Tracing the 6-D Orbital and Formation History of the Complete M31 Satellite System
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Scientific Justification

Andromeda and its satellites are the next frontier for testing the Cold Dark Matter (CDM) paradigm and the physics governing the growth of galactic ecosystems across cosmic time. HST-enabled star formation histories (SFHs) and proper motions (PMs) of satellites around the Milky Way (MW) have established the relationship between dwarf galaxies and reionization (Brown et al. 2014; Weisz et al. 2014a; Boylan-Kolchin et al. 2015), and provided stringent tests of CDM and the physics of galaxy formation (Boylan-Kolchin et al. 2012; Wetzel et al. 2016; Simon 2019). PMs have been central to determining the 3-D orbits, infall times, and quenching timescales of several satellites (e.g., Kallivayalil et al. 2013; Sohn et al. 2013; Fritz et al. 2018; Simon 2018); and studying the internal motions and rotation of individual stellar orbits, themselves dictated by dark matter (van der Marel & Kallivayalil 2014). These results are fundamental to our understanding of all low-mass and satellite galaxies (e.g., Bullock & Boylan-Kolchin 2017). *This program will expand HST's role in these key areas of study to include M31 and its satellites, allowing us to comprehensively study an entire galactic ecosystem outside the MW halo for the first time.*

There is growing evidence that the MW satellites may not be broadly representative. Compared to the MW, satellite systems throughout the local Universe show varying luminosity functions, stellar populations, quenching properties, and spatial configurations, often in excess of cosmic variance (e.g., McConnachie & Irwin 2006; Brasseur et al. 2011; Tollerud et al. 2012; Chiboucas et al. 2013; Geha et al. 2017; Greco et al. 2018; Müller et al. 2018; Pawlowski 2018; Smercina et al. 2018; Pawlowski et al. 2019). Furthermore, current data suggest important differences in the internal (e.g., kinematics, stellar content; Collins et al. 2014; Martin et al. 2017) and global (e.g., "plane of satellites"; Ibata et al. 2013; Pawlowski 2018) properties of M31 and MW satellites. Thus, it is unclear whether the fundamental insights established in MW satellites are generally applicable to low-mass systems or stem from the specific accretion history of the MW.

Direct comparisons between the lifetime evolution of MW satellites and systems outside the Local Group (LG) are not currently possible. Even in the nearest groups (e.g., M81, Cen A; D ~ 3.5 Mpc), severe crowding and multi-decade time baselines limit the measurement of accurate SFHs and prohibit PMs, even with HST (and/or JWST). Exploring such distant systems in detail similar to the MW satellites requires a 12-16m space telescope. M31 is thus the only logical target and it is now or never to start this survey. Measuring PMs with precisions similar to MW satellites (~ 40 km/s) at the typical distance of M31 (~ 800 kpc) requires an 8-12 year baseline with HST and JWST. PMs for M31 satellites cannot be measured with Gaia (stars are too faint and crowded) or AO (small field of view, insufficient PSF stability). It is imperative to establish first-epoch imaging now in order to leverage JWSTs full lifetime for optimal PM measurements.

Through this Treasury program, we propose a comprehensive ACS/WFC3 survey of the M31 satellite system, enabling unique and transformative HST science including critical issues in galaxy formation, cosmic reionization, and the nature of dark matter. Our imaging will target all known satellites within ~300 kpc of M31, encompassing its full halo profile out to the virial radius. It will have the depth to measure robust SFHs, the cadence to provide secure and precise distances using RR Lyrae, and the astrometric precision for optimal first-epoch proper-motion measurements, all comparable in quality to current measurements of the entire MW system.

