The effect of unbound stars on the mass modelling of the Fornax dwarf

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Abstract We discuss how different approaches to selecting member stars in kinematic samples of dwarf spheroidal galaxies affect the estimates of their mass and anisotropy of stellar orbits. We demonstrate that the selection of members is an additional source of error compared to the usual uncertainties due to the sampling of velocity moments. As an example we use the kinematic data set for 202 stars in the Fornax dwarf galaxy for which we model the velocity dispersion profile and estimate the mass-to-light ratio and anisotropy assuming that mass follows light. We also show that stronger constraints on these parameters can be obtained if kurtosis of the velocity distribution is included in the analysis. Using the Besançon model of the Milky Way we demonstrate that the majority of contamination in Fornax probably comes from the Milky Way stars.

1 Which stars are members?

Dwarf spheroidal (dSph) galaxies of the Local Group are believed to be the most dark matter dominated galaxies. One of the major problems in determining their masses and mass-to-light ratios lies in the selection of members which we can trust to trace the dynamics of the galaxies reliably. Due to their proximity to the Milky Way (MW) the galaxies are strongly affected by tidal forces, their stars are stripped and form tidal tails. Most of the stars in the tails are not bound to the dwarf and including them in kinematic modelling may overestimate the inferred mass-to-light ratios dramatically. Another possible source of contamination are the stellar populations of the MW which can however be dealt with using detailed photometric studies (Majewski et al. 2000). On the other hand, the tidally stripped stars will have the same photometric properties as the population of the dwarf. It is therefore essential to reject them via other methods.

We illustrate a number of methods to deal with such interlopers using a recently published kinematic sample of 202 stars in the Fornax dwarf (Walker et al. 2006). The sample may contain both tidally stripped stars and those from the MW since the selection has been done only by choosing stars along the red giant branch and no colour-colour information was used. Figure 1 shows the line-of-sight heliocentric velocities of the stars as a function of their projected distance from the dwarf centre. In each panel the filled circles correspond to
Figure 1: The kinematic sample of 202 stars in the Fornax dwarf after application of different schemes for the removal of unbound stars (open circles).

the stars adopted as members and open circles are interlopers. We present the results of four interloper rejection methods described in detail in Wojtak et al. (2007): the method based on finding the maximum velocity available to a star proposed by den Hartog & Katgert (1996) (HK), the method based on the ratio of two mass estimators proposed by Perea et al. (1990), the method based on iterative rejection of stars outside $\pm 3\sigma(R)$ (where $\sigma(R)$ is the velocity dispersion in different radial bins) and a simple constant cut-off in velocity which retains a similar number of stars as the other methods. In the upper left corner of each panel we give the number of members and rejected stars.

2 Modelling of velocity moments

The velocity dispersion profiles calculated from the different samples are shown in Figure 2. As we can see, in the two lower panels the velocity dispersion...
profiles show a secondary increase at larger $R$ signifying incomplete removal of unbound stars. The velocity dispersion profiles have been fitted with the solutions of the Jeans equation (see Lokas 2002, Lokas et al. 2005) assuming that mass follows light. The parameters of the light distribution were adopted from Irwin & Hatzidimitriou (1995). For each sample we estimated two constant parameters, the mass-to-light ratio $M/L_V$ and the anisotropy parameter $\beta$ which describes the type of orbits the stars follow. The results in terms of the best-fitting parameters (dots) and $1\sigma$, $2\sigma$ and $3\sigma$ constraints on the parameters (contours) are presented in Figure 3. As we can see, going from the upper left to the lower right panel, more and more negative $\beta$ values (corresponding to more tangential orbits) are preferred. This is the consequence of the increasing velocity dispersion profiles. If the assumption of mass following light were relaxed this type of behaviour could also lead us to overestimate the mass (since extended mass distribution can also fit the increasing $\sigma_{los}$ profile).
Figure 3: The 1σ, 2σ and 3σ constraints on the parameters β and M/L\textsubscript{V} from fitting the velocity dispersion profiles of Figure 2 with the assumption that mass follows light and β = const. Dots mark the best fits.

