Resolved SPLASH Chemodynamics in Andromeda’s PHAT Stellar Halo and Disk: On the Nature of the Inner Halo along the Major Axis

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Abstract

Stellar kinematics and metallicity are key to exploring formation scenarios for galactic disks and halos. In this work, we characterized the relationship between kinematics and photometric metallicity along the line of sight to M31’s disk. We combined optical Hubble Space Telescope/Advanced Camera for Surveys photometry, from the Panchromatic Hubble Andromeda Treasury survey, with Keck/DEIMOS spectra, from the Spectroscopic and Photometric Landscape of Andromeda’s Stellar Halo survey. The resulting sample of 3512 individual red giant branch stars spans 4–19 projected kpc, making it a useful probe of both the disk and inner halo. We separated these stars into disk and halo populations, by modeling the line-of-sight velocity distributions as a function of position across the disk region, where ∼73% stars have a high likelihood of belonging to the disk and ∼14% to the halo. Although stellar halos are typically thought to be metal-poor, the kinematically identified halo contains a significant population of stars (∼29%) with disk-like metallicity ([Fe/H]_{db} ≈ −0.10). This metal-rich halo population lags the gaseous disk to a similar extent as the rest of the halo, indicating that it does not correspond to a canonical thick disk. Its properties are inconsistent with those of tidal debris originating from the Giant Stellar Stream merger event. Moreover, the halo is chemically distinct from the phase-mixed component previously identified along the minor axis (i.e., away from the disk), implying contributions from different formation channels. These metal-rich halo stars provide direct chemodynamical evidence in favor of the previously suggested “kicked-up” disk population in M31’s inner stellar halo.

Unified Astronomy Thesaurus concepts: Galaxy stellar disks (1594); Andromeda Galaxy (39); Galaxy formation (595); Galaxy stellar content (621); Stellar kinematics (1608); Stellar abundances (1577); Galaxy stellar halos (598)

1. Introduction

The formation and evolution of stellar disks constitute a significant part of the mass assembly history of galaxies. In the local universe, disk galaxies have been observed to possess dynamically hot “thick” disk components in their vertical structure (e.g., Chiba & Beers 2000; Yoachim & Dalcanton 2006; but see also Bovy et al. 2012). Multiple physical mechanisms have been proposed to explain the formation of thick disks, including early in situ star formation within a turbulent gaseous disk (Bournaud et al. 2009; Forbes et al. 2012) and the heating of an initially thin stellar disk by internal perturbations (e.g., Lacey 1984; Sellwood & Carlberg 1984; Jenkins & Binney 1990; Schönrich & Binney 2009a, 2009b; Loebman et al. 2011). However, the hierarchical assembly process may also provide channels for thick disk formation via the accretion of gas (e.g., Brook et al. 2004) and ex situ stellar material (Abadi et al. 2003) deposited at large scale heights or heating driven by satellite impacts (Quinn et al. 1993; Velazquez & White 1999; Hopkins et al. 2008; Kazantzidis et al. 2008; Villalobos & Helmi 2008; Purcell et al. 2009). The formation of the dynamically hot thick disk may therefore be inextricably connected to the inner stellar halo by merger history.

M31’s proximity (785 kpc) and inclination (77°) present an unrivaled opportunity to study galaxy disks beyond the Milky Way (MW). Resolved stellar spectroscopy along the line of sight to M31’s disk has transformed our understanding of the galaxy’s inner structure. Based on spectra of over 5000 red giant branch (RGB) stars, Dorman et al. (2012) discovered a rotating spheroid (σ_r ~ 140 km s^{-1}) that exceeded ~10% of the total stellar population in a region dominated by the disk in UV/optical images (R_{proj} ~ 4–20 kpc). However, surface brightness decompositions indicated that the bulge should not contribute to stellar populations beyond M31’s inner few kiloparsecs (Courteau et al. 2011; Gilbert et al. 2012; Williams et al. 2012). The structural decomposition of Dorman et al. (2013), which simultaneously accounted for surface brightness...
profiles, the luminosity function, and kinematics, demonstrated that the spheroid corresponded to a stellar halo. Dorman et al. (2013) also found evidence for an excess of stars with a disk-like luminosity function compared to dynamically based expectations for the disk contribution. These stars could have been born in the disk, but kinematically heated into the stellar halo.

Further studies imply a possible merger origin for the connection between the formation of the halo and the disk. Dorman et al. (2015) revealed a steep relationship between age and velocity dispersion in M31’s disk region ($\sigma \sim 90$ km s$^{-1}$ for 4 Gyr ages), concluding that this could be explained by a combination of continuous but nonuniform heating of the disk by mergers. Quirk et al. (2019) identified a trend of monotonically increasing asymmetric drift (AD) with stellar age that was consistent with a 4:1 merger event occurring within the last 4 Gyr (Quirk & Patel 2020). Moreover, a recent major merger (as explored by D’Souza & Bell 2018; Hammer et al. 2018) could simultaneously explain M31’s 2–4 Gyr old global burst of star formation (Bernard et al. 2015; Williams et al. 2015), its chemically homogeneous extended disk (15–40 kpc; Ibata et al. 2005), and its thickened disk structure and kinematics (Dorman et al. 2012, 2015; Dalcanton et al. 2015; but see also Collins et al. 2011). Studies of planetary nebulae in M31’s disk have similarly concluded that its age–dispersion relation could have resulted from a major merger (Bhattacharya et al. 2019).

Despite the wealth of kinematical information, comprehensive chemodynamical investigations are lacking across M31’s disk region. Prior studies of resolved stellar populations have been largely restricted to either chemical analyses informed by photometry (e.g., Gregersen et al. 2015; Telford et al. 2019) or focused on dynamics (e.g., Dorman et al. 2012, 2013, 2015; Quirk et al. 2019). In order to circumvent crowding, previous chemodynamical efforts have been limited to the outer disk ($\lesssim 15$ kpc) in the northeast (Ibata et al. 2005) and the southwest (Collins et al. 2011). To date, chemical abundances ([Fe/H] and [$\alpha$/Fe]) for individual stars have been measured for only a small sample of stars in M31’s outer disk (at 26 projected kpc; Escala et al. 2020a). Recently, oxygen and argon abundances from the emission lines in planetary nebulae have provided an additional method for probing the chemical evolutionary history of M31’s inner disk (Arnaboldi et al. 2022; Bhattacharya et al. 2022).

In this work, we combine resolved spectroscopy from the Spectroscopic and Photometric Landscape of Andromeda’s Stellar Halo (SPLASH) survey (Guhathakurta et al. 2005; Gilbert et al. 2006) and photometry from the Panchromatic Hubble Andromeda Treasury (PHAT; Dalcanton et al. 2012; Williams et al. 2014) to perform the first large-scale stellar chemodynamical analysis of M31’s inner disk region ($\lesssim 15$ kpc), in an effort to explore disk–halo formation scenarios. This approach enables us to disentangle the inner stellar halo from the disk, as well as identify chemically distinct stellar populations. In Section 2, we introduce the photometric and spectroscopic data sets used in this work. We evaluate M31 membership and perform a kinematical decomposition of the disk region in Section 3. We correct for dust effects and describe photometric metallicity measurements for RGB stars in Section 4. Section 5 investigates the chemical and dynamical properties of the disk and halo, whereas Section 6 places these results in the context of the literature on M31, the MW, and disk galaxy formation in general. We summarize our main findings in Section 7.

2. Data

2.1. PHAT Photometry

We used stellar catalogs based on Hubble Space Telescope (HST) Wide Field Camera 3 and Advanced Camera for Surveys (ACS) images from the PHAT survey (Dalcanton et al. 2012; Williams et al. 2014). PHAT produced six-filter UV (F275W, F336W), optical (F475W, F814W), and IR (F110W, F160W) photometry across the northeastern disk of M31, out to 20 projected kpc from M31’s center, for 117 million stars. In particular, we used second-generation PHAT photometry, in contrast to Dorman et al. (2012, 2013, 2015; Section 2.2). The primary difference between the second- (Williams et al. 2014) and first- (Dalcanton et al. 2012) generation photometry is the simultaneous use of all six HST filters for source identification and point-spread function fitting, which enables significant increases in the completeness-limited photometric depth (F475W $\sim 28$ in the outer disk) and photometric and astrometric accuracy (<5–10 mas). We matched the R.A. and decl. (based on v1 PHAT photometry) of the SPLASH stars to the updated positions in the PHAT v2 catalog. We searched for matches within a 2′′ on-a-side box centered on the v1 astrometry, without applying shifts or offsets between the astrometric versions. If there were multiple matches based on this criterion, we additionally matched by optical photometry within the $2\sigma v 2$ uncertainties in the F475W and F814W filters (median 0.015 and 0.004 mag, respectively).

2.2. SPLASH Spectroscopy

The SPLASH survey collected $\sim$10,000 Keck/DEIMOS (Faber et al. 2003) spectra across M31’s northeastern disk to investigate its line-of-sight velocity distribution and stellar properties (Dorman et al. 2012, 2013, 2015). The SPLASH stars were targeted based on a mixture of Canada–France–Hawaii Telescope MegaCam photometry and PHAT v1 photometry (Section 2.1). Each slitmask was observed for $\sim 1$ hr using the 1200 $\ell$ mm$^{-1}$ (pre-2012 observations; Dorman et al. 2012, 2013) or 600 $\ell$ mm$^{-1}$ (post-2012 observations; Dorman et al. 2015) grating on DEIMOS. The 1200 (600) $\ell$ mm$^{-1}$ grating configuration resulted in a spectral resolution of $R \sim 6000$ ($R \sim 3000$) at the Ca II triplet ($\lambda \lambda 8500$) and a wavelength coverage of $\sim 6300$–9100 (4500–9100) Å when combined with the OG550 (GG455) order-blocking filter.

