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Determining the Local Dark Matter Density with SDSS G-dwarf data

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Abstract. We present a determination of the local dark matter density derived using the integrated Jeans equation method presented in Silverwood *et al.* (2016) applied to SDSS-SEGUE G-dwarf data processed by Büdenbender *et al.* (2015). For our analysis we construct models for the tracer density, dark matter and baryon distribution, and tilt term (linking radial and vertical motions), and then calculate the vertical velocity dispersion using the integrated Jeans equation. These models are then fit to the data using MultiNest, and a posterior distribution for the local dark matter density is derived. We find the most reliable determination to come from the α-young population presented in Büdenbender *et al.* (2015), yielding a result of $\rho_{\rm DM} = 0.46^{+0.07}_{-0.09}\,{\rm GeV\,cm^{-3}} = 0.012^{+0.001}_{-0.002}{\rm M_\odot\,pc^{-3}}$. Our results also illuminate the path ahead for future analyses using Gaia DR2 data, highlighting which quantities will need to be determined and which assumptions could be relaxed.

Keywords. dark matter, Galaxy: kinematics and dynamics, Galaxy: disk, etc.

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1. Introduction

The proper interpretation of results from in-laboratory searches for cosmological Dark Matter (DM) is reliant on a high quality determination of the local DM density $\rho_{\rm DM}$ from astrometry and astrophysics. The detection rates of these experiments feature a degeneracy between the local DM density, and the coupling of DM to Standard Model particles. This latter quantity is crucial in investigating the particle physics nature of DM and its role in Beyond-the-Standard-Model theories, and so systematic problems in the determination of $\rho_{\rm DM}$ can flow from astrometry through experimental physics to theoretical physics. See Read (2014) for a review of the local DM density.

In this work we give a synopsis of results presented at the IAU Symposium 330 in Nice, France (24-28 April 2017), and published in full in Sivertsson *et al.* (2017).

2. Method

The method used for this analysis is an evolution of that presented in Silverwood *et al.* 2016. Broadly speaking we use a Jeans equation based method to analyse the vertical motions of stars in the Milky Way disc plane and determine the total mass distribution in the vicinity of the Sun. The inclusion of a model for the baryon distribution then allows us to make a determination of the local DM density.

2.1. *Mathematical Details*

The starting point for the method is the z-direction Jeans equation with the assumption of axisymmetry and dynamical equilibrium (Binney & Tremaine (2008), Silverwood *et al.* (2016)):

$$\frac{1}{\nu}\frac{\partial}{\partial z}(\nu\sigma_z^2) + \underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz})}_{\text{tilt term: } \mathcal{T}} = -\frac{\partial\Phi}{\partial z}, \tag{2.1}$$

where ν is the tracer density, σ_z^2 is the z-direction velocity dispersion, σ_{Rz} is the (R, z) cross term of the velocity dispersion tensor, and Φ is the total gravitational potential. From measurements of the positions, z- and R-velocities, we could derive all the terms on the LHS of equation 2.1 and derive the z-gradient of the total potential Φ from which we could derive the surface density profile $\Sigma_z(z)$. However this would require differentiating numerical data, which would amplify the noise present in the data. Thus we instead integrate equation 2.1, to yield (Sivertsson *et al.* (2017)):

$$\nu(z)\sigma_z^2(z) = \nu(z_0)\sigma_z^2(z_0) - \int_{z_0}^{z} \nu(z')[2\pi G\Sigma(z') + \mathcal{T}(z')]\mathrm{d}z'. \tag{2.2}$$

The surface density $\Sigma(z)$ is a sum of both baryons and DM:

$$\Sigma(z) = 2\int_{z=0}^{z} dz\,[\rho_{\text{baryon}}(z') + \rho_{\text{DM}}(z')]\,. \tag{2.3}$$

