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THE MILKY WAY'S GRAVITATIONAL ACCELERATION FIELD MEASURED FROM RR LYRAE IN GAIA

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Abstract. From ∼16,000 RR Lyrae with proper motions measured by Gaia, we have measured the kinematics of the Milky Way's stellar halo up to 20 kpc from the Galactic centre. By applying the Jeans equations to these kinematic measurements, we have non-parametrically measured the azimuthally averaged gravitational acceleration field. We thereby measure the acceleration field away from the Galactic plane, a region which otherwise has only measurements at the sparsely located stellar streams. By subsequently removing the baryonic contribution from these measurements we have inferred the contribution of dark matter. We find that the gravitational potential of the Milky Way's dark matter appears spherical with flattening $q_\rho = 1.00 \pm 0.09$, slightly more spherical than the average flattening of dark matter halos in simulations of disk galaxies.

Keywords: dark matter, Galaxy:kinematics and dynamics, Galaxy: halo, Galaxy: kinematics and dynamics

1 Introduction

The release of Gaia DR2 in April 2018 has, for the first time, provided us with kinematic information across a wide volume of the Milky Way's halo. This, in principle, provides us with data from which we can extract the gravitational accelerations acting though our halo. Unfortunately Gaia's horizon for accurate parallaxes is confined to a few kpc around the Sun (Figure 1, left side). However, if distances to stars are known then Gaia can provide accurate the proper motions to stars over a much wider volume of the Galaxy (Figure 1, right side).

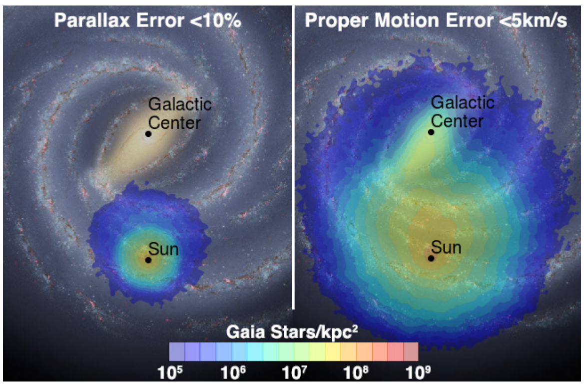

Fig. 1. Simulated Gaia catalog from models in Portail et al. (2017). **Left:** Gaia's horizon for accurate distances limits the volume of the Galaxy that can be directly studied. **Right:** For stars with accurate distances, Gaia proper motions provide accurate transverse velocities over a large volume.

Dynamical modelling of these velocities should allow us over the coming years to build up an accurate map of where both the stellar and dark matter mass lies. In other galaxies we can typically only measure line-of-sight velocities and so such modelling has uncertainties such as the well known mass-anisotropy degeneracy

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(e.g. Courteau et al. 2014). However in the Milky Way we can measure kinematics of individual stars in 3D and so these difficulties are circumvented. This allows us to uniquely infer the detailed properties of our own dark matter halo, and by comparison to simulations, understand if dark matter behaves as expected, a process termed near-field cosmology.

2 The Kinematics of the Halo As Traced By RR Lyrae

Motivated by the potential of Gaia's accurate proper motions, we utilised the catalogue of RR Lyrae in Pan-STARRS produced by Sesar et al. (2017). RRab are excellent standard candles and Sesar et al. (2017) estimates the distances in their catalogue to be precise to 3%. We limit the sample to stars at $|b| > 10\,\mathrm{deg}$ from the galactic plane (to avoid regions where extinction hampers RR Lyrae detection) and to stars within 20kpc of the Galactic centre (at which distances Gaia is still able to provide accurate proper motions). Cross matching to Gaia DR2 gives a sample of 16,000 stars with accurate distances and transverse velocities. The sample is centrally concentrated, approximately following a power law with index $\alpha = -2.7$ and flattening $q_{RR} = 0.72$, however the distribution appears too complex to be fully described by a simple parametric form.

Our sample of RR Lyrae have accurate 3D positions and velocities, but their radial velocities are unobserved. These radial velocities will be observed over the coming ~ 5 years by the WEAVE and 4MOST surveys, however, for now we have available 5 of the 6D phase space coordinates. In order to reconstruct the intrinsic kinematics of the halo from this kinematic information we have taken two approaches: (a) assuming that the kinematics are Gaussian and independent of azimuth. (b) a method that recovers the velocity moments of even non-Gaussian velocity distributions, assuming only that the kinematics are independent of azimuth.

For both methods we binned our data into 9 bins logarithmically spaced bins radially, and 5 bins in inclination, which span all azimuthal angles i.e. we make bins in $(\log r, \theta)$ which span all ϕ. Method (a) is more transparent: The 3D velocity ellipsoid is projected onto the sky plane differently at the position of each RR Lyrae, and so from a sample of RR Lyrae at different positions which share the same kinematics we can measure the 3D velocity ellipsoid. Method (b) is more general, but more opaque and less statistically efficient for Normally distributed velocities.

