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Mass of the Andromeda Galaxy on a scale of up to 300 kpc

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Abstract. By analysing the kinematics of the satellites of giant galaxies, it is possible to estimate the total mass of systems within 300 kpc. The Andromeda Galaxy (M 31) is the closest giant galaxy with a well known three-dimensional satellite system. Estimating its total mass is extremely important for understanding the halo distribution of dark matter, as well as for studying the kinematics and dynamics of the Local Group of galaxies. In this work we use the improvement of the projected mass method to take into account the three-dimensional distribution of the satellites, which allows us to obtain more reliable and accurate estimates of the total mass of the system. Using a sample of 29 satellites with precise distance measurements and radial velocities, we estimate the total mass of M 31 to be $M = (1.7 \pm 0.4) \times 10^{12}\ M_\odot$ on a scale of 300 kpc. This result is in good agreement with the work of other studies.

Keywords: galaxies: kinematics and dynamics, Local Group, dwarf

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1 Introduction

The determination of the virial masses of the Milky Way and the Andromeda Galaxy, or M 31, is one of the most important issues in the study of the Local Group. Knowledge of the mass distribution in the system is a significant contribution to the resolution of kinematic and dynamical processes. M 31 is the nearest giant galaxy and was one of the first galaxies for which mass determination was attempted. Over almost a century of research, a variety of approaches have been used, including the disk rotation curves, consideration of the kinematics of globular clusters and/or dwarf satellite galaxies, as well as the kinematics of the Local Group as a whole, construction of mass models, and, more recently, cosmological simulations. The results have varied over the decades, but as the accuracy of the measurements improves and more new galaxies are discovered in the Local Group, the task becomes increasingly feasible. We have collected recent distance and velocity measurements from the literature for 55 galaxies within 525 kpc of M 31. Their distribution shows the famous satellite plane and the well known skew towards our Galaxy (see Fig. 1).

In this work we use an improved method of the predicted mass that takes into account the three-dimensional distribution of satellites in space.

2 Projected mass

The classical way to estimate the mass of a galaxy group is to use the virial theorem. Bahcall & Tremaine (1981) noted that the virial theorem has a number of unrecoverable drawbacks due to projection effects and proposed an alternative approach, the so-called projected mass estimator. In the case of a central mass surrounded by test particles, which can be considered a good approximation for the system of satellites around the Andromeda Galaxy, Bahcall & Tremaine (1981) use $GM = \alpha V_{\rm los}^2 R_\perp$ as a proxy for mass estimation, where $V_{\rm los}$ is the line-of-sight velocity relative to the central body and $R_\perp$ is the projected distance from the central galaxy. The coefficient α is derived by averaging over all possible satellite orbits. Knowledge of the three-dimensional distribution of the satellites can reduce the uncertainty and improve the accuracy of the mass estimate in this relation. For the case where a group of galaxies is observed from the outside, and assuming an isotropic distribution of orbits, $\langle e^2 \rangle = 1/2$, we obtain the following relation: $GM = 4\langle V_{\rm los}^2 R_{\rm 3D} \rangle$, where $R_{\rm 3D}$ is the distance from the central galaxy.

From the total list of 55 satellites around M 31, we excluded all objects with unknown, questionable or imprecise distance measurements, as they could be a source of large systematic errors. These include 8 objects from the Pan-Andromeda Archaeological Survey (PAndAS) without distance measurements. We have also excluded

