RomAndromeda: The Roman Survey of the Andromeda Halo

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ABSTRACT

As our nearest large neighbor, the Andromeda Galaxy provides a unique laboratory for investigating galaxy formation and the distribution and substructure properties of dark matter in a Milky Way-like galaxy. Here, we propose an initial 2-epoch ($\Delta t \approx 5$yr), 2-band Roman survey of the entire halo of Andromeda, covering 500 square degrees, which will detect nearly every red giant star in the halo (10σ detection in F146, F062 of 26.5 26.1 AB mag respectively) and yield proper motions to ~ 25 microarcsec/year (i.e., ~ 90 km/s) for all stars brighter than F146 ≈ 23.6 AB mag (i.e., reaching the red clump stars in the Andromeda halo). This survey will yield (through averaging) high-fidelity proper motions for all satellites and compact substructures in the Andromeda halo and will enable statistical searches for clusters in chemo-dynamical space. Adding a third epoch during the extended mission will improve these proper motions by $\sim t^{-1.5}$, to ≈ 11 km/s, but this requires obtaining the first epoch in Year 1 of Roman operations. In combination with ongoing and imminent spectroscopic campaigns with ground-based telescopes, this Roman survey has the potential to yield full 3-d space motions of >100,000 stars in the Andromeda halo, including (by combining individual measurements) robust space motions of its entire globular cluster and dwarf galaxy satellite populations. It will also identify high-velocity stars in Andromeda, providing unique information on the processes that create this population. These data offer a unique opportunity to study the immigration history, halo formation, and underlying dark matter scaffolding of a galaxy other than our own.

1. SCIENCE CASE

Dark matter drives nearly every aspect of galaxy formation and evolution, yet its nature remains one of the most fundamental and persistent questions in astrophysics. In the ΛCDM paradigm, galaxies live in dark matter halos that form hierarchically, and their present-day state is determined by their merger histories. While dark matter is not directly observed, its influence on baryonic matter can be and observations of resolved stars provide a unique handle with which to set constraints on the properties of dark matter. For example, the motions of halo stars can reveal the spatial distribution of dark matter and the existence of dark-matter substructure. So far, such studies have only been

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feasible in the Milky Way and a handful of its dwarf galaxy satellites. However, with new ground-based spectroscopic facilities and the Roman telescope, it is now possible to perform such analyses in the Andromeda Galaxy (Andromeda), the Milky Way's nearest large galactic neighbor.

Andromeda is an ideal dark matter laboratory. Unlike the Milky Way, it offers an external view of a galaxy, its entire stellar halo is spread out over only ≈ 500 sq.deg. Andromeda's proximity (≈ 780 kpc away) allows individual stars to be resolved with sufficiently deep imaging and spectroscopy. As a result, extensive ground-based imaging and spectroscopy and space-based imaging studies of Andromeda have been undertaken. These hint at a complex formation history, in some ways similar to that of the Milky Way (e.g., PAndAS, PHAT, SPLASH, etc. Ferguson et al. 2002; Ibata et al. 2004; Brown et al. 2006; Koch et al. 2008; Guhathakurta et al. 2006; Kalirai et al. 2006; McConnachie et al. 2018; Gilbert et al. 2009; Dalcanton et al. 2012; Williams et al. 2014; Gilbert et al. 2019; Escala et al. 2022; Dey et al. 2023). Spectroscopic campaigns on new massively multiplexed spectrographs (e.g., Mayall/DESI; Dey et al. 2023 and Subaru/PFS; Takada et al. 2014), will soon deliver line-of-sight velocity measurements for potentially $> 10^5$ unique stars, but lack comparable tangential velocity information.

