A NEW METHOD OF ESTIMATING THE MASS-TO-LIGHT RATIO OF THE URSA MINOR DWARF SPHEROIDAL GALAXY

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ABSTRACT

Dwarf satellite galaxies undergo strong tidal forces produced by the main galaxy potential. These forces disturb the satellite and produce asymmetries in its stellar distribution, tidal tail formation, and modifications of the velocity dispersion profiles. Most of these features are observed in the Ursa Minor (UMi) dwarf spheroidal galaxy, which is one of the closest satellites of the Milky Way. These features show that UMi is being tidally disrupted and is probably not in virial equilibrium. The high-velocity dispersion of UMi would also be a reflection of this tidal disruption and is not the signature of the large dark matter content that would be deduced if virial equilibrium is assumed. In order to avoid the uncertainty produced when virial equilibrium is assumed in systems in strong tidal fields, we present a new method of calculating the mass-to-luminosity ratio of disrupted dwarf galaxies. This method is based on numerical simulations and only takes into account the shape of the dwarf density profile and the tidal tail brightness, but it does not depend on the kinematics of the dwarf. Applying this method to UMi, we obtain a mass-to-luminosity relation of 12, which is lower than the value obtained assuming virial equilibrium (M/L = 60). In addition, if UMi has a large dark matter content, it will be impossible to reproduce a tidal tail as luminous as the one observed.

Subject headings: galaxies: individual (Ursa Minor) — Galaxy: formation — Galaxy: halo — Galaxy: structure

1. INTRODUCTION

The simplest galactic systems, the dwarf spheroidal (dSph) galaxies, reveal high-velocity dispersions that imply high mass-to-light (M/L) ratios if virial equilibrium is assumed (see Mateo 1998 for a review). Alternative explanations are that these M/L ratios may be inflated owing to tidal effects (Hodge & Michie 1969; Gómez-Flechoso, Fux, & Martinet 1999) or that the dSph galaxies are long-lived tidal remnants oriented close to the line of sight (Kroupa 1997).

UMa Minor (UMi) is one of the closest satellites of the Milky Way (d = 69 kpc; Carrera, Aparicio, & Martínez-Delgado 2002) and, of these, shows, together with Draco, the highest observed velocity dispersion (M/L = 60; Mateo 1998). The discovery of a tidal extension in UMi (Martínez-Delgado et al. 2001) indicates that this galaxy is at an advanced stage of complete tidal disruption (see also Palma et al. 2003). In addition, the presence of lumpiness and asymmetry in the stellar distribution of UMi along its major axis (Olszewski & Aaronson 1985; Irwin & Hatzidimitriou 1995; Kleyne et al. 1998; Martínez-Delgado et al. 2001) could be reminiscent of tidal disruption (Kroupa 1997). The outer shape of the outer contours appears to be clearly S-shaped (Palma et al. 2003; Martínez-Delgado et al. 2003), as is expected for a tidally disrupted system (i.e., the globular cluster Pal 5; see Odenkirchen et al. 2001). So far, UMi may not be in virial equilibrium, which supports the idea of a possible tidal origin for UMi’s observed high radial velocity dispersion. This fuels the debate about the validity of the methodology used to infer the M/L ratios in dSph galaxies.

In this Letter, we introduce a new method of estimating the mass of satellite dSph galaxies that are subjected to tidal forces. This method does not involve assumptions about the internal dynamics of the satellite and can be used for dSph galaxies that are out of virial equilibrium. Using this method, we have analyzed UMi and obtained a new value for its M/L ratio.

2. OBSERVATIONS AND TIDAL TAIL FORMATION MODEL

The observations, data reduction, and photometry of the UMi dSph galaxy used in this Letter are described in Martínez-Delgado et al. (2001) and Carrera et al. (2002). Our wide-field survey revealed the presence of stellar members of UMi beyond the previous measured tidal radius. This indicates the existence of a tidal extension in UMi that could be spread out well beyond the area covered in our survey (R > 80'), as suggested by the presence of a “break” to a shallower slope observed in its density profile (see Fig. 3 in Martínez-Delgado et al. 2001).

