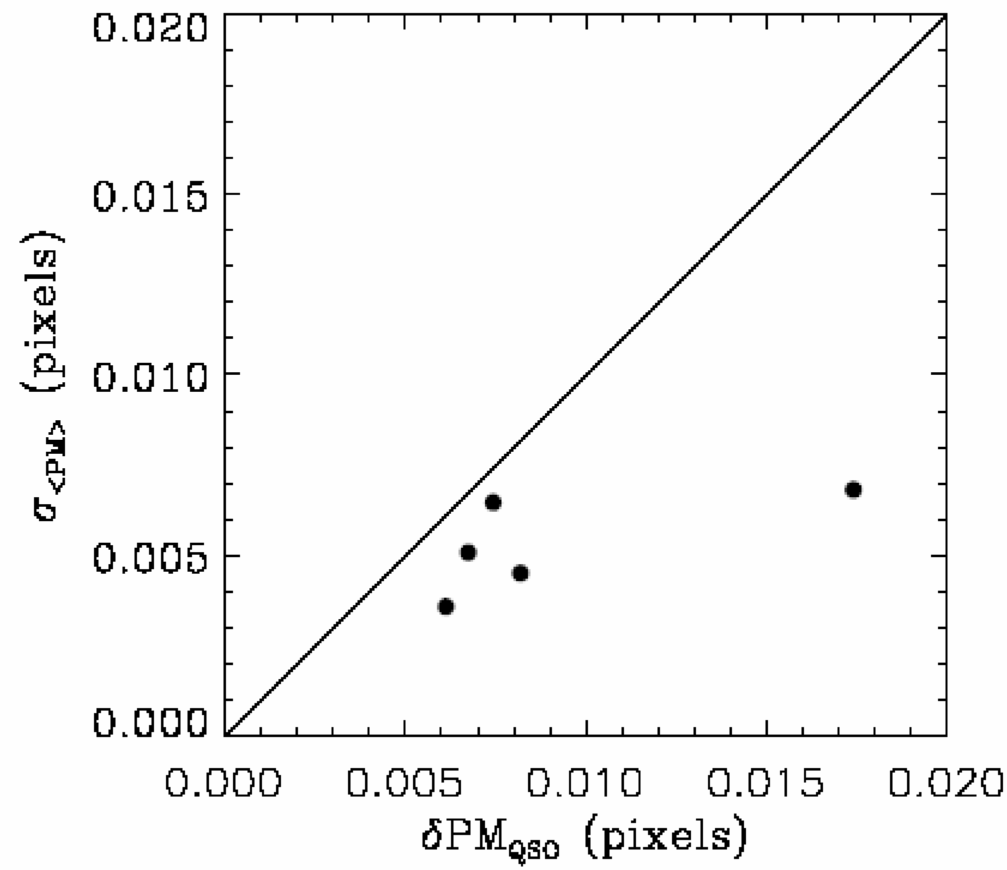


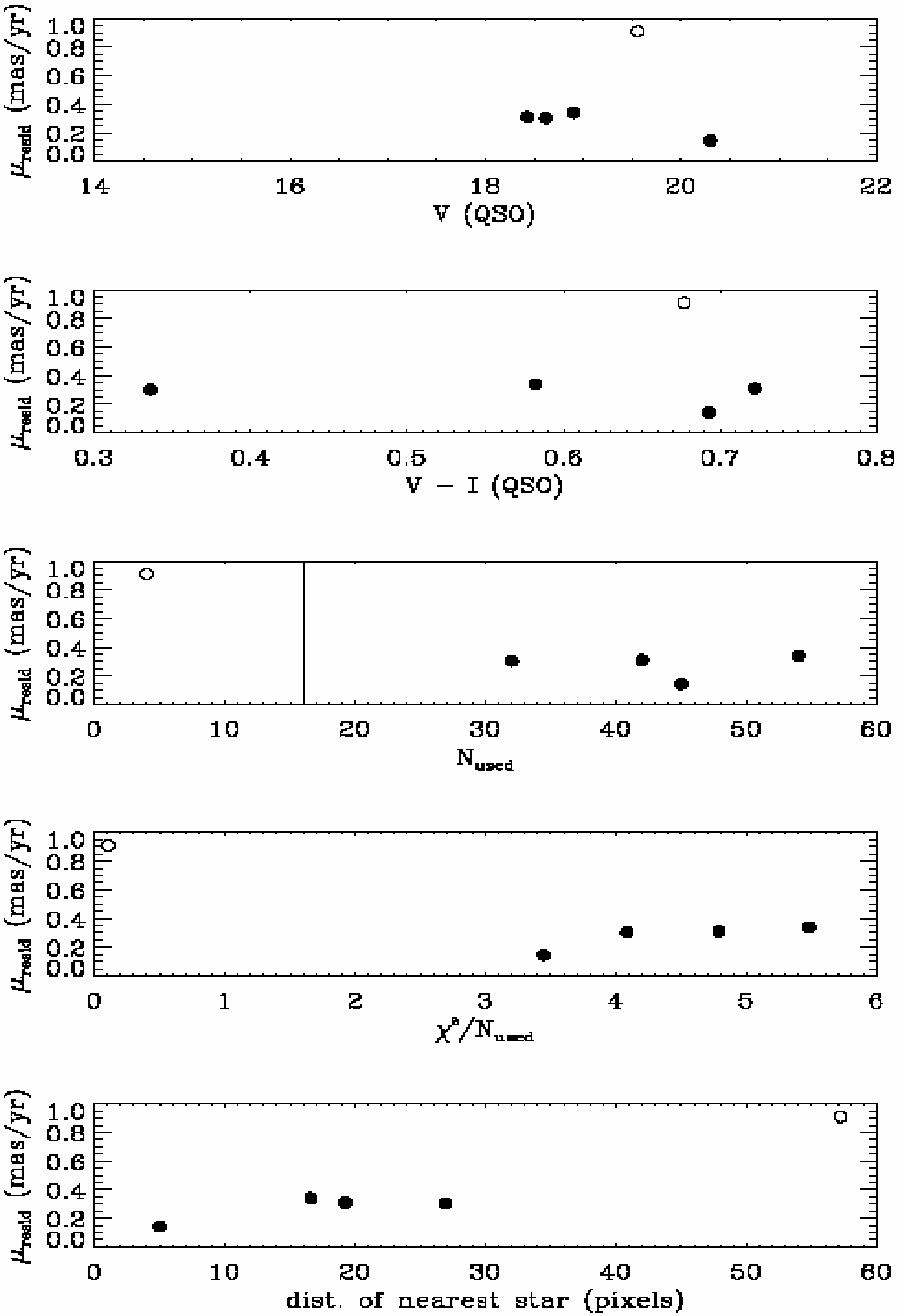
Fig. 3.—Distribution of errors in our linear transformations for each field. The x-axis shows the error in the PM of the QSO, and the y-axis shows the error in the average PM of the star field.

PM results for the SMC

- Each observed QSO PM provides an independent estimate of the PM of the SMC center of mass.
- No obvious systematic trends associated with *V*-mag, (*V*-*I*) color, N_{used}, X^2/N_{used}, and distance of nearest star (fig. 7)
- Reflex motions of the QSOs are distinguishable from the star motions (fig. 8)

ID (1)	$N_{sources}$ (2)	N_{master} (3)	N_{used} (4)	μ_N (mas yr^{-1}) (5)	μ_W (mas yr^{-1}) (6)	$\delta\mu_N$ (mas yr^{-1}) (7)	$\delta\mu_W$ (mas yr^{-1}) (8)	Used? (9)
S1	247	71	32	−1.136	−0.860	0.095	0.113	Yes
S2	303	117	54	−1.208	−0.825	0.076	0.073	Yes
S3	235	87	45	−1.201	−1.022	0.109	0.091	Yes
S4	68	10	4	−0.866	−0.303	0.177	0.073	No
S5	242	100	42	−1.143	−1.471	0.130	0.108	Yes

NOTES.—The quantity $N_{sources}$ refers to the number of real sources (detected in at least half of the images), N_{master} refers to the number or sources in the master list; that is, that were detected in every image in every epoch, and N_{used} refers to the number of sources that were used in the final linear transformations after the PM and δPM cuts. Cols. (5)–(8) contain the PM estimates and their errors for each field. The last column notes whether the particular field was used in our final estimate of the center-of-mass motion of the SMC (eq. [1]).