The Roman Observatory provides the _only_ near-term opportunity to map the entire Andromeda halo at ≈ 0.1 arcsec resolution, and to measure proper motions for individual stars and substructures in the stellar halo. These data are critical to understanding galaxy formation. With Roman's unique combination of wide-field, high spatial resolution, and low background, it is now possible to observe the entire Andromeda halo and identify nearly every compact or tidally disrupted satellite within the system and discover new stellar streams in the halo. Thin, dynamically cold (low velocity-dispersion) stellar streams, such as those from tidally disrupted globular clusters, are of particular interest for constraining the nature of dark matter. Roman can photometrically detect Palomar 5-like globular cluster streams in Andromeda (Pearson et al. 2019, 2022), and (from the stream morphologies) can also detect gaps (Aganze et al. 2023) in such streams induced by interactions with dark matter subhalos (see e.g., Yoon et al. 2011). The morphology of streams and their underdensitites can help constrain the overall dark matter halo potential of Andromeda (Nibauer et al. 2023). In Andromeda we will have the advantage of searching for globular streams far from the galactic center, where streams are less susceptible to dynamical torques from baryonic perturbers associated with Andromeda's disk or bulge (e.g., Amorisco et al. 2016; Pearson et al. 2017; Banik & Bovy 2019). The distribution of the properties of stellar substructures in the halo can be used to test the ΛCDM paradigm of structure formation (Bell et al. 2008; Shipp et al. 2023). More importantly, the distribution of substructure properties can be related to a galaxy's accretion history in terms of the characteristic epoch of accretion and the mass and orbits of progenitor objects (Johnston et al. 2008; Sharma et al. 2011). Characterizing the population of dark matter subhalos with stellar streams allows constraints on the particle nature of dark matter (e.g., Benito et al. 2020) in addition to the overall halo structure.

In addition, by obtaining two epochs of observations spread out over the 5-year baseline mission, Roman can provide proper motions for almost every spectroscopically observable Andromeda halo giant star, thus enabling the first detailed 3-d dynamical study of the halo of a galaxy beyond the Milky Way. The survey, combined with ground-based spectroscopy, will yield the orbits of all the globular clusters and Andromeda satellite galaxies, providing additional constraints on Andromeda's accretion history (e.g., Mackey et al. 2019a,b) and the 'planes of satellites' problem (e.g., Ibata et al. 2013). These proper motions will be anchored by background QSOs and galaxies identified by the previous, current, and ongoing spectroscopy campaigns (as in Sohn et al. 2012, 2020). For example, DESI is spectroscopically targeting more than 300 QSO candidates per square degree, and each Roman field should include ∼80 confirmed QSOs (i.e., stationary point sources) in addition to ∼ 10^5 faint galaxies to tie down the reference frame and measure differential proper motions for the stars, cf. measurements using HST by Sohn et al. (2012). The wide-field imaging of the stellar halo from CFHT/PAndAS also provides a ≈ 20 year baseline for proper motions when combined with the proposed Roman data. Similarly, in Andromeda's disk, the combination of Roman and existing HST/PHAT survey data can provide more accurate stellar motions in the disk of the galaxy, as well as a 3-d reddening map of the Andromeda disk. These proper motions, combined with spectroscopy (from e.g. JWST or DESI), can enable analyses of the chemo-dynamical trends of different populations in the disk, probing its evolution.

