Dynamical modelling of dwarf spheroidal galaxies

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with

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Tides in Milky Way dSphs?

- Tidally perturbed, mass-follows-light models shown to reproduce data for Carina (Munoz et al. 2008)

- Similar claims for LeoI and Fornax (Lokas et al., 2008; Klimentowski et al., 2007)

- All dSphs orbit Milky Way: expect tidal perturbation at some level

- Need systematic study of allowed orbits/mass models and degeneracies
Modelling tidally disturbed dSphs: a new approach

- Combine full N-body simulations with Markov Chain Monte Carlo
- Explore degeneracies between orbit and mass estimates

Ural et al., in prep.
The method

• Generate present-day position and velocity for Carina using observed error bars on proper motion
• Integrate orbit backwards 5 Gyr in Milky Way potential
• Insert N-body realisation of Carina (stars + dark matter)
• Evolve model forward to present day
• Calculate surface brightness profile and line of sight velocity dispersion profile and compare with observations
• Use MCMC to generate sequence of models with varying $\rho_0$, $r_s$, $\rho_0, \ast$, $r_s, \ast$, $\mu_\alpha \cos \delta$, $\mu_\delta$
Assumptions

- dSph progenitors were initially spherical
- 2-component models (stars + dark matter)
- No significant evolution of Milky Way potential over past 5 Gyr
- Initial halo profile has form ($\gamma = 0, 0.5, 1$):
  \[ \rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \frac{r}{r_s}\right)^{4-\gamma}} \]
- Stellar profile based on fit to current distribution
Tests with artificial data

- Progenitor placed on eccentric orbit
- Approx. 3000 models in MCMC analysis
An MCMC based search for dynamical models of the Carina dSph 4.3. Artificial data test.

On the left, the distribution of the initial halo masses that the MCART set’s good models. On the right, the distribution of the masses with $\chi^2$ values.

In this set we also check whether we can obtain consistent final masses from our chains, to match the model ART1’s final mass. The mass inside the last data point of the velocity dispersion profiles ($r = 0.82$ kpc) is $6.2 \times 10^6 M_\odot$ for the ART1 model.

The distribution of the final masses at the end of N-Body integrations are shown in Figure 4.7. The mean of the Gaussian is $6.8 \times 10^6 M_\odot$ where the $2\sigma$ limit covers the range of values between $6.2 \times 10^6 M_\odot$ to $7.4 \times 10^7 M_\odot$. The results are consistent with ART1.

Tests with artificial data:
Chains recover correct mass of dSph at end of simulation.
Velocity gradient in Carina?

- Relies on data on outer bins, i.e. small numbers of stars
- Initially, use only surface brightness and velocity dispersion as constraints

Munoz et al. 2008
Carina: Mass follows light models

\( \log M_{\text{halo}} \)
Carina: mass follows light models

Good match to surface density and velocity dispersion profiles
Carina: alternative scenarios
Carina: cusped halo models

- Enclosed mass is similar to estimate from mass-follows-light models
- Results follow locus of constant halo density
Carina: cusped halo model

- No tidal perturbation in this model - doesn’t match outer stellar distribution
- Removing $r_h > 0.5\text{kpc}$ restriction may allow perturbed, extended halo models as well
The future: breaking the tidal degeneracy

\[ 1.5 < R < 1.7 \]
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Time independent modelling

• General halo profile (spherical):

\[ \rho_{\text{halo}}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \left(\frac{r}{r_s}\right)^{1/\alpha}\right)^\alpha(\beta-\gamma)} \]

• 2-integral distribution functions \( F(E,L) \) constructed using scheme of Gerhard; Saha

• Data analysed star-by-star: no binning

• No assumptions of Gaussianity

• Markov-Chain-Monte-Carlo used to scan 13 dimensional parameter space
Tests with isotropic models

- Artificial data sets of similar size, radial coverage and velocity errors to observed data set in Fornax
Fornax - PRELIMINARY density profile

\[ \log_{10}(N) \]
Log-slope of mass profile

$d \ln \xi(r)/d \ln r$ vs $\log_{10}(r)$

$\log_{10}(N)$
\[ \beta(r) = 1 - \frac{v_t^2(r)}{2v_r^2(r)} \]
NB: Dispersion data not used to constrain models

Fornax - dispersion profile

\[ \sigma(R) / \text{km s}^{-1} \]

All data

\[ \Delta V < 2 \text{km s}^{-1} \]
Conclusions

• Combination of MCMC with N-body simulations yields reliable modelling of tidally perturbed dSphs (Ural et al. in prep.)

• Carina can be modelled by both tidally perturbed and pristine halo models

• Future surveys of outer reaches of dSphs have potential to break tidal-mass degeneracy fully (Ural et al. in prep.)

• Un-binned radial velocity data can be used to measure density profiles of dSph dark matter haloes

• Modelling of Fornax dSph suggests halo is cusped on scales $\sim 100\text{pc}$ - additional work underway to confirm robustness of models.