New Views of the Magellanic Clouds
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Review of N-Body Models of Tidal Interactions

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Abstract. Considerable progress has been made in the current decade with the help of N-body simulations towards a deeper understanding of the nature of the dynamical relationship between the Large and Small Magellanic Clouds and the Galaxy. The origin of such features as the Magellanic Stream, the inter-Cloud Bridge, the Wing and large extension in depth of the SMC has come to be interpreted in the context of the tidal interactions among the members of the LMC-SMC-Galaxy triple system. The inclusion of gas-dynamical effects and star formation in the latest models has added further refinements to this picture and confirmed the enhancement of the star formation rate in the SMC as a result of the recent LMC-SMC encounter.

1. Introduction and Numerical Models

Test particle models of the Magellanic Clouds system (e.g., Murai & Fujimoto 1980; Gardiner et al. 1994) have been successful in searching a large parameter space for orbits leading to simulation of the gross features related to the tidal disruption of the Clouds. However, in order to obtain a more realistic picture of the effects of tidal interactions on the Magellanic Clouds, it has been necessary to construct N-body models in which the global galactic potential responds dynamically to the evolution of the matter distribution.

There have been only a limited number of studies specifically of the Magellanic Clouds which have employed N-body techniques. Moore & Davis (1994) carried out a high-resolution simulation of tidal stripping of the LMC, and found that the tidal debris defined a thick plane centered on the Magellanic orbital plane. On this basis, they argued against the validity of a tidal origin for the Magellanic Stream (MS). Gardiner & Noguchi (1996) produced an N-body model of the SMC, Magellanic Stream and inter-Cloud region, which has been extended by Yoshizawa (1998) to include gas-dynamical effects and star formation. Kunkel et al. (1997) carried out smaller scale N-body simulations of the LMC-SMC system. Their work focussed mainly on the interpretation of the kinematics of carbon stars observed at the periphery of the LMC. Li & Thronson (1999, these proceedings) have recently developed a self-consistent smoothed-particle hydrodynamics (SPH) model of the Galaxy-LMC-SMC system. Their work emphasises the importance of accurate treatment of the gaseous components responsible for the production of the MS and the bridge between the Clouds.

In the remainder of this presentation, I review the major results produced by the Magellanic system models of Gardiner & Noguchi (1996, he reafter GN96) and Yoshizawa (1998, hereafter Y98), which represent the most extensive completed studies of the tidal interactions of the Magellanic system to date. In these models, which are based on the same assumptions (see GN96 for details), the Galaxy and the LMC were represented by fixed potentials, whereas the SMC was constituted as a self-gravitating system of 15000 collisionless (GN96) or 25000 gas/star particles (Y98) with a disk/halo mass ratio of 1:1 (GN96) or 3:7 (Y98). The Magellanic orbits used for the models were derived from test particle modeling of the Magellanic system by Gardiner et al. (1994). The latter models predicted polar orbits with the Clouds leading the MS and gave current space velocities consistent with subsequent proper motion measurements (Kroupa & Bastian 1997). The inclusion of gas-dynamics and star formation in the Y98 model was based on the use of the 'sticky-particle' method for gas cloud collisions together with the application of a Schmidt Law for star formation above some specified volume density threshold. The models were computed from $T = -2$ Gyr to the present, $T = 0$.

2. The Magellanic Stream and Leading Arm Feature

In the above-mentioned Magellanic system models, the MS is a tidal tail torn from the SMC as a result of the interaction between the Magellanic Clouds and the Galaxy. More specifically, a bridge-tail structure emerges from the SMC as a result of a relatively close encounter with the LMC 1.5 Gyr ago, and these features become extended by the tidal force of the Galaxy into a long trailing tail and a weaker leading counterpart (see Fig. 6 of GN96). Some major characteristics of the MS were reproduced by the simulations, including its emergence from a region between the Clouds to form a long ($> 100°$) arc in the sky, its mass of a few $10^8 M_\odot$, and its velocity profile.