2. SURVEY STRATEGY

We propose a 500 square degree Roman Wide Field Instrument (WFI) public survey of the region covering the entire halo extent of the Andromeda and Triangulum galaxies (see Figure 1) in the F062 and F146 filters. WFI can cover this area in a single non-overlapping tiling of 1785 fields. The F146 filter provides the most efficient option for deep imaging due to its width. F062 provides the longest possible color baseline from F146, and therefore the best option
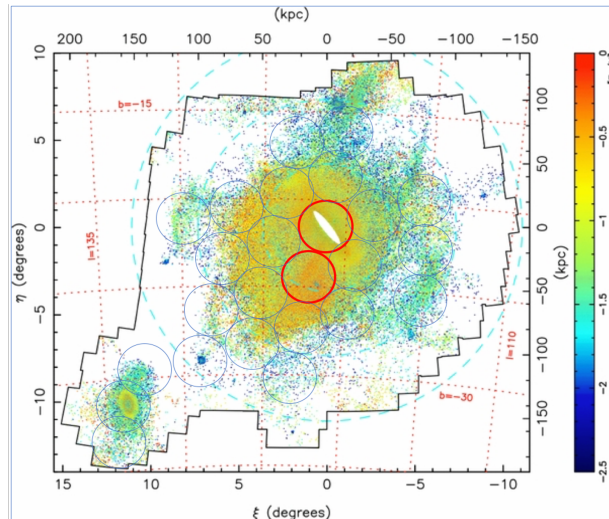
Figure 1. The metallicity distribution of stars in the Andromeda halo and the Triangulum galaxy (from Ibata et al. 2014) estimated using photometric data from the PAndAS survey (McConnachie et al. 2018). The proposed Roman survey will encompass the entire 500 square degree area shown in this figure, reaching beyond the outline of the PanDAS field (solid black line). The dashed cyan circles are at projected radii of 50, 100, and 150 kpc. Much of the halo can be covered by spectroscopic observations using the Mayall Dark Energy Spectroscopic Instrument (DESI; potential pointings shown in the blue circles) and the Subaru PFS surveys. Image credit: Ibata et al. (2014)
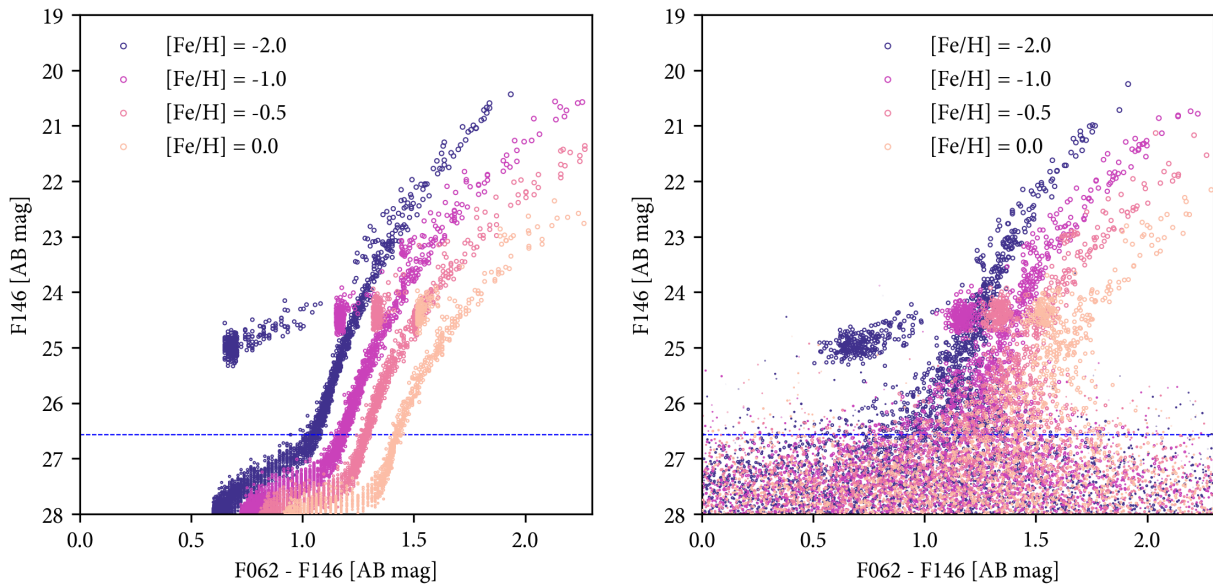
Figure 2. *Left:* Color-magnitude diagram for stars with a range of metallicities distributed at distances of 780±50 kpc in Andromeda's halo. The horizontal dashed line represents the 10σ depth of the proposed survey achieved for the full survey (14x30 sec exposure time). *Right:* The photometric color-magnitude diagram (with expected scatter) resulting from the proposed Roman observations will be sensitive to nearly the entire red giant branch across the entire Andromeda halo. Thus, it will be capable of identifying nearly all the faint satellite companions (including ultra-faint dwarfs) and stars from most of the tidally stripped streams originating from clusters $M_V \approx -5$ and brighter. The photometry are computed using the MIST isochrones (Choi et al. 2016) and converted to AB mags assuming offsets of 0.122 and 0.993 mag for F062 and F146 respectively (See http://mips.as.arizona.edu/~cnaw/sun.html; Willmer 2018). Figure credit: Jesse Han.

for measuring the optical-to-near-infrared colors for the individual stars. In addition, F062 provides the smallest PSF, which when sampled with the multiple passes, can help us improve the centroids derived from the F146 data.

