On the Andromeda to Milky Way mass ratio

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ABSTRACT

We have explored the hypothesis that the total mass ratio of the two main galaxies of the Local Group, the Andromeda galaxy (M31) and the Milky Way (MW), can be constrained by measuring the tidal force induced by the surrounding mass distribution, M31 included, on the MW. We argue that the total mass ratio between the two groups can be approximated, at least qualitatively, by finding the tidal radius where the internal binding force of the MW balances the external tidal force acting on it. Since M31 is the massive tidal ‘perturber’ of the local environment, we have used a wide range of M31 to MW mass-ratio combinations to compute the corresponding tidal radii. Of these, only a few match the distance of the zero-tidal shell, i.e. the shell identified observationally by the outermost dwarf galaxies which do not show any sign of tidal effects. This is the key to constraining the best mass-ratio interval of the two galaxies. Our results favour a solution where the mass ratio ranges from 2 to 3, implying a massive predominance of M31.

Key words: galaxies: individual: Andromeda – galaxies: individual: Milky Way.

1 INTRODUCTION

The total mass ratio between the Andromeda galaxy (M31) and the Milky Way (MW) is an intriguing puzzle. Very recent papers favour a mass ratio close to unity, suggesting that M31 is as massive as the MW (hereafter M31 and MW are intended as groups including their satellite dwarf galaxies). Comparing the H i rotation curve of M31 with the analogue of the MW obtained from trigonometric parallaxes and proper motions of masers in star formation regions, Reid et al. (2009) concluded that the dark matter halo of M31 and MW is comparably massive, confirming the previous suggestion of Evans et al. (2000). Furthermore, Evans & Wilkinson (2000) and Gottesman, Hunter & Boonyasait (2002) claimed a total mass of M31 smaller than that of the MW. On the other hand, Karachentsev et al. (2009), studying the peculiar velocity pattern around the Local Group, inferred a M31/MW mass ratio of 1.25, evidence for a small mass predominance of M31 over the MW. This recent result partially confirms an older one based on timing arguments which found a larger mass ratio of between 1.3 and 1.7 (Zaritsky 1999). In the last decade, great effort has been made to improve the mass evaluation of the two galaxies. The large number of dwarf galaxies recently discovered even at large Galactocentric distances (Willman et al. 2005a,b; Belokurov et al. 2006a,b, 2008; Zucker et al. 2006a,b; Irwin et al. 2007; Walsh, Jerjen & Willman 2007) has been used for better modelling of the structural properties of the halo, deriving new estimations of the total mass of the MW (Battaglia et al. 2006; Dehnen, McLaughlin & Sachania 2006; Besla et al. 2007; Kalberla et al. 2007; Smith et al. 2007; Li & White 2008; Xue et al. 2008). Similar objects have been found around M31 (Zucker et al. 2004, 2007; Martin et al. 2006; Majewski et al. 2007) which helped to improve the mass estimation of M31 (Majewski et al. 2007; Seigar, Barth & Bullock 2008). However, even if the new data have greatly increased our knowledge of both M31 and the MW, there is not a general concordance between their estimated masses. For example, in a recent paper, Xue et al. (2008) estimated the mass of the MW dark matter halo using a set of 2401 halo stars from the Sloan Digital Sky Survey as kinematic tracers and assuming a Navarro, Frenk & White halo profile; they found a value of ~1 × 10^{12} M_☉, reopening the question of whether all of the MW satellite dwarf galaxies are on bound orbits. The new sample of discovered satellites is generally assumed bound within the MW dark halo, but the assumption seems to hold only if the mass is ≥2 × 10^{12} M_☉ (Peebles 1995; Wilkinson & Evans 1999; Sakamoto, Chiba & Beers 2003; Loeb et al. 2005; Li & White 2008). It is noteworthy that almost all previously published estimations fall within the above mass interval (e.g. Klypin, Zhao & Somerville 2002; Bellazzini 2004; Karachentsev 2005). More controversial is the case of M31 after the recent study of Seigar et al. (2008) which found a total mass of 0.8 × 10^{12} M_☉ which confirms similar low-mass estimations (e.g. Evans & Wilkinson 2000; Gottesman et al. 2002; Klypin et al. 2002; Karachentsev 2005; Majewski et al. 2007), but in contrast with other estimations ≥3 × 10^{12} M_☉ (Peebles 1996; Loeb et al. 2005). From such mass intervals, a very wide range of possible M31 to MW mass ratios can be assumed. Can this issue be disentangled by using a different approach? Karachentsev (2005) suggested a strategy based on the tidal relationships among gravitationally interacting bodies, for example the tidal interactions between a dominant galaxy and its satellites. However, this method may significantly

