Dark matter distribution in the Galactic dwarf spheroidal galaxies

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Abstract. The Galactic dwarf spheroidal (dSph) galaxies are excellent laboratories to shed light on fundamental properties of dark matter. In particular, the dSphs are promising targets for the indirect searches for particle dark matter. In order to set robust constraints on properties of dark matter particles, revealing dark matter distributions in these galaxies is of crucial importance. However, there are various non-negligible systematic uncertainties on the estimate of dark matter distributions in these galaxies. Therefore, it is necessary to address the development of dynamical models considering the effects of these systematic uncertainties. In this talk, we will introduce our constructed dynamical models taking into account these uncertainties and present the inferred dark matter profiles in the classical dSphs using their current kinematic data. In addition, as an intriguing result, we will show that some of dSphs favor cusped dark halo rather than cored one even considering a mass-anisotropy degeneracy. Using these dark matter profiles, we will revisit the core-cusp problem and discuss a possible link between the inner slope of their dark halos and the star formation history.

1. INTRODUCTION

The Galactic dwarf spheroidal (dSph) galaxies are ideal sites for studying the basic properties of dark matter. This is because these galaxies have high dynamical mass-to-light ratio ($M/L \sim 10 - 1000$), which means these are the most dark matter dominated systems. Owing to their proximity of the Sun, the dSph galaxies have the advantage that individual member stars can be resolved [1]. Thus, it is possible to measure accurate line-of-sight velocities for their member stars, so that we are able to constrain their internal structures of dark halo using these high-quality data. The cold dark matter (CDM) theory has well-reproduced the cosmological and astrophysical observations on large spacial scales such as cosmic microwave background and large-scale structure of galaxies [2, 3]. Meanwhile, on galactic and sub-galactic scales there have been several outstanding discrepancies between the predictions from pure dark matter simulations based on ΛCDM models and some observational facts [4]. One of the controversial issues in ΛCDM models is the so-called “core-cusp” problem: dark matter halos predicted by ΛCDM simulations have strongly cusped central density profiles [5], whereas the dark halos in the observed galaxies, especially dSph galaxies and low surface brightness galaxies, are suggested to have cored dark halo profiles [6, 7].
In order to resolve the problem, there are various possible mechanisms such as baryonic effects (e.g., supernova feedbacks) and alternative dark matter models (e.g., ultralight dark matter). On the other hand, whether the Galactic dSph galaxies are cusped or cored is yet unclear because of the presence of degeneracy in some mass models. Dynamical studies typically treat dSph galaxies as spherical symmetric systems with respect to both stellar and dark components, even though dSph’s stellar distributions are not spherical but elongated and ΛCDM models predict non-spherical dark matter halos. However, in such models, there is a degeneracy between the velocity anisotropy of their stars and dark matter mass profiles due to the assumption of spherical symmetry [8]. Motivated by the aforementioned problem, we have constructed non-spherical mass models for the dSphs based on axisymmetric Jeans equations to obtain more realistic limits on their dark matter density profiles and to revisit “core-cusp” problem.

2. MODELS AND ANALYSIS

We describe our constructed non-spherical mass models as follow. For surface stellar density distributions of the dSphs, we assumed oblate Plummer profile generalized to an axisymmetric form:

\[ I(x, y) = L(\pi b^2 [1 + m^2]/b^2)^{-2}, \]

where \( m^2 = x^2 + y^2/q^2 \), and \( q' \) is a projected axial ratio, which is related to a true axis ratio \( q \) and inclination of a galaxy \( i \):

\[ q'^2 = \cos^2 i + q^2 \sin^2 i. \]

\( b \) is the half-light radius along the major axis. For dark matter density profile, we assume a generalized Hernquist profile:

\[ \rho_{DM}(r) = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{\frac{\beta - \gamma}{\alpha}},} \]

where \( \rho_s \) and \( r_s \) are a scale density and a scale length, respectively. Profiles with \( \gamma > 0 \) indicate centrally cusped, whilst those with \( \gamma = 0 \) have constant-density cores. In this work, we assume axisymmetric dark matter distributions, so that \( r \) is transformed from spherical to axisymmetric form:

\[ r^2 = R^2 + z^2/Q^2, \]

where \( Q \) denotes an axial ratio of a dark matter halo. Utilizing these density profiles, we solve the axisymmetric Jeans equations [9], where a velocity anisotropy \( z = 1/v^2_z \) is taken into account. We assume that the stellar density distribution has the same orientation and symmetry as that of dark halo, and \( z \) is assumed to be constant for the sake of simplicity. Integrating \( v_R^2 \) and \( v_\phi^2 \) (solved by Jeans equations) along the line-of-sight, we estimate the model parameters \( (Q, r_s, \rho_s, \beta_2, \alpha, \beta, \gamma, i) \) by fitting to the observed line-of-sight velocity dispersion. We apply these axisymmetric models to eight luminous dSphs (Carina, Fornax, Sculptor, Sextans, Draco, Leo I, Leo II, and Ursa Minor) to obtain the limits on their parameters. Detailed discussion will be presented in Hayashi et al. (2020, in preparation).

