How to access the stellar halo of Andromeda

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Cooper et al. (2010), Aquarius

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Martin et al. (2013; PAndAS)
A metal-rich M31 halo

Mould & Kristian (1986)

Durrell et al. (2001)

Brown et al. (2003, 2007)
The 21st century revolution

Ibata et al. (2001)
Ferguson et al. (2002)
Irwin et al. (2005)

INT survey
CFHT survey
PANdAS
SPLASH
Why is it hard?

- Stellar halos are **low surface brightness**
  ➞ need to go faint for M31 (>3.5m telescope)

- Stellar halos are **huge**
  ➞ need to go wide for M31 (need wide-field cameras)

- Stellar halos are **structured and complex**
  ➞ requires in-depth characterization (need 8+m telescopes for spectroscopy)

- *The MW disk is in front of M31!!*
Going in-depth — SPLASH

see also Chapman et al. (2006), Koch et al. (2008)

Figure 1.
Locations of the spectroscopic fields. The location and orientation of each spectroscopic mask is denoted with a small rectangle; green rectangles denote spectroscopic masks with kinematically identified substructure. Larger rectangles denote the location and extent of the KPNO/Mosaic (black), CFHT/MegaCam (dark grey) and Subaru/Suprime-Cam (light grey) images used to design the masks. The location of the dwarf elliptical (black circles) and dwarf spheroidal (open triangles) satellites of M31 are also shown. M31’s center is marked by an open circle, and the orientations of M31’s major and minor axes are illustrated with the long and short solid lines. The dotted circles have radii of 2, 4, 6, 8 and 11 degrees from M31’s center.

2002–2011
KPNO photometry
~20–30 nights of Keck spectroscopy
Dealing with the MW foreground?

Figure 6. The stellar velocity distribution ($v_{pec}$, Section 4.1) in each of the seven radial bins. Overlaid are 150 samples of the parameterized velocity distribution, drawn from the MCMC chain. The blue curves include only the M31 components, while the green curves include all M31 and MW components. Observed line of sight velocities have been transformed to the Galactocentric frame, and the bulk motion of M31 has been removed (Section 4): a star with no peculiar velocity relative to M31’s bulk motion will have $v = 0$ km s$^{-1}$.

5.2. Sensitivity to Modeling Choices

Gilbert et al. (2018)

Andromeda + Milky Way

("smooth" + substructures)
Combining all diagnostics

\[
R > 80 \text{ kpc}
\]

Radial velocity: \( v_{\text{hel}} \) (km/s)
-600 -400 -200 0

Number of stars

- Secure M31 RGB
- Secure MW dwarfs
- RGB PDF
- Dwarf PDF

Gilbert et al. (2012)
Combining all diagnostics

Combining all diagnostics

Combining all diagnostics

Combining all diagnostics

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Figure 2. Locations of stars in four of the five empirical diagnostics (Section 2.2) for M31 RGB stars and MW dwarf stars in fields of R > 80 kpc. The data is divided into two panels: (a) vs. radial velocity and (b) vs. DDO51 parameter. Each panel shows the PDF contours for secure M31 RGB stars (red) and secure MW dwarf stars (blue) normalized to equal area. The PDFs are calculated using empirical probability distribution functions (PDFs) to determine the likelihood of a star being a red giant or a dwarf. The analysis is restricted to stars with velocities typical of M31 halo stars. The line-of-sight velocity distributions of M31 halo stars fail the DDO51 test, and the velocity distribution of MW dwarf stars extends well into the red giant (RGB) region. Moreover, the line-of-sight velocity distributions of M31 halo stars and MW dwarf stars overlap, and the velocity distribution of MW dwarf stars along the line of sight constitutes a significant foreground MW stars.

Gilbert et al. (2012)
Combining all diagnostics

Figure 2. The Astrophysical Journal
(A color version of this figure is available in the online journal.)

Locations of stars in four of the five empirical diagnostics (Section 2a and 2b) in fields from R ∼ 11,000:76076(21pp), 2012 November 20, Gilbert et al. (2012).

Combining all diagnostics of secure M31 RGB and MW dwarf stars in fields interior (left panels) and exterior (right panels) to R ∼ 80 kpc.