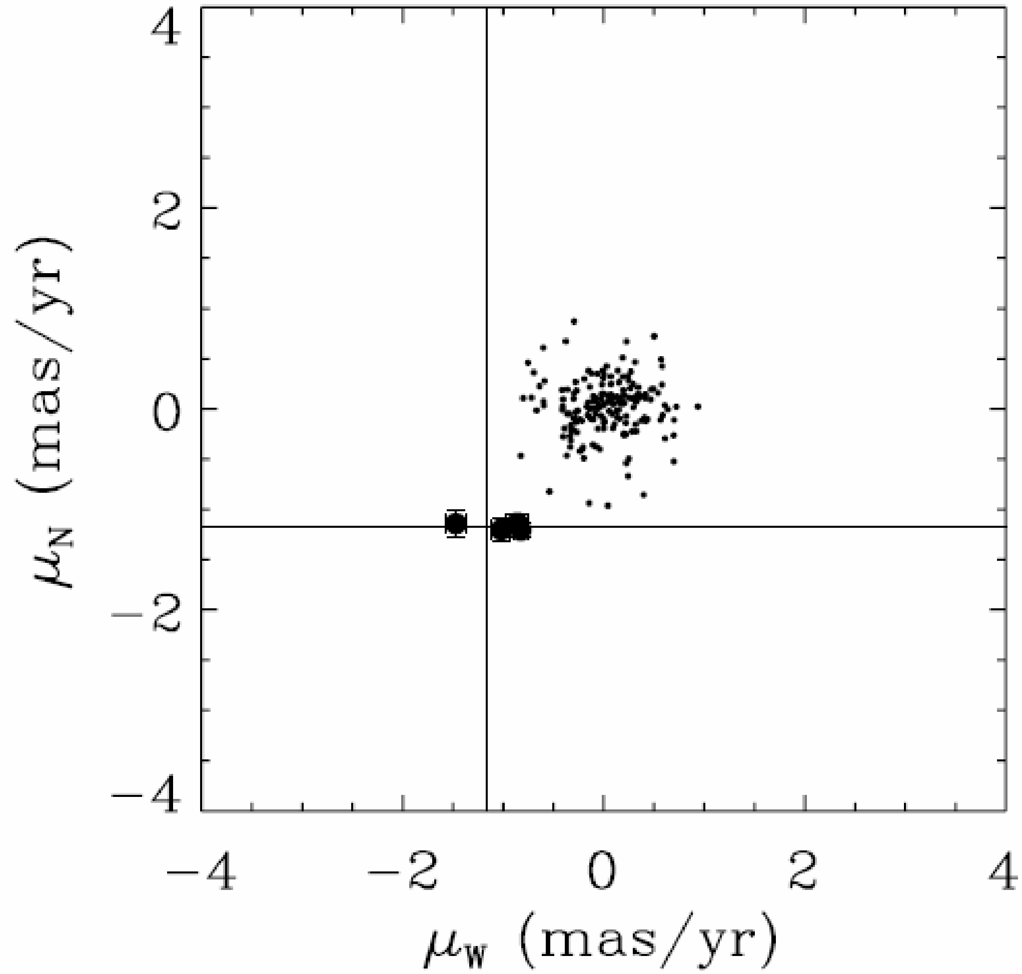
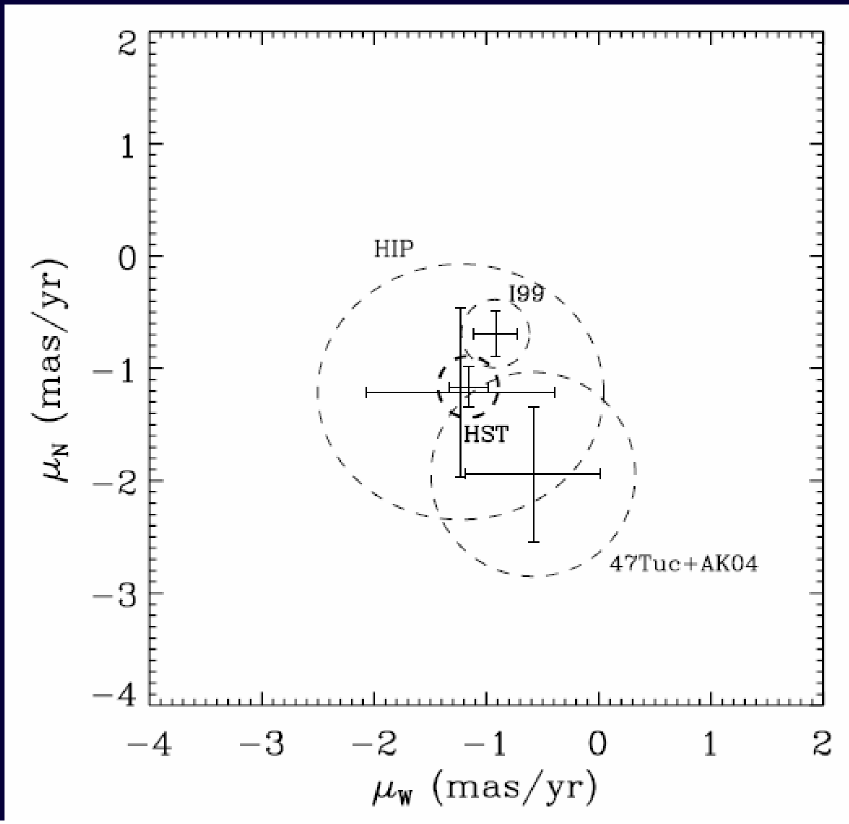


