

First Results from the Triangulum Extended Survey: Insights into the Dynamical History of M33

K. M. Gilbert^{1,2}, A. C. N. Quirk³, L. R. Cullinane²,
A. Smercina⁴ and P. Guhathakurta⁵

¹Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA
email: kgilbert@stsci.edu

²The William H. Miller III Department of Physics & Astronomy, Bloomberg Center for Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218

³Department of Astronomy, Columbia University, New York, NY, USA

⁴Department of Astronomy, University of Washington, Box 351580,
U.W., Seattle, WA 98195-1580, USA

⁵Department of Astronomy & Astrophysics, University of California, Santa Cruz,
1156 High Street, Santa Cruz, CA 95064, USA

Abstract. The Triangulum Extended (TRES) Survey is a spectroscopic survey[†] that targets resolved stars of all ages throughout the disk of Triangulum (M33). We summarize the first results from the TRES Survey, including the discovery of a kinematically hot, halo-like population throughout M33's inner disk in both the old and intermediate-age populations and evidence that the youngest stars have been dynamically heated. We also discuss the implications for our understanding of M33's dynamical history in the context of recent results from the Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER) Survey.

Keywords. Galaxy stellar halos, Triangulum Galaxy, Local Group, Galaxy evolution, Disk galaxies

1. Introduction

As the closest low-mass spiral galaxy, M33 provides a unique laboratory in which to study the secular evolution and stability of low mass stellar disks. M33 is slightly more massive than the Large Magellanic Cloud (LMC), and intermediate in metallicity between the LMC and the Local Group's two massive spiral galaxies, M31 and the Milky Way. M33 presents a relatively undisturbed central disk, with distortions at large radius observed in both the H I gas and the stellar surface density. While a close previous encounter with M31 has been posited to explain the distortions in the H I and stars seen at large radius (McConnachie et al. 2009; Putman et al. 2009; Semiczuk et al. 2018), analyses which take into account the proper motion of M31 argue that M33 is more likely on its first infall into the M31 system (Patel et al. 2017a,b; van der Marel et al. 2019).

Significant observational campaigns have provided contiguous mapping of the spatial distribution and line-of-sight velocity of the gas in M33 to large projected distances

[†] The data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation.

(including H I, H α , and CO, e.g., Gratier et al. 2010; Druard et al. 2014; Kam et al. 2015), as well as large scale, contiguous imaging of the stellar populations in the inner disk of M33 (PHATTER; Williams et al. 2021), and to large distances from M33's center (Pan-Andromeda Archaeological Survey, or PAndAS; McConnachie et al. 2018). TREX aims to increase our understanding of M33's stellar populations and disk dynamics with resolved stellar spectroscopy throughout M33's inner disk and in its extended stellar structures. Via the measurement of the stellar disk dynamics as a function of stellar age, and chemo-dynamical analysis of the older stellar populations, TREX aims to shed light on the forces that have driven the large-scale disturbances in M33's stellar and gaseous disks, determine if M33 has a stellar halo, and if so, constrain it's origin.

This contribution summarizes the recent results by Gilbert et al. (2022) and Quirk et al. (2022), and places those results in context with recent work by Smercina et al. (submitted) and Cullinane et al. (in prep.).

2. First Results From The TREX Survey

2.1. The TREX Dataset

The TREX Survey has obtained stellar spectra for more than 5000 stars in M33's disk and extended stellar structures to date. Spectra were obtained with the DEIMOS multi-object spectrograph on the Keck II telescope. Spectroscopic masks that targeted primarily red populations (e.g., red giant branch (RGB) stars or asymptotic giant branch (AGB) stars) were generally observed with the 1200 line mm⁻¹ grating, resulting in a resolution of $R \sim 6000$ and wavelength range of $\lambda \sim 6300 - 9800$ Å. Masks that targeted the full range of ages, or primarily blue populations (e.g., massive main sequence stars or blue helium burning stars) were observed with the 600 line mm⁻¹ grating, resulting in a resolution of $R \sim 2000$ and larger wavelength range of $\lambda \sim 4600 - 9800$ Å. The work discussed below analyzes stars in the disk of M33, from the innermost regions to projected distances of ~ 11 kpc from M33's center (~ 18 kpc, or ~ 10 scale lengths, in the plane of the disk).