The 2D and 1D spectra were reduced and extracted using the spec2d and spec1d pipelines (Cooper et al. 2012; Newman et al. 2013). Dorman et al. (2012, 2013, 2015) measured radial velocities from SPLASH spectra using the cross-correlation technique of Simon & Geha (2007), including A-band corrections for slit miscentering (Sohn et al. 2007) and heliocentric corrections. To assess the reliability of the velocity measurements, the raw 2D spectra, extracted 1D spectra, and best-fit empirical templates were visually inspected in the zspec software (D. Madgwick; DEEP2 survey) and assigned a quality code (Q; e.g., Guhathakurta et al. 2006). The velocity measurements deemed successful ($Q = 3$ or $Q = 4$) were those that were based on at least one strong spectral feature. The typical statistical velocity uncertainty derived from the cross-correlation was roughly a few km s$^{-1}$ ($\sim 10$ km s$^{-1}$) for spectra obtained with the 1200 (600) $\ell$ mm$^{-1}$ grating.
likely to be intervening MW dwarfs (Gilbert et al. 2006), especially given that the SPLASH target selection procedure does not account for interstellar reddening (Sections 4.1, 4.2.1), to favor a complete sample of giant star candidates. Alternatively, these blue stars may also be M31 disk stars in a different stellar evolutionary stage. SPLASH includes a large population of main-sequence turnoff stars in M31 (Figure 2), which are near the most contaminated portion of the CMD bounded by $m_{F475W} < 21$ and $1 < m_{F475W} - m_{F814W} < 2$ (Dorman et al. 2015).

Next, we evaluated the probability of M31 membership for stars based on their NaI equivalent widths (EW$_{Na}$) and measurement uncertainties ($\delta$EW$_{Na}$). We measured EW$_{Na}$ and $\delta$EW$_{Na}$ from all spectra, following the method of Escala et al. (2020b). We were unable to measure EW$_{Na}$ for 51.6% of the SPLASH stars, owing to factors such as weak absorption, convergence failures in line profile fits, or low signal-to-noise ratios. For stars with EW$_{Na}$ measurements, we computed the membership probabilities from likelihood ratios derived by constructing nonparametric probability distribution functions (PDFs) using EW$_{Na}$ and $\delta$EW$_{Na}$ measurements (assuming Gaussian uncertainties) for thousands of MW and M31 stars securely identified by the SPLASH survey as being in M31’s halo (e.g., Gilbert et al. 2012). The PDF-weighted sample means and standard deviations are $\mu_{Na,M31} = 0.54$ Å, $\sigma_{Na,M31} = 1.00$ Å and $\mu_{Na,MW} = 2.27$ Å, $\sigma_{Na,MW} = 1.96$ Å. For stars without EW$_{Na}$ measurements, we determined membership solely based on the CMD position. Using the Besançon model for the MW foreground (Robin et al. 2003), we expect that only $\sim 0.2\%$ of the SPLASH stars in the M31 giant star region of the CMD are MW contaminants (Appendix A).

Figure 2 shows the CMD of the SPLASH disk stars color-coded by the EW$_{Na}$-based M31 membership probability ($p_{Na}$) calculated from the PDFs. Stars with $p_{Na} \leq 0.25$, which are $\geq$three times more likely to belong to the MW foreground than M31, preferentially populate the heavily contaminated portion of the CMD identified by Dorman et al. (2015), in addition to the region above the tip of the red giant branch (TRGB), which has a higher incidence of contamination by bright MW foreground stars (Gilbert et al. 2006). Figure 2 also demonstrates that stars with $p_{Na} \leq 0.25$ tend to have MW-like velocities ($v_{helio, MW} \sim 50$ km s$^{-1}$), while few of these stars are present at velocities that are highly consistent with M31’s stellar halo ($v_{helio} < 300$ km s$^{-1}$). In contrast, defining MW foreground stars by $p_{Na} < 0.5$, which are $>one$ times more likely to belong to the MW than M31 based on EW$_{Na}$ alone, would exclude many targets with CMD positions and velocities that are fully consistent with M31 membership. The high surface density of M31’s disk relative to the MW foreground ensures that the majority of targets are true M31 giant stars. We thus adopted $p_{Na} \leq 0.25$ in addition to our CMD criterion, to eliminate MW contaminants. The CMD and NaI criteria classify 1443 and 118 stars, respectively, as nonmembers.

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11 Note that “weak absorption” refers specifically to the lack of detectable absorption in at least one NaI line. This is distinct from a negative EW$_{Na}$ measurement (Figure 2), which can be caused by features such as poorly subtracted sky lines.

12 43.6% (34.9%) of M31 giant stars (RGB stars only) do not have EW$_{Na}$ measurements. In particular, EW$_{Na}$ measurements preferentially fail for stars above the TRGB. M31 giant stars (RGB stars only) without EW$_{Na}$ measurements are not biased in color compared to the full sample of M31 giant (RGB) stars.
This membership determination method stands in contrast to our previous work, which relied on EW\textsubscript{Na}, calcium triplet–based metallicity, CMD position, and radial velocity to probabilistically evaluate membership for stars along the line of sight to M31 (e.g., Gilbert et al. 2006; Escala et al. 2020b). The primary reason that we did not use these membership determination methods was to avoid relying on the transformations between HST/ACS and Johnson–Cousins photometry (e.g., Sirianni et al. 2005; Saha et al. 2011) that are required for Ca II triplet–based metallicity calibrations (e.g., Ho et al. 2015). Additionally, we did not use radial velocity as a diagnostic measurement for membership, because the velocity distribution of M31’s northeastern disk shows significant overlap with that of the MW disk (Ibata et al. 2005; Dorman et al. 2012). Excluding radial velocity as a diagnostic does not preclude the use of probabilistic membership determination methods, but it restricts their usage to two dimensions for stars without spectroscopic metallicity measurements, such that those methods do not confer a significant advantage over the adopted approach (see Section 3.4 of Gilbert et al. 2006). Again, the high stellar surface densities of M31’s disk ensure that contamination from MW foreground stars is minimal prior to membership selection.

### 3.2. Velocity Distribution Modeling

Previous studies have suggested that M31’s stellar velocity distribution in the disk region consists of a dynamically hot component and a kinematically colder component(s) corresponding to the halo and disk, respectively. To perform a chemodynamical analysis of M31’s disk, we therefore separated the stars likely belonging to the disk and the halo over a spatial region spanning \( R_{\text{proj}} = 4–18.5 \) kpc.

#### 3.2.1. Disk Regions

We followed the methodology of Dorman et al. (2012), where we assumed only that the stellar disk is locally cold, with a symmetric velocity distribution, and that each region of M31’s disk has a contribution from the inner halo. We similarly divided the disk into regions along the northeast major axis, based on the projected radial distance: R1, R2, and R3, which are bounded by \( R_{\text{proj}} = \) 8, 12, and 18.5 kpc, respectively. The median radii of the stars in each bin are 6.3, 10.3, and 14.4 kpc, respectively. To model the velocity distribution, we fixed the halo component in each region using the Gaussian parameters determined by Dorman et al. (2012), which are corrected for the presence of tidal debris at \( v_{\text{halo}} < -500 \) km s\(^{-1}\) that is likely related to the Giant Stellar Stream (GSS; Fardal et al. 2013; Escala et al. 2022). The stellar halo component in the regions (R1, R2, R3) is described by \( \mu_{\text{halo}} = (-258.2, -268.7, -238.8) \) km s\(^{-1}\) and \( \sigma_{\text{halo}} = (134.4, 135.3, 117.5) \) km s\(^{-1}\).

To fit for the disk component, we divided each region by the position angle relative to the major axis (\( \Delta \text{P.A.} \)). As in Dorman et al. (2012), we defined the angle subtended by each subregion as either the \( \Delta \text{P.A.} \) that contained 100 stars, at minimum, or the \( \Delta \text{P.A.} \) such that the predicted change in the line-of-sight velocity of M31’s disk (\( v_{\text{obs}} \)) owing to the \( \Delta \text{P.A.} \) was 10 km s\(^{-1}\) (comparable to the velocity measurement precision; Section 2.2), choosing whichever was larger. As noted by Dorman et al. (2012), the predicted velocity spread due to \( \Delta \text{P.A.} \) within a subregion merely approximates the true spread, which is affected by additional factors, such as the change in the deprojected radius, deviations from perfectly circular rotation, and variations in the intrinsic local velocity distribution.

We calculated \( v_{\text{obs}} \) using a simple model for the perfectly circular rotation of an inclined disk (Guhathakurta et al. 1988), with inclination angle \( i = 77^\circ \) and major axis P.A. = 38°, given...
by

\[ v_{\text{obs}}(\xi, \eta) = v_{\text{sys}} + v_{\text{rot}} \frac{\sin(i)}{\sqrt{1 + \tan^2(\Delta \text{P.A.}) / \cos^2(i)}}, \]

(1)

where \((\xi, \eta)\) are M31-centric tangent plane coordinates, \(v_{\text{sys}} = -300 \text{ km s}^{-1}\) is the systemic velocity of M31, and \(v_{\text{rot}} = 250 \text{ km s}^{-1}\) is the disk rotation speed, which is approximately the median value measured from HI kinematics for the deprojected radii in the disk plane \((R_{\text{disk}} > 5 \text{ kpc}; \text{Chemin et al. 2009})\). Figure 3 shows the locations of the regions and subregions in M31-centric coordinates, where we divided R1, R2, and R3 into 11, 10, and 4 subregions, respectively. Table 1 summarizes the spatial properties of each subregion bounded by lines of constant P.A., where we designate each subregion based on the absolute angular distance from the major axis.

### 3.2.2. Fitting for the Disk Contribution

We modeled the velocity distribution for each subregion using a two-component Gaussian mixture composed of a kinematically hot halo and colder disk (Dorman et al. 2012). The log likelihood function for a given subregion is described by

\[ \ln L = \sum_{i=1}^{N_s} \ln (f_d N(v_i|\mu_d, \tau_d^{-1}) + (1 - f_d) N(v_i|\mu_f, \tau_f^{-1}), \]

(2)

where \(i\) is an index corresponding to an M31 giant star, with successful velocity measurement \(v_i\) located in subregion \(s\) within region \(r\), and \(N_{s, r}\) is the total number of such stars. Each Gaussian distribution \(N\) has mean velocity \(\mu\) and inverse variance \(\tau = 1/\sigma^2\), where \(\mu\) and \(\sigma\) are constant within a given region and correspond to the halo component. The fractional contribution of the disk, \(f_d\), varies across subregions, where the halo fraction is constrained to \(f_h = 1 - f_d\).