3. DARK MATTER DENSITY PROFILES

Using Markov Chain Monte Carlo techniques based on Bayesian parameter inference, we obtain the posterior probability distribution function (PDF) of each parameter. Figure 1 shows the dark matter density profiles along the major axes of Draco and Fornax galaxies computed from the posterior PDFs of their model parameters\(^1\). The solid lines indicate the median values of dark matter density profiles, and the light and dark contours mark the 95 per cent and 68 per cent confidence levels of our models.

Firstly, notice that our models for Draco favor a cusped dark matter density profile, consistent with a ΛCDM cusp, which has \( \gamma \sim 1 \). On the other hand, Fornax dSph prefer to have a less cusped inner density profile, \( \gamma \sim 0.53 \), even though there are still large uncertainties on these profiles. For the other dSphs, we find Ursa Minor, Leo I, Leo II and Carina dSphs suggest to have cusped dark matter densities, while Sculptor and Sextans favor less cusped one. Therefore,

\(^1\) In this paper, we show the dark matter density profiles of the galaxies with smallest and largest stellar masses only. For all dSphs, we will present in a forthcoming paper (Hayashi et al. 2020 in preparation).
Figure 1. Dark matter density profiles of Draco (left) and Fornax (right) dwarf spheroidal galaxies. The solid lines in each panel are the median density profiles and the light and dark shaded regions encompass the 95 per cent and 68 per cent confidence levels computed from the posterior PDFs of their parameters. The vertical dashed lines in each panel correspond to their half-light radii. The dotted-dashed lines in the upper left panel denote cusped ($\gamma = 1$) and cored ($\gamma = 0$) inner density profiles as references.

It is found from our dynamical models that there is a diversity of inner slopes of the dark matter density profiles in the classical dSphs.

4. WHAT IS THE ORIGIN OF THIS DIVERSITY?
Recent high-resolution dark matter plus hydrodynamical simulations have predicted that the shape of dark matter inner density profiles depends largely on stellar mass and star formation history [10, 11]. This means that less massive galaxies cannot transform from cusped to cored dark matter density profiles, while massive one can create significant cores because there are enough stellar feedback energy to do that. Motivated by these predictions, we compare our estimated inner dark matter density slopes of the dSphs with their stellar masses. Figure 2 shows the comparison between the inner slopes of dark matter density profiles and stellar masses of the dSphs. It is found from this figure that there is no significant correlation between them with considering there are uncertainties. Moreover, although we make an attempt to compare between dark matter halo parameters (e.g., the amplitude of the dark matter density profile at 150 pc, $\rho_{DM}(150 \text{ pc})$, and at their half-light radii, $\rho_{DM}(R_{\text{half}})$) and stellar properties (e.g., star formation history, surface density, and so on.), we cannot find any relations between them.

Consequently, we do not have any clear answer to the question yet. To this end, it is necessary to get photometric and kinematic data over much larger areas as well as a substantial data volume. Further observational progress implementing space and ground-based telescopes will enable us to measure a huge number of stellar data and, in the more remote future, provide phase-space information for stellar systems, thereby allowing us to set more robust constraints on the dark matter density profile in dSphs.
Figure 2. The comparison between the inner slopes of dark matter density profiles and stellar masses of the dSphs. The error bars correspond with the 68 per cent confidence levels computed from the posterior PDFs of their parameters. The dashed horizontal line denotes the value of the NFW cusped inner density slope.

References
[1] McConnachie, A. W. 2012, AJ, 144, 4
[2] Tegmark, M., Eisenstein, D. J., Strauss, M. A., et al. 2006, Phys. Rev. D, 74, 123507
[3] Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2018, arXiv e-prints, arXiv:1807.06209
[4] Bullock, J. S., & Boylan-Kolchin, M. 2017, ARA&A, 55, 343
[5] Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
[6] Gilmore, G., Wilkinson, M. I., Wyse, R. F. G., et al. 2007, ApJ, 663, 948
[7] de Blok, W. J. G. 2010, Advances in Astronomy, 2010, 789293
[8] Battaglia, G., Helmi, A., & Breddels, M. 2013, New A Rev., 57, 52
[9] Binney, J., & Tremaine, S. 2008, Galactic Dynamics: Second Edition
[10] Oñorbe, J., Boylan-Kolchin, M., Bullock, J. S., et al. 2015, MNRAS, 454, 2992
[11] Fitts, A., Boylan-Kolchin, M., Elbert, O. D., et al. 2017, MNRAS, 471, 3547