The models address two major criticisms of the tidal theory for the origin of the MS: (1) the lack of observational evidence for an equally prominent leading bridge counterpart to the striking trailing tail, and (2) the absence of stars in the gaseous MS. The GN96 model predicted the existence of a relatively weak leading arm feature (LAF) on the opposite side of the Clouds to the MS whose overall geometry resembled the distribution of scattered high-velocity clouds in the region $260° < l < 310°$, $-30° < b < 30°$. The HI survey results of Putman et al. (1998) have confirmed that the section of the proposed LAF with $b < -8°$ comprises a continuous feature. These observations, combined with a metallicity determination for HVC 287.5+22.5+240 by Lu et al. (1998), strongly suggest that the material in the proposed LAF originated in the Clouds. The weakness of the LAF is explained by the models as resulting from the asymmetry introduced by the LMC-SMC binary interaction. The lack of stars in the MS, considered enigmatic since tidal forces should affect stars and gas equally, is likely to be explained by the fact that the material in the simulated MS was torn from the outer part of the SMC disk beyond 3 kpc from the SMC center. The Y98 model, whose initial configuration comprised a compact stellar disk (radius ~ 3 kpc) embedded in a more extended gaseous component (radius ~ 5 kpc), introduced very few stars into the MS. Furthermore, the low gas density of material in

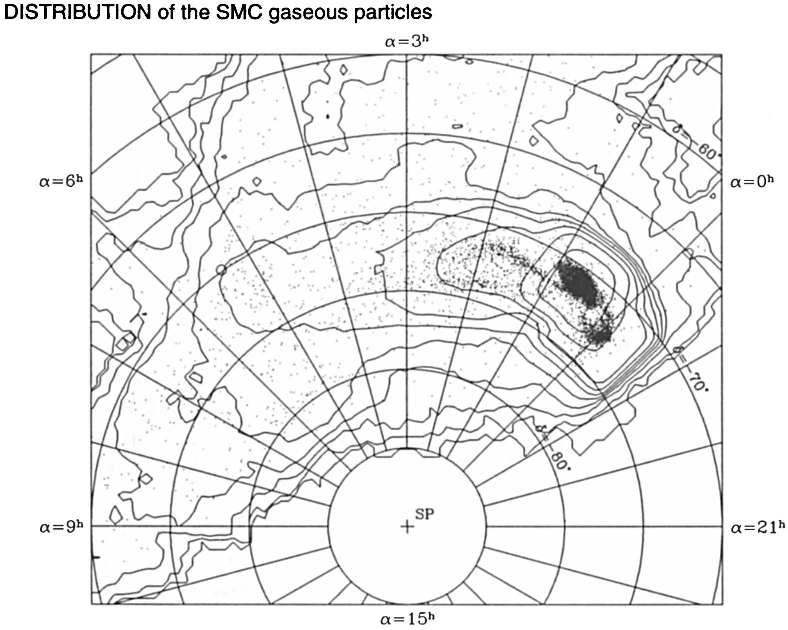

Figure 1. Distribution of SMC gas particles projected on the sky in the Y98 simulation. Contours denote the surface number density of particles weighted by the inverse square of distance.

the simulated MS accounts for the absence of star formation activity since its creation.

3. Structure of the SMC and the Inter-Cloud Region

The orbits employed in the models predict a close encounter between the LMC and the SMC occurring 0.2 Gyr ago at a separation of 7 kpc. This close passage drew out a prominent bridge-tail feature which can account for many characteristics of the structure and kinematics of the SMC and the inter-Cloud region (ICR). Fig. 1 shows the gas particle distribution produced by the Y98 model projected on the sky in the region of the Clouds. This distribution shows the beginnings of the MS in the north and an extension of material from the SMC towards the LMC forming the inter-Cloud bridge. The gas forms a narrower distribution in the ICR than in the GN96 model owing to the inclusion of gas dissipation, which keeps the SMC gas disk dynamically cold.

The tidal bridge and tail structures produced by the simulation are seen roughly superposed along the line-of-sight, leading to a large proposed depth for the ICR. In Fig. 2, the distances of particles from the sun given by the GN96 model are shown plotted against right ascension. The figure clearly indicates the separation between the bridge (closer) and tail (farther) structures along the line-of-sight, and suggests that stellar associations in the ICR may be related to one or other of these structures. Future accurate distance and velocity measurements