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underestimate the total amplitude of the tidal force since it does not take into account further tidal influences (even if small) coming from the external surrounding mass distribution. In contrast, in a similar but statistical approach, Baiesi Pillastri et al. (2006) took into account the gravitational potential induced by extended environments to estimate the tidal fields acting on 11 galaxy groups used as test particles. Their total masses have been established by examining the tidal limits set by the surrounding mass distributions on these groups. In the present work, instead of attempting to constrain the total mass of the MW (thought of as a group), since M31 is the major tidal 'perturber' of the local environment, the best M31 to MW mass ratio has been identified using a wide range of combinations of mass ratio to compute the corresponding tidal radii around the MW. Of them, only a few will match the distance of the zero-tidal shell, i.e. the shell where all forces cancel each other out. The location of this shell will be identified observationally by looking at the physical properties of the outermost dwarf galaxies surrounding the MW. They should not show any sign of observational effects of tidal stripping like mass (stars) or gas (H I) loss, streaming tail, irregular morphology and so on. This is the key to constraining the best interval of M31 to MW mass ratios and the corresponding total masses of each system. To disentangle this issue, in Section 2 we present the method based on the tidal theory. The application of the method is performed in Section 3. Then, in Section 4 we discuss our results. Finally, in Section 5 we present the concluding remarks.

2 THE TIDAL APPROXIMATION

Following Baiesi Pillastri et al. (2006), the strategy involves approximate descriptions of external influences incorporating the larger external influence through a static tidal field estimated on the basis of the present-day locations of nearby objects enclosed in a spherical volume representative of the external density distribution. In other words, we assume that the source of the tidal force is due to a time-independent gravitational potential generated by the 'point mass' distribution of the surrounding galaxies and galaxy groups centred on the MW frame of reference. We assume the tidal effect as a static tidal limitation spatially fixed by the tidal radius beyond which the binding force dominates the internal dynamics of the MW, while external objects would be torn apart by the tidal field. Then, the tidal force acting on the MW and its satellites can be expressed by

$$F_{\text{tidal}, a} = -\frac{d^2 \Psi_{\text{ext}}}{dR_a dR_b} R_b \equiv F_{ab} R_b,$$

(1)

where $\Psi_{\text{ext}}$ is the external potential and $R$ is the radius vector in the MW reference frame. Then, if the MW is subjected to the action of $N$ nearby galaxy groups and galaxies at a position vector $r_g$ and mass $m_g$, the external potential is given by

$$\Psi_{\text{ext}} = -G \sum_N \frac{m_g}{|r_g|},$$

(2)

and the tidal tensor is

$$F_{ab} = \sum_N \left( \frac{m_g}{|r_g|^3} \right) \left[ \frac{3 (r_a)_g (r_b)_g}{|r_g|^2} - \delta_{ab} \right],$$

(3)

where the gravitational constant $G = 1$ and $\delta_{ab}$ is the Kronecker delta. It follows that the amplitude of the tidal force is

$$F_{\text{tidal}} = |F_{ab} R_a|,$$

(4)

where $F_{ab}$ are the three eigenvalues corresponding to the principal axes of the $3 \times 3$ symmetric matrix $F_{ab}$. By assuming that the MW and its satellites are a group which is approximately spherically symmetric and dynamically relaxed, the condition $F_{\text{tidal}} = F_{\text{binding}}$ must be satisfied. Plugging in

$$F_{\text{tidal}} = \frac{M}{R_t^2},$$

(5)

where $M$ and $R$ are the fiducial virial mass and radius of the MW, then the tidal radius is

$$R_t = \left( \frac{M}{F_{\text{tidal}}} \right)^{\frac{1}{2}}.$$

(6)