In this Letter, UMi’s observed surface brightness profile is compared with a theoretical model of tidally disrupted dSph satellites. The tidal tail is assumed to be formed by the Milky Way tidal forces, which also produce the disruption and deformations in the dwarf. These forces are important at the Galactocentric distance of UMi. The limit of the bound material (i.e., the tidal radius) is determined by the equilibrium between the satellite potential well and the Milky Way potential well. This gives place to a relation between the satellite mass density at the tidal radius and the Milky Way potential. Details of the tidal limit calculations are given in Gómez-Flechoso & Domínguez-Tenreiro (2001). The unbound material, which forms the tidal tail and is placed beyond the tidal radius, is diffused into the Milky Way halo. As explained in Johnston, Sigurdsson, & Hernquist (1999), the tidal tail surface density approximately follows a power-law profile in the regions close to the dwarf. The exponent of this power law depends on the amount of extratidal material close to the dSph galaxy. This correlates with the strength of the tidal force and therefore varies along the orbit, since the satellite travels through regions with different tidal fields. If the amount of stripped material is low, the tail has a steeper density profile, and vice versa. The tidal tail can reach an almost flat density profile if the amount of stripped material

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is large (e.g., the UMi tidal extension). In this case, the tidal tail mass density close to the dSph galaxy is similar to the satellite mass density at the tidal radius, which is proportional to the Milky Way potential, as mentioned above. So, for a given Milky Way potential, shape of the dSph density profile, and satellite position in the Galaxy, the tidal tail mass density close to the tidal radius is fixed independently of the dSph mass. In Figure 1a, the projected mass density profiles of three evolved satellite models have been plotted. The models have different initial masses and form a tidal tail after a few orbits. As can be seen, the central region of the projected mass density differs by up to a factor of 10 when comparing the different models; however, the tail mass density is almost the same independent of the models. More details are given in § 3.

Using these results, if we know the Milky Way potential, we can estimate the tidal tail mass density. The dSph M/L ratio can be calculated then by forcing the model density profile to reproduce the tail surface brightness and the central luminosity of the satellite at the same time. Given two satellites with different mass densities and with the same central luminous surface brightness, the highest mass density satellite has a larger M/L ratio than the low-mass density one. Following this relation, if the two satellites with the same central luminosity are placed at the same point in the main galaxy potential, the tail surface brightness of the densest satellite will be fainter than that of the low-mass density satellite since the tidal tail mass density is the same for both dwarfs (we assume the same M/L ratio for the dwarf and for its tail). In Figure 1b, the three models of Figure 1a have been plotted by assuming that all of them have a central surface brightness of 26 mag arcsec$^{-2}$. As can be seen, the densest model needs to have a larger M/L ratio to reproduce the same central surface brightness as the other models, and therefore its tidal tail is fainter. If the same central luminous surface brightness is assumed for the dSph models, the differences in the central mass density will translate into differences in the tail surface brightness. Only one satellite model will be able to reproduce, at the same time, the central and the tail luminous surface brightness of an observed satellite dwarf galaxy. Using this method, we can estimate the M/L ratio of the dwarf independently of its internal kinematics.

3. CALIBRATION OF THE TIDAL TAIL MODEL

As explained in the previous section, the mass density of a satellite tidal tail is independent of the satellite mass (given the shape of the satellite density profile and its orbital position). Using the observed surface brightness profile of the dSph galaxy, we can select the model that fits the luminous surface brightness of the satellite+tail system, and therefore the mass of the best-fit model is a good estimate of the mass of the observed dSph galaxy, and consequently its M/L ratio can be calculated. Before using this method to estimate the satellite masses, we have to calibrate the sensitivity of the method to variations of the satellite mass (that is, whether satellite models with different masses can reproduce the same satellite+tail density profile or not), to variations of the shape of the main galaxy potential, and to variations of the dwarf orbit. In this way, we will know the accuracy of the calculations.

