Can the Magellanic Stream form in a First Passage Scenario?

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Abstract

Recent proper motion measurements of the Large and Small Magellanic Clouds (LMC and SMC, respectively) by Kallivayalil et al. (2006a,b) suggest that the 3D velocities of the Clouds are substantially higher (~100 km/s) than previously estimated and now approach the escape velocity of the Milky Way (MW). Motivated by these new observations, **we have re-examined the orbital history of the Clouds and find that the L/SMC may be on their first passage about the MW**. All phenomenological studies pertaining to the Clouds have implicitly assumed that LMC and SMC have been bound to the MW for a Hubble time, i.e., their orbits have been described as quasi-periodic and thought to be slowly decaying due to dynamical friction as the Clouds move through the dark matter halo of the MW. We show that this assumption is inconsistent with the recent proper motion measurements. Theories concerning the origin of the Magellanic Stream (MS), a stream of HI gas trailing the L/SMC that extends ~100° across the sky, need to be revisited. **Specifically, as a consequence of the new orbital history of the Clouds, the origin of the MS is not explainable by a combination of tidal and ram pressure stripping**. Instead, we advocate for a model in which the MS formed via stellar outflows induced by a recent collision between the L/SMC.

New vs Old LMC Orbital Parameters: **r_{LMC} (x,y,z) = (-0.8, -41.5, -26.9) kpc ; $|r_{LMC}|$ = 49.5 kpc** (Freedman et al 2001)

OLD THEORY: Gardiner & Noguchi (1996; **GN96**)	OLD Pre-2002 Proper Motions: van der Marel et al (2002; **vdM02**)
Proper Motion (μ_W, μ_N) (mas/yr): ~ (-1.7, 0.1)	Proper Motion (μ_W, μ_N) (mas/yr): (-1.68 ± 0.16, 0.34 ± 0.16)
V_{tan} = 287 km/s ; V_{rad} = 82 km/s	V_{tan} = 281±39 km/s ; V_{rad} = 84 ±7 km/s
|V| = 297 km/s	**|V| = 293 ± 41 km/s**

→

NEW: Kallivayalil et al (2006a; **K1**)
Proper Motion (μ_W, μ_N) (mas/yr) : (-2.03 ± 0.08, 0.44 ± 0.05)
V_{tan} = 367 ± 18 km/s ; V_{rad} = 89 ± 4 km/s
|V| = 378 ± 18 km/s

Allowed Orbital Histories for the LMC

Figure 1: Isothermal Sphere Model Following Murai & Fujimoto (1980), we trace the orbital history of the LMC by integrating its equation of motion backward in time for both the new (blue) and old (GN96, vdM02) LMC velocities.

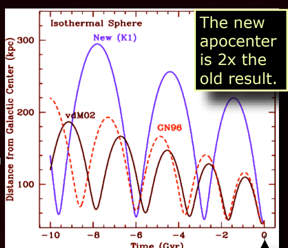
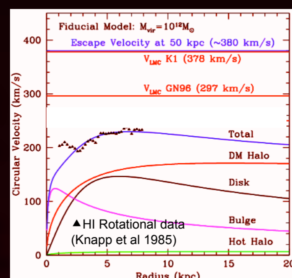


Figure 2: Fiducial MW Model Instead of an isothermal sphere model, we describe the MW as a smooth, axi-symmetric, 4-component model. The escape velocity is ~380 km/s at the current location of the LMC (50 kpc), meaning that, **with the new velocities, the orbit of the LMC is close to parabolic.**



THE LMC IS CURRENTLY MOVING AT ~ THE ESCAPE VELOCITY

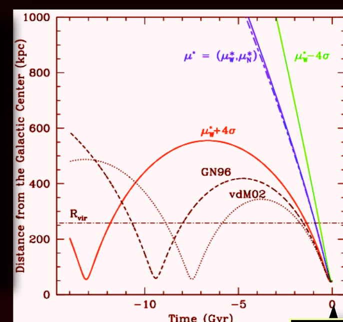


Figure 3: The orbital evolution of the LMC as a function of time The orbital period and apogalacticon distances allowed by the new orbits are bounded by the red and green lines. The orbits for the mean values with(without) dynamical friction are indicated by the solid(dashed) blue lines. Even for the old values, the orbital period is > 6 Gyr.

In the best case scenario the orbital period is roughly a Hubble time:
The LMC is on its first passage about the MW.

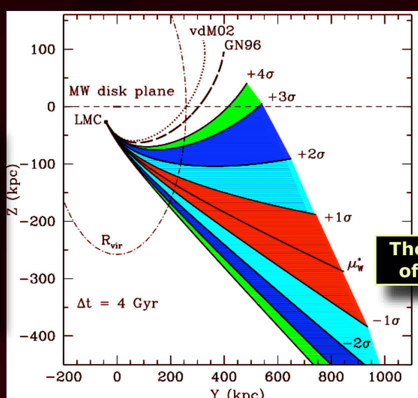
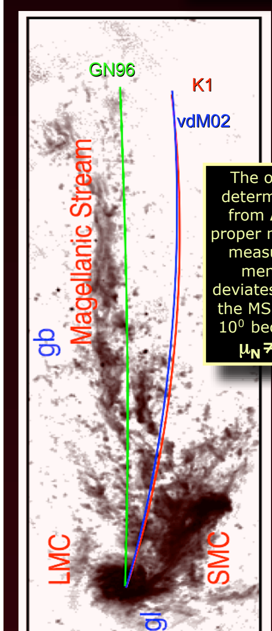


