A New Study of the LMC's Kinematics

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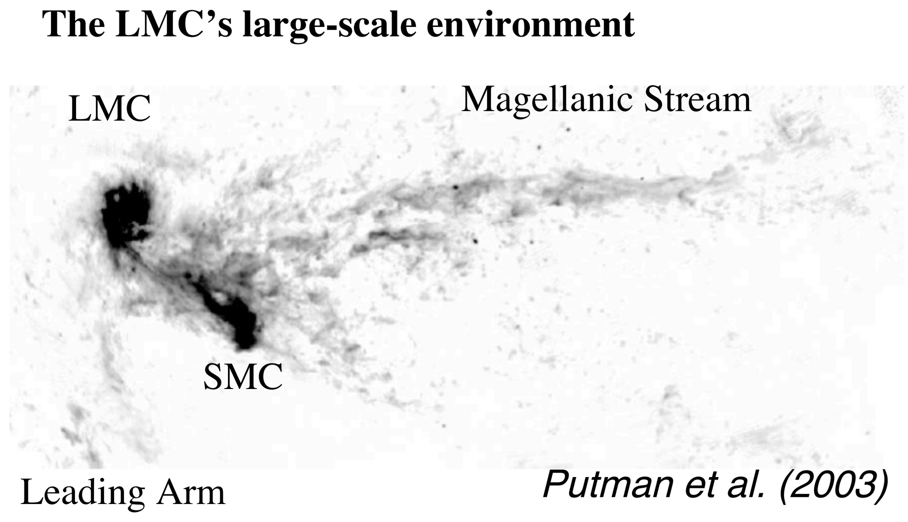
In a recent analysis of previously published data on the H I gas, carbon stars, and red supergiant stars of the Large Magellanic Cloud, we found striking new evidence of the effect of the LMC's ongoing interactions with the Small Magellanic Cloud and Milky Way. First, ~10% of the 857 carbon stars studied were found to be associated with tidal HI streamers, the first instance in which tidally drawn out stars have been identified in the LMC. Second, we found rotation curve amplitudes ranging from 61 km s^{-1} for the carbon stars to 107 km s^{-1} for the 168 red supergiants, casting new doubt on previous estimates of the LMC's total mass based on the carbon stars. Finally, from the velocity and spatial distributions of the HI and the red supergiants, we found that the LMC's disk is significantly lopsided, thus requiring that its populations lie on predominantly elliptical orbits, not circular ones as is generally assumed. In order to investigate the questions raised by these findings, we have collected high quality spectra of 5292 stars in the direction of the LMC, including 481 LMC red supergiants and 1950 carbon stars. Based on these spectra, we present a new analysis of the LMC's internal kinematics.

Introduction

The LMC's large-scale environment



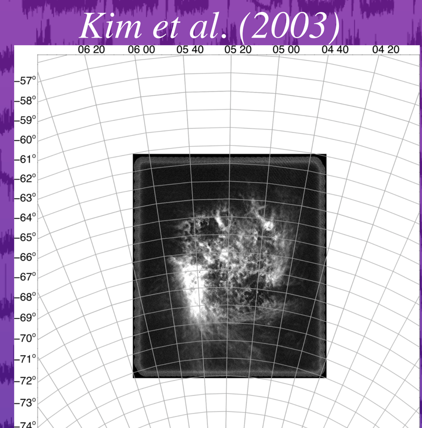
Putman et al. (2003)

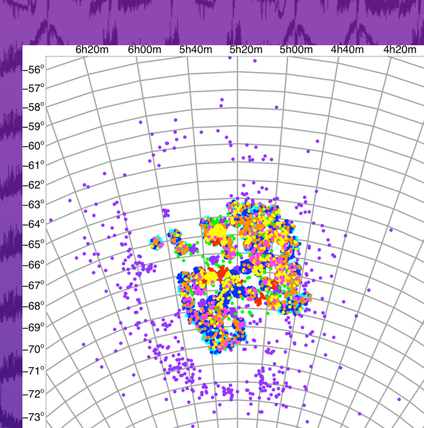
Why study the LMC's stellar kinematics?