2.2. A Kinematically Hot Component Present Throughout M33's Disk

The presence or absence of a significant stellar halo component in M33 has been a matter of debate within the literature, with observational evidence on both sides (see Gilbert et al. (2022) for a detailed discussion, and references therein). Gilbert et al. (2022) analyzed the velocity distribution of 1667 RGB stars (Figure 1). A two-component model for describing the velocity distribution is strongly preferred. One component is consistent with rotating in the plane of the H I disk, at rotation speeds similar to that of the H I gas, and with a velocity dispersion of ~ 19 km s⁻¹. The second component, comprising 22% of the full RGB sample, is consistent within 1.5σ of having no rotation in the plane of the H I disk, and has a velocity dispersion of 59 km s⁻¹. The lack of rotation in the plane of the disk, combined with the high dispersion, favors interpreting this component as a stellar halo rather than a thick disk. The fraction of RGB stars in the kinematically hot population decreases with increasing distance from M33's center. In the outermost radial bin, where the majority of the stars lie beyond the break in the surface brightness profile of M33's disk (Ferguson et al. 2007), 90% of the RGB stars belong to the disk component, providing strong evidence that M33's disk break does *not* reflect the transition to a halo-dominated region, as had been previously hypothesized (Barker et al. 2011; Cockcroft et al. 2013).

Recent work by Cullinane et al. (in prep.), modelling 671 intermediate-age AGB and spectroscopically identified Carbon stars, finds that the kinematically hot component seen in the older RGB population is also present in M33's intermediate-age population,

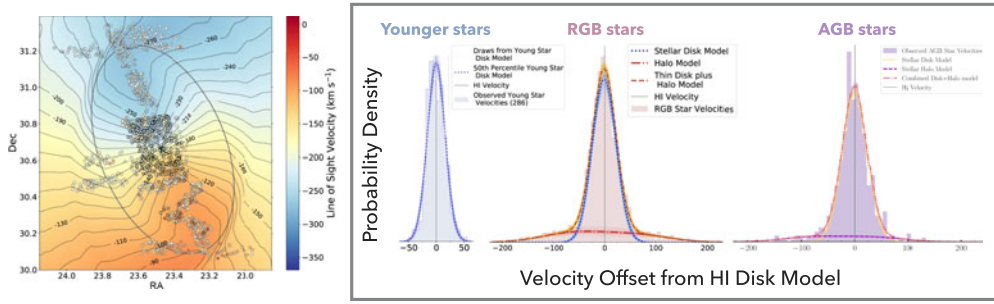


Figure 1. To model the stellar kinematics of M33’s disk, each star’s line-of-sight velocity (points, left panel) is compared to the expectation from a tilted ring model of M33’s disk based on HI observations (Kam et al. 2017, contours, left panel). At each star’s position, we calculate the velocity offset of the star’s line-of-sight velocity from that of the HI Disk Model. If the stars follow the gas exactly, expect no mean velocity offset, and an approximately Gaussian distribution. In Gilbert et al. (2022), we find this is true for a young, red star comparison sample, while the RGB sample requires a second, higher dispersion component to match the observed distribution. In Cullinane et al. (in prep.), we find a second, higher dispersion component is also required to fit the intermediate-age AGB star population. Figure adapted from Gilbert et al. (2022) and Cullinane et al. (in prep.).

with a two-component model decisively preferred over a single-component disk model (Figure 1). Approximately 12% of the intermediate-age population is in a high velocity dispersion component ($\sigma_v \sim 50 \text{ km s}^{-1}$) that is statistically consistent with having no rotation in the plane of the disk, and which appears to have a systematic offset in its mean velocity.

2.3. Evidence of Recent Dynamical Heating of M33’s Stellar Disk

Quirk et al. (2022) measured M33’s stellar disk kinematics as a function of stellar age, utilizing a sample of ~ 4500 disk stars to make local, empirical measurements of the stellar mean velocity and velocity dispersion. Quirk et al. (2022) also paired stellar and gas line-of-sight velocity measurements, comparing the inferred stellar rotation velocities to the inferred gas rotation velocity in order to make a local, empirical measure of the asymmetric drift of the stars relative to the gas. No trend with age is observed in either velocity dispersion or asymmetric drift ((Figure 2). Compared to the vast majority of M33 analogs in the IllustrisTNG simulations, the youngest age bin ($\sim 20 - 180 \text{ Myr}$) in M33 has an unusually high asymmetric drift, suggesting some phenomenon is dynamically heating the youngest stars in M33’s disk.

3. Implications for M33’s Dynamical History and Future Prospects

The TREX results demonstrate that a kinematically hot component is present throughout M33’s disk, and that there is evidence the young stars in M33’s disk have been dynamically heated.