3.1. Effects of Satellite Total Mass on Tidal Tail Formation

To analyze how the satellite mass content is related to the tidal tail surface brightness, we have selected three satellite models with a King-Michie profile with the same dimensionless central potential, $W_0 = 4$, and the same core radius, $r_0 = 0.3$ kpc (corresponding to a tidal radius $r_t = 2.1$ kpc), but with a different total mass. The three total masses are $0.4 \times 10^7$, $1.6 \times 10^7$, and $4 \times 10^7 M_\odot$. These models have been placed in an orbit similar to that of UMi (Schweitzer, Cudworth, & Majewski 1997). To roughly reproduce the halo of the Milky Way potential, we have used an analytical logarithmic potential given by $\Phi_H = rv^2 \log [R^2 + (zh)^2 + a^2]$, where $v = 170$ km s$^{-1}$, $a = 19.9$ kpc, and $h = 1.0$. For this potential, the satellite apogalacticon and perigalacticon are roughly 80 and 20 kpc, respectively.

In Figure 1b, we have plotted the surface brightness of the three satellite models described above. The masses inside 1 kpc of each model are listed in the figure since the satellites have undergone tidal disruption and since the initial masses do not give information about the masses of the models at the moment of the figure snapshot. The three models have been calibrated in luminosity to have the same central surface brightness ($\mu_{_0} = 26$ mag arcsec$^{-2}$), which translates into different...
The MIL ratios, as explained in §2. The three brightness profiles have the same slope in the central regions, but the tidal tail luminous surface brightness are related to the dwarf mass content. The lowest mass model, with MIL = 3.5, develops quite a luminous tidal tail. In contrast, the highest mass model forms a low brightness tidal tail ($\mu_{\text{satellite}} \sim 33.5$ mag arcsec$^{-1}$) and has a larger tidal radius ($r_1 \sim 1.5$ kpc). The tidal tail of this massive model ($\text{MIL} = 50$) will not be observationally detected, assuming a typical satellite central surface brightness. Finally, the model with a moderate MIL ratio ($\text{MIL} = 13$) develops a tidal tail with $\mu_{\text{satellite}} \sim 32$ mag arcsec$^{-1}$, which could be detected with the present observational resolution. To compare the models properly, the observational surface brightness of UMi is also plotted (filled circles) in the same figure.

Summarizing these results, the effect of satellite mass content on tidal tail formation is quite important since a variation of a factor of 10 in mass produces a variation of a factor of 15 in the MIL ratio for dSph galaxies with the same central surface brightness.

3.2. Effects of Halo Potential Oblateness of the Main Galaxy on Tidal Tail Formation

The satellite tidal tail surface brightness is related to the oblateness of the main galaxy potential since it affects the satellite disruption. To study this, we have modeled the halo of the primary galaxy using the logarithmic potential described in the previous section with the same $\alpha$ and $\beta$ parameters, but with three different oblateness values, $h = 1.0$, 0.8, and 0.6 (oblateness values smaller than 0.6 in the potential are unrealistic since they cannot be reproduced with any mass distribution). The satellite model is a King-Michie model with an initial total mass $M_{\text{ini}} = 2 \times 10^7\, M_{\odot}$, a core radius $r_0 = 0.3$ kpc, and a dimensionless central potential $W_0 = 4$. The satellite orbit has been fixed on the assumption that it has the energy needed to reproduce the present position and velocity of UMi.

Figure 1c shows the satellite surface brightness after a few orbits for the three halo potential models. The snapshots used in this plot represent a satellite with the same position and velocity as UMi. The same satellite and tidal tail profiles are reproduced using different halo potentials; however, the final satellite mass content varies. The dense tidal tails are formed more efficiently in oblate potentials (for orbits such as that of UMi). In highly oblated halo potentials, to reproduce a given satellite+tail surface brightness profile, the satellite mass content and, therefore, its MIL ratio have to be larger than in spherical halos.