We sampled from the posterior probability distribution of Equation (2) using an affine-invariant Markov Chain Monte Carlo ensemble sampler (emcee; Foreman-Mackey et al. 2013) with 10^5 walkers and 10^4 steps. We implemented flat priors for \(\mu_d\) and \(f_d\) over the parameter ranges of \([-600, +100]\) km s^{-1} and \([0, 1]\), respectively. We assumed a Gamma prior on \(\tau_d\), with \(\alpha \approx 14\) and \(\beta \approx 28.476\), which penalizes values of \(\sigma\) below roughly 35 km s^{-1} and above 70 km s^{-1}, based on the results of Dorman et al. (2012), and boundary conditions on \(\sigma\) of \([5, 150]\) km s^{-1}. We determined the kinematical parameters for the disk component in each subregion from the latter 50% of the samples, where Table 1 summarizes these parameters in terms of the 16th, 50th, and 84th percentiles of the marginalized posterior distributions. Figure 4 provides an example of the velocity distribution models fitted to the four subregions in region R3. We show the fits to the subregions in R1 and R2 in Appendix B.

In general, the trends between the mean velocity of the disk component and the absolute \(\Delta \text{P.A.}\) from the major axis follow those that are expected for an inclined rotating disk, in agreement with Dorman et al. (2012), where the disk velocity approaches M31’s systemic velocity \((-300 \text{ km s}^{-1})\) with increasing angular distance. These trends are not apparent in R3 (Figure 4), because it spans a smaller angular range in position angle, but this relationship is clearly visible in Table 1 (see also Figures 16 and 17 in Appendix B). We also find that the halo component becomes more dominant with increasing angular distance from the major axis.

We emphasize that the purpose of the modeling is not to perform a detailed structural decomposition of the disk (e.g., into a thin and a thick disk; Section 6.1), but rather to reliably distinguish disk stars from halo stars, for the interpretation of the metallicity distributions (Section 5). As discussed by Dorman et al. (2012), the assumption of a single locally cold disk component in each subregion provides a good fit to the velocity distributions and is sufficient for a simple decomposition. We compute the probability of belonging to the disk \(p_{\text{disk}}\) for M31 giant stars, based on their observed velocities and positions. Using the velocity model for each star’s assigned subregion (Table 1), we calculate \(p_{\text{disk}}\) from the likelihood ratio of the disk and halo components.

Figure 5 illustrates the spatial distribution of the M31 giant stars color-coded by the disk probability, where \(p_{\text{disk}}\) is highest near the major axis and in the outer disk. Although the disk
Figure 4. Heliocentric velocity distributions for region R3 (Section 3.2.1). From left to right, the panels show the velocity distribution in each subregion (gray histograms; Figure 3; Table 1), where R3 straddles the major axis and R3 is the most distant from the major axis. We also show the fitted velocity model for each subregion (thick purple lines; Section 3.2.2), which is composed of a stellar halo component (Dorman et al. 2012) with fixed mean and dispersion, but variable fractional contribution (dotted blue lines), and a disk component (dashed green lines). Figures 16 and 17 show the velocity distributions and models for R1 and R2. In general, the trends between the disk component velocity and ΔP.A follow those expected for an inclined rotating disk approaching M31’s systemic velocity (−300 km s⁻¹) with increasing ΔP.A. (Dorman et al. 2012). The stellar halo component also becomes more dominant with increasing ΔP.A.

### Table 1

Kinematical Model Parameters for the Disk

| Subregion | P.A.₆₀(deg) | P.A.₆₀(deg) | P.A.₆₀(deg) | P.A.₆₀(deg) | μₛ₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆₆}_{12}

Note. The disk regions are based on the projected radial distance: R1, R2, and R3 are bounded by R₉₀ = 8, 12, and 18.5 kpc, respectively. Each region is divided into subregions based on the absolute angular distance from the major axis (P.A. = 38°; Section 3.2.1), where we indicate the positive and negative P.A. boundaries (relative to the major axis) of each symmetric subregion in degrees east of north. The parameters describing the disk component in each subregion are velocity (μ), velocity dispersion (σ), and normalized fractional contribution (f). The stellar halo component in each region is fixed to the values determined by Dorman et al. (2012) when correcting for tidal debris. The parameter values are the 50th percentiles of the marginalized posterior probability distributions, where the errors are calculated from the 16th and 84th percentiles (Section 3.2.2).
foreground. We assumed $A_{V,MW} = 0.2$ for the foreground reddening, which corresponds to the median value over the low-extinction PAndAS footprint (McConnachie et al. 2018), based on the dust maps by Schlegel et al. (1998), with corrections by Schlafly & Finkbeiner (2011). We used this value, given that the foreground dust maps are inaccurate when restricted to M31’s disk region, where its dust emission dominates over that of the MW. This translates to $A_{F814W} \sim 0.12$ and $A_{F475W} \sim 0.38$ (Gregersen et al. 2015).

We classified 3874 M31 members as red giants, when correcting for foreground reddening. We defined the TRGB using 4 Gyr PARSEC isochrones (Marigo et al. 2017) spanning $-2.2 < [\text{Fe}/H]_{\text{phot}} < +0.5$. We assumed a distance modulus of $m-M = 24.45 \pm 0.05$. Stars were assigned to the RGB if they were below the TRGB within the photometric uncertainty: $m_{F814W} + \sigma_{F814W} > m_{\text{TRGB}}$ (median $\sigma_{F814W} = 0.004$). The number of stars classified as red giants has a small dependence on the adopted foreground reddening, as well as the uneven reddening within M31’s disk (Section 4.2.1).

The direction of the reddening vector may have resulted in a few young AGB stars being reddened into the RGB CMD region, but old AGB stars will not be reddened into this region, owing to the shape of the TRGB. The net effect of the reddening is therefore to increase the number of stars classified as red giants. The predominant—but still minimal—source of contamination in the RGB region is red helium-burning stars, given that MW dwarf stars can be distinguished from genuine giant stars (Section 3.1). Contamination by red helium-burning stars would increase the number of stars in the metal-poor tails of the predominantly metal-rich distributions, but should not bias their median values (Section 5.1).

We determined the photometric metallicity for M31 RGB stars by interpolating dereddened (F475W, F814W) photometry on a grid of 4 Gyr PARSEC isochrones in the relevant filters (Escala et al. 2020a). We did not extrapolate to determine the $[\text{Fe}/H]_{\text{phot}}$ for stars blueward of the most metal-poor isochrone, thereby introducing an effective blue limit on the RGB region.

We assumed a relatively young age for RGB stars, although the mass-weighted average age for all stellar populations in M31’s disk is 10 Gyr (Williams et al. 2015, 2017), because stars on the upper RGB are biased toward younger ages, as a consequence of variable RGB lifetimes. Gregersen et al. (2015) used the star formation history measured over the PHAT footprint (Williams et al. 2015) to simulate the stellar populations in M31’s disk, finding that it produced an upper RGB with a mean age of 4 Gyr. Dorman et al. (2015) found similar results for the mean RGB age when adopting a constant star formation history. If we instead assume 10 Gyr ages for RGB stars, the median difference in the photometric metallicity is $-0.22$, when accounting for foreground reddening. The assumed stellar age therefore affects the absolute metallicity scale, although we are primarily concerned with relative metallicities in this work. If the dominant halo population is systematically older than the assumed 4 Gyr old disk, the halo metallicity scale would decrease by a maximum of 0.26 (Section 6.2).

4. Photometric Metallicity Measurement

We measured the photometric metallicity for M31 RGB stars, accounting for all sources of dust extinction. We determine the initial metallicity by correcting for foreground reddening in Section 4.1 and for internal reddening due to M31’s gaseous disk in Section 4.2.

4.1. Initial Metallicity Determination

We first corrected the PHAT photometry (Section 2.1) for the effects of dust extinction that are caused by the MW disk probability $p_{\text{disk}}$ is based on the velocity model for the subregion in which a star is located and its heliocentric velocity (Section 3.2.2). Stars with $p_{\text{disk}} \geq 0.75$ ($p_{\text{disk}} \leq 0.25$) are $\geq$three times more likely to belong to the disk vs. the halo (and vice versa).

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We adopt $\text{[Fe/H]}_{\text{phot}}$ to refer to the final (initial) metallicities. We introduce the internal reddening maps and perform a preliminary assessment of the dust effects on the metallicity distribution in Section 4.2.1. We describe the adopted internal extinction correction and final metallicity measurements in Section 4.2.2.

### 4.2.1. Internal Reddening Maps

We used the maps by Dalcanton et al. (2015), who used a novel approach to directly measure the dust extinction from IR PHAT photometry of RGB candidates, assuming constant dust extinction from the MW foreground. Based on the difference between the unreddened and reddened RGB sequences over the PHAT footprint, Dalcanton et al. (2015) modeled the spatial variation in reddening using the following parameters: the median extinction ($A_{V,\text{Dal}}$), the dimensionless width of the log-normal extinction distribution ($\sigma_V$), and the fraction of reddened stars ($f_{\text{red}}$). This latter parameter reflects the geometry of the dust relative to the RGB stars, where $1 - f_{\text{red}}$ percent of stars are assumed to be located in front of the thin dust layer of M31’s disk.

Figure 6 presents maps of $f_{\text{red}}$ and $A_{V,\text{Dal}}$ for SPLASH RGB stars, obtained from 2D interpolation of each star’s position on the Dalcanton et al. (2015) dust maps. We omit showing $\sigma_V$, since it is relatively constant at $\sigma_V \sim 0.30$ over the survey region. Figure 6 shows that the value of $f_{\text{red}}$ increases from the southeast to the northwest edge of the survey footprint, because the RGB population is located in a thick ($h_z = 0.77$ kpc) and moderately inclined ($i = 77^\circ$) disk, viewed in projection (J. Dalcanton et al. 2022, in preparation), where the expected value of $f_{\text{red}}$ is 50% at the major axis location (P.A. = 38°).

The sky locations of the M31 RGB stars in SPLASH, color-coded by (left) the fraction of reddened RGB stars ($f_{\text{red}}$) and (right) the median extinction ($A_{V,\text{Dal}}$) from the maps of the dust in M31’s disk by Dalcanton et al. (2015; Section 4.2.1). We do not show the spread in extinction, where $\sigma_V \sim 0.30$ over the entire sample. RGB stars with $\Delta$P.A. < 0 (Section 3.2.1) are more likely to be reddened, given that M31’s inclined thick disk is viewed in projection (J. Dalcanton et al. 2022, in preparation). The dust extinction is highest in the 10 kpc star-forming ring (Gordon et al. 2006). We use these maps to assess the impact of the dust in M31’s disk on the photometric metallicity measurements in Section 4.2.2.

