**DEEP PHOTOMETRY OF ANDROMEDA REVEALS STRIKING SIMILARITIES IN THE TIDAL STREAM AND SPHEROID POPULATIONS**

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**ABSTRACT**

We present a color-magnitude diagram (CMD) for a field in the giant tidal stream of the Andromeda galaxy (M31). These observations, taken with the Advanced Camera for Surveys on the Hubble Space Telescope, are 50% complete at $V \approx 30$, reaching 1 mag below the oldest main-sequence turnoff. Striking similarities between the stream and a previous spheroid CMD imply they have very similar age and metallicity distributions, but present something of an enigma; we speculate on possible interpretations of this result, but note that none are without problems. Distinct multiple turnoffs, as might be expected from pulses of star formation caused by interaction with Andromeda, are not apparent in the stream CMD. Star formation in both fields lasted about 6 billion years, building up to relatively high metallicities and being largely complete 6 billion years ago. The close similarity of the spheroid and stream suggests that both may have derived from the same event; it would be worth exploring to what extent stars in these structures are the remnants of a disk galaxy that interacted with M31, or even were disrupted from the M31 disk itself by the interaction.

**Subject headings:** galaxies: evolution – galaxies: stellar content – galaxies: halos – galaxies: individual (M31)

1. **INTRODUCTION**

According to hierarchical models of galaxy formation, spheroids form in a series of mergers between galaxies and proto-galaxies. These models generally predict more dwarfs than observed, leading to suggestions that most of the proto-dwarfs in the early universe have since dissolved into the spheroids of giant galaxies (e.g., Bullock et al. 2000). Until relatively recently, traces of such activity were not obvious in the two giant galaxies of the Local Group. However, the discovery of the Sgr dwarf (Ibata et al. 1994), cannibalized by the Milky Way, sparked renewed interest in the formation of spheroids via the accretion of dwarfs. Subsequently, a spectacular tidal stream was discovered in Andromeda (Ibata et al. 2001), along with a variety of substructures in the spheroid and outer disk (Ferguson et al. 2002), suggesting an active merger history.

Further insight into the formation of galaxies can be found by studying their star formation histories. Photometry extending below the oldest main-sequence turnoff in a population can yield its complete formation history, but until the advent of the Advanced Camera for Surveys (ACS; Ford et al. 1998) on the Hubble Space Telescope (HST), it was not feasible to obtain such data for populations much beyond our own Milky Way and its satellites. However, Brown et al. (2003) used the ACS to obtain extremely deep photometry of a minor-axis field in the Andromeda (NGC 224; M31) spheroid; the resulting CMD shows a dominant intermediate-age population of 6–11 Gyr along with a significant, old, metal-poor population. The age distribution, high metallicity (Mould & Kristian 1986; Durrell, Harris, & Pritchet 2001), and substructure in the Andromeda spheroid all point to a violent merger history. Given these disturbances, our use of the term “spheroid” in this Letter does not imply a smooth and relaxed structure, but simply refers to the extraplanar stars of M31.

Andromeda’s tidal stream remains the most prominent merger remnant in the Local Group, and several years of intense study have yielded important constraints on its origin. Ibata et al. (2004) found that the stream is kinematically cold, with a velocity dispersion ($\sigma_v$) of only 11 km s$^{-1}$, and that the stream is increasingly blue-shifted as it approaches Andromeda, implying that the stream is falling into Andromeda from behind the galaxy. More recently, Kalirai et al. (2005) found two distinct kinematic stream components – both cold ($\sigma_v \approx 15$ km s$^{-1}$) and blue-shifted with respect to the spheroid (Figure 1a).

In all of these studies, the stream’s age distribution has remained largely unconstrained. Ferguson et al. (2005) published a stream CMD reaching a few magnitudes below the horizontal branch (HB); they found no evidence for very young populations, but speculated that the presence of a strong RGB bump might indicate a narrow age dispersion. In late 2004, we obtained deeper stream photometry, extending 1 mag below the oldest main-sequence turnoff, thus revealing the entire star formation history. In this Letter, we report on our initial analysis, which shows a remarkable similarity between the stream population and the spheroid population of Brown et al. (2003), in both the age and metallicity distributions.

