Estimating masses of dwarf spheroidal galaxies

Klaudia Kowalczyk[1] and Ewa L. Łokas[1]

1. Nicolaus Copernicus Astronomical Center
Bartycka 18, 00–716 Warszawa, Poland

Precise measurements of mass in dark matter dominated dwarf spheroidal galaxies are of great importance for testing the theories of structure formation. We use N-body simulations of the tidal evolution of a dwarf galaxy orbiting the Milky Way to generate mock kinematical data sets and use them to test the reliability of a simple mass estimator proposed by Wolf et al. The evolution of the initially disky dwarf galaxy embedded in a dark matter halo was traced for 10 Gyr on a rather tight orbit. After about half of the time a dwarf spheroidal galaxy is formed that retains some remnant rotation and a non-spherical shape. Observing the triaxial galaxy along each of its principal axes we measure its half-light radius and the line-of-sight velocity dispersion and use them to estimate the mass. We find that the mass is significantly overestimated when the dwarf is seen along the longest axis of the stellar component and underestimated when observed along the shortest axis. We provide a formula that quantifies the systematic error in the estimated mass with respect to the true one as a function of the galaxy shape and line of sight.

1 Introduction

Determining accurate masses of dwarf spheroidal (dSph) galaxies usually requires strong assumptions about the internal structure of galaxies, in particular about the anisotropy of stellar orbits, due to the degeneracies between model parameters. Numerous methods including solving higher-order Jeans equations (Łokas, 2002) or orbit superposition (Chanamé et al. 2008; Breddels et al. 2013) are being adopted to lift those degeneracies. However, such approaches are significantly object-dependent and require significant amounts of computation time so looking for simple methods is still appealing. One such method was recently proposed by Wolf et al. (2010) who offered a simple mass estimator based on observables such as the half-light radius an the line-of-sight velocity dispersion. The mass in this case is estimated at a radius where the result is least sensitive to the anisotropy.

In this work we test the reliability of this mass estimator in the context of the tidal stirring scenario for the formation of dSph galaxies in the Local Group. In this scenario, dSphs form as a result of tidal interaction of initially disky dwarfs with a bigger host, such as the Milky Way. Inherent in the process is the formation of a triaxial stellar component that gradually becomes more spherical. We use an N-body simulation following such an evolution to generate mock kinematic data sets and measure the observables needed for the mass estimates. We demonstrate that the inherent non-sphericity of the objects introduces systematic errors in their mass estimates.

2 The simulation

Our simulation setup was composed of two galaxies: the Milky Way-like host and the dwarf galaxy, generated by the procedures described in Widrow & Dubinski (2005) and Widrow et al. (2008). Each object was modelled using two components: an exponential disk and a cuspy NFW (Navarro et al., 1997) dark matter halo. To make the total masses finite, the haloes were smoothly truncated at the radii close to the virial radii for both galaxies. In total the simulation contained 8×10^5 particles, 2×10^5 particles per component for each galaxy, with the numerical gravitational softening scales of $\epsilon_d = 0.02$ kpc and $\epsilon_h = 0.06$ kpc for the dwarf's disk and halo and $\epsilon_D = 0.05$ kpc and $\epsilon_H = 2$ kpc for the Milky Way, respectively.

For the dwarf galaxy we applied a model consistent with those used previously in similar studies (Kazantzidis et al. 2011; Łokas et al. 2011). The dark matter halo had a mass $M_h = 10^9$ $M_\odot$ and a concentration $c = 20$. The disk had a mass $M_d = 2 \times 10^7$ $M_\odot$, an exponential scale-length $R_d = 0.41$ kpc and a thickness $z_d = 0.2$ R_d.

The host galaxy was based on the model MWb of Widrow & Dubinski (2005). Its dark matter halo had a mass $M_H = 7.7 \times 10^{11}$ $M_\odot$ and a concentration $c = 27$ while its disk had a mass 3.4×10^{10} $M_\odot$, a length-scale $R_D = 2.82$ kpc and a thickness $z_D = 0.44$ kpc. The neglect of the structural features of the Milky Way (like the bar, bulge, thick/thin disk) was motivated by the simplicity and their relatively small impact on the evolution of the dwarf which is of main interest here.