Figure 4: Orbital evolution of the LMC in the Galactocentric YZ plane. The orbital path of the LMC in the YZ plane is plotted for the GN96 values (long-dashed line) and the weighted average of pre-2002 proper motions (vdM02, dotted line). In addition, 10,000 points were randomly sampled from the (4σ) proper motion error ellipse for the LMC. For each point the orbital history of the LMC was computed by integrating the equation of motion backward in time for our fiducial MW model. The orbital path in YZ plane for μ_W values within ±1σ of the mean, μ_W^* = -2.03, are indicated by the red region; ±2σ (cyan region); ±3σ (blue region); ±4σ (green region).

The orbit for the mean value (μ_W^*) is parabolic and no solutions within 3σ of the mean cross the disk plane < 4 Gyr ago or at distances < 400 kpc.



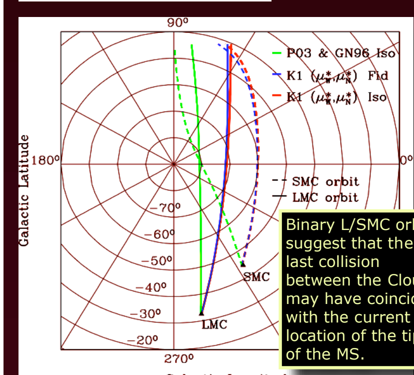
The orbit determined from **ALL** proper motion measure-ments deviates from the MS by ~ 10^0 because **$\mu_N \neq 0$**

Figure 5: Comparison to location of the MS The HI distribution of the MS from the data of Putman et al 2003, is plotted as a polar projection in Galactic (l,b). Over plotted are the LMC's orbit corresponding to the theoretical work of GN96 (green), the weighted average of pre-2002 proper motion measurements (vdM02, blue) and the new *HST* values (K1, red).

How can the Magellanic Stream (MS) form in a first passage scenario ?

PROBLEMS INTRODUCED BY THE NEW PROPER MOTIONS:

- Without multiple pericentric passages, the strength of the MW/L/SMC interaction is severely limited.
- The L/SMC's orbit is not co-located with the MS (Figure 5, 6).
- The orbital line of sight velocities are ~twice those of the MS (Figure 7)



Binary L/SMC orbits suggest that the last collision between the Clouds may have coincided with the current location of the tip of the MS.

Figure 6: Role of the SMC The inclusion of the SMC does not ameliorate the situation: if the L/SMC form a binary system, the SMC deviates from the current location of the MS more markedly than the LMC. The green lines indicate the old GN96 orbits which were chosen *apriori* to approximate the current location of the MS.

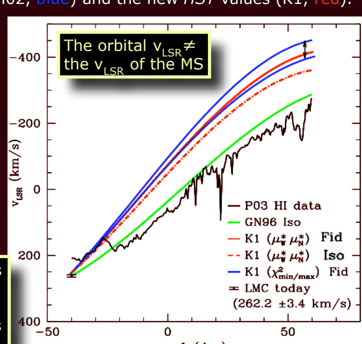


Figure 7: Velocity Gradient along the MS The line of sight velocity with respect to LSR is plotted as a function of Magellanic Longitude (L) along the orbit shown by the red line in Figure 5. GN96 assumed that the orbital v_{LSR} = that of the MS in order to break the degeneracies in the determination of the tangential velocity. This is a faulty assumption. "Iso" indicates an isothermal sphere model, "Fid" indicates the fiducial model (Figure 2).

Tidal Stripping: NOT SUPPORTED

- The tidal radius of the L/SMC is too large along the fiducial orbits.
- Most of the mass is lost at PERICENTER

Ram Pressure Stripping (ρv^2): NOT SUPPORTED

Requires high gas densities: the 3D distance of the LMC near the tip of the MS was ~120 kpc. Instantaneous ram pressure is insufficient and continuous stripping (e.g. Mastropietro et al 2005) requires multiple pericentric passages

Stellar Feedback: MAY BE VIABLE

New evidence suggests that MS filaments originate from star forming regions within the LMC disk (see Nidever et al 2007)

THEORY: Stellar feedback-related outflows induced by a close passage between the L/SMC ~300-500 Myr, which also coincides with the formation of the Magellanic Bridge, may have formed the MS.

A total gas mass of only ~50% of the total stellar mass that formed within the past 1-2 Gyr would need to be removed to account for the HI mass determined from the HIPASS data (Putman et al 2003, Brüns et al 2005).

FUTURE WORK: We are currently testing this scenario for the formation of the MS using the smoothed-particle hydrodynamic (SPH) /N-body code GADGET2 (Springel et al 2005). We model the L/SMC/MW system using the orbits and galaxy models of Besla et al (2007) and include stellar feedback in an effort to reproduce the spatial location and kinematic properties of the MS.