Magellanic Clouds in interaction – evolutionary search for good models

Is the dark matter halo of the Milky Way flattened?

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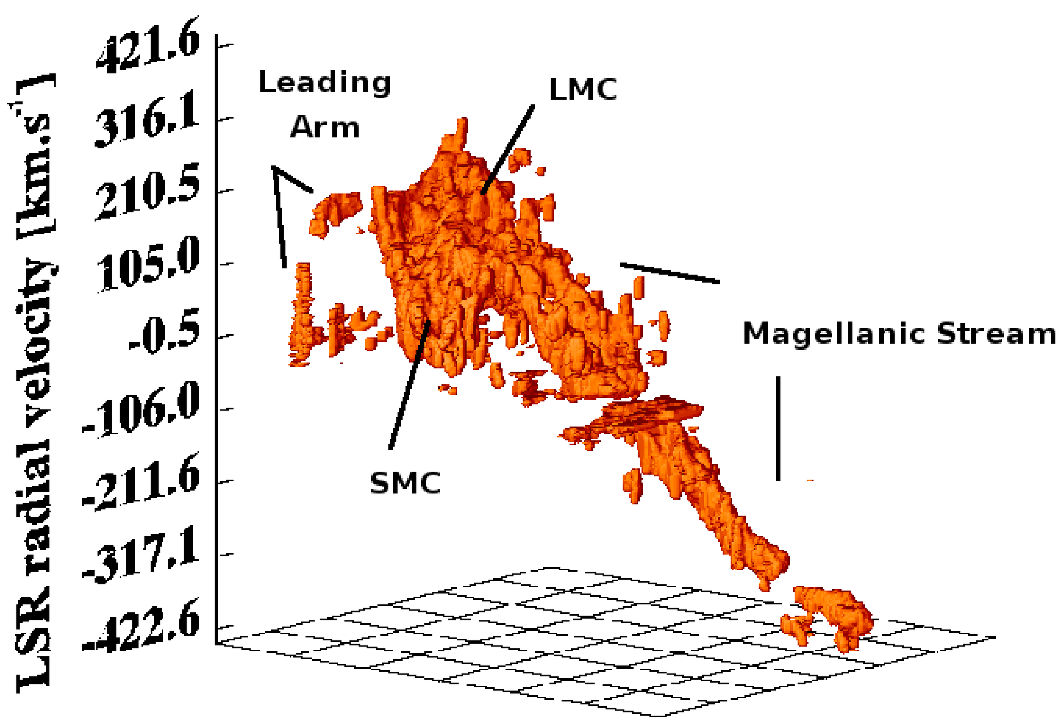
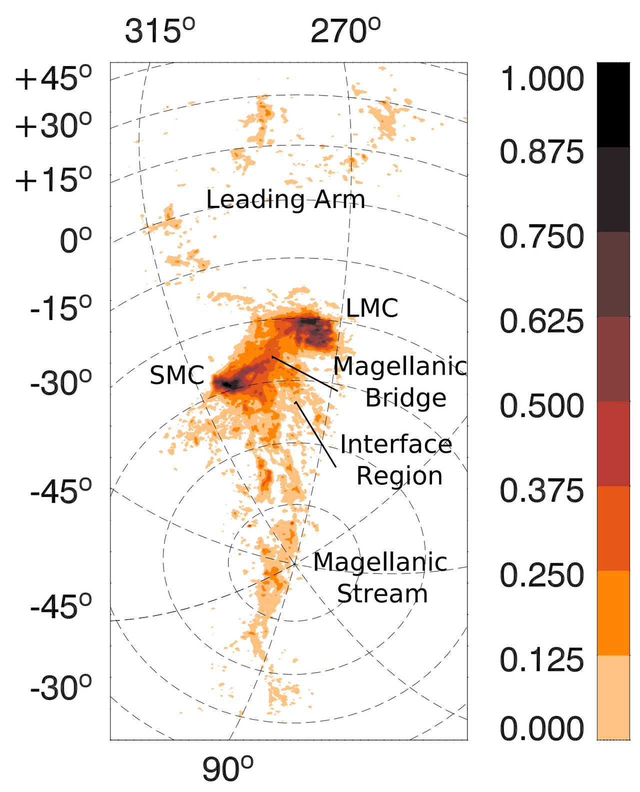
ABSTRACT: We performed an extended analysis of the parameter space for the interaction of the Magellanic System (LMC and SMC) with the Milky Way (MW). The varied parameters cover the phase space parameters, the masses, the structure, and the orientation of both Magellanic Clouds, as well as the flattening of the dark matter (DM) halo of the MW. The analysis was done by a special optimization code – genetic algorithm (GA) – searching for the best match between numerical models and the detailed H I map of the Magellanic System by Brüns et al. (2005). By this, we were able to analyze more than 10^6 models, which makes this study one of the most extended ones for the Magellanic System. Here we focus on the flattening q of the axially symmetric MW DM halo potential, that is studied within the range $0.74 \le q \le 1.20$. We show that creation of a trailing tail (Magellanic Stream) and a leading stream (Leading Arm) is quite a common feature of the LMC–SMC–MW interaction, and such structures were modeled across the entire range of halo flattening values. However, important differences exist between the models, concerning density distribution and kinematics of H I, and also the dynamical evolution of the Magellanic System. Detailed analysis of the overall agreement between modeled and observed distribution of neutral hydrogen shows that the models assuming an oblate ($q < 1.0$) DM halo of the MW allow for better satisfaction of H I observations than models with other halo configurations.