Mode	Exposure Time	F146		F062	
	(sec)	5σ	10σ	5σ	10σ
Single Exposure	30	25.32	24.52	24.82	23.92
Single Epoch	210	26.92	26.13	26.95	26.10
Combined 2-epoch	420	27.35	26.57	–	–

Table 1. Point-source depths (in AB mags) reached by the proposed Roman survey of Andromeda for single exposures, the combined first epoch observations (i.e., 7 × the single exposure depth), and the full 2-epoch depth. Including the slew time overheads, the entire proposed survey takes a total time of ≈ 35 days. Depths were computed using the Roman ETC Jupyter Notebook and assuming typical Zodiacal light contributions 1.4× the average.

We propose a total of 21 passes over this field, 14 dithered observations in the F146 filter (split into two epochs of 7 dithers each), and 7 dithered observations in the F062 filter. For an individual exposure time of 30 sec per observation, each tiling would require 1785 x (30 sec exposure + 50 sec slew) ≈ 40 hours/tiling; thus, the entire survey would require a total of ≈ 35 days of observation. Each epoch of 7 × 30 sec will result in a 10σ detection of ≈ 26.1 AB mag in both the F062 and F146 bands (see Table 1). This will reach every red giant star in Andromeda with absolute magnitudes $M_{(F146,F062)} \leq +1.5$ AB mag. This depth is nearly 1.5-2 mag deeper in F146 than a typical Andromeda red clump star (see figure 2), and should enable detection of every ultra-faint dwarf galaxy to −4 to −4.7 mag (for detecting 10 or 20 stars per UFD). Even in Andromeda's bright disk, ∼20 arcmin from the center, Roman's excellent spatial resolution will allow us to reach the horizontal branch before the photometry is limited by crowding, as determined by applying the method of Olsen et al. (2003) to the surface brightness data from Jarrett et al. (2003). In the bulge, ∼2 arcmin from the center, we will resolve the brightest individual red giants. To put this in context, the proposed Roman survey of Andromeda will provide a depth equivalent to what was achieved by the Sloan Digital Sky Survey at a distance of 100 kpc in the Milky Way Galaxy!

Since deriving constraints on the proper motions of Andromeda stars, clusters, and satellite galaxies are the most critical part of the science, we propose to maximize the time baseline by scheduling the two epochs in years 1 and 5 of Roman science operations. In the event that there is an extended mission, we propose adding a third epoch later to extend the time baseline. Color information is critical to identifying clusters and coherent streams and determining their distances, and hence we propose to obtain imaging in 2 filters during the first epoch. This implies a time commitment of 23.14 days in year 1 and 11.57 days in year 5.

The number of passes is driven by both astrometric and depth requirements. The Roman PSF is undersampled at the 0.11 arcsec pixel scale, and an accurate reconstruction of the PSF for centroiding at each epoch requires a large number of dithers. Rather than small dithers at each position, we propose 14 separate (but spatially staggered) tilings for the first epoch (7 in F146 and 7 in F062) in year 1, and then the last 7 tilings (in F146) during the second epoch in year 5. This has the advantage of providing a photometric time sequence (7 separate photometric points in each filter) during the first astrometric epoch which would allow for the identification of variable stars, especially RR Lyrae and Cepheids, for distance measurements and anchoring the distance scale for cosmological studies. The availability of color information in the first year will allow the community to work on identifying all the substructure in the Andromeda halo, and thus mount more targeted spectroscopic campaigns for measuring line of sight velocities and abundances. The total of 14 (7) passes in the F146 (F062) filter should allow for super-sampling of the PSF and thus more accurate per-epoch positions. The combination of the F062 and F146 data (and the existing ground-based imaging and imminent spectroscopic data) will allow us to model the spectral energy distribution through the wide F146 band for more accurate extraction of colors.