Each diagnostic provides separation between M31 red giant or MW dwarf: (1) line-of-sight velocity (v_{hel} (km/s)), (2) photometric probability of being a red giant based on absorption line (surface-gravity and temperature sensitive), (3) the equivalent width of the Na I absorption line (DDO51) color–color diagram, (4) position in the RR Lyrae color–color diagram, (5) spectroscopic (based on the EW of the Ca H absorption line (surface-gravity and temperature sensitive))

The likelihoods for each diagnostic are combined to give the overall likelihood, L_i, for which a velocity measurement was not possible due to insufficient signal-to-noise ratio (S/N).

The analysis is restricted to stars with sufficient S/N or a lack of strong sky emission lines (Simon & Geha 2007). The RGB and dwarf probability distribution functions shown in panels (a) and (b) are normalized to equal area. The PDF contours in panels (c) and (d) show the 90%, 50%, and 10% contours. Although significantly fewer in number and primarily failures (3.4%).

Secure M31 red giants and MW dwarfs in the outer fields (to which readers are referred for full details of the technique).

Stars identified as secure M31 red giants or MW dwarfs because the brightness of a given M31 field, the relative fractions of stars in velocity range typical of M31 halo stars. To estimate the surface distribution of foreground MW stars has a tail that extends well into the RGB and MW dwarf stars overlap, and the velocity distribution of spectroscopic targets consists primarily of objects that have been correctly classified in each of the two populations must be securely measured.
Access the M31 halo

Gilbert et al. (2014, 2018)

Figure 9. One- and two-dimensional distributions of the best-fit power-law parameters describing the change in the velocity dispersion of M31’s halo with projected radius. Each point comes from fitting a power-law to random draws from the M31 halo velocity dispersion posterior probability distributions in all but the outermost radial bin (Figure 8).

Figure 10. Same as the lower panel of Figure 7, with the power-law fits of the velocity dispersion of M31’s halo as a function of projected radius overlaid. The light blue curves show a subset of the power-law fits to 10000 random draws from the marginalized one-dimensional posterior distribution functions for the M31 halo velocity dispersion in each of the first six radial bins. The dark gray curve shows a power-law composed of the 50th percentile values of the normalization and slope distributions.

M31 also appears to have a sharply decreasing velocity dispersion in the inner regions (Dorman et al. 2012 measured a velocity dispersion of 140 km s\(^{-1}\) at \(R_{\text{proj}} = 7\) kpc in M31), followed by a relatively flat dispersion to large radii. However, the reader should note that the MW profiles measure primarily the radial velocity of MW halo stars. Given the large spread of the SPLASH spectroscopic fields on the sky, the M31 line of sight velocity dispersion profile measures a combination of the stars’ tangential and radial velocities in the M31 coordinate frame, with the relative contributions changing with field position.

To date, there have been few analyses of the velocity dispersion profiles of MW- or M31-like stellar halos in ⇤CDM simulations (one example is Abadi et al. 2006). The stellar density profiles, substructure characteristics, and metallicity profiles of the M31 and MW halos have proven to be useful constraints and checks on ⇤CDM simulations of stellar halo formation, and comparisons of the simulations to observations have provided insight into the physical origins of the stellar halos of M31 and the MW (e.g., Font et al. 2006, 2008; Zolotov et al. 2010; Font et al. 2011; McCarthy et al. 2012; Gilbert et al. 2012, 2014). We expect future comparisons of the observed MW and M31 velocity dispersion profiles with simulated halos will yield further insights into the origins of stellar halos.

6. CONCLUSION

We modeled the velocity distribution of more than 5000 stars observed in M31 halo fields as part of the SPLASH survey, including all major MW and M31 components in the halo fields. Photometric and spectroscopic information on likely MW or M31 membership for each star was incorporated into the Gaussian mixture model as a prior probability. Tidal debris features in M31 halo fields were included in the model, and the marginalized posterior distributions for each are presented in the appendix.

Marginalizing over all model parameters, we parameterized the dispersion of stars in M31’s halo as a function of projected radius. The dispersion of M31’s halo stars is found to decrease only mildly with projected radius, over a radial range of 9 to 100 kpc. Our measurement finds a significantly flatter profile with radius than that measured for M31’s globular cluster population.