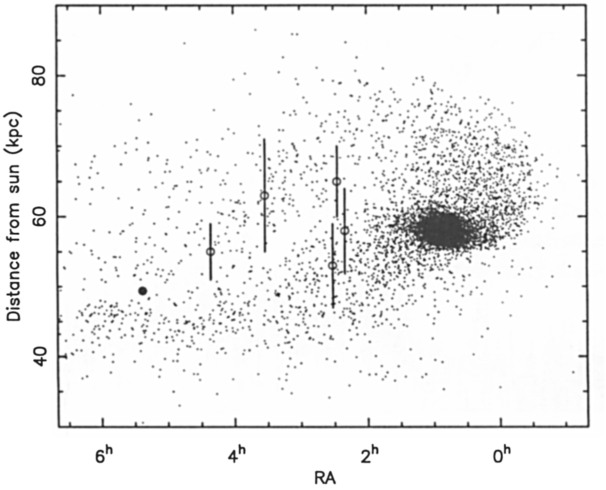

Figure 2. Line-of-sight structure in the GN96 simulation. The distances of the particles have been plotted against right ascension. The LMC is represented by a large dot. Also shown (large open circles) are the distances of five stellar associations in the inter-Cloud region with measurement errors (Grondin et al. 1992).

for the ICR associations can provide important data for evaluation of current models.

The existence of the bridge-tail structure originating in the SMC also gives rise to a large SMC depth, as indicated by Cepheid (Caldwell & Coulson 1986) and red clump star observations (e.g., Hatzidimitriou & Hawkins 1989). The simulations suggest that the SMC is elongated along the line-of-sight with material spanning a distance range of 50 kpc to nearly 80 kpc. The largest depths are predicted in the eastern regions, in agreement with red clump star studies.

The structure and kinematics of the central regions of the SMC appear to result directly from the existence of a strong bar ~ 5 kpc in length seen almost end-on (see GN96; note, however, that the Y98 model did not develop a bar due to the stabilising influence of the heavier halo). In particular, the highly non-circular motions of particles in the SMC bar result in a steep gradient in the radial velocity–right ascension plane (refer to Fig. 10 of GN96).

4. Star Formation in the SMC

The inclusion of a star-formation algorithm in the numerical code employed by Y98 allows useful insight to be gained into the effects of tidal interactions on star formation activity in the SMC. Fig. 3 shows the star formation rate (SFR) as a function of time. The plot indicates that the SFR in the SMC is strongly enhanced by the tidal encounters with the LMC occurring 1.5 Gyr (14 kpc separation) and 0.2 Gyr ago (7 kpc separation) by up to a factor of $\sim 3-4$. Interestingly, the peak of the SFR following the first interaction occurs 200-300

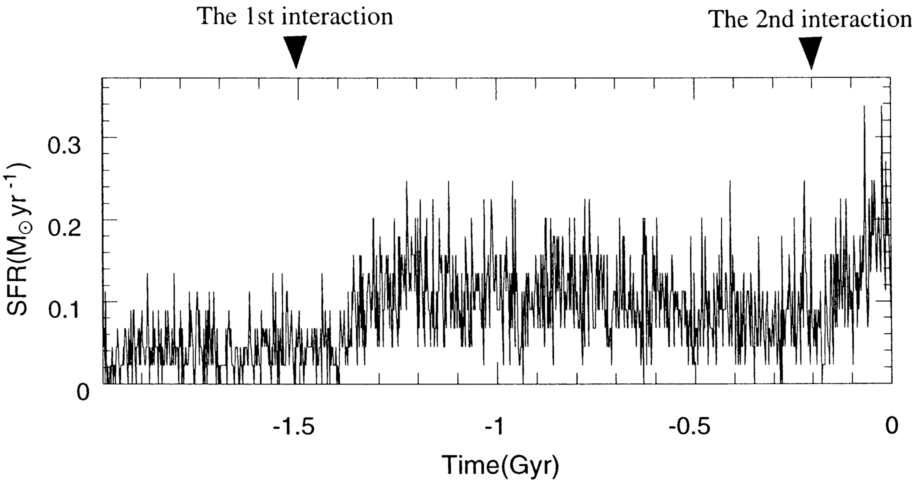

Figure 3. Star formation history (star-formation rate versus time) from the Y98 model.

Myr after the encounter event, while the SFR may still be rising at the present epoch 200 Myr after the second interaction. These enhancements and delays are consistent with the results of interacting galaxy models by Noguchi (1986), which suggest that star formation is triggered in spiral features produced by the tidal interaction.

The SMC Wing, containing numerous young stellar associations, is associated with star formation activity occurring less than 100 Myr ago. There is a correspondingly strong feature in the gas distribution in the model between $1^h < \alpha < 2^h$ in Fig. 1. In the Y98 model, a significant enhancement of star formation activity within the past 300 Myr is found in this region, confirming that the SMC Wing is a direct product of tidally induced star formation. The model did not give rise to star formation further east of $\alpha = 2^h$ because of the low gas density in the region between the Clouds. Nevertheless, a small number of faint stellar aggregates have been detected between the Clouds (Irwin et al. 1990).