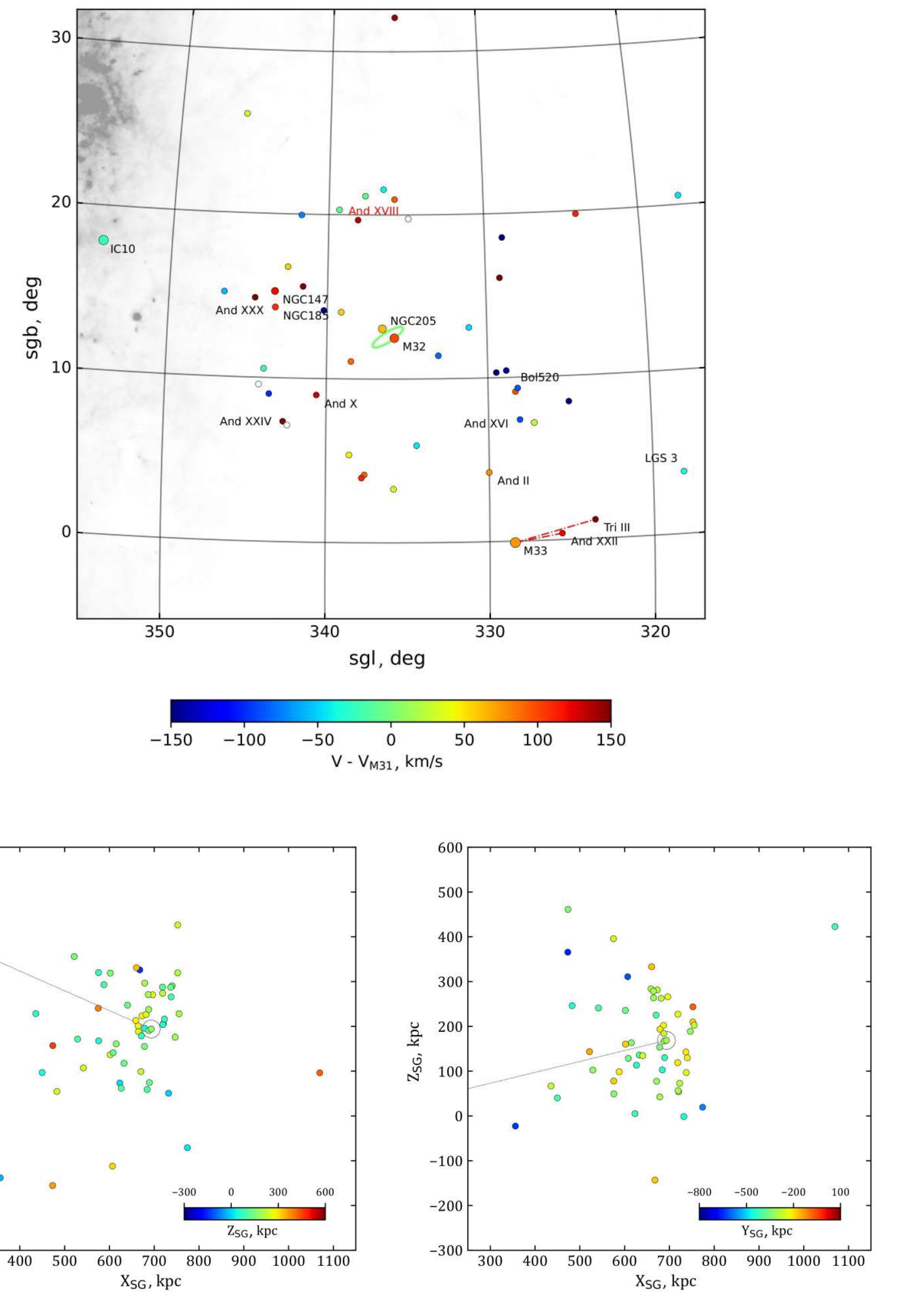

Fig. 1. *Top panel*: distribution of the M 31 satellites in the Aitoff projection on the celestial sphere. M 31 itself is indicated by a central ellipse. The color reflects the velocity difference relative to the central galaxy. The open dots mark galaxies with unknown line-of-sight velocities. The IRAS interstellar extinction map is given by gray clouds. *Bottom panel*: Distribution of objects within a sphere of radius 520 kpc from M 31 in Cartesian Supergalactic coordinates. The dotted line indicates the direction towards the Milky Way.

all objects with a relative distance measurement error greater than 5 %. Among them is Tri III ($e/D = 23.2\%$) probably belongs to the first infall group associated with M 33; the globular cluster Bol 520 (9.6%); IC 10 (5.7%) and And XXVII (5.7%) are in the high extinction region of the Milky Way. After careful analysis, we have also excluded M 33 with its suite of And XXII and Tri III, which completed its first flyby of M 31, and And XXX as a galaxy undergoing a primary infall into the M 31 group. Thus, based on a sample of 30 satellites within 300 kpc of M 31, we estimate the total mass of the Andromeda Galaxy equal to $M = (1.70 \pm 0.37) \times 10^{12}\ M_\odot$ with a maximum variation between $M = 1.3 \times 10^{12}\ M_\odot$ for purely circular orbits, $\langle e^2 \rangle = 0$, and $M = 2.6 \times 10^{12}\ M_\odot$ for purely radial orbits, $\langle e^2 \rangle = 1$.

The classical approach of Bahcall & Tremaine (1981), based on using only projected distances and radial velocities, using the same galaxies, gives a very close mass estimate of $M = (1.74 \pm 0.50) \times 10^{12}\ M_\odot$, but with worse accuracy. However, it also allows us to include objects in the analysis without precise distance measurements in the analysis and improve the accuracy through statistics. Using all 41 confirmed satellites and candidates within 300 kpc of the Andromeda Galaxy, we obtain a mass estimate of $M = (1.74 \pm 0.44) \times 10^{12}\ M_\odot$. Note that the accuracy is still lower than in our approach. This indicates the importance of knowing the distribution of satellites in space for a more accurate estimate of galaxy mass.

3 Summary

We estimate the total mass within 300 kpc of the Andromeda Galaxy equal to $M = (1.70 \pm 0.37) \times 10^{12}\ M_\odot$. This result is in good agreement with the estimates of other authors over the last 10—15 years. The last time a similar method was used for satellites by Watkins et al. (2010). On the same scale, they obtained an estimate of $M = (1.4 \pm 0.3) \times 10^{12}\ M_\odot$, which is within the measurement errors of our estimate. By applying the tracer mass estimator to globular clusters, Veljanoski et al. (2013) obtained a mass of $M = (1.35 \pm 0.35) \times 10^{12}\ M_\odot$. The difference in estimates may also be due to a more complete sample in our work, supplemented by the discovery of new satellites and refinement of parameters over the last decade.

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