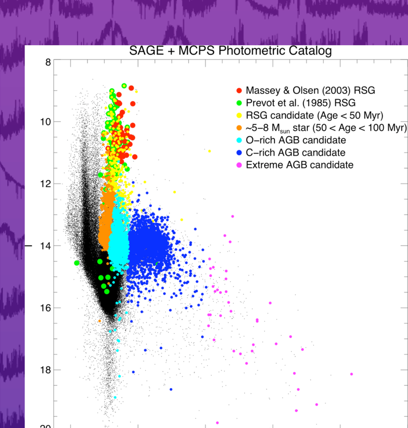
- The ages, abundances, and kinematics of stars contain clues to how nearby galaxies formed and evolved
- The evidence for interaction between the LMC, SMC and Milky Way is especially clear in the HI gas, but much less so in the stellar populations. Do the stellar kinematics contain hints of the interaction?
- The mass of the LMC depends on a clear understanding of the kinematics
- Olsen & Massey (2007) found evidence for tidally stripped stars in the LMC

Observations

Kim et al. (2003)





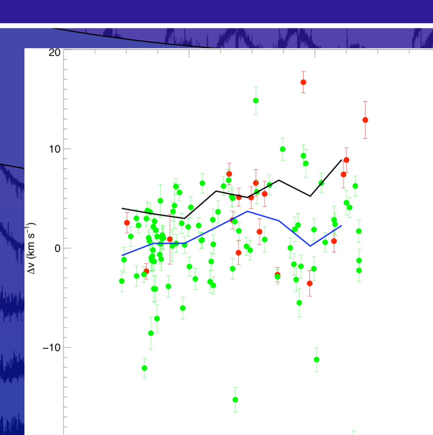


Observational data consisted of:

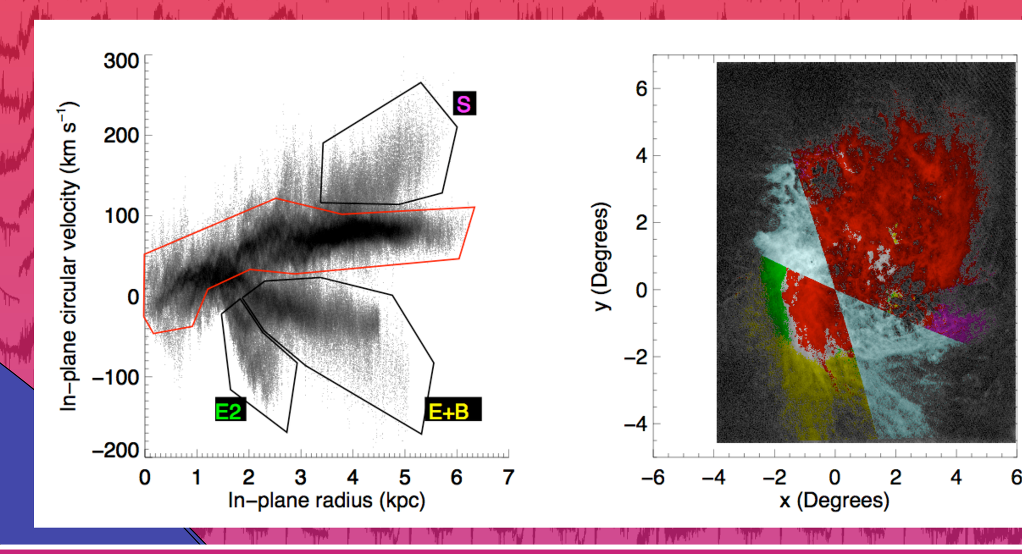
- HI datacube from Kim et al. (2003), which has 1.65 km s^{-1} velocity resolution and 1′ spatial resolution; computed flux-weighted average velocity at every pixel
- 5292 velocities of red supergiants, intermediate mass evolved stars, and O-rich and C-rich AGB stars, with candidates selected from combined Spitzer SAGE survey (Meixner et al. 2006) and Magellanic Clouds Photometric Survey (Zaritsky et al. 2004)
- 857 carbon star velocities from Kunkel et al. (1997), σ_v~5 km s^{-1}, and Hardy et al. (in prep.), σ_v~14 km s^{-1}; previously studied by Alves & Nelson (2000) and van der Marel et al. (2002)
- 494 red supergiant velocities from Massey & Olsen (2003), σ_v < 1 km s^{-1}, and Prévot et al. (1985), σ_v = 1-2 km s^{-1}

Comparison of RSG velocities with Massey & Olsen (2003):