We then build models for the tracer density profile $\nu(z)$, the baryon density $\rho_{\text{baryon}}(z)$, the DM density $\rho_{\text{DM}}(z)$, and the tilt term $\mathcal{T}(z)$. Using equation 2.2 we can then calculate the vertical velocity dispersion $\sigma_z^2(z)$. Finally we fit these models to data using Bayesian nested sampling as implemented by MultiNest (Feroz & Hobson (2007), Feroz *et al.*(2008), Feroz *et al.*(2013)). The comparison between model and data is made with a χ^2 test on $\nu(z)$, $\sigma_z^2(z)$, and $\sigma_{Rz}(z)$. From the output of the MultiNest we can derive a posterior distribution on the local DM density.

The link between potential Φ and the density ρ includes a rotation curve term $\mathcal{R}$:

$$\frac{\partial^2\Phi}{\partial z^2} + \underbrace{\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial\Phi}{\partial R}\right)}_{\mathcal{R}} = 4\pi G\rho, \tag{2.4}$$

For this study we assume a flat rotation curve, and thus $\mathcal{R} = 0$, but any deviation from this would manifest itself as a shift in the local DM density (Silverwood *et al.* (2016), Sivertsson *et al.* (2017)).

2.2. *Input Data*

The data we use to derive the local DM density here is taken from Büdenbender *et al.* (2015). In this paper they process observations of G-type dwarf stars from SDSS/SEGUE into tracer density $\nu(z)$ and velocity dispersions $\sigma_z^2(z)$ and $\sigma_{Rz}(z)$. The extract two populations from the sample using metallicity cuts: an α-old population, with $0.3 <$ [α/Fe] and $-1.2 <$ [Fe/H] < -0.3, and an α-young population with [α/Fe] < 0.2 and $-0.5 <$ [Fe/H]. We take their derived data for $\nu(z)$, $\sigma_z^2(z)$ and $\sigma_{Rz}(z)$ and feed it into our method.

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2.3. *Parameterised Models*

For the tracer density we assume an exponential distribution, as this was also assumed by Büdenbender *et al.* (2015) and fits the data well. The DM density is assumed to be constant in height above the disc plane, and so is described by a single parameter.

The baryon model is derived from data drawn from a number of sources, primarily McKee *et al.*(2015). We use a total surface density of $46.85\,\mathrm{M}_\odot\,\mathrm{pc}^{-2} \pm 13\%$. We only model the profiles of components with significant contributions to the mass density above the minimum z-value for which we have data. All other components can be modelled as a constant surface density term, i.e. modelling them as concentrated in the disc plane. The components we model are a thick disc component of all stars, the thin disc component of the dwarfs (consisting of M dwarfs, brown dwarfs, white dwarfs, plus a smaller contribution from neutron stars and black holes), and the HII gas component.

The tilt term links the vertical and radial velocity dispersions. Any potential that is symmetric in z is separable up to second order at the midplane ($z = 0$). Thus the radial and vertical motions will decouple at $z = 0$, and the tilt term will vanish. Though it can increase rapidly with z the tilt term is generally small at low z and has an increasing impact further from the midplane. From equation 2.2 the tilt term is given by (Sivertsson *et al.* (2017))

$$\mathcal{T}(R_\odot, z) \equiv \frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz}) \tag{2.5}$$

The radial variation of the tracer density and (R, z) cross term of the velocity dispersion tenor are modelled as

$$\nu(R,z) = \nu(R_\odot, z)\exp(-k_0(R - R_\odot)) \quad \text{and} \quad \sigma_{Rz}(R,z) = \sigma_{Rz}(R_\odot, z)\exp(-k_1(R - R_\odot)), \tag{2.6}$$

which yields a tilt term of

$$\mathcal{T}(R_\odot, z) = \left(\frac{1}{R_\odot} - k\right)\sigma_{Rz}(z) = \left(\frac{1}{R_\odot} - k\right)Az^n, \tag{2.7}$$