5. Future Work

The continued accumulation of observational data related to the Magellanic Clouds system offers new challenges for future modelling of tidal interactions. The spectacular observational confirmation by Putman et al. (1998) of the existence of the leading counterpart to the Magellanic Stream which was predicted by the GN96 model testifies to the importance of numerical simulations in understanding the dynamical interactions of the Magellanic Clouds–Galaxy system. Recent work (see Gardiner 1999) indicates that the inclusion of a weak drag force due to ram pressure exerted by diffuse gas in the Galactic halo may lead to improved modelling of the leading arm feature. The effects of tidal interactions on the LMC have so far been little explored. It is now clear from HI observations (Putman et al. 1998) that the LMC also makes a significant contribution to the gas in the ICR. In addition, it would be interesting to discern whether the LMC's off-center bar is a result of tidal interactions or due to a spontaneous internal instability. As for numerical techniques, models are becoming increasingly detailed ($> 10^5$ particles) and sophisticated, involving accurate treatment of the gaseous component and/or star formation. However, there is still an important role for relatively straightforward (and less CPU-intensive) collisionless N-body models and test particle simulations in surveying the parameter space of possible orbits and model configurations that are hitherto only loosely constrained by observations.

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References

Caldwell, J.A.R., & Coulson, I.M. 1986, MNRAS, 218, 223

Gardiner, L.T. 1999, in "Proceedings from the Stromlo Workshop on High-Velocity Clouds", eds Gibson, B.K., & Putman, M.E., p.292

Gardiner, L.T., & Noguchi, M. 1996, MNRAS, 278, 191 (GN96)

Gardiner, L.T., Sawa, T., & Fujimoto, M. 1994, MNRAS, 266, 567

Grondin, L., Demers, S., & Kunkel, W.E. 1992, AJ, 103,1234

Hatzidimitriou, D., & Hawkins, M.R.S. 1989, MNRAS, 241, 667

Irwin, M.J., Demers, S., & Kunkel, W.E. 1990, AJ, 99, 191

Kroupa, P., & Bastian, U. 1997, New Astron., 2, 77

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

Lu, L., Savage, B.D., Sembach, K.R., Wakker, B.P., Sargent, W.L.W., & Oosterloo, T.A. 1998, AJ, 115, 162

Moore, B., & Davis, M. 1994, MNRAS, 270, 209

Murai, T., & Fujimoto, M. 1980, PASJ, 32, 581

Noguchi, M. 1986, MNRAS, 219, 305

Putman, M.E., Gibson, B.K., Staveley-Smith, L. et al., 1998, Nature, 394, 752

Yoshizawa, A. 1998, PhD thesis, Tohoku University, Sendai, Japan (Y98)

Discussion

Despina Hatzidimitriou: We do not yet know how big a kinematic halo (if any) the SMC has. So, it may be a good idea to explore the possibility that the SMC is a pure disk, as a limiting case. It may be worth investigating what happens to the rotation curve, if you assume a rotation curve before the last two close encounters.

Gardiner: In future models it will be good to explore the effect of changing the disk-to-halo mass ratio. However, I believe the observational evidence does support the existence of a kinematic halo in the SMC.

K. Innanen: If the Magellanic Clouds are natural, primodial satellites of the Galaxy, one asks the question: how did they acquire the angular momentum of their orbit(s) around the Galaxy? One possibility is that they may not be primodial satellites, but have arrived by some other dynamical event in the Local Group many Myr ago.

Gardiner: Yes, I agree. The Magellanic Clouds could have been subjected to torques exerted by other Local Group galaxies.

Hans Zinnecker: What was the critical threshold gas density or surface gas density that was used to describe the star formation rate in the Yoshizawa model? Secondly, what is the reason for the (model) 200 Myr delay for the onset of star formation after a close LMC-SMC encounter?

Gardiner: The critical surface density threshold was 25×10^{20} H cm^{-2} (Kennicutt et al. 1995). A scale height of ≈ 450 pc was assumed for the HI layer in the SMC, giving a critical volume density of 0.04 $\mathrm{M}_{\odot}\mathrm{pc}^{-3}$.

The delay appears to be related to the time taken for the tidal bridge and tail to form and produce density enhancements in the gas.