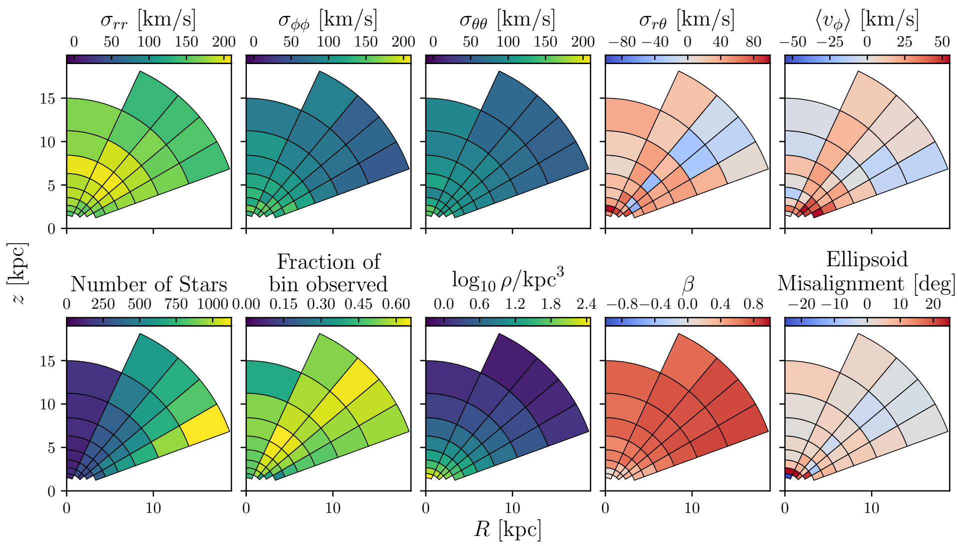

Fig. 2. The azimuthally averaged kinematics of our sample of RR Lyrae. **Upper row:** the elements of the dispersion tensor σ_{rr}, $\sigma_{\phi\phi}$, $\sigma_{\theta\theta}$ and $\sigma_{r\theta}$ and the rotation $\langle v_\phi \rangle$. **Lower row:** the number of stars in each bin and the completeness of each bin. These are combined to compute the azimuthally averaged density in the third plot. The final two plots show the radial anisotropy parameter β and the misalignment of the velocity ellipsoid from spherical.

In Figure 2 we show the results of method (b). However, both methods give the same results: (i) The sample of RR Lyrae is strongly radially anisotropic with anisotropy parameter $\beta \equiv 1 - (\sigma_{\theta\theta} + \sigma_{\phi\phi})/(2sigma_{rr}) \approx 0.8$ over most of the volume with Galactocentric radii < 20kpc. (ii) The velocity ellipsoid is nearly spherically aligned over most of the halo, only near the Galactic plane, or in the innermost regions of the halo does it tilt towards cylindrical alignment. (iii) Most of the volume studied rotates very slowly, or even counter rotates.

However, the inner regions, at < 5kpc from the Galactic center, rotate at up to 50km s^{-1}. This rotation may reflect the early build up of the innermost regions of our stellar halo, but there will also be significant angular momentum transfer from the non-axisymmetric bar at these radii.

3 The Milky Way's Acceleration Field

We have applied the Jean's equations to the kinematics measured in Figure 2. There are two Jeans equations containing F_r and F_θ, the accelerations in the two-dimensional (r, θ)-plane. While the equations are long, they are straightforward, and for the sample of RR Lyrae we have measured all of the required kinematic quantities. Therefore, after discretising the Jeans equations for our bins, we have applied them and the resultant accelerations are plotted in Figure 3.

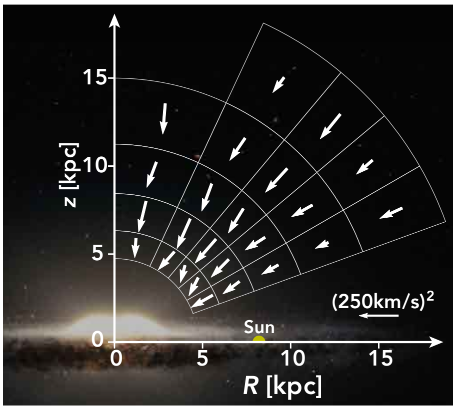

Fig. 3. The Milky Way's acceleration field measured non-parametrically using Gaia data (adapted from Wegg et al. 2019. Artists impression Credit:ESO/NASA/JPL-Caltech/M. Kornmesser/R. Hurt). The resultant velocities have almost equal length, which is the 3D equivalent of the Milky Way's flat rotation curve. To normalise, the forces, in $(\text{km/s})^2$/kpc, have been multiplied by galactocentric radius: this provides a 3D equivalent of the squared circular velocity.