The dwarf galaxy was initially placed at the apocenter of the eccentric, rather tight orbit with apocenter $r_{apo} = 100$ kpc and pericenter $r_{peri} = 20$ kpc, which induced its faster (when compared to more extended orbits) transition towards the spherical shape (Łokas et al. 2012; Kazantzidis et al. 2013). The evolution of the system was followed for 10 Gyr with the GADGET-2 N-body code (Springel et al. 2001; Springel 2005) and the outputs were saved every 0.05 Gyr, giving 201 outputs in total.

Figure 1 shows the evolution of the stellar kinematics and the shape of the stellar component of the dwarf galaxy measured within a fixed radius $r < 0.5$ kpc therefore probing its central region. The quantity V/σ plotted with a solid line is the ratio of the mean rotation velocity around the shortest axis to the 1D velocity dispersion (calculated by averaging the dispersions measured along three spherical coordinates) so it quantifies the amount of the ordered versus random motion. The shape is presented with a dashed line in terms of the ratio of the shortest to the longest axis of the stellar component c/a determined using the inertia tensor.

3 Estimating masses

We assume that a dSph galaxy forms when the amount of stellar rotation drops below half of its initial value and the dwarf galaxy shape is sufficiently spherical, i.e. the shortest-to-longest axis ratio is $c/a > 0.5$. Adopting this criteria, we selected 110 simulation outputs (in the time range $t = 4.55 - 10$ Gyr) out of the total 201 outputs saved (see Figure 1). For each selected output we determined the principal axes of the stellar component and the dwarf was rotated so that the x axis was oriented along the major, the y axis along the intermediate, and the z axis along the shortest axis.

Next, we 'observed' the dwarf along each of these axes creating for each line of sight a mock data set including the projected stellar positions and radial velocities as would be available for a distant observer. The stellar positions were binned equally in the logarithm of the projected radius $\log R$ to measure the number density profile

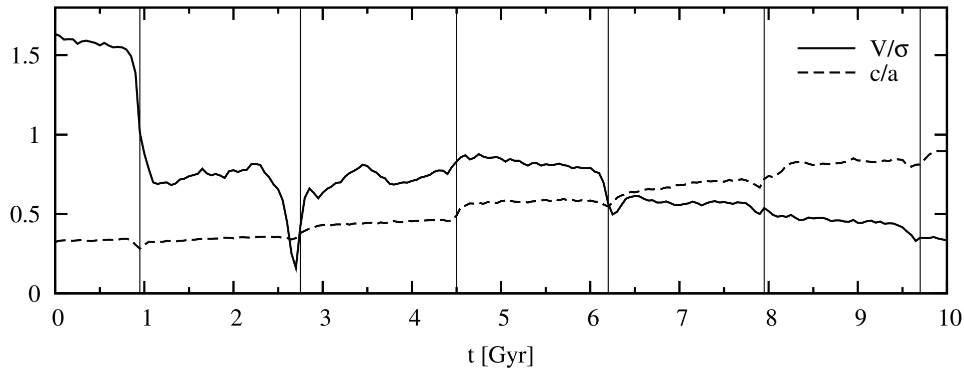

Fig. 1: The evolution of the amount of rotation with respect to random motions, V/σ (solid line), and the ratio of the shortest to the longest axis c/a (dashed line) of the stellar component of the dwarf galaxy in time. Both quantities were measured within a fixed radius $r < 0.5$ kpc. Thin vertical lines indicate pericenter passages.

and to each such profile we fitted the projected Plummer distribution

$$\Sigma(R) = \frac{NR_h^2}{\pi(R^2 + R_h^2)} \tag{1}$$

by adjusting the projected half-light radius R_h and the normalization N. We then measured the line-of-sight velocity dispersion σ_{los} within R_h removing for each sample the stars stripped earlier by the tidal force with a converging 3σ clipping procedure until no more stars were removed. The estimated values of R_h and σ_{los} for all selected outputs and different lines of sight are plotted as a function of time in the top and bottom panels of Figure 2, respectively.