The method of HK has been shown by Wojtak et al. (2007) to be the most effective in removing unbound particles from samples generated from simulated dark matter haloes. It has also been shown to perform well on the stellar samples drawn from simulated two-component models of dSph galaxies by Klimentowski et al. (2007). We can therefore conclude that the results obtained for the HK sample are the most reliable. One must however keep in mind when modelling the kinematics of dSph galaxies that in addition to the uncertainties due to sampling errors of velocity moments there is always additional uncertainty due to the method by which the member stars were selected. Since the simple cut-off in velocity is still the most common method used for interloper rejection many results are biased towards tangential orbits or extended mass distributions. For example, Walker et al. (2006) using the same data concluded that if mass follows light in Fornax then isotropic orbits (β = 0) are excluded while we show that the data are perfectly consistent with β = 0 if the unbound stars are properly
removed from the sample.

Once the interlopers are reliably removed one can also consider with confidence the higher moments of the velocity distribution. Figure 4 (left panel) shows the profile of the variable \( k = \frac{1}{10} \log (\kappa_{\text{los}}) \) where \( \kappa_{\text{los}}(R) = \frac{v_{\text{los}}(R)}{\sigma_{\text{los}}(R)} \) is the kurtosis of the line-of-sight velocity distribution. The kurtosis was calculated for the most reliable sample generated by the HK method of interloper rejection. The fourth velocity moment \( v_{\text{los}}^4(R) \) is governed by the higher-order Jeans equation (see Lokas 2002, Lokas et al. 2005). The solid line in the Figure is the best-fitting solution when the dispersion and kurtosis are fitted simultaneously. In the right panel we plot the 1σ, 2σ and 3σ confidence regions on the fitted parameters. Comparing with Figure 3 we see that the anisotropy parameter is now much more constrained, at 68% confidence we get \( \beta = -0.03^{+0.23}_{-0.37} \), \( M/L_V = 11.4^{+2.7}_{-1.7} \) M\(_\odot\)/L\(_\odot\) with \( \chi^2/N = 10.9/10 \) while when fitting only the dispersion profile (for the same HK sample) we had \( \beta = -0.17^{+0.37}_{-0.63} \), \( M/L_V = 11.3^{+2.1}_{-1.8} \) M\(_\odot\)/L\(_\odot\) with \( \chi^2/N = 3.4/4 \). We see that when kurtosis is added the best fitting anisotropy is even closer to \( \beta = 0 \).

3 The origin of unbound stars

As discussed in detail by Klimentowski et al. (2007) using an N-body simulation of a dSph galaxy, the contribution from the tidally stripped stars to the kinematic samples depends strongly on the orientation of the tidal tails with respect to the line of sight. If the tails are along the line of sight then the contamination is strongest. This kind of contamination should also be symmetric.
in velocity: we should see similar amount of unbound stars at velocities above and below the mean velocity of the dwarf galaxy. As Figure 1 demonstrates, this is not the case: there are much more stars rejected with velocities below the systemic velocity of Fornax. There is also evidence for the visibility of tidal tails in Fornax from the photometric study of Coleman et al. (2005) which means that they cannot be oriented exactly along the line of sight. These two facts lead to the conclusion that the majority of the contaminating stars in the sample come from the MW stellar population.

We have verified this conjecture by referring to the Besançon model of the MW (Robin et al. 2003). The results are illustrated in Figure 5 where we plot the histograms showing the expected number of stars with a given velocity. The open histogram refers to all stars expected to be seen in the direction of Fornax, the half-filled one to stars along the red giant branch of Fornax and the filled one is for stars expected to be seen in a small kinematic sample of 202 stars. As expected, the maximum of the distribution falls around the velocity of 20 km s\(^{-1}\) which confirms that most of the contamination in Fornax indeed comes from the MW stars.

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