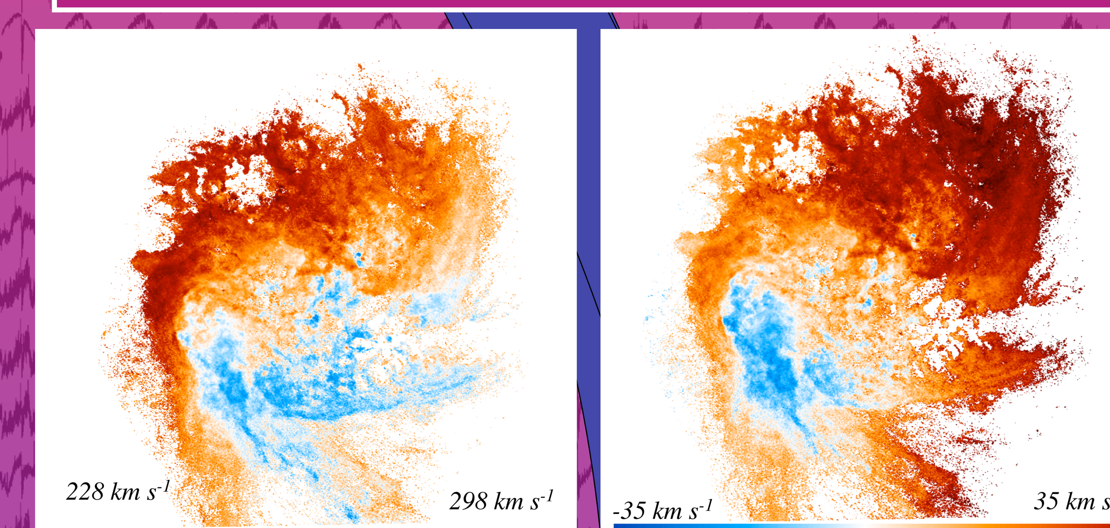
- The average velocity difference is ~1 km s^{-1}, within the error on an individual RSG
- The dispersion in the velocity difference is ~5 km s^{-1}, or 5x the average individual velocity error
- The dispersion appears to grow with redder J-[24] color, suggesting that the dispersion may be related to intrinsic behavior in the RSGs



