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The mass of the Milky Way based on the kinematics of satellites

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Abstract. The Milky Way satellite system is the most studied group of galaxies. Currently, 64 satellites within 260 kpc are known. We have measured high-precision distances, radial and tangential velocities for most of them. We have estimated the total mass of our galaxy to be $M = (7.9 \pm 2.1) \times 10^{11}\ M_\odot$ using a modification of the projected mass method that takes into account the three-dimensional distribution of galaxies in the group, assuming an isotropic distribution of satellite orbits. The infall of galaxies located outside the virial zone at a distance of 400 kpc allows us to estimate the mass of the system to be of the order of $9 \times 10^{11}\ M_\odot$, which is in excellent agreement with the mass inside the virial zone of our Galaxy.

Keywords: The Galaxy; Galaxy: kinematics and dynamics

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1 Introduction

Recently, thanks to deep optical surveys, our knowledge of the satellite system around our Galaxy has expanded dramatically. Currently, there are 64 known satellites of our Galaxy within the 260 kpc region. Thanks to the Gaia (Gaia Collaboration et al. 2018) mission, the proper motions of most of our Galaxy's satellites have been measured, allowing us to unambiguously determine all 6 components of satellite position in phase space. This information is being actively used to refine the structure of our Galaxy and to estimate its total mass. However, even a simple analysis of the radial velocity distribution can reveal unexpected and interesting effects. Recently, it was discovered that the dipole component of the radial velocity field of nearby satellites at distances less than 100 kpc has an unexpectedly large amplitude of bulk motion of about 200 km/s (Makarov et al. 2023). The analysis showed that this anomaly is caused by only 8 galaxies (crossed out with red crosses in the left panel of Fig. 1), including the Large Magellanic Cloud (LMC) and three galaxies from its escort. Numerical simulations show that the velocity pattern is consistent with the assumption of the first flyby of the massive LMC around our Galaxy and the perturbation it causes in the motion of the Galaxy's satellites. This example shows the importance of a careful selection of "the test particles" for the kinematic analysis. Such objects have not had time to virialize and should be excluded from consideration when estimating the total mass of the system.

2 Mass inside the virial zone

The radial velocity-distance distribution of the satellites around our Galaxy is shown in Fig. 1. There is a clear separation between well randomized companions below 260 kpc, indicating the extent of the virial zone, and three galaxies with systematic negative velocity at a distance of 400 kpc. The galaxies Eridanus II, Phoenix, and Leo T are probably in the stage of approaching the Milky Way halo. To estimate the mass of our Galaxy, we exclude 8 objects that most strongly distort the behavior of the solar apex (Makarov et al. 2023). We use a modification of the projected mass method (Bahcall & Tremaine 1981) that takes into account the three-dimensional distribution of galaxies in the group. Assuming an isotropic distribution of the satellite orbits, we estimate the total mass of the Milky Way to be $M_{\rm MW} = (7.9 \pm 2.1) \times 10^{11}\ M_{\odot}$ (left panel of Fig 2).The known presence of satellite planes does not affect this estimate, since it depends only on the shape of the orbits, but not on their distribution in space. As can be seen from Fig. 3, our estimate is in good agreement with numerous estimates by other authors (see reviews Wang et al. 2020; Bobylev & Bajkova 2023).