FIG. 8.—Observed PMs (μ_W, μ_N) for the four QSO fields (i.e., -1 times the observed reflex motion of the QSO; see cols. [5] and [6] of Table 2) that pass all our criteria. The residual PMs of the SMC stars in the fields are plotted with points. The reflex motions of the QSOs are clearly separate from the star motions. The straight lines mark the weighted average of the four fields, as listed in eq. (1).

FIG. 7.—Plots of μ_{resid} as a function of QSO V magnitude, $V - I$ color, N_{used}, χ^2/N_{used}, and distance to the nearest neighboring star. We used the same criteria here as in Paper I, retaining only those fields with $N_{used} > 16$ and $\chi^2/N_{used} < 15$ (*vertical line*) in our final sample (*filled circles*). The field that is rejected on the basis of these cuts (S4) is shown with an open circle in each panel.

PM results for the SMC (cont'd)

- Weighted average PM of S1, S2, and S3 as a S123
  - Similar telescope orientation
  - (μ_W, μ_N) = (-0.89 $\pm$ 0.05 mas yr^{-1}, -1.18 $\pm$ 0.05 mas yr^{-1})
- Weighted average of S123 and S5 (*HST* only)
  - With the same systematic error of the LMC
  - μ_W = -1.16 $\pm$ 0.18 mas yr^{-1}
  - μ_N = -1.17 $\pm$ 0.18 mas yr^{-1}
- Weighted average
  - with the previous work $\langle\mu_W\rangle$, $\langle\mu_N\rangle$
  - μ_W = -1.04 $\pm$ 0.13 mas yr^{-1}
  - μ_N = -1.19 $\pm$ 0.16 mas yr^{-1}



3D space motion of the SMC

- SMC velocity in a Cartesian system on the sky
  - ($v_{x(W)}$, $v_{y(N)}$) = (-340 $\pm$ 52, -341 $\pm$ 53) km s^{-1}
  - Assume a distance modulus of 18.95
  - Transverse velocity is 481 km/s at a position angle 135 °
  - Line-of-sight velocity is 146 $\pm$ 0.6 km/s (Harris & Zaritsky 2006)
- SMC velocity in a Galactocentric rest frame