### 4.2.2. CMD-based Extinction Correction

We incorporated information about the optical CMD position, as opposed to solely using spatial position, as in the case of the low-extinction regions (Section 4.2.1), to account for the effect of the dust in M31’s disk on the metallicity determination. We constructed an extinction probability
distribution for each RGB star with index $i$:

$$P_i(A_V|\alpha_i, \delta_i) = C(f_{\text{red}, i}) \times \frac{1}{A_V \sqrt{2\pi\sigma_{V,i}}} \exp \left[ -\frac{(\ln(A_V/A_{V,\text{Dal}, i}))^2}{2\sigma_{V,i}^2} \right]$$

(3)

where $A_V$ is a variable representing $V$-band extinction, $A_{V,\text{Dal}, i}$, $\sigma_{V,i}$, and $f_{\text{red}, i}$ are the star’s dust model parameters assigned from its sky coordinates ($\alpha_i, \delta_i$), and $C \in \{0, 1\}$ is a constant sampled with probability $\{1 - f_{\text{red}, i}, f_{\text{red}, i}\}$. We drew 10$^3$ values of the $A_V$ from Equation (3) for each star, which we then converted to $A_{V475W}$ and $A_{V814W}$ (Section 4.1). These HST-band extinction distributions were then used with the constant $A_{V,\text{MW}}$ to shift each star’s observed CMD position, thereby creating a statistical distribution of CMD positions corrected for all sources of dust extinction. We measured the metallicity (Section 4.1) for each corrected CMD position for each star, given its fixed classification on the RGB (Section 4.1). From this distribution, we calculated a median [Fe/H]$_{\text{phot,init}}$ value, corrected for all sources of dust extinction for each star.

Figure 8 shows CMDs for RGB stars color-coded by the difference between [Fe/H]$_{\text{phot}}$ and [Fe/H]$_{\text{phot,init}}$. It also shows the spread in [Fe/H]$_{\text{phot}}$, as quantified by the 16th ($\sigma_{16}$) and 84th ($\sigma_{84}$) percentile errors of the [Fe/H]$_{\text{phot}}$ distribution. For most stars, [Fe/H]$_{\text{phot}}$ is unchanged from the original [Fe/H]$_{\text{phot,init}}$ value. We adopted [Fe/H]$_{\text{phot}}$ as the photometric metallicity for stars with precise [Fe/H]$_{\text{phot}}$ determinations ($|\sigma_{16} + \sigma_{84}|/2 < 0.03$), where 0.03 is the median statistical metallicity uncertainty ($\sigma_{\text{phot}}$), from the propagation of photometric uncertainties. We also incorporated the spread in [Fe/H]$_{\text{phot}}$ as an error term contributing to the total metallicity uncertainty. Stars without precise [Fe/H]$_{\text{phot}}$ measurements are excluded from the following analysis.

These selection criteria reduce the RGB sample from 3874 to 3512 stars. The median difference between the final [Fe/H]$_{\text{phot}}$ and the original [Fe/H]$_{\text{phot,init}}$ distribution is $-0.04$. We note that aside from the decrease in metallicity, the overall structure of the MDFs is unaltered, especially in the metal-poor regime. The metallicity difference is similar to that of the low-extinction region selection (Figure 7). However, the approach involving Equation (3) has the advantage of using both the CMD and spatial information to construct a sample of RGB stars with relatively certain metallicity determinations, despite the effects of the dust in M31’s disk.

5. Chemodynamics of the Disk and Halo

In this section, we analyze the kinematical and chemical properties of RGB stars along the line of sight to M31’s disk, separating them into disk, halo, and “mixed” subpopulations (Section 3.2), to ultimately investigate evolutionary scenarios for the disk and the halo. We present MDFs and AD measurements for each subpopulation in Sections 5.1 and 5.2, respectively. We measure the metallicity gradients for the disk and the halo in Section 5.3.

5.1. MDFs

We explored the MDFs of the RGB stars corrected for all sources of dust extinction (Section 4.2), in the stellar halo and disk populations (Section 3.2), along the line of sight to M31’s disk. We defined the disk (halo) stars using $p_{\text{disk}} > 0.75$ ($p_{\text{disk}} < 0.25$), which corresponds to stars that are at least three times more likely to belong to the disk (halo), based on kinematics and spatial position. We designated all other RGB stars as “mixed.” In total, 554, 458, and 2500 stars belong to the halo, mixed, and disk populations, respectively. Figure 9 shows the MDFs for each population, while Table 2 summarizes their properties.

The disk MDF (median [Fe/H]$_{\text{phot}} = -0.19$) has a dominant metal-rich population and an extended metal-poor tail. Modeling the MDF using a two-component Gaussian mixture (analogous to Section 3.2.2) yields [Fe/H]$_{\text{phot}} = -0.10 \pm 0.90$, $\sigma_{\text{phot}} = 0.23 \pm 0.54$, with a fractional contribution of 71% (29%) for the metal-rich (metal-poor) disk population. The similarity between the mixed (median [Fe/H]$_{\text{phot}} = -0.16$) and disk MDFs implies that this intermediate population may be dominated by genuine disk stars that are located in subregions with larger halo fractions or similar mean velocities for the halo and the disk (Section 6.1), resulting in an uncertain separation between structural components. The halo MDF (median [Fe/H]$_{\text{phot}} = -0.46$) is best described by a metal-rich (metal-poor) component with [Fe/H]$_{\text{phot}} = -0.18 \pm 0.89$, $\sigma_{\text{phot}} = 0.22 \pm 0.44$ and a fractional contribution of 48% (52%).

The presence of halo stars with similar metallicity to the disk is unusual, given the expectation of halos typically being metal-poor. However, the metal-rich halo population appears to be genuine, where $\leq 4\%$ of the metal-rich halo stars are expected to be disk interlopers. In Appendix D, we estimate this fraction by calculating the expected number of disk (halo) contaminants, given the $p_{\text{disk}}$-based definition for the halo (disk) population from the velocity models (Section 3.2). We then assess the maximal impact expected on the fiducial disk (disk)
MDF from the contamination by metal-rich disk (metal-poor halo) stars, using the MDF models (Figure 9).

Figure 10 shows the relationship between [Fe/H]_{phot} and $v_{\text{helio}}$ for each population. The halo population is concentrated at $v_{\text{helio}} \lesssim -200$ km s$^{-1}$, owing to the high likelihood that stars with $-200$ km s$^{-1} \lesssim v_{\text{helio}} \lesssim 0$ km s$^{-1}$ belong to the disk (Table 1), regardless of metallicity. Figure 10 further demonstrates that the dominant metal-rich disk population ([Fe/H]_{phot} $\sim -0.10$ and $v_{\text{helio}} \sim -100$ km s$^{-1}$) appears to continuously extend toward M31’s systemic velocity, where a similarly metal-rich group of stars is evident at $v_{\text{helio}} \sim -200$ km s$^{-1}$ ($-280$ km s$^{-1}$) in the mixed (halo) population. The metal-rich halo stars mainly belong to this group, where a second kinematically hotter population encompasses the majority of the metal-poor halo stars. In order to identify the stars in the metal-rich group, we modeled the halo in metallicity versus velocity space as a combination of bivariate normal distributions:

$$G(v, x | \mu, \sigma, r) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r^2}} \times \exp \left( -\frac{1}{2(1-r^2)} \left[ \frac{(v - \mu_v)^2}{\sigma_v^2} + \frac{(x - \mu_x)^2}{\sigma_x^2} - \frac{2r(v - \mu_v)(x - \mu_x)}{\sigma_v\sigma_x} \right] \right),$$

$$G = f_{\text{mp}} G_{\text{mp}} + (1 - f_{\text{mp}}) G_{\text{mr}},$$

where $v$ is $v_{\text{helio}}$, $x$ is [Fe/H]_{phot}, $\mu = (\mu_v, \mu_x)$, $\sigma = (\sigma_v, \sigma_x)$, and $r$ are the mean, standard deviation, and correlation coefficient of the normal distribution. The halo is separated into a metal-poor population, with fractional contribution $f_{\text{mp}}$, and a metal-rich group, with $f_{\text{mr}} = 1 - f_{\text{mp}}$. We sampled from the posterior probability distribution (Foreman-Mackey et al. 2013) of Equation (5) to obtain $\mu = (-280.9 \pm 6.1$ km s$^{-1}$, $-0.15 \pm 0.03$), $\sigma = (42.9 \pm 4.9$ km s$^{-1}$, 0.20 $\pm 0.02$), $r = 0.25 \pm 0.12$, and $f_{\text{mr}} = 0.26 \pm 0.03$, for the metal-rich group of halo stars. For the metal-poor group, we found $\mu = (-347.1 \pm 7.4$ km s$^{-1}$, $-0.69 \pm 0.03$), $\sigma = (141.0 \pm 4.9$ km s$^{-1}$, 0.50 $\pm 0.02$), and $r = 0.04 \pm 0.05$. For each halo star, we calculated the probability of belonging to the metal-rich group, $P_{\text{mr}}$, based on the likelihood ratio between $G_{\text{mr}}$ and $G_{\text{mp}}$. We assigned stars to this group if $P_{\text{mr}} > 0.75$, where $<2.2\%$ are expected to be disk interlopers (Appendix D). We further explore the properties of this interestingly metal-rich halo group—and the broader halo

| Pop. | med([Fe/H]_{phot}) | $\langle$[Fe/H]_{phot}$\rangle$ | $\sigma$([Fe/H]_{phot}) |
|------|-------------------|-----------------|------------------|
| Halo | $-0.46$           | $-0.55 \pm 0.02$ | 0.50             |
| Mixed | $-0.16$          | $-0.31 \pm 0.02$ | 0.48             |
| Disk | $-0.19$          | $-0.33 \pm 0.01$ | 0.51             |

Note. The columns show the populations and the simple medians, means, and standard deviations of their metallicity distributions, where [Fe/H]_{phot} has been corrected for all sources of dust extinction (Section 4.2). The populations are defined using the spatially and kinematically based probability that an RGB star belongs to the disk (Sections 3.2.2 and 5.1).
to the high likelihood that stars with metal-poor.

We show a histogram in the higher-density region of the disk population from Quirk et al. Various RGB subpopulations. We used the AD measurements stellar rotation velocity at a given deprojected radius, for the in Section 5.2. The halo population is more metal-poor, but still has metal-rich stars (Section 5.1).