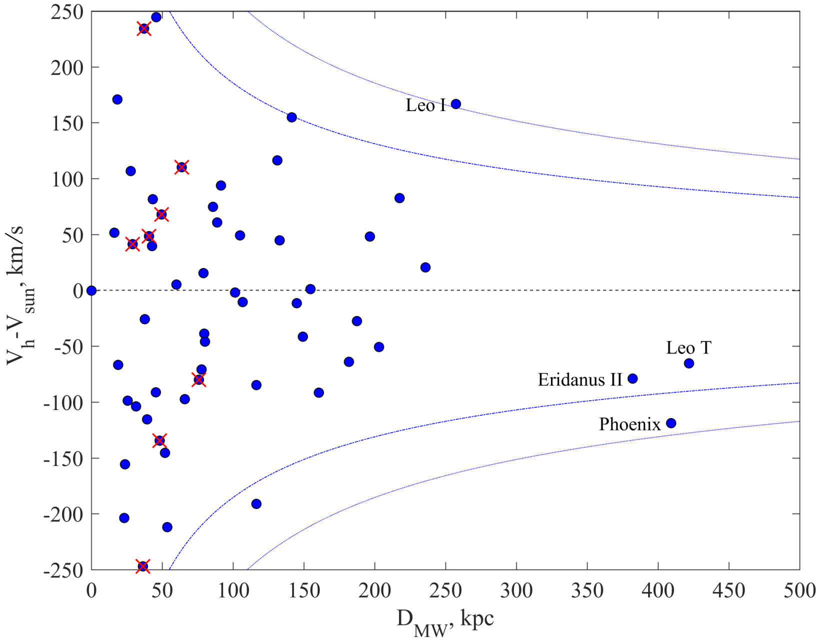

Fig. 1. Velocity-distance distribution of the nearest galaxies. The line-of-sight velocity is given relative to the center of the Galaxy. The dot-dashed and dotted lines correspond to circular and escape velocities for a point mass of $8 \times 10^{11}\ M_{\odot}$, respectively.

3 Mass from the infall region

We can try to use the Eridanus II, Phoenix, and Leo T galaxies outside the virial zone of the Milky Way to estimate the total mass within 400 kpc. Note that these galaxies are deep inside the Local Group stop radius of about 1 Mpc and to describe their infall the linear approximation is not applicable and more complex models must be used. Baushev (2020) found an exact analytical solution to the Hubble flow for a spherically symmetric distribution of matter, which we can use to estimate the mass of our Galaxy. Using the distances and radial velocities of Eridanus II and Leo T, we estimate the mass of the Milky Way from the flow model to be $M_{\rm MW} = 9.1 \times 10^{11}$ and $8.6 \times 10^{11}\ M_{\odot}$, respectively. These values are slightly larger, but still in excellent agreement with our previous mass estimate of $M_{\rm MW} = (7.9 \pm 2.1) \times 10^{11}\ M_{\odot}$ within the virial zone (see Section 2). This shows the validity of the spherically symmetric Hubble flow model for estimating mass even deep inside the stop radius of galaxy groups, and provides a tool for measuring mass outside the virial zones of groups.

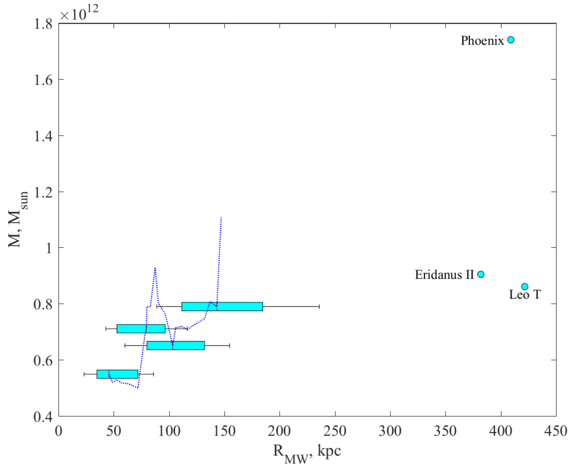

Fig. 2. Estimation of the Milky Way mass versus the distance within the virial zone (cyan boxes) and from the Hubble flow model (cyan dots).

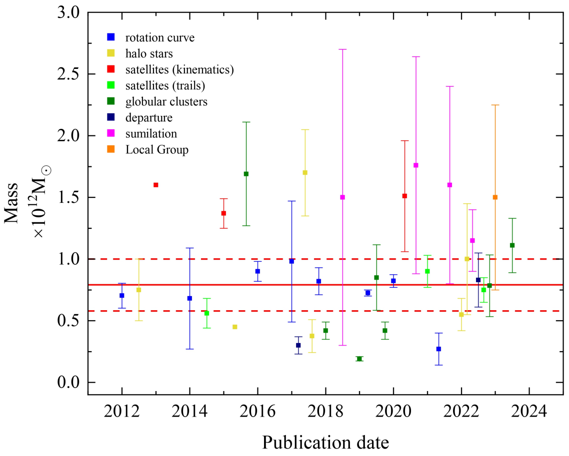

Fig. 3. Comparison of our estimate of the mass of the Milky Way with recent measurements obtained by other authors.

However, using the Phoenix galaxy we obtain a mass value of $17 \times 10^{11}\ M_{\odot}$, which does not fit into this picture. Observations show that the HI gas in the Phoenix galaxy is significantly offset from the stellar body (St-Germain et al. 1999) and it is likely that Phoenix has experienced a recent impact and cannot be considered as a free-falling test particle.

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