Parameter	LMC	SMC
Line-of-sight velocity (km s^{-1})	262.1 $\pm$ 3.4	146 $\pm$ 0.6
Proper motions (W, N) (mas yr^{-1})	-2.03 ± 0.08, 0.44 ± 0.05	-1.16 ± 0.18, -1.17 ± 0.18
Distance moduli	18.50 $\pm$ 0.1	18.95 $\pm$ 0.1
Current positions (α, δ) (deg)	81.9 ± 0.3, -69.9 ± 0.3	13.2 ± 0.3, -72.5 ± 0.3
Galactic coordinates (l, b)	280.5, -32.5	302.8, -44.6
Current positions (X, Y, Z) (kpc)	-0.8, -41.5, -26.9	15.3, -36.9, -43.3
Space velocities (v_X, v_Y, v_Z) (km s^{-1})	-86 ± 12, -268 ± 11, 252 ± 16	-87 ± 48, -247 ± 42, 149 ± 37
Galactocentric radial velocities (km s^{-1})	89 $\pm$ 4	23 $\pm$ 7
Galactocentric tangential velocities (km s^{-1})	367 $\pm$ 18	301 $\pm$ 52

Orbits of the Clouds around the MW

- Fiducial model includes the assumption of
  - Gravitational potential of the Galaxy and of the Clouds
  - Total masses and mass profiles of the Clouds
  - Dynamical friction between the Clouds and the Galactic halo
  - Dynamical friction between the Clouds themselves
- To calculate orbits, need many physical assumptions and parameterizations
- Goal of this paper
  - What we obtain orbital evolution of the Clouds when the new results are combined with a typical model that has been used before

Fiducial model

- Gravitational Potential of the Galaxy and the Clouds
  - $\varphi_{Gal}(r) = -(V_0)^2 \ln r$
    - r : distance from the center
    - Circular velocity $V_0 = 220$ km/s
  - $\varphi_{L,S}(r) = GM_{L,S} / [(r - r_{L,S})^2 + (K_{L,S})^2]^{1/2}$
    - Effective radii $(K_L, K_S) = (3, 2)$ kpc
- Masses of the Clouds from the estimated relative velocity
  - $M_L = 1 \times 10^{10}$ (analysis of carbon stars),

    $= 2 \times 10^{10}$ (separation 23 kpc),

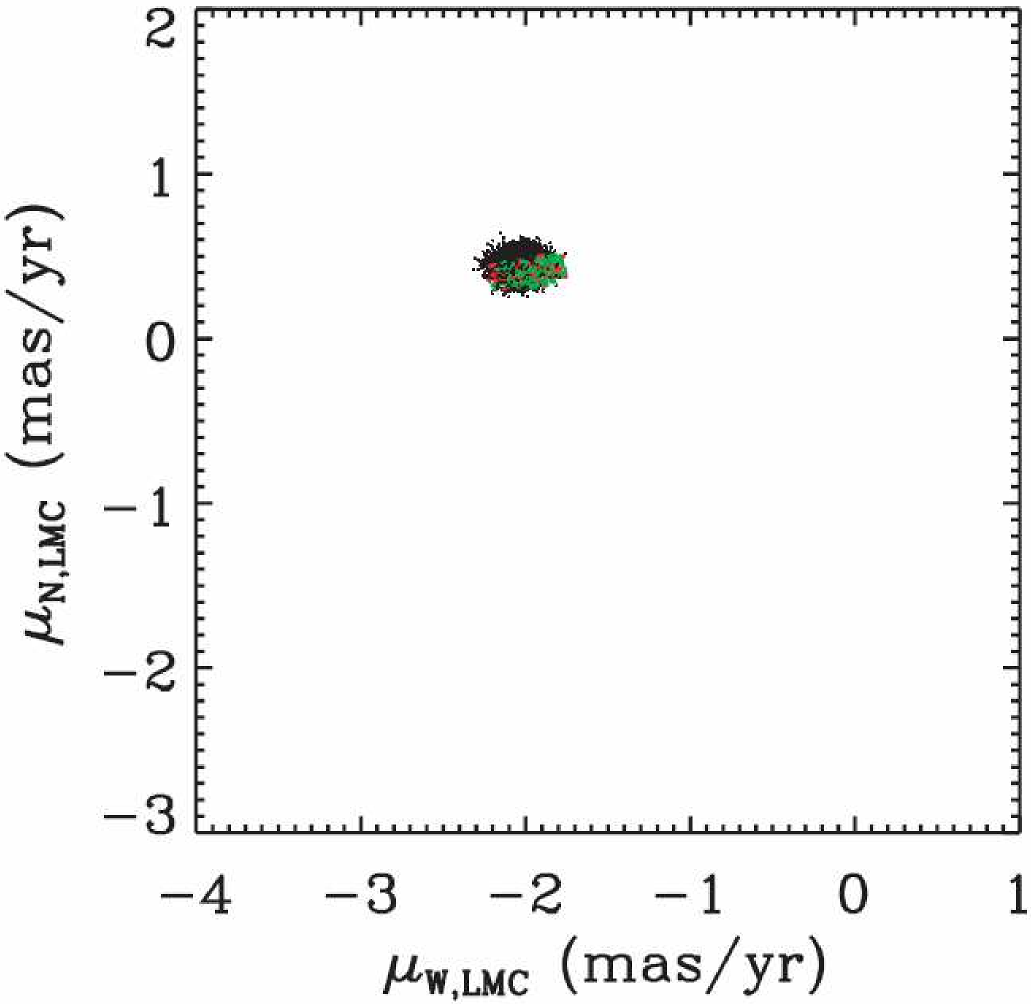
    $= 3 \times 10^{10}\ M_\odot$ (gravitationally bound)
  - $M_S = 3 \times 10^9\ M_\odot$ & $M_{Stream} = \sim 2 \times 10^8\ M_\odot$