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Figure 9. MDFs of the RGB stars (black outlined, gray filled histograms; Section 5.1), corrected for all sources of dust extinction ([Fe/H]_{phot}. Section 4.2). We separate the stars into halo (left; p_{disk} < 0.25; Section 3.2.2), mixed (middle; 0.25 < p_{disk} < 0.75), and disk (right; p_{disk} > 0.75) populations. The bin size is 0.10, where the median δ[Fe/H]_{disk} is 0.03. The median metallicity for each population is indicated by the arrows. For the halo, mixed, and disk populations, the median [Fe/H]_{phot} are −0.46, −0.16, and −0.19, respectively (Table 2). The dotted histogram shows the resulting halo (disk) MDF in the most extreme case of contamination by metal-rich disk (metal-poor halo) interlopers (Appendix D). The blue shading defines the uncertainty region between the fiducial (solid) and contamination-corrected (dotted) MDFs. The MDFs for the disk and mixed populations are similar. The halo population is more metal-poor, but still has metal-rich stars (Section 5.1).

Figure 10. Photometric metallicity vs. heliocentric velocity for the RGB stars in SPLASH (Section 5.1). We omit showing the [Fe/H]_{phot} and v_{helio} measurement uncertainties for clarity (with typical values of 0.03 and 5–10 km s\(^{-1}\), respectively). From left to right, the stars are separated into halo, mixed, and disk populations. We show a histogram in the higher-density region of the disk population (bins 25 km s\(^{-1}\) and 0.1). The halo population is concentrated at v_{helio} ≲ −200 km s\(^{-1}\), owing to the high likelihood that stars with −200 km s\(^{-1}\) ≲ v_{helio} ≲ 0 km s\(^{-1}\) belong to the dominant disk component (Table 1). Most disk stars are concentrated around [Fe/H]_{phot} ≈ −0.10 and v_{helio} ≈ −100 km s\(^{-1}\), although a metal-poor tail is also present. The mixed population is dominated by stars with disk-like [Fe/H]_{phot}, but lower v_{helio} ≈ −200 km s\(^{-1}\). The halo shows evidence of a population with disk-like [Fe/H]_{phot} at v_{helio} ≈ −280 km s\(^{-1}\), and another that is kinematically hotter and more metal-poor.

population—with respect to the rotation of M31’s gaseous disk in Section 5.2.

5.2. AD

We examined AD, or the difference between the gas and stellar rotation velocity at a given deprojected radius, for the various RGB subpopulations. We used the AD measurements from Quirk et al. (2019), determined using the SPLASH stellar velocities (Dorman et al. 2012, 2013, 2015), and H I 21 cm data (Chemin et al. 2009) in combination with a tilted ring model, to derive stellar and gaseous rotation curves for M31’s disk. Quirk et al. (2019) found that the AD increases with mean stellar age, as traced by various stellar types, where old RGB stars (4 Gyr) lag the gas the farthest at 63.0 km s\(^{-1}\). The variation in AD between the stellar types is significantly larger than within the population of a given stellar type, such as RGB stars (Quirk et al. 2019).\(^{14}\)

Figure 11 shows the relationship between AD and v_{helio} for RGB stars, as defined in this work (Sections 3.1 and 4.1), color-coded by disk probability. We separated the stars into groups on and off the major axis, with the former containing the stars in subregions that straddle the major axis (i.e., with the subscript “1”; Table 1) and the latter containing all the other stars. The AD distribution for off-axis stars exhibits more

\(^{14}\) We also note that AD measurements are only available for RGB stars with [Fe/H]_{phot} ≥ −1, due to the shape of the CMD-based RGB selection box used by Quirk et al. (2019). For the 71.8%, 84.7%, and 79.5% of stars in the halo, mixed, and disk populations that have [Fe/H] > −1 and AD measurements, we find that the AD is independent of the metallicity for each RGB subpopulation. We therefore do not expect this metallicity bias to significantly impact the comparison of the relative ADs between subpopulations.
scatter than those for on-axis stars, due to the geometrical effects that are associated with measuring AD in an inclined disk (Quirk et al. 2019). Considering both on- and off-axis RGB stars, the median ADs are 61.0$^{+8.9}_{-0.8}$, 57.6$^{+3.5}_{-2.6}$, and 66.4$^{+1.5}_{-2.2}$ km s$^{-1}$ for the disk, mixed, and halo populations, respectively. At face value, this suggests that the halo and disk ADs are marginally consistent at the 1.8σ level, and that the mixed and disk populations have fully consistent ADs. However, given the geometrical effects impacting the empirical AD measurements in areas off the major axis, the on-axis RGB stars provide a more precise representation of the underlying AD distribution. In this case, the median AD increases between the disk (68.7$^{+0.9}_{-0.8}$ km s$^{-1}$) and the mixed (75.1$^{+1.4}_{-1.2}$ km s$^{-1}$) and halo (74.6$^{+1.4}_{-1.4}$ km s$^{-1}$) populations, in accordance with the expectations for dynamically colder to hotter populations. The disk and halo ADs are distinct at the 2.9σ level, whereas the mixed population AD is consistent with the halo, but differs from the disk by 2.7σ. The finding that the halo lags the gaseous disk to a greater extent than the stellar disk is likely robust, given the supporting results from both the on-axis sample and the full sample of RGB stars. Although the MDF of the mixed population is similar to that of the disk (Section 5.1), it is not immediately clear whether its AD is disk-like or halo-like. We favor the latter interpretation, based on the more precise AD distribution from on-axis RGB stars, which may suggest that the mixed population is dominated by disk stars on kinematically hotter orbits (Section 6.1).

The metal-rich group of halo stars ([Fe/H]$_{\text{phot}}$ $\sim$ −0.10) identified in Section 5.1 has a median AD of 77.4$^{+5.0}_{-5.9}$ km s$^{-1}$, based on the RGB tracers on the major axis, and a median AD of 63.8$^{+2.9}_{-3.2}$ km s$^{-1}$, based on all the RGB tracers. In Figure 11, this metal-rich halo group corresponds to stars clustered near $v_{\text{helio}}$ $\sim$ −280 km s$^{-1}$, with $p_{\text{disk}}$ < 0.25. The rest of the halo ($p_{\text{dis}}$ < 0.75) has ADs of 73.4$^{+1.6}_{-1.5}$ and 67.9$^{+1.0}_{-1.0}$, based on the on-axis and all the RGB tracers, respectively. For both RGB samples, the AD of the metal-rich halo group is consistent with the rest of the halo within 1σ. For the full RGB sample, the metal-rich halo group AD is marginally consistent with the disk at 1.3σ, but is more distinct at 1.9σ, when comparing the median ADs computed from the on-axis RGB sample. However, we again interpret the on-axis ADs as being more accurate.

Thus, regardless of its disk-like metallicity, the metal-rich halo group has kinematics that are inconsistent with a stellar disk. We also note that despite the minor yet meaningful differences in AD, the RGB ADs are remarkably similar as a whole. This indicates that the stellar disk is almost as removed from the gaseous disk as the stellar halo, providing evidence that the disk has experienced significant dynamical disturbance (s) (Section 6.3).

### 5.3. Radial Metallicity Gradients

We investigated whether radial metallicity gradients are present in M31’s disk and halo populations across the SPLASH survey region ($R_{\text{disk}}$ $\sim$ 6–18 deprojected kpc). Based on photometry alone, M31’s disk was previously found to possess a negative metallicity gradient ($-0.020 \pm 0.004$ dex kpc$^{-1}$) between $R_{\text{disk}}$ $\sim$ 4–20 deprojected kpc, from a sample of 7 million RGB stars in the PHAT survey (Gregersen et al. 2015). The authors accounted for photometric effects, due to crowding and dust extinction, but not for the effects of contamination from stars in the MW foreground or M31’s halo.

We measured the gradients using all the stars in the disk ($p_{\text{disk}}$ > 0.75) and halo ($p_{\text{disk}}$ < 0.25) populations. We parameterized the gradients in terms of angles and transverse distances (Hogg et al. 2010), which we converted to traditional slopes and intercepts, after sampling from the posterior probability distribution of the linear model (Foreman-Mackey et al. 2013). Figure 12 shows the relationship between $R_{\text{disk}}$
and [Fe/H]$_{\text{phot}}$ for the RGB stars in SPLASH, along with the radial gradients measured for the disk and the halo. We found a slope of $-0.0176 \pm 0.0002$ dex kpc$^{-1}$ for the disk, in agreement with Gregersen et al. (2015), and a weak slope of $-0.0029 \pm 0.0004$ dex kpc$^{-1}$ for the halo. The associated intercept is $[\text{Fe/H}]_{\text{phot}} = +0.037 \pm 0.004$ ($-0.335 \pm 0.005$) for the disk (halo).

The treatment of dust extinction (Section 4) has a minor effect on the measured gradients. Using the low-extinction RGB sample, defined by $f_{\text{red}} \times A_{V,\text{Gal}} < 0.25$, instead yields a slope of $-0.0200 \pm 0.0003$ ($-0.0031 \pm 0.0005$) dex kpc$^{-1}$ and an intercept of $+0.092 \pm 0.005$ ($-0.318 \pm 0.007$) for the disk (halo). Disregarding the dust in M31’s disk entirely yields a slope of $-0.0200 \pm 0.0002$ ($-0.0055 \pm 0.0004$) and an intercept of $+0.092 \pm 0.004$ ($-0.269 \pm 0.005$) for the disk (halo). Our main findings of a gradient of approximately $-0.02$ dex kpc$^{-1}$ in the disk and a weak negative gradient in the halo are therefore robust against dust effects. We adopted $-0.018_{-0.001}^{+0.003}$ ($-0.003_{-0.003}^{+0.003}$) as an encompassing range for the disk (halo) gradient slope.

In contrast to the slopes, the gradient intercepts are sensitive to the treatment of dust within 0.1 dex. Moreover, changes in the assumed stellar age result in absolute metallicity differences up to 0.26 (Section 4). However, the fiducial isochrone age should not affect the gradient slopes, owing to the relatively constant shape of the RGB with stellar age. Instead, Gregersen et al. (2015) found that the presence of a negative age gradient with a magnitude larger than 0.1 Gyr kpc$^{-1}$ could flatten an apparent metallicity gradient in M31’s disk. Nonetheless, the resolved PHAT-based star formation histories for M31’s disk do not show notable variations in the stellar age distribution with spatial position (Williams et al. 2015, 2017). $^{17}$ Moreover, observations of massive external disk galaxies suggest that M31’s age gradient should be $\lesssim 0.1$ Gyr kpc$^{-1}$ (e.g., Sánchez-Blázquez et al. 2014; Goddard et al. 2017).