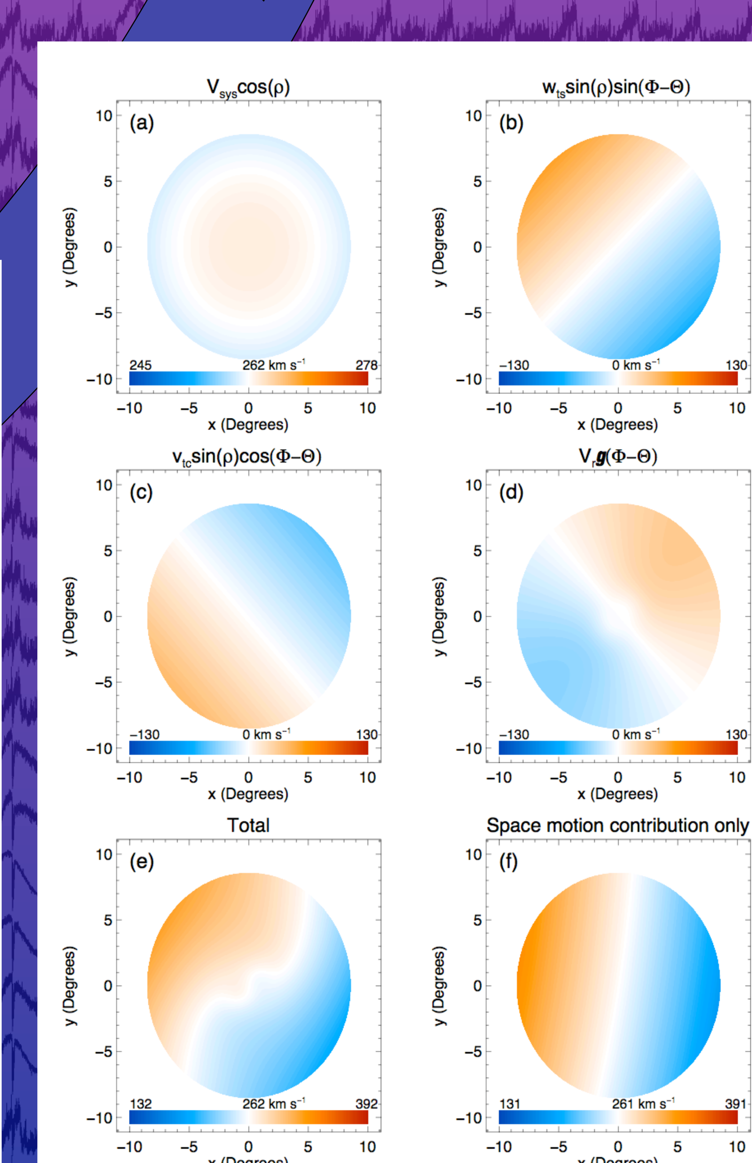
Analysis



Left: After removing kinematic signatures related to the LMC's space motion, in Olsen & Massey (2007) we assumed the remaining velocity residuals are all due to in-plane circular motions. From the rotation curve diagram, we identified four regions with clearly distinct kinematic signatures. The red box outlines the main LMC rotation curve, which has a peak velocity of ~80 km s^{-1}. The others are a region containing velocities like those of arm S, a region encompassing arms E and B, and a region with distinct kinematics that we label ``E2''. *Right:* The HI gas contained within the regions drawn at left are plotted with different colors: the region that traces the main rotation curve is red, the arm S region is magenta, the combined arm E and B regions are yellow, and the newly defined E2 region is green. Many of these features correspond to tidal HI arms identified by Staveley-Smith et al. (2003).

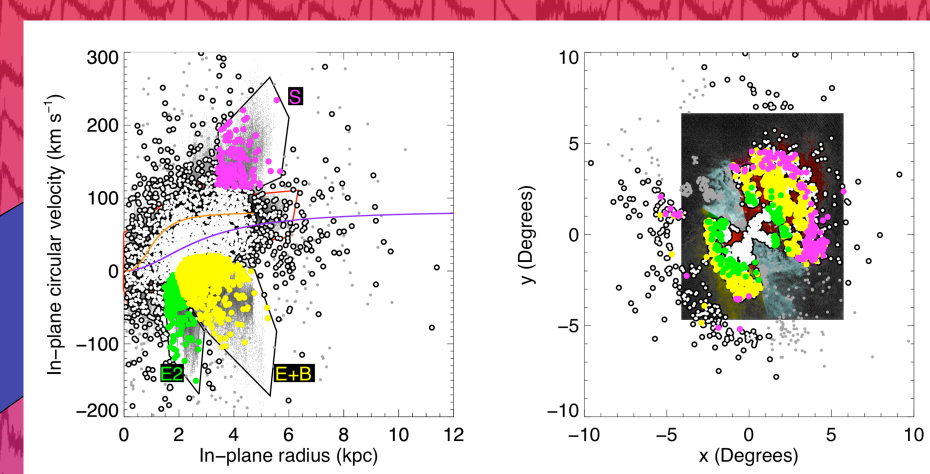


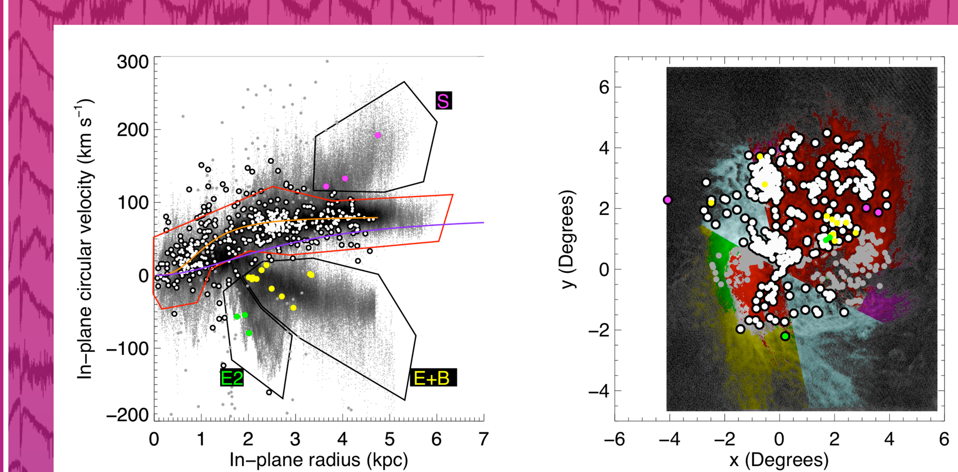
At left, we show the average flux-weighted HI velocity map of the LMC, as derived from the Kim et al. (2003) HI datacube. At right is the velocity map after subtracting the space motion contribution, using the Kallivayalil et al. (2006) proper motion measurement and the radial velocity of the dynamical center fitted to the carbon stars.



Following the parameterization of the LMC's kinematics from van der Marel et al. (2002), in the above figure we show the various components that contribute to the LMC's line-of-sight velocity field. The LMC's large angular size on the sky results in its space motion dominating the line-of-sight velocities. The panels above show the contribution from the motion along the line of sight to the dynamical center (a), the proper motion (as measured by Kallivayalil et al. 2006) component perpendicular to the line of nodes (b), the proper motion component parallel to the line of nodes (c), and the internal rotation as fitted to the carbon stars (d). At bottom, we show the total model line-of-sight velocity field (e), and the portion due only to the space motion (f).

