Probing the Disk Kinematics of M31 with DESI

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Abstract

M31's stellar rotation curve and disk line-of-sight dispersion is presented using kinematic data from a novel DESI M31 survey in combination with similar datasets. After removing the foreground, the disk region is isolated and the velocity field deprojected. A flat ring model is fit to the velocity field of M31 out to 30 kpc using a maximum-likelihood routine. The stellar rotation curve is found to flatten to $\sim$ 220 km/s, and a disk line-of-sight velocity dispersion of $\sim$ 60 km/s is derived. The results extend M31's rotation curve to 30 kpc and support the picture in which M31 has thicker disk than the Milky Way.

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Introduction

The internal motions of stars within galaxies are challenging to measure, but offer significant insight into a galaxy's evolution, matter distribution, and immigration history. The typical structures which form in a spiral galaxy include a bulge, disk, and stellar halo. However, external influences, such as immigrating satellites, can leave a unique distribution of stellar substructure in the form of streams and shells. Mapping out the overall velocity field of a galaxy provides a powerful tool for investigating not only its physical properties but also its accretion history. Due to its proximity, our nearest galactic neighbour M31 provides a detailed view of resolved galaxy dynamics in-action. In contrast to the Milky Way, M31 can be captured from an outsider perspective, allowing its disk to be fully observed while unobscured by a central bulge or dust, and hence more intuitively analysed. Surveys such as the Pan-Andromeda Archaeological Survey (McConnachie *et al.* 2009) have revealed a complex map of substructure within the halo of M31, revealing the pathways of chaotic mergers (McConnachie *et al.* 2018).

The rotation curve of M31 has been the subject of extensive investigation (Rubin *et al.* 1970; Roberts *et al.* 1975; Carignan *et al.* 2006), often probed via HI, Hα, and C0 emission lines, and continues to be a subject of interest (Chemin *et al.* 2009; Sofue 2015). Robust tilted ring models have been developed (Begeman 1989; Corbelli *et al.* 2010) which translate line-of-sight velocities into kinematic properties of the host galaxy, and continue to be advanced (Di Teodoro *et al.* 2015). One such kinematic property, the rotation curve, can be used to determine the mass profile of M31, including a constraint on the dark matter distribution (Zhang *et al.* 2024).

Shortly after the debut of the Dark Energy Spectroscopic Instrument (DESI), a powerful wide-field spectroscopic surveyor, Dey *et al.* (2023) completed a short survey campaign on the region around M31 and found evidence for a wealth of substructure in the halo of M31. Using the kinematics of substructures such as the Great Stellar Stream (a prominent stellar stream feature in the halo of M31), the immigration history and enclosed mass of M31 was inferred. However, there remains limited investigation into the kinematics of the disk within this DESI dataset despite thousands of stars captured within this region. Thus, the primary aim of this paper is to explore the DESI dataset further to develop a better understanding of M31's disk kinematics.

In this report, DESI data of M31 obtained by Dey *et al.* (2023) is decontaminated of Milky Way foreground stars and merged with kinematic datasets of planetary nebulae (Merrett *et al.* 2006) and globular clusters (Caldwell *et al.* 2016). The region around the disk is isolated and the velocity field deprojected. A flat ring model is fit, using a Gaussian mixture likelihood distribution in a maximum-likelihood routine, returning the stellar rotation curve and line-of-sight velocity dispersion profile.

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Data & Analysis

Data

This paper uses data published in Dey *et al.* (2023), consisting of a short survey of M31 performed by DESI. Although short, this survey captured 11,554 astronomical targets in the region of M31, including 10,414 stars belonging to either M31 or the Milky Way foreground, representing one of the most comprehensive kinematic investigations of M31 to date. While Dey *et al.* (2023) probed the kinematics of the stellar halo, the kinematics of M31's disk remained unexamined. Members of the dataset belonging to M31 were isolated under the criteria: $\mathrm{RVS\_WARN} = 0$ and $\log(g) < 3.8$. The former criterion flags any targets which were poorly fitted in the RVS pipeline used to assign stellar parameters to DESI spectra (Koposov *et al.* 2011; Koposov 2019), and the latter removes most of the Milky Way foreground. Milky Way foreground stars consist of disk dwarfs, which have a strong surface gravity, $\log(g)$, relative to the mostly red giant M31 targets. The exact boundary was inferred via the ratio of two fitted Gaussians on a histogram over the stellar surface gravity.