We refer the reader to Gregersen et al. (2015) for a discussion of the metallicity gradient in M31’s disk in the context of the literature. Recent developments regarding the thickness of M31’s disk (J. Dalcanton et al. 2023, in preparation) imply that this shallow radial gradient may be the result of merger-driven mixing combined with projection effects. In addition, populations of high-extinction, kinematically colder and low-extinction, kinematically hotter intermediate-age planetary nebulae along the line of sight to M31’s disk have recently been found to have radial argon gradients of $-0.02$ dex kpc$^{-1}$ and $-0.005$ dex kpc$^{-1}$ (Bhattacharya et al. 2022), respectively, similar to the disk and halo RGB populations in this work. We also note that although the halo metallicity gradient is weak over the scale of the probed disk region, it is similar to the photometric metallicity gradient previously measured for the halo along the minor axis (1 dex over 100 kpc, Gilbert et al. 2014).

6. Discussion

In this section, we place our findings relating to the chemodynamical properties of the disk, halo, and mixed populations (Section 5) in a broader context. We discuss the nature of the mixed population and its implications for M31’s thickened disk structure in Section 6.1. We show that the metal-rich group of halo stars (identified in Section 5.1) is inconsistent with its origins being in the GSS merger event in Section 6.2. We also demonstrate that M31’s inner halo, as probed along the major axis (i.e., near the disk), is distinct from the phase-mixed component that has previously been studied along the minor axis (i.e., away from the disk). We put forward the hypothesis that this metal-rich halo group was kicked up from the disk and that M31’s inner halo possesses an in situ population similar to the MW in Section 6.3.

6.1. Disk Structure

The “mixed” population defined in Section 3.2.1, which constitutes 13.0% of the sample, consists of stars that cannot be securely associated with the stellar halo or dynamically colder disk. These stars have a disk-like MDF (Section 5.1), but kinematical properties that are intermediate between the disk and the halo (Section 5.2). This raises the question of whether the mixed population is dominated by disk stars with uncertain kinematical classifications, potentially representing a “thicker” disk that is not captured by the adopted two-component velocity model (Section 3.2). Alternatively, the mixed population could simply correspond to a transition region between a uniformly thick disk and the stellar halo, possibly including kicked-up disk stars (Section 6.3).

We found that modifying the line-of-sight velocity distribution models (Section 3.2.2) to allow for a two-component disk does not result in better descriptions of the data, as evaluated using Bayesian information criteria (BICs; Appendix E). Currently, evidence in favor of a multiple-component disk structure in the PHAT region is lacking. Instead, the dominant RGB population in M31’s disk region traces a thickened disk with a scale height of 0.77 kpc, as probed by the fraction of reddened stars (J. Dalcanton et al. 2022, in preparation). This is substantially larger than the scale height of the integrated stellar disk of the MW (0.40 kpc; Bovy & Rix 2013), despite the

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$^{17}$ The PHAT-based star formation histories have only a few age bins for stellar populations older than 5 Gyr, such that they cannot resolve age gradients at the 0.1 Gyr kpc$^{-1}$ level.
relatively young age (4 Gyr; Section 4) and high metallicity (−0.19; Section 5.1) of M31’s disk. Moreover, the fundamentally thick nature of M31’s disk is corroborated by its large line-of-sight velocity dispersion (≈50–60 km s⁻¹), as traced by RGB stars (Ibata et al. 2005; Dorman et al. 2012; this work) and planetary nebulae (e.g., Bhattacharyya et al. 2019).

We note that the coarse relationship between velocity dispersion and metallicity found by Dorman et al. (2015) does not necessarily support a multiple-component disk structure, but rather likely reflects the metallicity differences between the spatial regions that are dominated by the stellar halo or the disk. This is because Dorman et al. (2015) did not separate the disk and halo stars, but considered all the RGB stars together, though their analysis is based on the same spectroscopic data set as this work, with similar membership criteria applied. For example, we found that separating the RGB stars into metal-rich and metal-poor bins, analogous to Dorman et al. (2015), reproduces a negative correlation between metallicity and velocity dispersion, which is driven by the relative fractional contribution of the halo stars to each metallicity bin. Furthermore, the thick disk component argued for by Collins et al. (2011) on the outskirts (≥15 kpc) of M31’s southern disk probably does not translate to the inner regions of M31’s northern disk, as probed in this work (see the discussion by J. Dalcanton et al. 2022, in preparation).

We therefore favor the hypothesis that the mixed population mostly consists of stars from a thickened disk (with some halo contamination) that can be reasonably described by a single kinematical component. In general, an unambiguous kinematical detection of multiple structural components in a projected disk would require comparisons to predicted line-of-sight velocity distributions obtained via forward modeling.

6.2. The Minor-axis Halo and Northeast Shelf

We compared the stellar populations in M31’s halo along its major axis (i.e., near the disk) to those previously studied along its minor axis (i.e., away from the disk). Our aim was to assess whether there was an evolutionary connection between the major-axis halo and the disk or whether the major-axis and minor-axis halo share the same likely accretion-dominated origin (e.g., Gilbert et al. 2014; McConnachie et al. 2018; Escala et al. 2020b). We also compared the major-axis halo to the Northeast (NE) shelf, a tidal shell likely associated with the GSS (e.g., Ferguson et al. 2002, 2005; Dey et al. 2022; Escala et al. 2022), given the prediction that it may overlap with the PHAT region and may therefore pollute the major-axis halo (Fardal et al. 2007, 2013). The metal-rich nature of the GSS progenitor (Gilbert et al. 2007, 2009, 2019; Ibata et al. 2007; Fardal et al. 2012; Escala et al. 2021, 2022) also raises the possibility that the metal-rich group of halo stars (Section 5.1) could correspond to GSS-related tidal debris.

We used data for the minor-axis halo (Gilbert et al. 2012, 2014) and NE shelf (Escala et al. 2022) from SPLASH. We defined the minor-axis halo using spectroscopic fields spanning 8–18 projected kpc (Gilbert et al. 2012), covering a radial range comparable to the disk region data (4–18 projected kpc). We also excluded known kinematically cold tidal debris from the Southeast shelf (Gilbert et al. 2007) and GSS (Kalirai et al. 2006; Gilbert et al. 2009) in the minor-axis halo, by requiring a star’s probability of belonging to the substructure to be low (p_{sub} < 0.2), where p_{sub} is defined analogously to p_{disk} using the velocity models of Gilbert et al. (2018). For the NE shelf, we used the criterion p_{sub} > 0.75, which excludes the majority of the stars that are suspected to be disk contaminants (Escala et al. 2022).

To eliminate the [Fe/H]_{phot} scale as a source of uncertainty in the comparison to the major-axis halo, we determined [Fe/H]_{phot} homogeneously for the minor-axis halo and NE shelf, using 4 Gyr isochrones (Section 4). However, previously published [Fe/H]_{phot} measurements from SPLASH for these stellar structures assume 12 Gyr ages, where the mean ages of the minor-axis halo and NE shelf are 10–11 Gyr (Brown et al. 2007, 2008) and 8 Gyr (Ferguson et al. 2005; Richardson et al. 2008), respectively. Assuming 12 Gyr instead of 4 Gyr ages shifts the [Fe/H]_{phot} distributions by −0.26 dex, where the median [Fe/H]_{phot} = −0.15 and −0.16 for the minor-axis halo and the NE shelf, respectively, in the 4 Gyr case.

We note that whether the innermost minor-axis halo field (f109) at R_{proj} = 9 kpc is included also impacts the associated [Fe/H]_{phot} distribution, where the exclusion of this field changes the median [Fe/H]_{phot} to −0.29. Although M31’s extended disk reaches beyond R_{disk} ∼ 40 kpc (Ibata et al. 2005), and is expected to have a line-of-sight velocity on the minor axis equivalent to M31’s systemic velocity (≈300 km s⁻¹), the disk fraction is predicted to be ≤10% at R_{disk} = 38 kpc in f109 (Guhathakurta et al. 2005). Furthermore, no evidence of a kinematically cold disk feature has been detected in the velocity distribution of this field (Gilbert et al. 2007; Escala et al. 2020a), so we included f109 for a more accurate representation of the minor-axis halo [Fe/H]_{phot} distribution over this radial range.

Figure 13 shows [Fe/H]_{phot} distributions, v_{helio} distributions, and the relationship between [Fe/H]_{phot} and v_{helio} for the minor-axis halo, major-axis halo, and NE shelf. Regardless of the adopted age, the metallicity versus velocity distribution of the major-axis halo is distinct from those of the minor-axis halo and NE shelf. Performing Anderson–Darling tests, where the [Fe/H]_{phot} measurements were perturbed by their (Gaussian) uncertainties, yields that the major-axis halo is inconsistent with being drawn from the same distribution as the minor-axis halo or NE shelf at the 0.1% significance level, with 95% confidence. Moreover, the pronounced cluster of major-axis halo stars at [Fe/H]_{phot} ~ −0.10 and v_{helio} ~ −280 km s⁻¹ is missing from the other stellar structures. Even for different locations in M31, the velocity of any metal-rich cluster with the same origin would remain close to M31’s systemic velocity of −300 km s⁻¹, given that it corresponds to a dynamically hot population characterized by a lack of rotation relative to the disk (Section 5.2).

Thus, M31’s major-axis halo likely contains stellar populations that are absent from the phase-mixed component of the minor-axis halo and not dominated by GSS-related tidal debris. Even when restricting the major-axis halo population to stars with p_{ms} < 0.25, it remains distinct from the minor-axis halo

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18 This includes fields f109, H11, f116, f115, f207, f135, and f123. We classified stars with likelihoods (L_i) > 0 when including radial velocity as a diagnostic (Gilbert et al. 2006) for M31 members.

19 Field f109 may also contain Southeast shelf stars (i.e., GSS-related tidal material), but at a level not kinematically distinguishable from the phase-mixed halo (Gilbert et al. 2007).

20 When excluding field f109 from the minor-axis halo sample, the major-axis halo is distinct from the minor-axis halo at the 1.8% significance level within this confidence interval.
and NE shelf. This is also the case when limiting the MDFs of each stellar structure to [Fe/H]_{phot} > −1, which corresponds to the RGB region in the CMD that should be entirely free of contamination by metal-rich helium-burning stars (Section 4).