Recent results from the PHATTER survey provide critical additional context for interpreting the TREX results. Smercina et al. (submitted) finds that the observed morphology of M33’s disk is age-dependent, with the distribution of RGB, AGB, and HeB stars all showing clear evidence of a bar, as well as two asymmetric spiral arms, providing potential evidence that a tidal disturbance has affected M33’s inner disk. Smercina et al. use the PHATTER stellar catalog in conjunction with archival Spitzer IRAC $3.6 \mu\text{m}$ imaging to model the stellar surface brightness profile of M33’s RGB stars from M33’s center to a semi-major axis distance of 4.7 kpc. Smercina et al. find the RGB

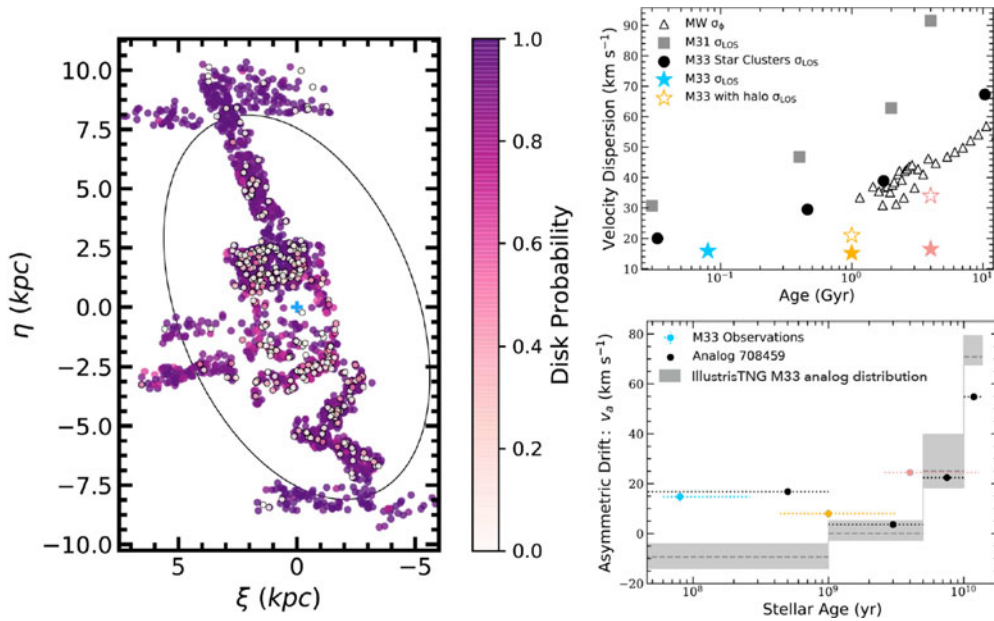


Figure 2. Quirk *et al.* (2022) measured the velocity dispersion and asymmetric drift of stars with respect to the gas as a function of stellar age, restricting the primary analysis to stars with a high probability of belonging to M33's disk (rather than M33's halo; left panel). In contrast to measurements made in the disks of M31 and the MW, there is no trend of increasing velocity dispersion with age for M33's disk stars (top right panel). Furthermore, the asymmetric drift of the youngest stars is higher than expected, relative to both the asymmetric drift of the intermediate-age and old stellar populations, and expectations based on cosmological simulations of M33 analogs (bottom right panel). This likely indicates that the young stars in M33 have been dynamically heated. Figures from (Quirk *et al.* 2022).

surface brightness profile is well described by the combination of a bar, an exponential disk, and a broken-power-law halo. The best-fit radial profile produces average halo fractions as a function of radius that are fully consistent with the halo fractions measured from the kinematical modelling described above (Gilbert *et al.* 2022). A power-law profile is consistent with expectations for the surface brightness profile of accreted stellar halos based on the profiles of observed and simulated galaxies at larger mass scales.

Together, the TREX and PHATTER observations strongly indicate the likelihood of significant dynamical disturbances acting on M33's disk, and conclusively demonstrate that M33 does contain a stellar halo. The surface brightness profile of the halo drops off rapidly with projected radius, consistent with the lack of an observed stellar halo component at large radii in the PAndAS survey (McMonigal *et al.* 2016). However, the origins of M33's stellar halo remain unclear: is it the product of dynamical heating mechanisms acting on M33's stellar disk, or was it formed primarily from stars accreted during one or more mergers? The lack of rotation in the plane of the disk and the power-law profile are consistent with expectations for accreted stellar halos based on the stellar halos of larger mass galaxies. However, the presence of a kinematically hot component in M33's AGB stars with properties consistent with the RGB halo component presents a challenge to an accretion scenario, since the accreted satellite(s) would be of low stellar mass, and thus would not be expected to have formed a significant amount of stars at intermediate ages. While the photometry-based metallicity distribution of RGB stars in M33's halo and disk components are very similar (estimated by comparing the stars' colors and magnitudes with stellar isochrones; Gilbert *et al.* 2022), the mean metallicity

of M33's halo component is also consistent with an accretion scenario (Smercina et al., submitted). Readers are referred to Gilbert et al. (2022) and Smercina et al. for more detailed discussion. Future measurements of the $[\alpha/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ distribution of stars in M33's halo and disk have the potential to discriminate between these two scenarios.