Magellanic Clouds and the Galaxy

The Galaxy together with its close dwarf companions the LMC and the SMC form an interacting system.





Left plot: The figure depicts the original 3 D H I data cube of the Magellanic System by Brüns et al. (2005); we offer 3 D visualization of the column density isosurface $\Sigma_{\rm H\,I} = 0.2 \cdot 10^{18}\,{\rm cm}^{-2}$. Right plot: Contour map of the observed H I integrated relative column density in the Magellanic System. Data by Brüns et al. (2005) is projected on the plane of sky. Galactic coordinates are used.

We apply the GA search strategy with a restricted N–body code for the Magellanic System. In the case of encounters between two galaxies Wahde (1998) and Theis (1999) showed that such an approach is able to reproduce the parameters of the interaction. For details on our 3 D restricted N–body model and the implementation of GA see Ruzicka et al. (2007).

Restricted N–body model

Both LMC and SMC are represented by Plummer spheres, initially surrounded by disks of 10 000 test–particles. The potential of the DM halo of the MW is modeled by a flattened axisymmetric logarithmic potential

$$\Phi_{\rm L} = \frac{1}{2}{\upsilon_0}^2 \ln\left({R_c}^2 + R^2 + \frac{z^2}{q^2}\right), \tag{1}$$

where q describes the flattening of the MW halo potential.

Dynamical friction causes the orbital decay of the Magellanic Clouds. We adopted the analytic dynamical friction formula by Binney (1977):