It is remarkable that the effect of the potential shape on the MIL ratio determination is fainter than the effect of the satellite mass. The MIL ratio only varies a factor of 2 for the whole range of realistic values of the potential oblateness ($h$, between 1.0 and 0.6); therefore, the potential shape only introduces a small indeterminacy in the dSph mass calculation.

3.3. Effects of Small Variations in the Satellite Orbit on Tidal Tail Formation

Variations in the satellite velocity within the observational errors produce differences in the dwarf orbit and, consequently, in its apo- and peri-galacticon. Since the satellite tidal stripping depends on the orbit (the smaller pericenter, the larger the tidal stripping), small variations in the orbit can affect the tidal tail formation. To calibrate this, a satellite model has been placed in three different orbits. One of these fits UMi’s velocity and position at the end of the simulation, while the other two orbits differ by $\pm 10\%$ in velocity from the previous one. The satellite model is a King-Michie model with a core radius $r_0 = 0.3$ kpc, an initial total mass $M_{\text{ini}} = 1.6 \times 10^7\, M_{\odot}$, and a dimensionless central potential $W_0 = 4.0$. The main galaxy potential is the spherical logarithmic potential described in §3.1. In Figure 1d, the model surface brightness profiles are shown. The three profiles, corresponding to the three orbits, are quite similar; only small differences in the MIL ratio can be observed. The model in the highest velocity orbit shows the largest MIL ratio and vice versa, but the MIL ratio differences between models are of the same order as their differences in orbital velocity. The dSph mass content is more important in the MIL ratio estimate than the effects caused by variations of its orbit, for typical observational errors of $10\%$–$20\%$ in the dSph velocity.

4. The MIL Ratio of the UMi dSph

UMi shows observational features that reveal large tidal forces. Then the simplified virial equilibrium theorem is not justified for measuring the MIL ratio, but we should include all the variables in a more generalized expression. Instead of doing this, we have introduced a new method of mass calculation that does not involve the dSph kinematics. In this section, we analyze the UMi MIL ratio using the method described in §§2 and 3.

The Milky Way potential is one of the parameters that determines the tidal tail density; therefore, it is very important to assume a realistic value for it. Such a potential can be inferred from the dynamics of the Milky Way’s stars and the orbits of the dwarf satellite galaxies. Observational data of the Sagittarius dwarf tidal stream are therefore very valuable. The shape of the Sagittarius orbit is traced with the tidal debris of this satellite in a strip 100° long (see Martínez-Delgado et al. 2003 for details). We have used these observational data to fix the parameters of the Milky Way model, given by a quite realistic three-component model, halo+disk+bulge (see Fux 1997 for details). The parameters of the final numerical model that reproduce the Milky Way potential are described in Gómez-Flechoso et al. (1999). Other density distributions of the Milky Way can also reproduce a similar potential well, compatible with the Sagittarius orbit. It is important to remark that the physical quantity that determines the satellite orbits is the potential of the main galaxy, not its density distribution, and that, therefore, Milky Way density distributions with different shapes and oblateness could reproduce the same results if they had similar potential wells. However, we recall that small variations in the shape of the main galaxy potential do not significantly change the results of the MIL ratio of the analyzed satellite, as shown in §3.2.

The UMi satellite has been represented by an N-body model orbiting in the previously described Milky Way potential. The orbit is consistent with the observational proper motion of UMi (Schweitzer et al. 1997). We assume an UMi model of one component given by a King-Michie model. The parameters of the King-Michie model that reproduce more accurately the shape of the UMi luminosity profile and its tidal tail are a core radius $r_0 = 0.3$ kpc and a dimensionless central potential $W_0 = 4.0$. However, the total mass of the model is still a free parameter that we calculated by reproducing the central brightness of the dwarf and the tidal tail brightness at the same time (as described previously). The best model (Fig. 2, dashed line) has a total initial mass $M_{\text{ini}} = 4 \times 10^7\, M_{\odot}$ and fits the observed UMi profile (Fig. 2, filled circles) after roughly seven orbits, when the total mass of the model in the inner kiloparsec
is 0.79 \times 10^7 M_\odot. We have assumed $M/L = 12$ in order to adjust the central surface brightness of the model to the observed one.