Fiducial model

- Dynamical Friction between each Cloud and the MW center
  - $$F_{\mathrm{Gal}} = -0.428 \ln \Lambda_{\mathrm{Gal}} \frac{GM_{L,S}^2}{r^2}$$ Coulomb logarithm $\ln \Lambda_{Gal} = 3$ (circular orbit)
- Dynamical Friction between the LMC and the SMC
  - $$F_{LS} = -0.428 \ln \Lambda_{LS} \frac{GM_S^2}{r_{LS}^2}$$ $\ln \Lambda_{LS} = 1.2$ & $r_{LS} = 15$ kpc (tidal radius)
  - Only acts on to the SMC when it comes within the tidal radius of the LMC
  - *Any* energy gain felt by the LMC is not expected to affect its orbital motion, but would go into puffing up its halo
- First-order solution (without dynamical friction)
  - Distribution of dark matter in the LMC is not well known
  - Clouds have been bound for ~ t_{Hubble}, then merged already

Search for Bound Orbits

- Propagate the orbits backward for 9 Gyr using the fiducial model and a leapfrog integration scheme (Springel et al. 2001)
  - Clouds become unbound very quickly in the past
  - Interesting to see if any orbits will remain bound for ~ t_{Hubble}
  - For the SMC, bound orbits are more probable
  - More massive LMC requires less of a shift in a proper motions of both Clouds to bind the SMC
- Representative bound orbits from this simulation
  - CM of the Clouds has an orbital period of ~2.5 Gyr, & inclination of 103°
  - Fraction of bound orbits always increases as the masses of the Clouds increase
  - Effect of dynamical friction is not significant to the bound fraction



- Black (duration < 1 Gyr, unbound)
- Green (1~5 Gyr)
- Red (>5 Gyr, bound)
- $M_L = 3 \times 10^{10}\ M_\odot$, $M_S = 3 \times 10^9\ M_\odot$

