The General Assembly of Galaxy Halos: Structure, Origin and Evolution
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Tracing the Galactic Halo: Obtaining Bayesian mass estimates of the Galaxy in the presence of incomplete data

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Abstract. The mass and cumulative mass profile of the Galaxy are its most fundamental properties. Estimating these properties, however, is not a trivial problem. We rely on the kinematic information from Galactic satellites such as globular clusters and dwarf galaxies, and this data is incomplete and subject to measurement uncertainty. In particular, the complete 3D velocity vectors of objects are sometimes unavailable, and there may be selection biases due to both the distribution of objects around the Galaxy and our measurement position. On the other hand, the uncertainties of these data are fairly well understood. Thus, we would like to incorporate these uncertainties and the incomplete data into our estimate of the Milky Way's mass. The Bayesian paradigm offers a way to deal with both the missing kinematic data and measurement errors using a hierarchical model. An application of this method to the Milky Way halo mass profile, using the kinematic data for globular clusters and dwarf satellites, is shown.

Keywords. dark matter, Galaxy: general, halo, kinematics and dynamics; methods: statistical.

1. Introduction

The mass and mass profile of the Galaxy can be estimated using the kinematic data of tracer objects such as globular clusters (GCs) and dwarf galaxies (DGs). Armed with the tracers' position and velocity data, one can assume models for the gravitational potential and tracer density profile, and obtain parameter estimates for the mass profile. One problem with using the kinematic data of tracers, however, is that we do not always have their 3-dimensional velocity vectors; often, the proper motions of tracers have not been measured, rendering their velocity data incomplete.

Eadie, Harris, & Widrow (2015) (hereafter EHW) developed a way to use both complete and incomplete data simultaneously when estimating the mass of the Milky Way. They used a Bayesian method that employs a model's Galactocentric distribution function (DF)— similar to the method first suggested by Little & Tremaine (1987)— and that treats the unknown tangential velocities as parameters. Using a Hernquist (1990) model, they found a total mass estimate that was in agreement with many other studies (see Wang *et al.* 2015). Although measurement uncertainties were not included in the analysis, they performed a sensitivity analysis which revealed that uncertainties may contribute up to half of the uncertainty in the parameter estimates. Due to the latter finding, we now incorporate the measurements uncertainties in the analysis via a hierarchical model.

2. Method

We use the same general method as outlined in EHW to determine the mass of the Milky Way under the assumption of the isotropic Hernquist (1990) model DF, which is in the Galactocentric frame (GF). The measurement uncertainties of the kinematic data are in the Heliocentric reference frame, and are assumed to be independent and approximately Gaussian distributed. Thus, we incorporate the uncertainties into the Bayesian analysis via a likelihood in the Heliocentric frame, where the assumption of probability independence can be applied.

We use $\boldsymbol{y} = (r, v_{los}, \mu_\delta, \mu_\alpha \cos\delta)$ to denote the Heliocentric observations, and the vector $\boldsymbol{\Delta} = (\boldsymbol{\Delta v_{los}}, \boldsymbol{\Delta \mu_\delta}, \boldsymbol{\Delta(\mu_\alpha \cos\delta)})$ to denote the *known* measurement uncertainties of the velocities. We assume that $\boldsymbol{y}$ are drawn from Gaussian distributions centered on the true values $\boldsymbol{\vartheta} = (\boldsymbol{r}, \boldsymbol{v_{los}}, \boldsymbol{\mu_\delta}, \boldsymbol{\mu_\alpha \cos\delta})$, with standard deviation equal to the measurement uncertainties $\boldsymbol{\Delta}$. The likelihood, with $\boldsymbol{\vartheta}$ as parameters and $\boldsymbol{\Delta}$ as fixed, is then,

$$\mathcal{L}(\boldsymbol{y}|\boldsymbol{\vartheta}, \boldsymbol{\Delta}) = p(r|\boldsymbol{r}, \boldsymbol{\Delta r})p(v_{los}|\boldsymbol{v_{los}}, \boldsymbol{\Delta v_{los}})p(\mu_\delta|\boldsymbol{\mu_\delta}, \boldsymbol{\Delta\mu_\delta})p(\mu_\alpha \cos\delta|\boldsymbol{\mu_\alpha \cos\delta}, \boldsymbol{\Delta\mu_\alpha \cos\delta}). \tag{2.1}$$

Equation 2.1 is then used in a hierarchical Bayesian paradigm,

$$p(\boldsymbol{\theta}|\boldsymbol{y}, \boldsymbol{\Delta}) \propto \prod_{i}^{N} \mathcal{L}(\boldsymbol{y_i}, \boldsymbol{\Delta_i}|\boldsymbol{\vartheta_i})p(h(\boldsymbol{\vartheta_i})|\boldsymbol{\theta})p(\boldsymbol{\theta}) \tag{2.2}$$

where $p(h(\boldsymbol{\vartheta_i})|\boldsymbol{\theta})$ represents the model DF given parameters of interest, $\boldsymbol{\theta}$. The $\boldsymbol{\vartheta}$ parameters are transformed to the GF through a function $h(\boldsymbol{\vartheta})$, following Johnson & Soderblom (1987) (using updated values for the Solar motion). A more detailed explanation of this method will be available in Eadie, Harris, & Springford (2015) and in future works.

3. Results

The preliminary results shown in the lower part of the poster (see supplementary material), are noticeably different than the results presented in EHW. Their estimate for the total mass, assuming the isotropic Hernquist model, was $1.55 \times 10^{12} M_\odot$ with a 95% credible interval of $(1.73, 1.42) \times 10^{12} M_\odot$. Here, when the same model is assumed but the hierarchical method is adopted, the estimate is $0.78 \times 10^{12} M_\odot$, with a 95% credible interval $(0.69, 0.90) \times 10^{12} M_\odot$. The discrepancy in these two results may be explained by the incorporation of measurement uncertainties. EHW already showed that high-velocity objects such as Pal 3 have significant influence on the mass estimate— when these objects' velocity uncertainties are taken into account, the tracers may carry less weight.

References

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