3. DELIVERABLES

The main data deliverables of the survey are: (1) photometry in two bands for all stars and galaxies down to ≈ 26 AB mag (10σ); (2) proper-motion measurements or constraints for all stars brighter than ≈ 23.5 mag (due to the higher signal-to-noise constraints for proper motion measurements); (3) per-epoch photometry for all sources detected at $> 5\sigma$ (i.e., with F146, F062 $< 25.3, 24.8$ AB mag) in the individual epoch data. The photometric measurements and short-timescale single-epoch measurements will be available immediately after the first year. The proper motion catalog and long-term variability data will be available after the last epoch.
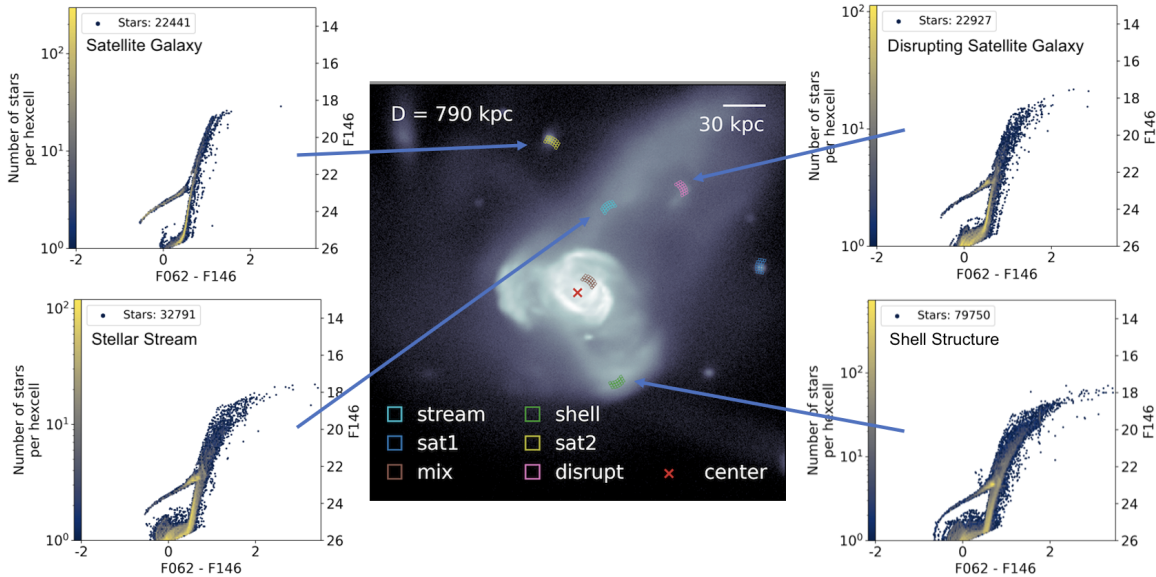
Figure 3. Mock observations with Roman of a simulation of a galaxy with a mass similar to that of Andromeda and observed from a comparable distance. The central image shows the stellar number density for a mock stellar catalog, limited to a 10σ detection in F146, F062 of 26.5, 26.1 AB mag, in which substructure is evident even by-eye. The example color-magnitude diagrams shown in the four panels surrounding the density image are constructed from the regions covered by single Roman WFI pointings and represent $\approx 0.22\%$ of the data from the proposed Roman survey. The model galaxy is from the FIRE simulation suite (`m12f`, Garrison-Kimmel et al. 2017) and the stellar catalogs were generated using the `py-ananke` software (https://github.com/athob/py-ananke) with isochrones for Roman photometry queried from the Padova/CMD database (http://stev.oapd.inaf.it/cmd). Figure credit: Adrien Thob.

With this plan, significant progress can be made immediately after the first year data are taken: e.g., measurements of the spatial distribution of halo stars; the photometric metallicity distributions; determination of the halo extent; source classification and star-galaxy separation; identifications of all overdense stellar substructures, i.e., clusters, dwarf galaxies and stream candidates; identification of nearly all short-term variables (e.g., RR Lyra, Cepheids, etc.). The addition of the second epoch enables the determination of proper motions for large numbers of stars in the halo and disk of Andromeda, and promises to revolutionize the study of Andromeda much in the same way that the *Gaia* astrometric data revolutionised dynamical analyses of the Milky Way.