The $M/L$ ratio obtained using this new method differs from that derived from the virial theorem \($\langle M/L \rangle_{\text{virial}} = 60$; Mateo 1998\). However, this lower value is consistent with the $M/L$ ratio estimated by Palma et al. (2003), who reduce it to $M/L \sim 16$ using a new UMi total luminosity estimate (which is 2.7 times greater than the previous values) and considering the (possible) effects of anisotropic velocity dispersions (Hodge & Michie 1969).

The UMi observed velocity dispersion is 7.6 km s\(^{-1}\) (Armandroff, Olszewski, & Pryor 1995), which could be inflated by the effects of the substructures in the main body. Our UMi model has a velocity dispersion of 4 km s\(^{-1}\) at the satellite center and rises to 8 km s\(^{-1}\) on the dwarf outskirts (D. Martínez-Martínez-Delgado, M. A. Gómez-Flechoso, J. Alonso-García & A. Aparicio 2003, in preparation). The low resolution of the numerical simulations avoids the formation of condensations inside UMi, and therefore the UMi models are not expected to fit the observed velocity dispersion. On the other hand, if UMi is assumed to be in virial equilibrium, and therefore with $\langle M/L \rangle_{\text{virial}} = 60$, the tidal tail surface brightness will be so faint that it could not be observationally detected (see Fig. 1b). Furthermore, the signatures of tidal disruption observed in UMi (internal substructure and tidal extension) make doubtful the existence of a simple virial equilibrium in the inner region of UMi. In these dynamical conditions, our method seems to be more reasonable for the satellite mass calculation. However, new models with a higher resolution reproducing the internal dynamics of the UMi dSph galaxy and new observations of the UMi velocity dispersion profile are needed in order to understand the dynamical state of the dwarf.

5. CONCLUSIONS

We have developed a new method of estimating the mass of satellite galaxies subjected to tidal forces. This method does not involve assumptions about the satellite internal dynamics and therefore can be used for satellites that are out of virial equilibrium. The main results are that massive and dense satellites form low brightness tidal tails (for a given satellite central surface brightness) and that low-density dwarfs undergo strong tidal forces that produce comparatively bright tidal tails. Once the central surface brightness and the shape of the density profile of the dwarf are known, the main parameter that determines the tail brightness in the region close to the satellite tidal radius is the mass content of the bound part of the dwarf. The shape of the primary galaxy potential can introduce small uncertainties in the dwarf mass estimates that are no larger than a factor of 2 over the whole physical range of oblateness. The larger the halo oblateness is, the denser the tidal tail that is formed. The observational errors of the dwarf orbital velocity can also introduce an uncertainty in the $M/L$ ratio estimate, but this uncertainty is no larger than the errors in the satellite velocity.

Since the tidal tail density and brightness depend on the halo potential, it could vary as the satellite travels along its orbit. Therefore, it is very important to know the satellite’s position in its orbit in order to estimate its mass content using this method.

Finally, we have applied the new method for the mass calculations to UMi. To reproduce the UMi luminosity profile and its tidal tail brightness, a mass-to-light ratio of $M/L \sim 12$ is needed. The tidal disruption features observed in UMi suggest that this dwarf is not in virial equilibrium. The observational data of the velocity dispersion profile could confirm this if they show the same rising profile as that of the model.

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![Fig. 2.—Surface brightness profile of the best UMi model (dashed line); an $M/L = 12$ has been assumed. The observational data with the error bars are also plotted (filled circles).](image-url)