3 APPLICATION

3.1 Methodology

The application has been organized in the following way. (i) We calculate the net tidal force acting on the MW assuming that it is induced by the local environment enclosed in a spherical volume of 5 Mpc radius as the first approximation of the sampling. (ii) We know that ~80 per cent of the tidal amplitude is generated by M31, the nearest and massive companion. Keeping fixed the remaining 20 per cent due to the farthest masses and running a grid of mass parametrization for M31, entering in equation (3), and the MW, in equation (6), as a function of a wide range of combinations of mass ratios, we obtain the corresponding range of computed tidal radii $R_t$. Knowing that the mass estimations of the MW range from 1 to 2.5 $\times 10^{12}$ M$_\odot$, while those of M31 range from 1 to 3.5 $\times 10^{12}$ M$_\odot$, the mass parametrization for M31 is 1, 1.5, 2, 2.5, 3, 3.5 ($\times 10^{12}$ M$_\odot$) and 1, 1.5, 2, 2.5 for the MW. Then, the grid of 6 $\times$ 4 = 24 combinations of mass ratios has been run to obtain the corresponding 24 tidal radii $R_t$. (iii) The $R_t$ (one or many) that best matches $R_{\text{ZTS}}$ (i.e. the distance of the zero-tidal shell discussed in Section 1) enables us to constrain the best M31 to MW mass ratio.

3.2 Data

To perform our analysis, we have used the data collected by Pasetto & Chiosi (2007) in order to study the planar distribution of galaxies in the Local Group. From their table 2, the Galactic coordinates, distances and mass estimations of six massive galaxy groups located approximately within 5 Mpc radius from the MW have been acquired. Similarly, from their table 3, a supplementary list of 22 galaxies lying in the same volume has been added to our data base in order to have a sample representative of the real mass distribution surrounding the MW. A detailed description of the data (references, corrections and uncertainties) can be found in their section 4. If the light is a tracer of the mass, these objects represent almost all light within the sampled sphere.

3.3 Simplifying assumptions

We have identified the location of $R_{\text{ZTS}}$ on the basis of the physical properties of the dwarf galaxy satellites lying at increasing distances from the MW. For instance, Leo V, a small dwarf galaxy discovered at a distance of ~180 kpc, shows clear signs of strong tidal stripping (Walker, Belokurov & Evans 2009). Another example of an apparent tidal effect has been found on the dwarf spheroid Leo I which resides at a Galactocentric distance of ~250 kpc (Sohn et al. 2007; Muñoz, Majewski & Johnston 2008) even if the tidal origin of this effect has been recently challenged (Penarrubia et al. 2009).
Besides, a recent analysis of the H\textsc{i} content of the MW satellites shows that almost all satellites within a radius of \( \sim 270 \) kpc are undetected in H\textsc{i} (Greevich & Putman 2009). Even if a gas-loss mechanism due to ram pressure stripping is preferred to a tidal stripping origin, such H\textsc{i} depletion suggests that these objects are likely in bound orbits within the MW halo potential. Therefore, it seems to us that inside \( \sim 300 \) kpc radius, the tidal influence of the MW on the structures of the satellite population is evident even if the lack of gas in such small dwarfs may be attributed to other physical phenomena of sweep-out such as stellar winds and supernova shell bursts. Therefore, it is not so clear that either the presence or lack of gas and interstellar dust can be used to discriminate objects subject to tidal influence, especially after the cases of NGC 185 and 205. They are two elliptical dwarf galaxies, both satellites near to M31, which show abundance of H\textsc{i} and dust content in contrast to the clear signs of gravitational tidal interaction visible in their structures (Young & Lo 1997). However, we can reasonably assume that the combination of finding a relevant H\textsc{i} (and/or dust) content within an undisturbed morphology is indicative of negligible tidal influence. This could be the case for two dwarf galaxies at \( \sim 400 \) kpc from the MW detected by their H\textsc{i} content: Leo T and Phoenix. Even if they have been added (singly or together) to satellite lists of the MW (Karachentsev 2005; Simon & Geha 2007; Madau, Diemand & Kuhlen 2008; Greevich & Putman 2009), their structures do not seem to be influenced by the Galactic tidal field, showing a relevant gas content with no signs of tidal stripping or ram pressure (Irwin et al. 2007; Simon & Geha 2007; Young et al. 2007). Besides, they are both located at comparable distances from the MW and M31. If this is the case, Leo T and Phoenix lie at the boundary of the MW sphere of influence, and their Galactocentric distances of \( \sim 400 \) kpc are assumed as our fiducial \( R_{\text{ZTS}} \) allowing an error of \( \pm 50 \) kpc. As already stated, this is a very simplified assumption based on a few observed features of only two objects. Besides, we do not know their orbits, in particular if they are bound to the MW. There are no proper motion measurements to establish them; we can only suppose that they are probably observed at the apogalacticon where dynamical friction and tidal effects would be negligible. In such a case, as well as in the unbound one, \( R_{\text{ZTS}} \) may turn out to be overestimated, dramatically increasing the mass ratio in favour of M31. Note that our \( R_{\text{ZTS}} \) is smaller than \( \sim 700 \) kpc, inferred by Karachentsev (2005), and slightly larger than \( \sim 300 \) kpc reported by Lin, Jones & Klemola (1995), but matches the predicted limit within which is expected to be the ‘missing’ ultrafaint dwarf population (Diemand, Kuhlen & Madau 2007; Tollerud, Bullock & Strigari 2008; Koposov et al. 2009).