4. POSSIBLE IMPLEMENTATION OPTIONS

(I) Cover Andromeda as part of the High Latitude Survey

(II) Design a custom survey of Andromeda as part of the Core Community Survey plan

Option I: The notional plan for the High-Latitude Wide-Area Survey (HLWAS) will cover ≈ 2000 square degrees in 4 bands (F106, F129, F158, F184) to depths of 25.8 to 26.7 AB mag. While this plan is much more extensive than that proposed here for Andromeda, at least half of the Andromeda halo footprint proposed here (e.g., the fraction which avoids the disks of Andromeda and Triangulum and lies at Galactic latitude < -20) could be completed as part of the HLWAS and attain the same goals. The pros of this implementation strategy would be: (a) larger number of (narrower) filters, which result in additional colors for stars and less PSF variation within each filter; (b) many more epochs than proposed here, which will improve the detection of variable stars and allow us to solve for parallax for foreground Galactic stars; (c) the weak-lensing survey goals would benefit from the wealth of spectroscopic data provided by DESI and PFS in these fields. The cons of this implementation would be: (a) the denser stellar regions near and including the disks of Andromeda and Triangulum would not be included (but could be done with a separate program); (b) the weak-lensing goals of HLWAS may be more difficult to achieve due to the closeness to the Galactic plane and the increased numbers of faint stars from the Andromeda and Triangulum halos; and (c) F062, which is not included in the HLWAS plan, would provide a better handle on photometric metallicities for Andromeda stars.

Option II: A custom survey of Andromeda as part of the core plan provides the cleanest approach and could be optimally designed to accomplish multiple goals: (1) the halo survey described here; (2) a deep color-based survey of the Andromeda and Triangulum disks; (3) time domain surveys with different cadences in the disk and halo to identify variable stars. The total area is small, and the basic survey described here can be accomplished in ~ 1 month. Adding these other components over a small area will only increase this commitment by a week of total time at the very most (the disk can be covered in < 5 Roman fields). The main constraint is that the first epochs of the survey must be completed in the first year of Roman science operations, to ensure the longest possible time baseline for proper motion measurements.

A third option may be to combine these; i.e., do a portion of the outer halo of Andromeda in the HLWAS and target the remainder of the footprint with a custom survey.

5. TRADE SPACE AND EXPANSION OPTIONS

The current proposed survey baseline is for covering 500 sq. deg. in 2 filters during the first epoch and one filter in the second epoch. The _minimal_ requirement is to deliver 2 filters (for color information) and 2 epochs (for proper motion information). While it is possible that ground-based imaging (e.g., from Subaru/Hyper-SuprimeCam) could provide useful deep optical imaging, these data would suffer from confusion in the very central parts of the halo and in the disk of the galaxy, and would require the Roman data for source disambiguation (i.e., star/galaxy separation) and deblending.

As a result, the only way to scale back the Roman survey proposed here without greatly impacting the science yield is to reduce the area. The 500 sq. deg. proposed area is defined to sample the Andromeda halo out to 200 kpc in certain directions, even beyond the imaging area covered by the PAndAS survey. The first scale-back option is to reduce the footprint to the ≈ 350 sq. deg. imaged in the PAndAS survey (i.e., the jagged black outline in Fig. 1), which covers the Andromeda halo out to slightly less than ~ 150 kpc and includes the region around Triangulum. The second scale-back option (not preferred) is to excise Triangulum from the survey.

If the Roman mission lifetime is extended beyond the baseline, this provides an invaluable opportunity to add a third epoch. This would increase the time baseline for the survey and improve the accuracy of the proper motion measurements; if Roman has a lifetime similar to that of the Hubble Space Telescope, it would potentially increase the proper motion measurement accuracy to $\approx 3\mu$as/year (since $\sigma(PM) \propto t^{-1.5}$), or ≈ 11 km/s at the distance of Andromeda. However, to maximize the future science return, it is _essential_ that the first epoch be obtained as early as possible during the Roman mission.

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