The measurement of the velocity dispersion profile is the first step towards using halo stars as tracers of M31’s mass. In future work, the dispersion M31’s halo stars will be used to model M31’s total mass distribution.

also Chapman et al. (2006)

• density profile
• velocity dispersion profile
• metallicity profile
• (kinematically) "smooth" vs. structured

also Koch et al. (2008)
Going wide — PAndAS

Ibata et al. (2014)

400 deg²
~60 nights with CFHT (+ many Keck nights)
The PAndAS CMD

M31 RGB box
Figure 3. PAndAS “Field of Streams” built from panels 2 (red; $D_{GC} \sim 17$ kpc), 3 (green; $D_{GC} \sim 22$ kpc), and 4 (blue; $D_{GC} \sim 32$ kpc) of Figure 2, displaying the highly structured nature of the Milky Way halo in the direction of Andromeda and Triangulum. North is to the top and east to the left.

(A color version of this figure is available in the online journal.)

Despite this map probing deeper parts of the CMD, the wispy feature that appears south of the masked Andromeda region, in the vicinity of ($\xi, \eta$) = (0°, −5°), neither correlates with the prominent stellar structures of the M31 halo, nor with the features of the survey's background galaxy distribution, or the foreground MW dust distribution (see Figures 3, 13, and 20 of Ibata et al. 2007, respectively), giving credence that this is yet another genuine stellar structure.

In addition, this feature is still present in the maps, albeit at lower significance, when restricting the selection to stars brighter than $i_0 = 22$. That should not be contaminated by M31 stellar populations, or background galaxies. The CMD of this region shows MS stars that have fainter magnitudes than the prominent MS visible in Figure 1. Since it overlapped with the footprint of the data at the time of the analysis of Martin et al. (2007b), it likely corresponds to the TriAnd2 structure discovered in that work.

The latest PAndAS photometric calibration (Ibata et al. 2014), combined with the re-observation of some low-quality fields that covered most of the region of this overdensity, means that it is now possible to trace the extent of this cloud of stars. It roughly covers a region of $\sim 3^\circ \times 5^\circ$ which, at this distance, corresponds to a physical extent of $\sim 1.5 \times 2.5$ kpc.

It is worth remembering at this stage that the PAndAS footprint covers less than 1% of the sky. It is therefore to be expected that, despite the revolution provided by panoramic sky surveys, many halo stellar structures have so far gone unnoticed due to their limited coverage and depth.

3.3. Stellar Populations

In Figure 4, we display the CMD so far for different fields which target various regions of interest within PAndAS (the...
The PAndAS CMD

M31 RGB box
The Milky Way contamination

Martin et al. (2013)
A variable MW contamination

\[(X_0, Y_0) = (-4.0\degree, 8.0\degree) \quad (X_0, Y_0) = (0.0\degree, 0.0\degree) \quad (X_0, Y_0) = (9.0\degree, -10.0\degree)\]
The M31 stellar halo

"Statistical" removal of Milky Way foreground model

Ibata et al. (2014)
"smooth" vs. structured

Ibata et al. (2014)
But is "smooth" really smooth? Only so down to the survey depth.
Decomposing PAndAS

For a given 15'x15' spatial pixel region:

\[ n(-2.3) \]

\[ n(-1.0) \]

\[ N_{\text{cont}} \]
Integrated counts $\rightarrow \Sigma_g$, modelling the full CMD without contamination removal

Only a single drawing from pdfs

$-2.3 \leq [\text{Fe/H}] < -1.4$

$-1.4 \leq [\text{Fe/H}] < -0.8$

$-0.8 \leq [\text{Fe/H}] < -0.1$
The future?

**Surveys:**
- HyperSuprimeCam on Subaru?
- Subaru Prime Focus Spectrograph for a systematic study?

**Going towards a *proper* observation/simulation comparison**
- Bringing the simulations to observational space
- "Dumbing them down" with the observations' limitations, noise, and systematics
Figure 1 – Maps of new data with the Pandas density map in the right lower panel based on Lowing et al. (2014)