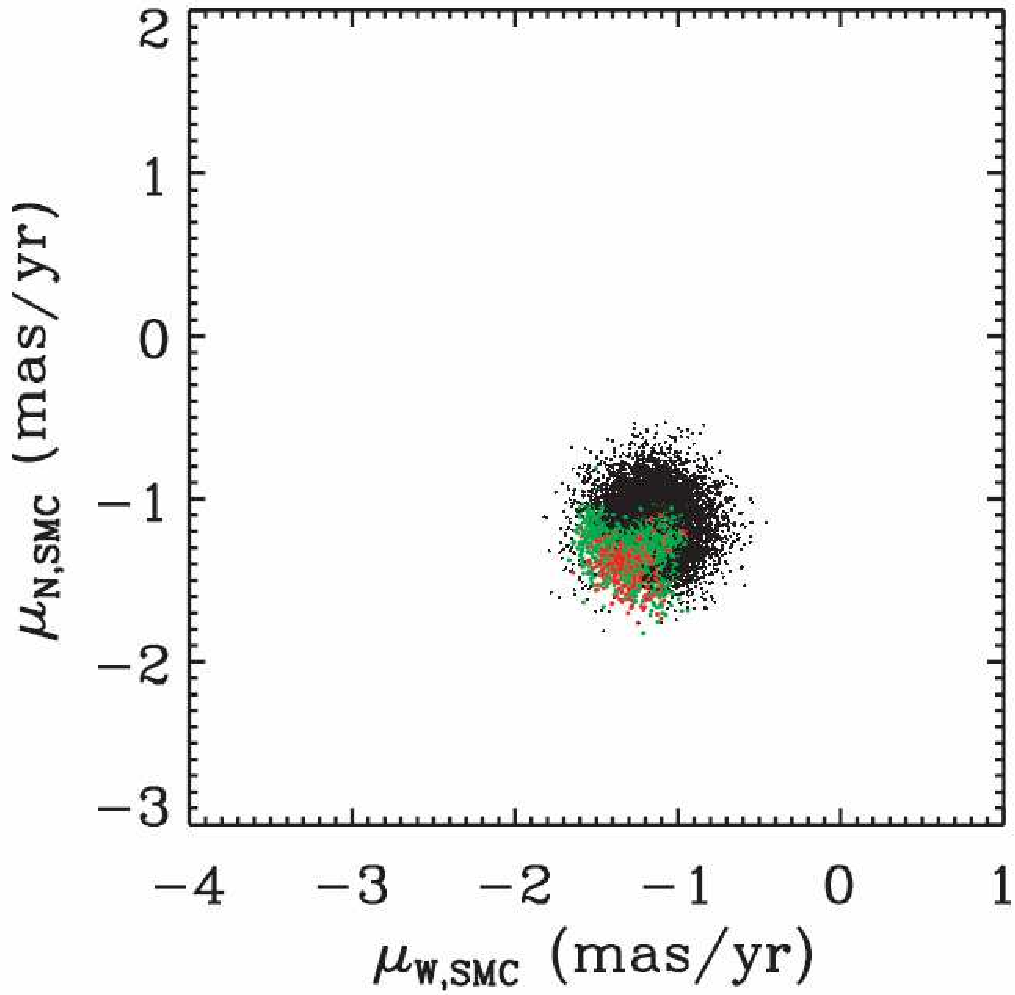
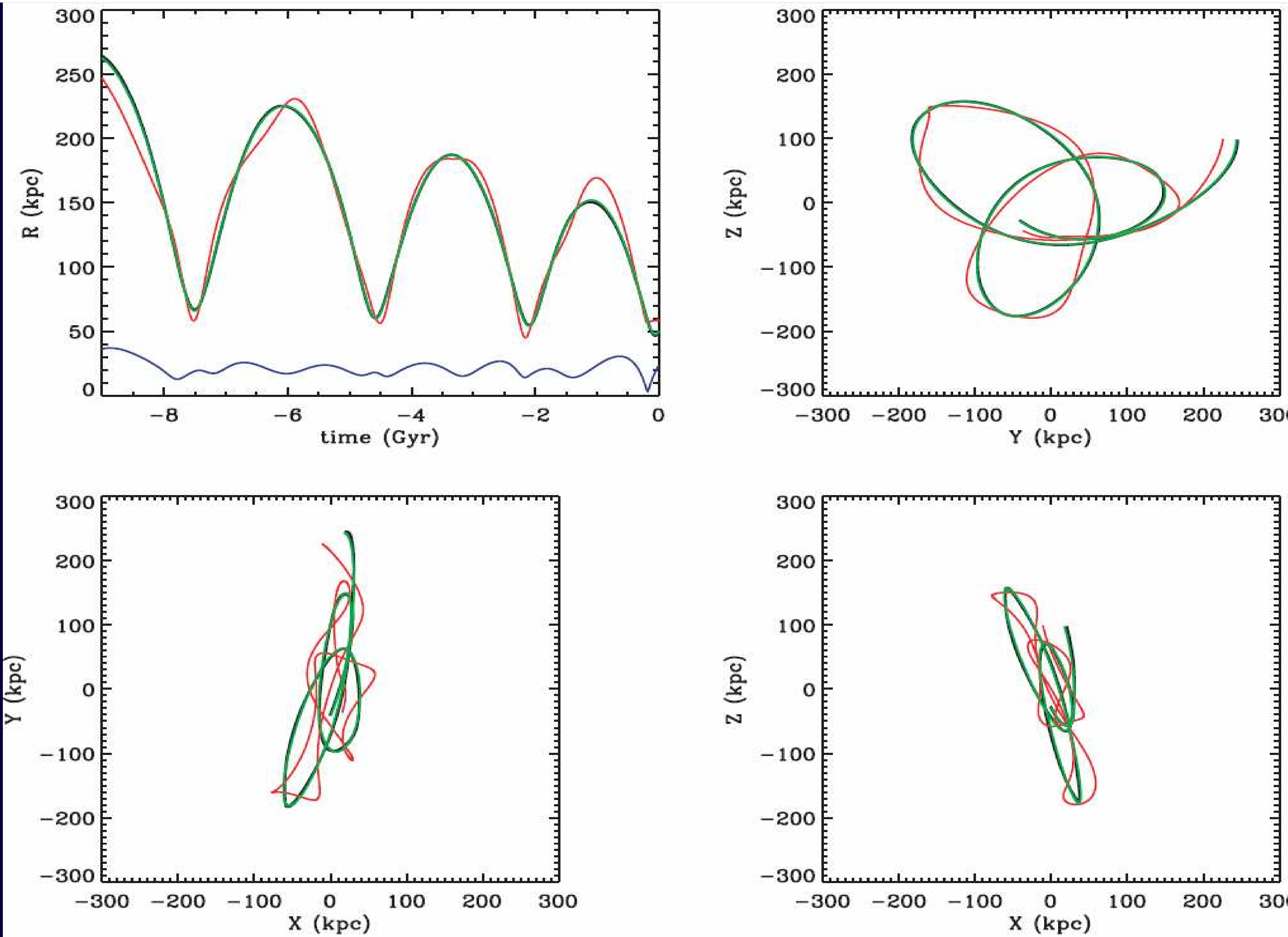