We additionally evaluated whether such tidal material was likely to pollute the major-axis halo, by comparing to predictions of N-body models for the formation of the GSS and the NE shelf. We utilized a re-simulation of the Fardal et al. (2007) model for the complete disruption of a satellite progenitor 0.8 Gyr ago, with stellar mass M_{sat} = 2.2 \times 10^{9} M_{\odot}, which broadly provides a good match to observations of the NE shelf (Escala et al. 2022). Figure 14 shows the projected phase-space distribution of the major-axis halo compared to the model predictions for the NE shelf tidal debris at the locations of the SPLASH disk fields (Figure 1). The model predicts that M31 host particles constitute 98.9% of the stellar material in the SPLASH survey region, with the caveat that the specific fractional contribution depends on the assumed mass (M_{host} = 1.1 \times 10^{13} M_{\odot}) and the structural components of the host model. We therefore expect the NE shelf to be most detectable in the SPLASH region at velocities far removed from the disk (v_{helio} ≈ −100 km s\(^{-1}\)) and along the high-density lower envelope of the tidal shell in the projected phase space (v_{helio} ≈ −500 km s\(^{-1}\) and R_{proj} ≈ 5–18 kpc; Figure 14; see also Dorman et al. 2012).\(^{21}\) Most stars in the major-axis halo, including the metal-rich group of stars concentrated near v_{helio} ≈ −280 km s\(^{-1}\), are unlikely to originate from a disrupted satellite progenitor, based on the expected debris pattern and the relative stellar density between M31’s disk and the putative debris.

We have established that the major-axis halo over the SPLASH survey region probably does not predominantly originate from the recent accretion of the GSS progenitor in a minor-merger scenario. Detailed predictions for GSS-related tidal debris in M31’s disk region in a major-merger scenario (D’Souza & Bell 2018; Hammer et al. 2018) currently remain unexplored, although any such realistic simulation must be able to broadly reproduce the shell pattern of the NE shelf (similar to Figure 14; Dey et al. 2022; Escala et al. 2022). The remaining halo formation channels involve ancient accretion

\(^{21}\) Interestingly, halo stars with v_{helio} < −500 km s\(^{-1}\) mostly have [Fe/H]_{phot} > −1, similar to the NE shelf (assuming 4 Gyr isochrones; Figure 13), and may have higher AD than the dominant halo population (Figure 11). These properties could be consistent with a GSS-related origin.
and/or dissipative collapse or kinematical heating of the disk for an in situ component. The dominant metal-poor halo population ([Fe/H]$_{\text{phot}} \sim -0.89$; Section 5.1) may have formed via accretion or in a “classical” in situ scenario; we discuss the possibility that the metal-rich group ($v_{\text{helio}} = -280.9$ km s$^{-1}$, [Fe/H]$_{\text{phot}} = -0.15$) could have been kinematically heated from the disk by M31’s last significant merger in Section 6.3.

### 6.3. Kicked-up Disk Stars

We have identified a metal-rich group of stars ($v_{\text{helio}} = -280.9$ km s$^{-1}$, [Fe/H]$_{\text{phot}} = -0.15$, $f = 0.26$; Section 5.1) in M31’s major-axis halo that lags the rotation of the gaseous disk to a similar extent as the rest of the halo population (Section 5.2). This group is inconsistent with the observed and predicted properties for GSS-related tidal debris, and it appears to be absent from M31’s minor-axis halo (Section 6.2). M31’s bulge is too compact ($r_p = 0.78$ kpc; Dorman et al. 2013) to contribute to the stellar populations in the surveyed disk region, such that M31’s “spheroid” is indeed the stellar halo.

Based on a structural decomposition of M31’s bulge, disk, and halo, using I-band surface brightness profiles, PHAT luminosity functions, and SPLASH kinematics, Dorman et al. (2013) found statistical evidence for an excess of stars (5.2\% ± 1.2\%) following a disk-like luminosity function, but having halo-like kinematics. We propose that the metal-rich group of halo stars identified in this work is the same “kicked-up” disk population. The primary difference between this work and Dorman et al. (2013) is that we have performed a resolved chemodynamical analysis that is minimally dependent on model assumptions. This has enabled us to characterize M31’s putative kicked-up disk stars in detail, as a distinct stellar population. These stars contribute 4.6\% of the total RGB sample (see Appendix D for the small effect of the disk interlopers). Using the fractional contributions from Table 1, the total statistical fraction of disk RGB stars in the sample is 74.9\% ± 4.5\%. The estimated kicked-up disk fraction is therefore 5.7\% ± 0.2\%.

The chemical and kinematical properties of these metal-rich halo stars are broadly consistent with the predictions for heated disk populations in simulations of in situ stellar halo formation. As noted by Dorman et al. (2013), Purcell et al. (2010) found that ~1% of the stars should be heated into the halo from the disk by a minor merger at a low impact angle, which is comparable to, but systematically lower than, the estimates of the kicked-up disk fraction in M31. Moreover, stars heated from the disk can fractionally constitute ~30\% of the inner stellar halo (e.g., Tissera et al. 2013; Cooper et al. 2015; Khoperskov et al. 2022b), as found in this work. Based on simulations including both major and minor mergers, Jean-Baptiste et al. (2017) found that kicked-up disk populations can appear structured in kinematical phase space and should exhibit some degree of rotation that is inversely correlated with the accreted mass. Although other studies have similarly found that disk-heated stars may show signs of rotational support, there can be significant halo-to-halo scatter (e.g., McCarthy et al. 2012; Tissera et al. 2013). M31’s metal-rich clump of halo stars has a similar degree of rotational support as the rest of the dynamically hot halo population (Section 5.2), where M31’s inner halo slowly rotates (Dorman et al. 2012).

### 6.3.1. Comparison to the MW

In the MW, stars that are born in the protodisk, but are kinematically heated onto high-eccentricity orbits by an early merger(s), constitute the sole in situ component of the stellar halo (e.g., Bonaca et al. 2017; Haywood et al. 2018; Di Matteo et al. 2019; Belokurov et al. 2020). In particular, the formation of an in situ halo, or “Splash,” has been connected to the the Gaia–Enceladus–Sausage (GES) merger event (e.g., Belokurov et al. 2018; Helmi et al. 2018; Gallart et al. 2019; Bonaca et al. 2020; Grand et al. 2020). This in situ halo component has chemical abundances similar to the thick disk (e.g., Di Matteo et al. 2019; Belokurov et al. 2020; Naidu et al. 2020), old stellar ages comparable to the accreted component of the stellar halo (e.g., Gallart et al. 2019; Bonaca et al. 2020), and smooth transitions in metallicity versus velocity space from the thin and thick disks (e.g., Belokurov et al. 2020). Furthermore, it fractionally constitutes <15\% of the MW’s stellar halo for disk heights above 2 kpc (Naidu et al. 2020).

Although we cannot perform one-to-one comparisons with the MW’s stellar halo, our results suggest that M31 may possess a fractionally larger (28.9\% of halo RGB stars; Section 5.1) in situ halo component than the MW. In contrast to M31, the MDF of the MW’s inner halo is strongly bimodal, due to in situ ([Fe/H] ~ −0.5) and accreted ([Fe/H] ~ −1.2) components that are dominated by the Splash and the GES merger remnant, respectively (e.g., Bonaca et al. 2017; Di Matteo et al. 2019). However, given M31’s more active merger history (e.g., McConnachie et al. 2018), there is no a priori reason to expect M31’s inner halo to exhibit the same metallicity signatures as the MW. In simulations of stellar halo formation, the in situ halo is generally more metal-rich than the accreted component (Zolotov et al. 2009; Font et al. 2011; Tissera et al. 2012, 2013, 2014; Cooper et al. 2015; Pillepich et al. 2015; Khoperskov et al. 2022a), but otherwise halo MDFs can vary, owing to the scatter in formation histories.
7. Summary

We have combined optical HST photometry from PHAT with Keck/DEIMOS spectra from SPLASH to execute the first large-scale chemodynamical analysis of M31’s inner disk region (4–19 kpc), based on metallicity and velocity measurements for 3512 RGB stars. We have performed a kinematical decomposition as a function of position across the disk region, where the line-of-sight velocity distributions are well described by the combination of a thick stellar disk and stellar halo. As originally found by Dorman et al. (2012), the disk-dominated (72.6% of RGB stars) region nevertheless has a substantial contribution from the inner stellar halo (14.4% of RGB stars) as well as an intermediate population with uncertain disk–halo classifications (13.0% of RGB stars). We have further found that:

1. Assuming 4 Gyr stellar ages, the disk is characterized by a dominant metal-rich population (median [Fe/H]_{phot} = −0.19, when corrected for dust effects; Sections 4 and 5.1). The stellar halo is more metal-poor ([Fe/H]_{phot} = −0.46), but contains a non-negligible fractional contribution (f = 0.26) from a stellar population with disk-like metallicity ([Fe/H]_{phot} = −0.15) that appears as a continuous extension of the disk in velocity space (v_{helio} = −280.9 km s⁻¹).

2. The AD, or rotational lag between the stellar and gaseous disks, is similar between the disk (68.7⁺⁻₀.₉₈ km s⁻¹) and halo (74.6₂⁺⁻₁.₁₄ km s⁻¹) populations (Quirk et al. 2019; Section 5.2), suggesting that the disk has experienced significant dynamical heating. Despite this similarity, the halo AD is inconsistent with that of the disk, and the metal-rich halo stars have an AD (77.4⁺⁻₁.₃₈ km s⁻¹) that does not correspond to a canonical thick disk.

3. The disk metallicity gradient is −0.018⁺⁻₀.₀₀₃ dex kpc⁻¹, in agreement with Gregersen et al. (2015). This shallow gradient may originate from merger-driving mixing combined with projection effects. The halo metallicity gradient is similar to that measured over 100 kpc scales along the minor axis (Gilbert et al. 2014) at −0.00₃⁺⁻₀.₀₀₁ dex kpc⁻¹ (Section 5.3).

4. RGB stars with uncertain disk–halo classifications have a disk-like MDF (Section 5.1) and AD intermediate between the disk and the halo (Section 5.2). Rather than corresponding to a second thicker disk component, this mixed population is likely dominated by stars from a single thickened disk as it transitions into a stellar halo (Section 6.1).

5. The MDF of M31’s inner halo along the major axis (i.e., near the disk) is distinct from the halo MDF probed along the minor axis (i.e., away from the disk) over an equivalent radial range (Section 6.2). The metallicity and projected phase-space properties of the metal-rich major-axis halo stars are also inconsistent with the observations of the NE shelf and the predictions for GSS-related tidal debris in a minor-merger scenario (Fardal et al. 2007; Escala et al. 2022). This indicates that they were probably not accreted onto the halo.