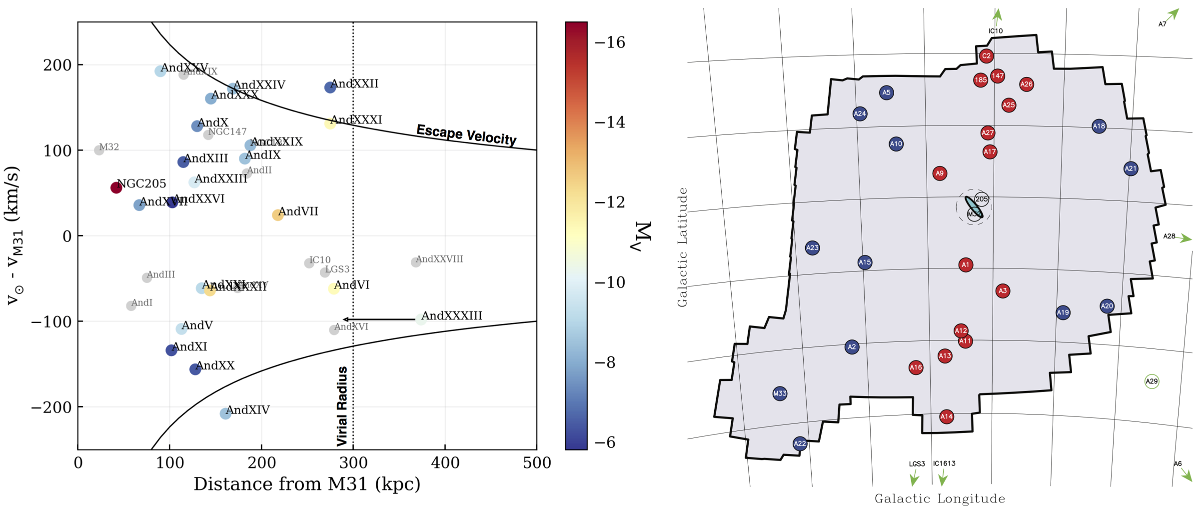

FIGURE 1: *M31 dwarf galaxies in context:* ***Left–*** *Distances and LOS velocities of M31 satellites relative to M31. Our proposed sample is color-coded by luminosity. Current distances are generally highly uncertain (e.g., Conn et al. 2012), highlighted by uncertainty in And XXXIII's location inside/outside M31's virial radius. Virtually all of these satellites are gas-poor, underlining the importance of the M31 halo environment in dwarf galaxy evolution.* ***Right–*** *The spatial distribution of all known M31 satellites as of 2013 (Ibata et al. 2013), with putative members of the thin plane in red and nominal non-plane members in blue. We will observe 23 systems that do not have existing deep HST imaging. Full phase-space information, detailed SFHs, and RR Lyrae-based distances provided by our observations will allow us to investigate the membership, coherence, and origin of the plane, as well as rewind the clock on each galaxy and study the effects of reionization and environment on its evolution.*

We will target the 23 known M31 dwarf galaxies that do not have adequately deep HST imaging. Our immediate science goals include: (1) measuring SFHs of all M31 satellites; (2) quantifying putative differences between the MW and M31 systems to better understand variations in low-mass systems between galactic ecosystems; (3) precisely locating M31 satellites within their host halo using homogeneous, accurate variable star distances; and (4) investigating the dependence of dwarf properties on radial position and location on or off the M31 satellite plane (Figure 1; Ibata et al. 2013). Over the next decade we will use HST and JWST to obtain second-epoch imaging to measure PMs and provide full 6-D phase space information for these dwarfs, all of which are too faint for Gaia. Our program will thus reconstruct the dynamical and star formation history of the M31 satellite system: *this is the only way to explore another galactic ecosystem at a similar level of detail as the MW.* We now describe the four most critical science goals enabled by our program.

(1) The effect of environment on low-mass galaxy evolution. Outside of the MW, M31 represents our best opportunity to study environmental effects on galaxy formation in exquisite detail. The halos of the MW and M31 exert strong environmental influence on their satellites (e.g., Wetzel et al. 2015), as evidenced by the well-known morphology-density relationship (e.g., Grcevich & Putman 2009; McConnachie 2012). The LG represents our one opportunity to measure these environmental effects using precise SFHs and full phase space information. The left panel of Fig-