The authors recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. Support for this work was provided by NSF grants AST-1909066 (K.M.G. and L.R.C.) and AST-1909759 (P.G.), DGE-1842400 (A.C.N.Q.), and NASA GO-14610 (A.S.).

References

- Barker, M. K., Ferguson, A. M. N., Cole, A. A., et al. 2011, *MNRAS*, 410, 504
 Cockcroft, R., McConnachie, A. W., Harris, W. E., et al. 2013, *MNRAS*, 428, 1248
 Druard, C., Braine, J., Schuster, K. F., et al. 2014, *A&A*, 567, A118
 Gilbert, K. M., Quirk, A. C. N., Guhathakurta, P., et al. 2022, *ApJ*, 924, 116
 Gratier, P., Braine, J., Rodriguez-Fernandez, N. J., et al. 2010, *A&A*, 522, A3
 Ferguson, A., Irwin, M., Chapman, S., et al. 2007, *Island Universes*, 3, 239
 Kam, Z. S., Carignan, C., Chemin, L., et al. 2015, *MNRAS*, 449, 4048
 Kam, S. Z., Carignan, C., Chemin, L., et al. 2017, *AJ*, 154, 41
 McConnachie, A. W., Irwin, M. J., Ibata, R. A., et al. 2009, *Nature*, 461, 66
 McConnachie, A. W., Ibata, R., Martin, N., et al. 2018, *ApJ*, 868, 55
 McMonigal, B., Lewis, G. F., Brewer, B. J., et al. 2016, *MNRAS*, 461, 4374
 Patel, E., Besla, G., & Mandel, K. 2017, *MNRAS*, 468, 3428
 Patel, E., Besla, G., & Sohn, S. T. 2017, *MNRAS*, 464, 3825
 Putman, M. E., Peek, J. E. G., Muratov, A., et al. 2009, *ApJ*, 703, 1486
 Quirk, A. C. N., Guhathakurta, P., Gilbert, K. M., et al. 2022, *AJ*, 163, 166
 Semczuk, M., Łokas, E. L., Salomon, J.-B., et al. 2018, *ApJ*, 864, 34
 van der Marel, R. P., Fardal, M. A., Sohn, S. T., et al. 2019, *ApJ*, 872, 24
 Williams, B. F., Durbin, M. J., Dalcanton, J. J., et al. 2021, *ApJS*, 253, 53

Discussion

SARAH BIRD: What is the comparison between the extent of your sample and that of M33's gas disk?

KAROLINE GILBERT: M33's H I disk is large compared to its stellar disk. The observations presented here lie well within the extent of M33's H I disk. As can be seen from Figure 1, while a small fraction of the stars lie beyond the warp in the H I disk, the majority of the stellar sample analyzed to date lies interior to the warp.

ANA BONACA: Do you have enough spatial coverage to measure the density profile of the halo component as a function of radius and height above the disk? Different formation scenarios might be differentiated this way.

KAROLINE GILBERT: M33's inclination is 54° , so constraining the height above the disk, or thickness, for different components would be very challenging. It also has significantly less dust than M31, likely limiting our ability to statistically determine the scale height of the disk. Still, perhaps some clever forward modelling of the line-of-sight velocities combined with constraints from the PHATTER data could shed some light on this.

KYLE OMAN: Thinking about an accreted halo component, usually the halo is dominated (in mass or star counts) by a single accretion event, or at least that's the conventional

wisdom I'd carry over from L_* galaxies. The extent of the halo - the part donated by that main progenitor - is fixed by the time of accretion (with some dependence on the detailed orbit). So I wonder if M33 might fit into a picture where it has had a fairly quiet accretion history with a last major accretion event a long time ago.

KAROLINE GILBERT: It might fit into such a picture. If a low mass halo progenitor deposited most of its stars near the central regions of M33 a long time ago, a small fraction of stars from that low mass progenitor at larger radius would be extremely difficult to detect. However, the presence of a kinematically hot component in the AGB population is hard to reconcile with this scenario. On the other hand, a non-rotating halo component that formed from heating of the disk yet contains intermediate-age stars also seems hard to reconcile.

KYLE OMAN: What is intermediate-age, in Gyr?

KAROLINE GILBERT: The AGB and Carbon stars in the Cullinane et al. intermediate-age sample span a range of roughly 1–3 Gyr, while the RGB stars are older (~ 3 Gyr on average), and are expected to span a range of roughly 1.4–9 Gyr. So there is some overlap in these age bins.