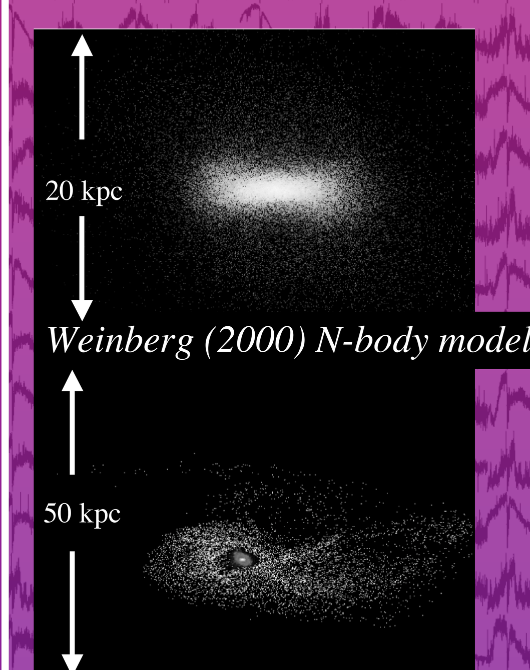
In the plots on the right, we compare the AGB star (top) and red supergiant (bottom) kinematics to that of the HI. Stars falling within the regions S (magenta), E+B (yellow), and E2 (green) are labeled in color. The small grey points are stars falling in the excluded region where in-plane circular orbits are nearly perpendicular to the line of sight. We also show the positions of the stars and HI on the sky, with symbols and color labels for the stars as on the left-hand plots. Many of the AGB stars that have kinematics like that of the tidal HI arms are also spatially coincident with those arms, implying physical association, a result also found by Olsen & Massey (2007) based on a smaller sample of stars. The AGB star rotation curve peaks at 83 km s^{-1}. Fitting instead to the kinematics of the RSGs, we find that the RSGs also define a rotation curve that flattens at 80 km s^{-1}, but with a different angle of the line of nodes. Because the RSGs are all confined to the region where the HI forms a flat rotation curve, we suggest that they formed after the LMC's latest tidal interaction, and thus are more likely to trace the LMC's true inner potential. The different line of nodes found by fitting to the AGB stars suggests that tidal interaction has twisted and distorted the LMC.





Conclusions

- A significant fraction of the LMC's periphery appears to be made up of tidally heated/stripped stars; this observation is well-motivated theoretically (Weinberg 2000)
- Tidal HI features should have ages >50 Myr, given that no RSGs are found in them
- The different angles of the kinematic line of nodes found by fitting to the RSGs and AGB stars suggests that tidal interactions have twisted and distorted the LMC
- The LMC's mass remains uncertain due to the evidence for non-circular streamlines; further analysis is necessary
- Analysis of the LMC's internal proper motion distribution (Piatek et al. 2008) finds a rotation curve amplitude of 120± 15 km s^{-1} at R~4 kpc in the disk plane, higher than what found here



Weinberg (2000) N-body model

References

Alves, D.R., & Nelson, C.A. 2000, ApJ, 542, 789

Kallivayalil, N., van der Marel, R.P., Alcock, C., Axelrod, T., Cook, K.H., Drake, A.J., & Geha, M. 2006, ApJ, 638, 772

Kim, S., Dopita, M.A., Staveley-Smith, L., & Bessell, M.S. 1999, AJ, 118, 2797

Kim, S., Staveley-Smith, L., Dopita, M.A., Sault, R.J., Freeman, K.C., Lee, Y., & Chu, Y.-H. 2003, ApJS, 148, 473

Kunkel, W.E., Demers, S., Irwin, M.J., & Albert, L. 1997, ApJ, 488, L129

Massey, P., & Olsen, K.A.G. 2003, AJ, 126, 2867

Meixner, M., et al. 2006, AJ, 132, 2268

Olsen, K.A.G., & Massey, P. 2007, ApJL, 656, L61

Piatek, S., Pryor, C., & Olszewski, E.W. 2008, AJ, 135, 1024

Prévot, L., et al. 1985, A&AS, 62, 23

Putman, M., et al. 1998, Nature, 394, 752

Staveley-Smith, L., Kim, S., Calabretta, M.R., Haynes, R.F., & Kesteven, M.J. 2003, MNRAS, 339, 87

van der Marel, R.P., Alves, D.R., Hardy, E., & Suntzeff, N.B. 2002, AJ, 124, 2639

Weinberg, M.D. 2000, ApJ, 532, 922

Zaritsky, D., Harris, J., Thompson, I., & Grebel, E. 2004, AJ, 128, 1606