Finally, we assume \( 280 \) kpc as the fiducial virial radius of the MW (Xue et al. 2008; Shattow & Loeb 2009).

### 3.4 Error in estimating the tidal force

The major source of uncertainty of \( F_{\text{tidal}} \) can be due to the assumed mass estimations of the sampled objects. Cen (1997) found that cluster virial mass estimations are, on average, 20 per cent underestimated with respect to the simulations. This result has been confirmed by Evans et al. (2003) who, on the basis of 10 000 Monte Carlo simulations, demonstrated that at least 87 per cent of the virial mass estimations of galaxy groups are below the true mass. If our data are affected in a likewise manner, we expect an overestimation of \( \sim 8 \)–10 per cent on the calculation of \( R_{\text{t}} \). As will be discussed later, such a percentage could change, even qualitatively, our result. Note that the error on \( R_{\text{t}} \) is significantly reduced by the 1/2 exponent of equation (6).

### 4 RESULTS AND DISCUSSION

As can be seen in Fig. 1, the expected decreasing sequence of the tidal radii \( R_{\text{t}} \) from low to high mass ratios intersects \( R_{\text{ZTS}} \) in correspondence with a M31/MW mass ratio \( \approx 3 \). Allowing an error of \( \pm 50 \) kpc, the mass-ratio interval that best matches \( R_{\text{ZTS}} \) ranges from 2.5 to 3.5.

This is a straightforward demonstration that M31 is more massive than the MW and, even if the uncertainties are unknown, this result can be considered quite reliable, at least qualitatively. In fact, one may doubt the reliability of the computed value of \( F_{\text{tidal}} \). As stated before, the tidal force is reasonably determined when its cumulative amplitude converges asymptotically within the sampled sphere. To test it, the amplitude of the tidal force has been computed for a set of concentric spheres with radii increasing in

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**Figure 1.** Plot of the tidal radii computed by equation (6) as a function of 24 combinations of the M31 to MW mass ratio. Dots are the tidal radii computed using the mass distribution within the sampled sphere of 5 Mpc radius. Crosses are those computed in the expanded sphere of 20 Mpc radius (see the text).
steps of 2 Mpc from the MW. We have found that the development of the cumulative amplitude of the tide tends to converge asymptotically but not completely, indicating that the boundary of the sampled sphere is not large enough to incorporate the major share of the gravitational influence. This means that the asymptote will be approached farther away at larger distances so that the tidal force turns out to be underestimated and \( R_t \) overestimated (even if moderately). Therefore, it becomes very important to quantify how large is the error on \( R_t \) due to insufficient sampling of the surrounding mass distribution. We proceed by expanding the sampled sphere up to 20 Mpc radius in order to include in the calculation the masses of the Virgo cluster and the most relevant galaxy groups within it. From table 1 of the UZC-SSRS2 group catalogue (Ramella et al. 2002), we extract Galactic coordinates, radial velocities and virial masses of the following objects: U478, U480, U490 (Virgo), S129 and S190 (for simplicity, the distances have been derived from the well-known Hubble relation, i.e. \( V_r/H_0 \), where \( V_r \) is the radial velocity and \( H_0 \) is the Hubble constant assumed as 70 km s\(^{-1}\) Mpc\(^{-1}\)).