The DESI focal plane spans a diameter of 3.2° (Cooper *et al.* 2023), which is able to capture M31 in its entirety with only a few exposures. This focal plane is evenly populated with 5000 spectral fibres, which naturally leads to an underdensity in the inner disk region of M31 due to its small area on the sky. The region was therefore strengthened by the addition of two similar but smaller datasets: one of planetary nebulae surveyed by Merrett *et al.* (2006) and another of globular clusters surveyed by Caldwell *et al.* (2016). To analyse galactic kinematics in the coordinate system of M31, the dataset was tangentially projected assuming M31 is centred on (RA, DEC) = $10^\circ.6847$, $41^\circ.26875$ (Dey *et al.* 2023). The line-of-sight velocity field was then made relative to the centre of M31 assuming it moves with a recessional velocity of -300 km/s (Dey *et al.* 2023), where all velocities were first converted to the Galactic Standard of Rest (GSR) frame.

Flat Ring Model

The main method of this paper consists of a 'flat ring model', which assumes the galactic disk is perfectly flat and investigates the kinematics of concentric rings at increasing radii. The velocity field was first deprojected assuming a constant tilt of 77° from the face-on position (Dey *et al.* 2023). After specifying the number of rings, an algorithm determines the position and width of each ring such that they are equally populated by stars. For each ring, a sinusoid was fit to the line-of-sight velocities over azimuthal angle in a maximum-likelihood routine, optimised using the Nelder-Mead method. To account for the presence of substructure contaminants, which do not follow the sinusoidal profile of the disk, an outlier likelihood distribution was chosen (Hogg *et al.* 2010). The use of a bimodal Gaussian mixture to represent a likelihood distribution containing both a sinusoid and a background of outlier points allowed substructure to be accounted for when fitting to the disk (at the cost of additional free parameters). In addition to optimising sinusoidal and outlier parameters, the Gaussian width of the sinusoidal distribution was allowed to vary and optimised, representing the line-of-sight velocity dispersion in each ring.

Results and Discussion

The results of the flat ring model are shown in Figure 1 for a set of 25 equally populated rings up to 30 kpc from the centre of M31. The top panel of Figure 1 shows the stellar rotation curve which adopts the expected profile, flattening to ~ 220 km/s, consistent with prior studies (Rubin *et al.* 1970; Sofue 2015; Zhang *et al.* 2024). Also plotted is both a HI rotation curve (dashed) and a potential model computed by the GALA software package (solid). The separation between the stellar and gaseous/model curves can be attributed to the effects of asymmetric drift, a naturally occurring phenomenon arising from collisionless nature of stars (Binney *et al.* 2008). Further investigation would include a calculation of the asymmetric drift and derivation of M31's mass distribution.

The central panel of Figure 1 shows the line-of-sight velocity dispersion in the disk over radii. The initial spike at low radii can be attributed to the bulge which is not rotationally supported. Towards larger radii the dispersion decreases as the disk population becomes dominant, but plateaus to ~ 60 km/s. These results contribute further evidence to the picture in which M31 has a thicker disk than the Milky Way, the thin disk of which has a dispersion of ~ 20 km/s (Vieira *et al.* 2022). If we adopt the theory that immigration events are a main contributor in thickening a galactic disk (Abadi *et al.* 2003), this