where $k \equiv k_0 + k_1$, and $R_\odot \simeq 8$ kpc is our distance to the galactic center. While the A and n parameters of the $\sigma_{Rz}(z)$ vertical profile model can be fit to the data from Büdenbender *et al.* (2015), the values of the k_1 and k_2 parameters controlling the radial variation of ν and σ_{Rz} must be imposed via a prior. Based on results from Bovy *et al.* (2016) we set a flat prior on k with range $-0.5 \leqslant k \leqslant 1.5\ \mathrm{kpc}^{-1}$ for the α-old population and $-1.3 \leqslant k \leqslant 1\ \mathrm{kpc}^{-1}$ for the α-young population. We take the galactocentric distance to be $R_\odot = 8$ kpc, though any uncertainty on this would be effectively marginalised over along with k.

3. Results

We perform five different analysis runs: α-young data only, with and without a tilt term included in the model; α-old, again both with and without tilt; and a combined analysis with tilt, using a common DM and baryon model but different tracer density and tilt term models for each population. The results are summarised in Table 1.

As expected the inclusion or exclusion of the tilt term has only a minor effect on the outcome of the α-young results. This is because the α-young population populates a canonical 'thin'-disc and is concentrated close towards the midplane, thus not experiencing a strong impact from the tilt term. The thick disc results, on the other hand, undergo a large shift in ρ_{DM} values, with the median shifting from $0.019\,\mathrm{M}_\odot\,\mathrm{pc}^{-3} = 0.73\,\mathrm{GeV\,cm}^{-3}$ when including tilt to $0.012\,\mathrm{M}_\odot\,\mathrm{pc}^{-3} = 0.46\,\mathrm{GeV\,cm}^{-3}$ when neglecting it.

Table 1. Limits on the credible regions (CRs) of the marginalised posterior of ρ_{DM}. The five different analysis runs are presented here: α-young and α-old analyses, done with tilt and without tilt, and a combined α-young and α-old analysis performed with tilt. The α-young with tilt analysis is considered the most reliable, and is shown in bold face.

		α-young		α-old		Combined analysis
		Tilt	No Tilt	Tilt	No Tilt	Tilt
68% CR upper	$M_\odot\,pc^{-3}$	**0.013**	0.014	0.021	0.013	0.012
	$GeV\,cm^{-3}$	**0.53**	0.53	0.79	0.48	0.43
Median	$M_\odot\,pc^{-3}$	**0.012**	0.013	0.019	0.012	0.011
	$GeV\,cm^{-3}$	**0.46**	0.48	0.73	0.46	0.40
68% CR lower	$M_\odot\,pc^{-3}$	**0.0098**	0.011	0.017	0.012	0.0097
	$GeV\,cm^{-3}$	**0.37**	0.42	0.68	0.44	0.37

The thick disc results with tilt are also anomalous compared to the other four results. Several factors lead us to distrust this result and instead favour the thin disc with tilt result. As commented on earlier the thick disc is more dependent on the tilt term, and so is more dependent on the model and assumptions we use to describe the tilt term. The posterior for the k parameter describing the radial variation of ν and σ_{Rz} appears to suffer from a prior dependency in the thick disc case, with tensions in the data driving the k to the edges of the prior (Sivertsson *et al.* (2017)). In the thin disc case however the posterior is generally flat within the prior range. Additionally the thick disc stars are further away with potentially greater errors, and are more susceptible to halo contamination. Furthermore the assumption of a flat rotation curve is informed by knowledge of galaxy close to the midplane - this assumption may be erroneous in the regions high above the midplane probed by the thick disc population.

These issues inform us as to how to proceed with Gaia data. For the stellar samples analysed with this method we must not only find the vertical distribution of the tracer density and velocity dispersions, but also their radial dependence, rather than relying on a prior for the latter. The assumption of the flat rotation curve must be tested at a range of z values. Beyond these immediately apparent avenues, Gaia data may also allow us to dispense with the assumption of axisymmetry, and the the associated assumption of time independence.

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