In Fig. 2, the cumulative amplitude of \( F_{\text{tidal}} \) is apparent. As expected, it increases sharply within the first 2 Mpc bin due to the presence of the massive M31 galaxy; the bump at 6 Mpc radius is due to the rich group U480; from 6 to 16 Mpc radius it increases very slowly, then a very small bump at the distance of Virgo followed by a flat line indicates that the mass of the Virgo cluster provides the largest tidal influence on the MW. However, as can be seen in Fig. 1, the small increment of \( F_{\text{tidal}} \) found inside 20 Mpc radius provides a negligible \( \sim 1 \) per cent decrement of \( R_t \) at high mass ratios and \( \sim 2-3 \) per cent at the low ones which do not change our result qualitatively. More serious could be the error affecting \( F_{\text{tidal}} \) due to systematic underestimations of the virial masses discussed in Section 3.4. If one takes into account such a bias, the values of \( R_t \) should be rescaled down by \( \sim 10 \) per cent, intersecting \( R_{\text{ZTS}} \) at a lower mass ratio = 2.5, allowing a re-evaluated mass-ratio interval ranging from 2 to 3. Therefore, assuming a conservative point of view, we assume this new result as our fiducial one. Finally, from the fiducial mass ratios we can evaluate the corresponding (fiducial) mass interval for both M31 and the MW having in mind the initial constraints derived from the published set of mass estimations. Roughly, the total mass of the MW would range from 1 to 1.5 \( \times 10^{12} M_\odot \), while for the Andromeda galaxy it would be between 2 and 3 \( \times 10^{12} M_\odot \).

5 CONCLUDING REMARKS

The main accomplishment of this paper is the introduction of a method based on tidal theory in order to study the total mass ratio between the two dominant galaxies of the Local Group: M31 (the Andromeda galaxy) and the MW. The mass ratio between the two galaxy groups has been established by examining the tidal limits set by the surrounding mass distribution on the MW and comparing them with the distance at which the outermost dwarf galaxies do not show any apparent effects of tidal stripping. We have demonstrated, at least qualitatively, that the Andromeda galaxy is more massive than the MW by a factor of between 2 and 3. The recent finding by Reid et al. (2009) predicting equivalent total masses for M31 and the MW is clearly in contrast with our result. As can be seen in Fig. 1, a unit mass ratio would be satisfied by tidal radii ranging from \( \sim 600 \) to 700 kpc, very close to the outskirts of M31! If our result is correct, the Andromeda galaxy is likely embedded in a larger and more massive dark halo than that of the MW. It seems to us that these discrepant results are characterized by the two different methodologies used to determine the total mass of the MW and M31. One investigates the physical properties by considering the objects as separate systems, while the other analyses the gravitational interactions in the context of the local environment. The
former leads to a lower mass estimation for M31 probably because the current constraints on the shape and extent of the dark matter haloes are still doubtful (the missing faint dwarf satellite problem) and model-dependent. The latter suffers from large uncertainties in the distances and mass determinations of the sampled objects as in the present work. In any case, one should take into account that the reliability of our result is weakened by the unknown uncertainties affecting the assumed parameters ($R_{\text{ZTS}}$ for instance) and kinematical data and, in spite of the very conservative behaviour on evaluation of the result, the lack of a detailed error analysis prevents its acceptance from a quantitative point of view. This is the true limit of our analysis which prevents a deeper study of many related problems connected with the tidal interactions among the MW, M31 and neighbouring galaxies and groups. For example, an interesting question arises from the physical meaning of $R_{\text{ZTS}}$: is it coincident with the dark halo radius or does it lie beyond? The question is not trivial. If coincident, the larger mass of M31 implies a larger tidal influence on the MW. Consequently, because of proximity of the two galaxies, it would follow that the M31 halo should overlap or encompass the MW one. The answer to this question will be possible only by obtaining proper motion determinations for the outer satellite orbits, which will enable us to understand if these extreme objects are bound and were already shaped by past central encounters with the host galaxy, and finally by providing constraints on the profile of the dark matter distribution out of the virial radius as well as the $R_{\text{ZTS}}$.

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