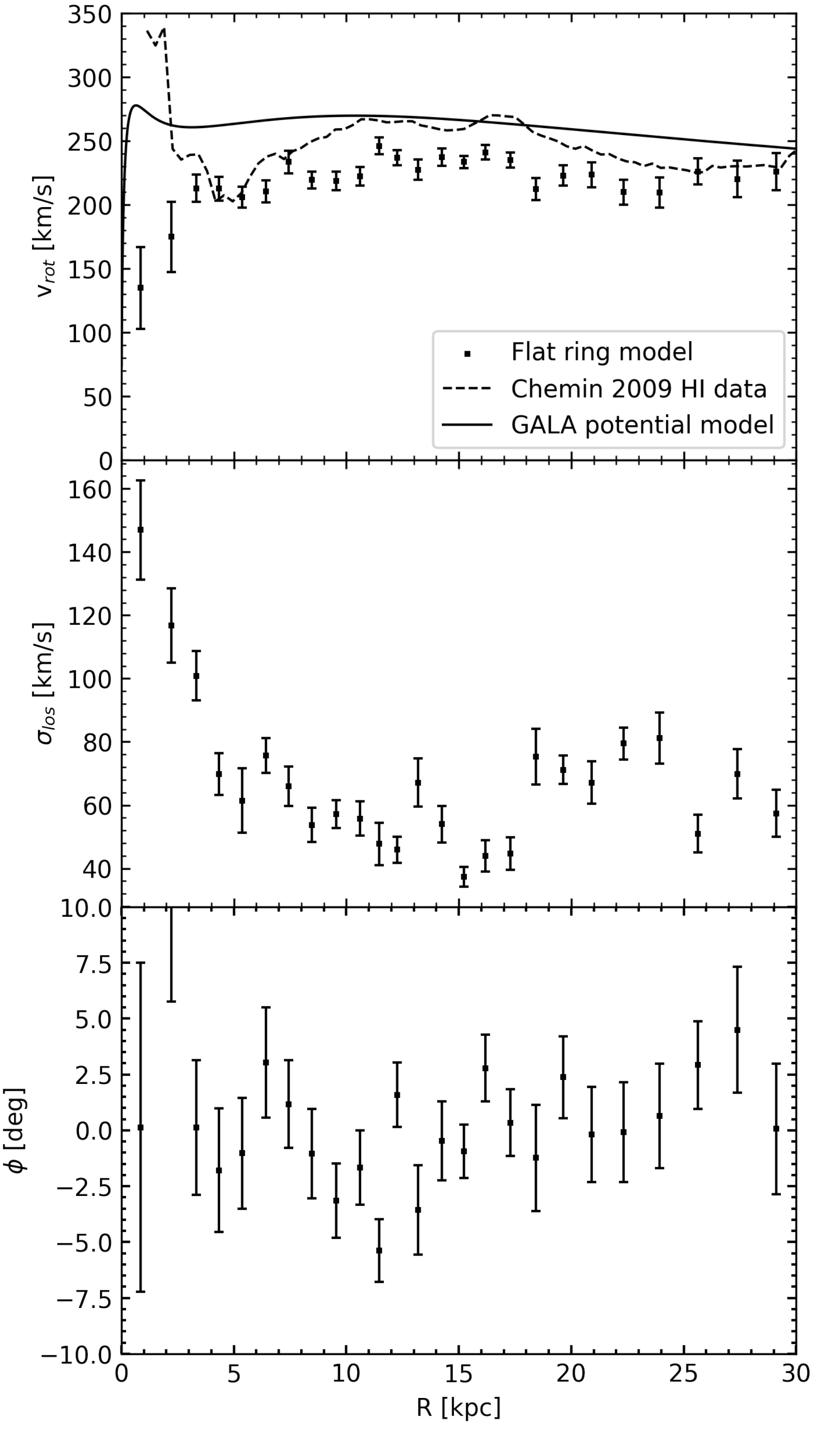

Figure 1: Results of a flat ring model applied to DESI, planetary nebulae and globular cluster kinematic datasets of M31, for 25 rings up to 30 kpc from the galactic centre. **Top:** The stellar rotation curve of this work (squares) compared with an HI rotation curve (dashed) obtained by Chemin *et al.* (2009) and a potential model rotation curve (solid) computed by GALA (Price-Whelan 2017). **Middle:** The line-of-sight velocity dispersion profile. **Bottom:** The azimuthal offset of each ring's sinusoidal line-of-sight velocity profile relative to the semi-major axis of M31 projected on the sky.

could suggest M31 has undergone a more violent accretion history than the Milky Way.

The lower panel of Figure 1 shows the azimuthal offset of the sinusoidal line-of-sight velocity profile in each ring, relative to the semi-major axis of M31 projected on the sky. For a perfectly flat disk this value should always be zero, as the line-of-sight velocity profile for a flat rotating disk is at its maximum/minimum along the semi-major axis, which alludes to the fact that the disk is warped in its inner (R $<$ 5 kpc) and outer (R $>$ 20 kpc) region. In further research, a tilted-ring model which varies ring inclination and position angle is recommended to return more robust ring parameters.

Conclusions

In this work a flat ring model was fit to the disk of M31 using a new survey by DESI in conjunction with previous surveys. The combined line-of-sight velocity field was deprojected and the disk of M31 split into 25 equally populated concentric rings. Using a Gaussian mixture likelihood distribution, a sinusoid was fit to disk star velocities over azimuthal angle, determining the rotational velocity, deprojected line-of-sight velocity dispersion and azimuthal offset of each ring. The stellar rotation curve of M31 was extended to 30 kpc and found to flatten at $\sim$ 220 km/s, agreeing with prior studies. The line-of-sight dispersion profile of the disk was derived and found to be $\sim$ 60 km/s, supporting the picture in which M31's disk is thicker than the Milky Way's and the possible explanation that this is due to a more violent accretion history. Further investigation would include a calculation of the asymmetric drift and subsequent derivation of the mass distribution, as well as a tilted ring model to map out any warps in the disk of M31 and provide a more robust rotation curve.

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