6. The chemical and kinematical properties of the metal-rich halo stars (Sections 5.1 and 5.2) broadly agree with the predictions for heated disk populations and some expectations for an in situ halo, based on current knowledge of the MW (Section 6.3). The estimated fraction of kicked-up disk stars is 5.7% ± 0.2% of the RGB stars in the surveyed region, in agreement with the statistically inferred value of 5.2% ± 1.2% from Dorman et al. (2013).

These findings point to a scenario in which M31’s inner stellar halo along the major axis is distinct from the minor-axis halo, implying potentially disparate origins for each stellar structure. In particular, the minor-axis halo may be dominated by accretion from the GSS merger and more ancient events (e.g., Brown et al. 2006; Gilbert et al. 2007, 2014; Ibata et al. 2014; McConnachie et al. 2018; Escala et al. 2020b; Dey et al. 2022), whereas the metal-rich nature of the major-axis halo and the thickened nature of the disk suggest an entangled evolutionary history, potentially driven by merger(s) and subsequent disk heating.

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Facilities: Keck (DEIMOS), HST (ACS).

Software: astropy (Astropy Collaboration et al. 2013, 2018), emcee (Foreman-Mackey et al. 2013), matplotlib (Hunter 2007), numpy (Harris et al. 2020), scipy (Virtanen et al. 2020).

Appendix A

MW Foreground Contamination

As discussed in Section 3.1, we expect the contamination from the MW foreground along the line of sight to M31’s disk to be significantly less than in other regions of M31, such as a stellar halo along the minor axis, given that the stellar surface density of M31’s disk is much higher than the MW. Here, we confirm the negligible contribution from MW contaminants by using the Besançon model (Robin et al. 2003). We simulated the MW foreground over the area and magnitude ranges spanned by the SPLASH survey, assuming all ages, spectral types, and distances out to 150 kpc for MW stars. We used photometric transformations from Sirianni et al. (2005) to convert the output BVRI photometry to the ACS system. We also refined the sample of MW foreground stars by limiting

22 https://model.obs-besancon.fr/modèle_home.php
their locations to the SPLASH fields on the sky (Figure 1). We calculated the expected fraction of MW contaminants in a given CM bin:

\[
f_{\text{MW, expected, CM}} = \frac{N_{\text{Besancon,CM}}}{N_{\text{PHAT,CM}}},
\]

where \(N_{\text{PHAT,CM}}\) is the number of stars observed by the PHAT survey in each CMD bin. We applied the CMD criterion for M31 membership (Section 3.1), to restrict the MW foreground population to the CMD region corresponding to M31 giant stars. Figure 15 shows the expected fraction of MW contaminants (\(f_{\text{MW, expected, CM}}\); left panel) compared to the number density of the SPLASH M31 giants (according to the CMD criterion) without EW\(_{\text{Na}}\) measurements (right panel). The most contaminated portions of the CMD are \(F814W_0 \lesssim 20.5\) and \((F475W - F814W)_0 \lesssim 4\), where there are few SPLASH stars in this region (corresponding to relatively blue stars above the TRGB; see also Figure 2). We therefore expect \(\sim 0.2\%\) of the SPLASH stars to be MW contaminants, based on CMD information alone.

**Appendix B**

**Velocity Models for Additional Regions**

Here, we show the velocity distributions and model fits (Section 3.2) for regions R1 (Figure 16) and R2 (Figure 17), for completion.
Figure 16. The same as Figure 4, except for region R1.

Figure 17. The same as Figure 4, except for region R2.
The black dashed lines are the estimated metallicity and age. Note that the axes are not shown to equal scale, for clarity.

RGB CMD, taking into account stellar surface density variations (that the majority of stars are in front of the dust layer and not significantly reddened.

Figure 18. IR (F110W, F160W) PHAT v2 CMD (Dalcanton et al. 2012; Williams et al. 2014) for the RGB stars in SPLASH (Appendix C). The RGB classification is based on the foreground reddening–corrected optical CMD (Section 4.1). The RGB stars follow a tight sequence that is insensitive to metallicity and age. Note that the axes are not shown to equal scale, for clarity. The black dashed lines are the estimated 2σ widths expected for an unreddened RGB CMD, taking into account stellar surface density variations (Dalcanton et al. 2015). The lack of a second broader sequence at redder colors suggests that the majority of stars are in front of the dust layer and not significantly reddened.

Figure 18 shows the observed PHAT v2 (F110W, F160W) CMD of the RGB stars in SPLASH, classified using the foreground reddening–corrected optical CMD (Section 4.1). The IR CMD consists of a tight sequence of unreddened stars, where this sequence is largely insensitive to age and metallicity variations, although it is weakly dependent on stellar surface density, due to the effect of crowding on the photometry (Dalcanton et al. 2015). We note that the apparent excess of blue stars in Figure 18 is partly a consequence of the unequal axis scales. This blue population corresponds to metal-poor blue stars in Figure 18, where this sequence is largely insensitive to age and metallicity.

The IR CMD consists of a tight sequence of unreddened stars, where the velocity models are derived using the halo and disk component velocity models for each subregion s in the radial region r (Equation 2, Section 3.2).

The presence of non-negligible groupings of metal-poor and metal-rich stars in the disk and halo (Section 5.1), respectively, raises the question of how much contamination from halo star interlopers is expected in the disk population (f^disk_contam) and vice versa for the halo population (f^halo_contam). We defined the halo (disk) populations using the threshold p^disk < 0.25 (p^disk > 0.75), as in Section 3.2. We computed f^disk_contam and f^halo_contam using the halo and disk component velocity models for each subregion s in the radial region r (Equation 2, Section 3.2).

For each subregion, we calculated the expected ratio of halo stars to disk stars (R^disk) in the “disk” velocity range and the “halo” velocity ranges, by integrating the velocity models over each domain. That is, for the disk velocity range:

R^disk = \frac{\int_{v_{lo,disk}}^{v_{hi,disk}} (1 - f^s) N^s(v) dv}{\int_{v_{lo,disk}}^{v_{hi,disk}} f^s N^s(v) dv},

where the velocity models are defined as in Equation (2), given the parameters in Table 1. Analogously, for the halo velocity ranges:

R^halo = \frac{\int_{v_{lo,halo}}^{v_{hi,halo}} (1 - f^s) N^s(v) dv + \int_{v_{hi,halo}}^{\infty} (1 - f^s) N^s(v) dv}{\int_{v_{lo,halo}}^{v_{hi,halo}} f^s N^s(v) dv + \int_{v_{hi,halo}}^{\infty} f^s N^s(v) dv}.

Based on the number of stars in each subregion (N^s), we converted R^disk to an expected number of halo stars, N^disk, and analogously for R^halo. Thus, f^contam is given by the expected number of interlopers in each subregion summed over the survey footprint:

\sum \sum N^s N^disk \times (N^disk + (1 - R^disk) \times N^s),

where f^halo_contam is the complementary formulation. This yields f^disk_contam = 7.8% and f^halo_contam = 7.4%.
These contamination fractions indicate that the metal-poor disk and metal-rich halo populations, which have fractional contributions to the disk and halo MDFs of 29% and 48% respectively, cannot be solely explained by interlopers originating from a predominantly metal-poor halo or metal-rich disk. This is particularly unlikely for the metal-poor disk population, owing to the high density of metal-poor stars with disk-like velocities (Figure 10). We estimated the maximal effect of the metal-rich disk (metal-poor halo) interlopers on the halo (disk) MDF by subtracting the approximate number of stars corresponding to $f_{\text{cont}}^{\text{halo}}/f_{\text{cont}}^{\text{disk}}$ from the halo (disk) sample. The stars are probabilistically removed according to their metallicity and the metal-rich (metal-poor) component model of the disk (halo) MDF, which we assumed to represent a “true” metal-rich disk (metal-poor halo) population. We performed 10^3 iterations to obtain a distribution on each statistical quantity, finding that the median and mean on [Fe/H]$_{\text{phot}}$ become $-0.50^{+0.003}_{-0.002}$ ($-0.17^{+0.001}_{-0.001}$) and $-0.58 \pm 0.002$ ($-0.31 \pm 0.002$) for the halo (disk) population (see Table 2). This corresponds a difference of $-0.08 \pm 0.05$ in the median (mean) metallicity of the halo, whereas the values for the disk are unchanged.

Figure 9 shows the effect on the fiducial halo (disk) MDF in the extremal case of contamination by disk (halo) interlopers. The halo MDF shape is affected more than the disk, although the halo population retains a significant contribution from stars with disk-like [Fe/H]$_{\text{phot}}$. The fraction of stars assigned to the metal-rich halo component, based on a simple likelihood ratio definition, decreases from 52.9% to 49.3% for the fiducial and contamination-corrected halo MDFs, respectively. We therefore do not expect more than 3.6% of metal-rich halo stars to be disk interlopers. Moreover, the fraction of stars assigned to the metal-rich halo group using the criterion $p_{\text{int}} > 0.75$ decreases from 28.9% to 26.7%, in the case of this comparison.

Appendix E

Three-component Velocity Models

To test whether the line-of-sight velocity distributions provide statistical evidence in favor of a two-component disk structure in M31 (Section 6.1), we fit the velocity distributions for each subregion with a three-component model that is nominally composed of a halo, a thick disk, and a thin disk. The likelihood function in this case is therefore

$$
\ln L = \sum_{i=1}^{N_{\text{f}}} \left[ \ln \left( f_{\mu} \mathcal{N}(v|\mu_{\mu}, \sigma_{\mu}^{-2}) + f_{\tau} \mathcal{N}(v|\mu_{\tau}, \tau_{\tau}^{-1}) \right) + (1 - f_{\mu} - f_{\tau}) \mathcal{N}(v|\mu_{\text{int}}, \tau_{\text{int}}^{-1}) \right],
$$

(E1)

in comparison to Equation (2). We required that $\mu_{\mu} > \mu_{\tau}$, $\sigma_{\mu} < \sigma_{\tau}$, and $f_{\mu} > f_{\tau}$ for the primary thin and secondary thick disk components, but otherwise we retained the same assumptions and used the same procedure as in Section 3.2.2.

We evaluated the goodness of fit of the three-component and two-component velocity models for each subregion using BICs (Figure 19). For each subregion, we found that a two-component model, consisting of a halo and single thickened disk component, provided a better description of the data. Regardless, the similarity between the BIC values indicates that a simpler two-component model provides an adequate statistical description of the data compared to a three-component model.

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