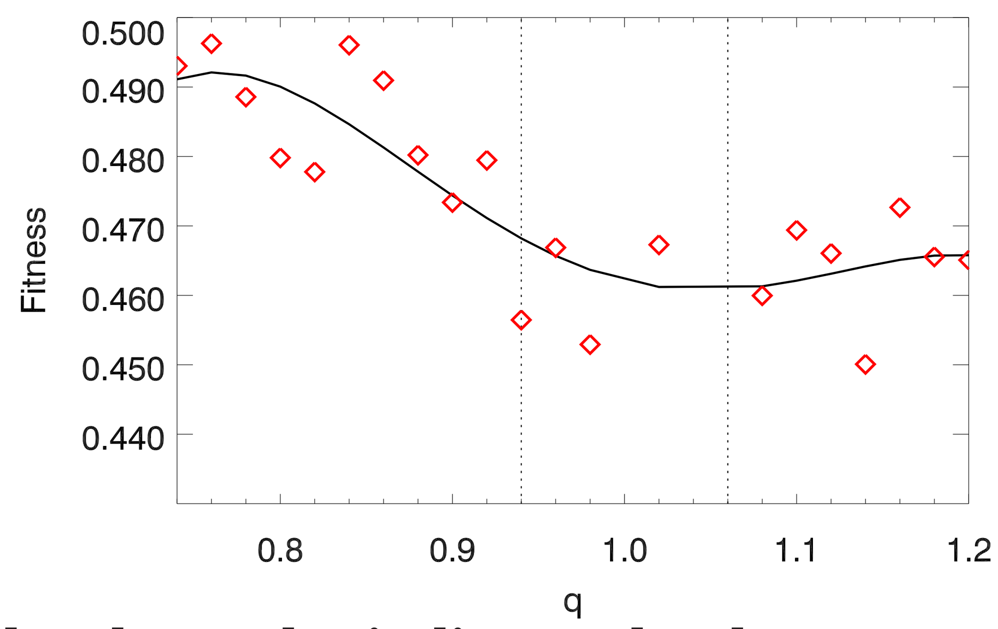
$$F^i_{\rm DF} = -\frac{2\sqrt{2\pi}\rho_{\rm L}(R,z)G^2M_{\rm S}\sqrt{1-{e_\upsilon}^2}\ln\Lambda}{{\sigma_R}^2\sigma_z}B_i\upsilon_i, \tag{2}$$

where $i = x, y, z$, (σ_R, σ_z) is the axially symmetric velocity dispersion ellipsoid, $\ln\Lambda$ is the Coulomb logarithm of the halo, $M_{\rm S}$ is the satellite mass, and $B_i = f(\upsilon_R, \upsilon_z, \sigma_R, \sigma_z)$. The resulting equations of motions were integrated from $T = -4$ Gyr.

Evolutionary search – genetic algorithms

GA interprets natural evolution of a population of individuals as an increasing adaptation of the population to given conditions. In our case the conditions are to match numerical models to the observations. Each single point in parameter space (individual) defines one interaction scenario which can be compared with the observations (after the N–body simulation is performed). The quality of each individual is characterized by the value of a **fitness function** (FF, $0 \le FF \le 1$).

The FF of the Magellanic System is a complicated landscape (Ruzicka et al. 2007). Thus, the GA optimizer was run repeatedly and over 100 high–fitness models distributed over the fitness landscape were collected. To discuss the models with respect to the MW DM halo flattening q, three model groups were defined:
A: $0.74 \le q \le 0.92$ B: $0.94 \le q \le 1.06$ C: $1.08 \le q \le 1.20$