Treating each output as an individual dwarf galaxy, we used the measurements to estimate the masses of the dwarfs by applying the formula proposed by Wolf et al. (2010):

$$M_{est}(r_3) = 3\ G^{-1}\sigma_{los}^2 r_3 = 3.7\ G^{-1}\sigma_{los}^2 R_h \tag{2}$$

where r_3 is the 3D radius found to contain mass least dependent on the orbital anisotropy. The radius r_3 is related to the 3D half-light radius r_h and to the 2D projected half-light radius R_h for the adopted Plummer profile by $r_3/r_h = 0.94$ and $r_h/R_h = 1.305$, so that $r_3 = fR_h$ where $f = 1.23$ (see the Appendix in Wolf et al. 2010). We then compared the masses estimated in this way with the real masses (M_{true}) contained within fR_h of the simulated dwarfs.

We calculated the mean values and dispersions of the ratio M_{est}/M_{true} averaged over the whole sample for each line of sight separately obtaining: 1.24 ± 0.02 for x axis, 1.12 ± 0.01 for y axis and 0.70 ± 0.02 for z axis. In Figure 3 we show the ratio M_{est}/M_{true} for each line of sight as a function of the two global properties of the dwarfs to which we trace the correlation: the amount of rotation V/σ (top panel) and the shape of the stellar component in terms of the ratio of the shortest to the longest axis c/a (bottom panel). With thin lines of different color we show the best-fitting linear relations of the form

$$M_{est}/M_{true}(c/a) = \alpha(c/a) + \beta \tag{3}$$

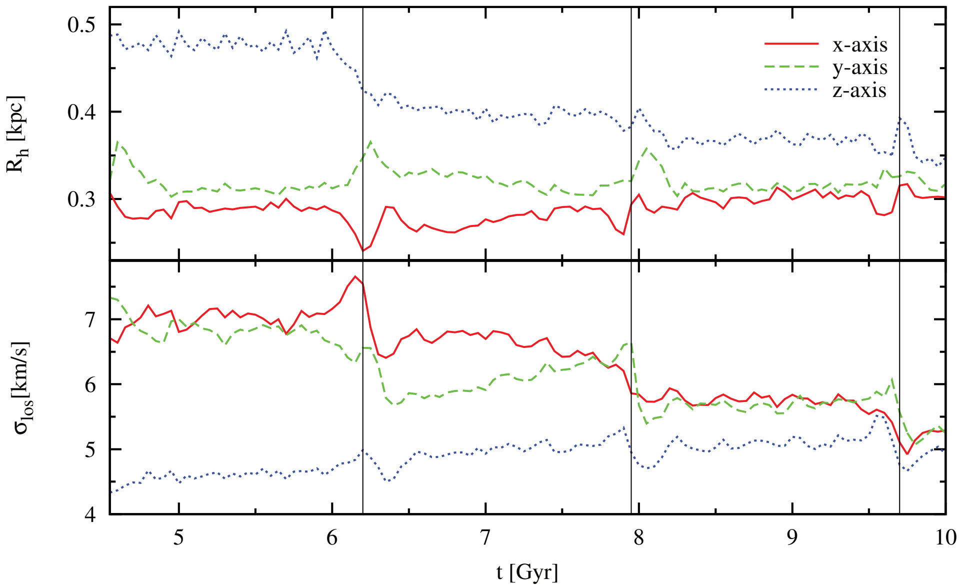

Fig. 2: The fitted values of the 2D projected half-light radii (top panel) and the line-of-sight velocity dispersions measured within the half-light radii (bottom panel) as a function of time. Red solid lines, green dashed lines and blue dotted lines show the results obtained for the observations along the longest (x), the intermediate (y) and the shortest (z) axis of the stellar component, respectively. Thin vertical lines indicate pericenter passages.

with a constraint $M_{est}/M_{true}(c/a = 1) = 1$. The obtained values of the slopes are: $\alpha = -0.82$ for the x axis, $\alpha = -0.38$ for the y axis and $\alpha = 1.03$ for the z axis, respectively. Clearly, the estimated masses are less biased for more spherical, non-rotating galaxies.

4 Discussion

Using an N-body simulation of the tidal evolution of a dwarf galaxy placed on an eccentric orbit around a Milky Way-like host we studied systematic errors in estimates of mass of dSph galaxies contained within a radius of the order of a half-light radius. Due to a large number of stars in the samples, with positions and velocities known to arbitrary accuracy of the numerical calculations, the statistical errors are diminished, revealing uncertainties underlying the method itself.