It is immediately clear from Figure 3 that the forces are mostly radial. To quantify this, and understand the implications for the Milky Way's dark matter distribution, we have subtracted models for the baryonic component. These models consist of the barred models of the inner Galaxy taken from Portail et al. (2017), together with exponential disk models for the stars and gas in the outer Galaxy. Subtracting these models provides us with the forces from the dark matter alone. We have tested the effect of our assumptions on the baryonic distribution, varying for example the stellar disk scale length and normalisation, and find that they are smaller than the statistical errors with our sample size.

Until this point in the modelling all methods have been non-parametric but, after subtracting the baryonic forces, the errors in the dark matter forces are larger, particularly in the baryon dominated inner regions. For this reason we have fit parametric models to the dark matter distribution: either (i) assuming a ellipsoidal dark matter distribution and fitting for the dark matter flattening as a function of radius (ii) fitting the entire dark matter forces to ellipsoidal parametric models of the dark matter such as the NFW and Einsasto profiles.

Both methods give consistent results: using (i) we find that, over the entire $5 - 20$kpc range where we can measure the flattening, the dark matter is consistent with a spherical potential with average flattening $q_\Phi = 1.01 \pm 0.06$. Using (ii) we find that a variety of different profiles fit the dark matter forces equally well, but all agree that the dark matter density is near spherical, with flattening in dark matter density of $q_\rho = 1.00 \pm 0.09$.

4 Tests Using Mock Halos

We have tested that the method is able to recover the kinematics, gravitational accelerations, and dark matter distribution, of two mock halos: (i) A mock halo constructed by disrupting a satellite on a nearly radial orbit in the fixed background potential of `MWPotential2014` taken from GalPy. The system was evolved for 6 Gyr before the particles were observed as mock RR Lyrae. The resultant mock halo demonstrated a similar level of non-axisymmetry to the Milky Way's stellar halo as traced by RR Lyrae, and we would expect it to demonstrate a similar level of phase-mixing. (ii) A mock halo constructed by selectively turning the dark matter particles in the models of Portail et al. (2017) into stars so that the mock stellar halo had similar kinematic properties to the Galaxy's stellar halo. In both mock halos we simulated a larger sample than available and found that the dark matter shape was recovered to within the statistical errors of the real sample size. This demonstrates that the systematic errors of the method (e.g. the finite size of the bin) and the assumptions (e.g. that the kinematics are axisymmetric) are likely to be smaller than the statistical errors.

The results using halo (i) in particular are reassuring because the RR Lyrae at our largest radii are not axisymmetric, and therefore not likely not fully phase mixed. This may reflect their accreted nature by e.g. Gaia-Enceladus/Sausage, and mock halo (i) was designed to test this.

5 Context and Future Prospects

Despite the observational advantage of having 3D velocities of stars, we are yet to reach a consensus on either the profile or shape of the Milky Way's halo. Similar methods to ours have been utilised by Loebman et al. (2014) finding the dark matter to have a flattened potential with $q_\Phi = 0.8 \pm 0.1$ and a corresponding density flattening of $q_\rho = 0.4 \pm 0.1$. However, in contrast using similar data, Bowden et al. (2016) favours a highly prolate dark matter potential with flattening $q_\Phi = 1.5 - 2.0$.

Both these results are in tension with recent work using tidal streams in the halo. For example using GD-1 ($R_{\rm gc} \approx 14$kpc), the flattening of the overall potential has been measured to be $q_\Phi \equiv \langle c/a \rangle_\rho = 0.87^{+0.07}_{-0.04}$ by Koposov et al. (2010), $q_\Phi = 0.90^{+0.05}_{-0.10}$ by Bowden et al. (2015) and $q_\Phi = 0.95 \pm 0.04$ by Bovy et al. (2016). Similarly at the location of Pal-5 ($R_{\rm gc} \approx 18$kpc) the overall potential was measured to be $q_\Phi = 0.95^{+0.05}_{-0.10}$ by Küpper et al. (2015) and $q_\Phi = 0.94 \pm 0.05$ by Bovy et al. (2016). Combining these constraints on the potential with baryonic models results in a dark matter halo with axes ratio $q_\rho = 1.05 \pm 0.14$ (Bovy et al. 2016).

Here we report a measurement using Gaia DR2, which allows us for the first time to apply the Jeans equations to stars over a large region of the Galaxy. In is reassuring that our result of $q_\rho = 1.00 \pm 0.09$ is consistent with those using streams.

In dark matter only CDM simulations, dark matter halos are highly flattened. The introduction of baryons however reduces this to a canonical value of $q_\rho \sim 0.8$ (Debattista et al. 2008, although the recent aurigaia simulations of Grand et al. 2018 appear to be slightly more spherical). Our result of a slightly more spherical halo that these expectations is therefore tantalising.

Spectroscopic surveys like WEAVE, 4MOST will soon begin measuring the kinematics of millions of halo stars. Dynamical modelling of this data, combined with Gaia proper motions, promises to unveil the distribution of dark matter throughout the Milky Way. In combination with modelling of Stellar streams, such as those observed by the S5 survey (Li et al. 2019), we should therefore be able to build a consensus on the dark matter distribution throughout our home Galaxy over the coming 5 years.

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