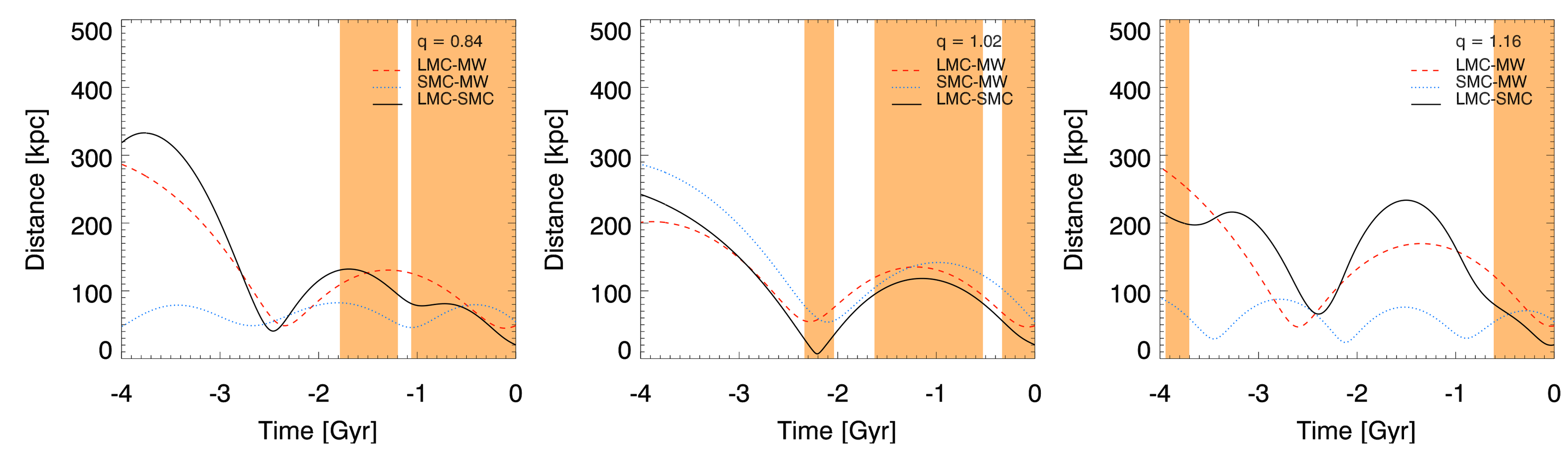


Maximum values of fitness as function of the MW DM halo flattening q. The plot depicts the fitness of the best GA fit of the Magellanic System that was found for each of the MW DM halo flattening values that entered the GA search. The values of q delimiting the model groups A, B and C are emphasized by dotted lines.

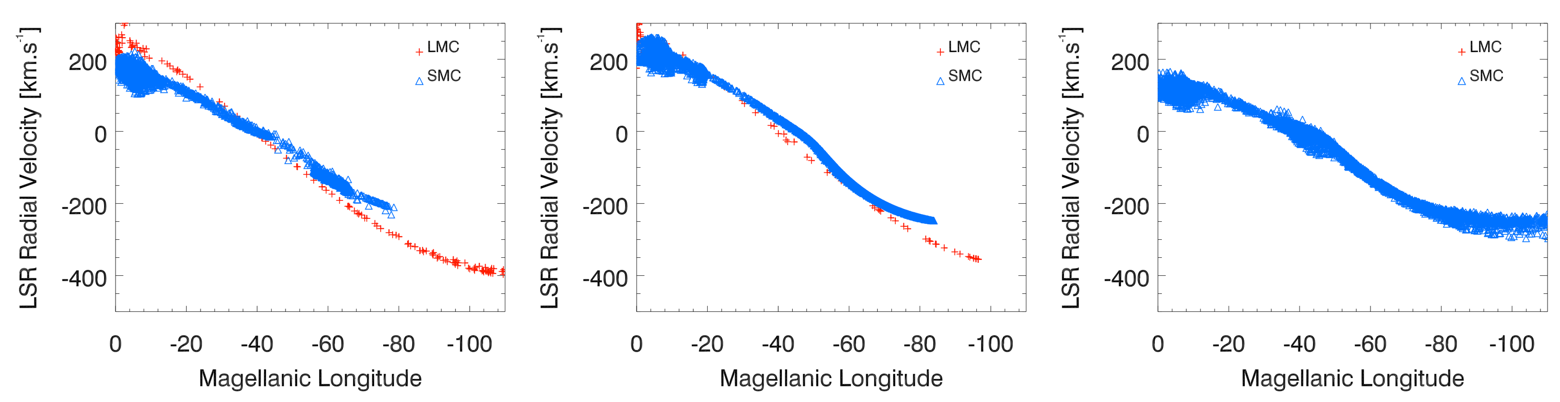
The above plot indicates that better agreement between the models and the H I observations of the Magellanic System is achieved for oblate (q < 1.0) DM halos of the MW than for either spherical or prolate configurations.