We have demonstrated the impact of the triaxiality of the stellar component on the obtained results. We have shown that the estimated masses can be either over- or underestimated depending on the line of sight along which the dwarf is observed. Similarly to the results presented in Kowalczyk et al. (2013) our estimated mass values are systematically larger than the actual ones for the observations performed along the longest axis of the stellar component and smaller for the observations along the shortest axis. The best agreement is achieved when we observe the dwarf along its intermediate axis.

In this work we used a new simulation of tidal stirring with the dwarf galaxy placed on a tighter orbit than in Kowalczyk et al. (2013). As a result, a dSph galaxy

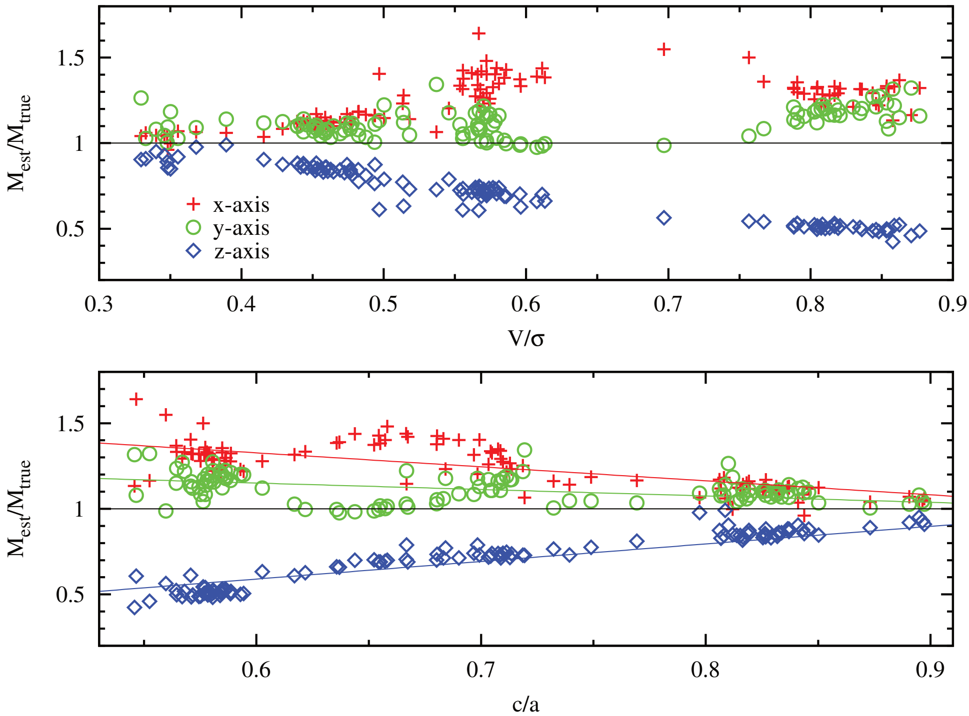

Fig. 3: The ratio of the estimated to the true masses as a function of the amount of rotation V/σ (top panel) and the shape in terms of the ratio of the shortest to the longest axis c/a (bottom panel). Symbols of different shape and colour (red crosses, green circles and blue squares) present the results obtained for the observations along the longest (x), the intermediate (y) and the shortest (z) axis of the stellar component, respectively. The horizontal black line indicates $M_{est}/M_{true} = 1$ (no bias). Thin lines of different colour show the best-fitting linear relations between M_{est}/M_{true} and c/a.

was formed before half of the total simulation time and became almost spherical at the end of the evolution. This allowed us to study dwarf realizations with a wider range of key parameters such as the shape c/a and the amount of remnant rotation V/σ. In addition, after the formation time ($t = 4.55$ Gyr) these quantities turned out to depend almost monotonically on time (c/a increasing and V/σ decreasing) giving us the opportunity to notice systematic dependence of the results of mass estimates on these quantities. In particular, we now notice a very clear dependence of the accuracy of mass estimates on the shape parameter c/a with an almost linear relation between M_{est}/M_{true} and c/a, and the convergence of the estimated masses to true ones when the object becomes spherical. The dependence on the amount of rotation is similar although less obvious and we believe it is to some extent a derivative of the dependence on the shape or at least the two are strongly correlated. It has been shown here and e.g. by Klimentowski et al. (2009) that the change of shape towards a more spherical one is always accompanied by the loss of rotation.

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