FIG. 11.—Past duration of the bound state of the Magellanic Clouds, shown in the (μ_W, μ_N)-plane. The top panel shows the 10,000 initial proper motions drawn at random from the error ellipse of the LMC, and the bottom panel shows the corresponding proper motions drawn from the error ellipse of the SMC. The duration of the bound state is represented by different colors: black for <1 Gyr, green for between 1 and 5 Gyr, and red for >5 Gyr.



Bound orbits from this simulations

Black : D_{LMC}, Red : D_{SMC}, Green : CM , Blue : D_{L-S}

Interpretation of Orbit Calculations

- Not the probability estimates for whether Clouds are bound
- Small # of bound orbits is due to the large observational error bars and small phase space in a 3-body problem
- Consistent with the past searches for bound orbits
- SMC error bars are not small enough to confirm or rule out the hypothesis that Clouds have been a bound system
- LMC doesn't show any systematic effects, but SMC maybe does due to the far fewer QSO fields

The “Recent Coupling” Model

- SMC PM in this study is consistent with a bound status for the Clouds
  - BUT there are many disrupted orbits.
  - Still possible that the Clouds are not bound and have only interacted long enough to produce the Stream
- Bekki & Chiba (2005) model with small total and relative vel.
  - very hard for the Clouds to maintain the bound status for very long backward in time
  - Discuss a recent coupling scenario

The “Recent Coupling” Model

- Include dynamical friction between the Clouds
- LMC has an asymmetric and irregular of young clusters and star formation regions
- Explain the “age gap” problem in the LMC
  - 13 Gyr & 3 Gyr-old globular clusters
  - Triggered by the strong tidal perturbations
  - Uncertain why there’s no continuous star formations if they have been bound
  - No age gap in the SMC, more influenced by the G-tide continuously
- Still, bound system is very compelling
  - Reproduce the structure and the kinematics of the M-Stream
  - Explain the recent star formation history of the SMC

Summary

- PM of the SMC with 4 QSOs and 2yr long baseline
  - μ_W = -1.16 $\pm$ 0.18 mas yr^{-1}
  - μ_N = -1.17 $\pm$ 0.18 mas yr^{-1}
- Consistent with orbits in which the Clouds have been bound to each other for ~t_{Hubble}
- Also many unbound orbits within the error circles