Representative models

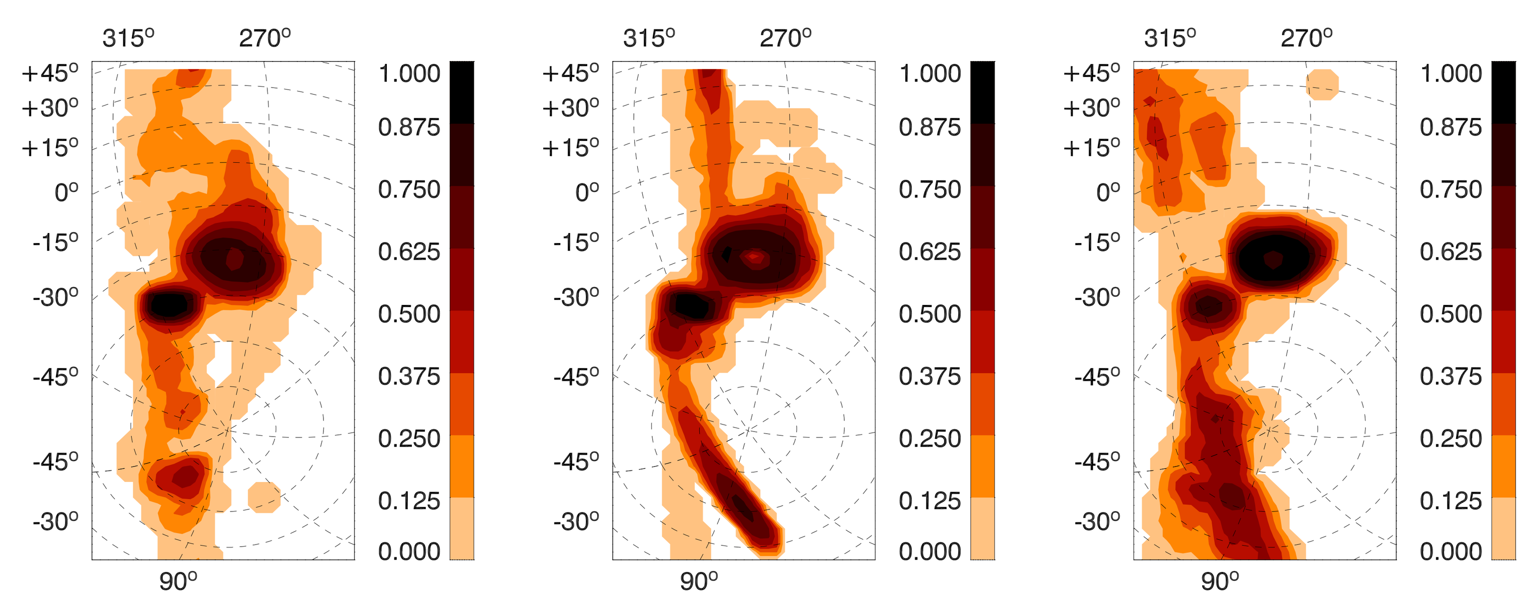
We describe the models of highest fitness selected from each of the groups A, B and C (the model A, B and C). All of them are typical representatives of their model groups.



Orbital evolution of the Magellanic Clouds for the model A (left plot), B (middle plot) and C. The plots correspond to logarithmic halos of the flattening $q = 0.84, 1.02$ and 1.16, respectively. Time dependence of the LMC and SMC galactocentric distances, and the LMC–SMC relative distance are plotted above. Plot areas with filling mark the time intervals when the Clouds were gravitationally bound to each other.



LSR radial velocity profile of the Magellanic Stream for the model A (left plot), B (middle plot) and C.



Contour map of the modeled H I integrated relative column density for the model A (left plot), B (middle plot) and C. Data is projected on the plane of sky. Galactic coordinates are used.

References

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