2. **OBSERVATIONS AND DATA REDUCTION**

Using the ACS Wide Field Camera, we obtained deep optical images of a field 1.5° (20 kpc) from the M31 nucleus, at $\alpha_2000 = 00^h44^m18^s$, $\delta_2000 = 39^\circ 47'36''$. The field is well-placed within the tidal stream, and is a few arcmin from the stream fields of Ferguson et al. (2005), also observed with ACS. The
Keck spectroscopy of Kalirai et al. (2005) is coincident with our field. Our field includes a “candidate” globular cluster (Bol D242; Galletti et al. 2004), intending to reach the cluster turnoff (cf. Brown et al. 2004b); unfortunately, our images show that Bol D242 is not a cluster. Rich et al. (2005, in prep.) also obtained Keck spectra for our original spheroid field (Brown et al. 2003). Velocities in our stream (Figure 1a) and spheroid (Figure 1b) fields show that they are kinematically distinct; approximately 77% of the stars in our stream field are associated with two stream components. The stars in common between the HST fields and the larger Keck fields follow the same velocity distributions.

From 30 Aug to 4 Oct 2004, we obtained 14.7 hours of images in the F606W filter (broad V) and 21.7 hours in the F814W filter (I), with every exposure dithered to enable hot pixel removal, optimal point spread function (PSF) sampling, smoothing of spatial variation in detector response, and filling in the detector gap. Our reduction process, briefly summarized here, is very similar to that employed by Brown et al. (2003), but updated to reflect the latest calibrations. The images were registered, rectified, rescaled to 0.03′′ pixel−1, and coadded using the DRIZZLE package (Fruchter & Hook 2002), with rejection of cosmic rays and hot pixels. PSF-fitting photometry, using the DAOPHOT-II software of Stetson (1987), was corrected to agree with aperture photometry of isolated stars, with the zeropoints calibrated at the 1% level. Several improvements to the process of Brown et al. (2003) resulted in a cleaner catalog; these include changing the detection threshold from 4σ to 5σ and rejecting PSF fits of poor quality (generally due to blends of stars and superposition with background galaxies). After rejection of ≈24,000 stars, the final stream catalog contains ≈100,000 stars. Our photometry is in the STMag system: m = −2.5 × log_{10} F − 21.1. For reference, ABMAG = STmag − 0.169 for m_{F606W}, and ABMAG = STmag − 0.840 mag for m_{F814W}. 3. ANALYSIS

The stream CMD (Figure 1c) looks strikingly similar to the spheroid CMD of Brown et al. (2003). For comparison, we show in Figure 1d the CMD for a subset of the spheroid data that approximates the depth and star counts in the stream data (the complete spheroid images are ≈0.5 mag deeper with 40% higher surface brightness). The spheroid and stream data were reduced in the same manner. We then shifted the spheroid 0.03 mag fainter to match the larger distance to the stream, and 0.014 mag to the blue, to account for small calibration errors in color (see below). To help guide the comparison, we also show the ridge line for NGC 104 (Brown et al. 2005), shifted to the distance (770 kpc; Freedman & Madore 1990) and reddening (E_B−V = 0.08 mag; Schlegel et al. 1998) of Andromeda. The 0.03 mag difference in (m − M)0 between our stream and spheroid fields is well within the distance uncertainties for Andromeda and NGC 104. To further guide comparisons, we also show the color distributions on the lower RGB (Figure 1e) and HB (Figure 1f), and the luminosity distributions at the red clump (Figure 1g) and subgiant branch (SGB; Figure 1h).

As shown in Figure 1g, the HB luminosities of the stream and spheroid agree very well if the spheroid is shifted fainter by 0.03 mag (11 kpc). The distributions are not identical, though. The spheroid distribution is 50% broader, presumably due to the depth of the flattened spheroid relative to that of the stream. We estimate the luminosity widths and offsets of the stream and spheroid by fitting Gaussians to these HB distributions, with errors of ≈0.014 mag (5 kpc). More accurate distances may come from a comparison of the stream RR Lyrae stars to those of the spheroid (Brown et al. 2004a), but this will be part of a future paper. Interpolating the results of McConnachie et al. (2003) to our position would suggest that the stream is 0.14 ± 0.05 mag (50 ± 20 kpc) behind the spheroid. However, McConnachie et al. (2003) estimate their stream distances by analyzing the I-band luminosity functions of stars on the upper RGB; it is plausible that they underestimate their distance errors. Support for our relative distances comes from the data of Ferguson et al. (2005); we independently reduced the images of their stream, spheroid, and “northeast shelf” fields. Their stream fields are within a few arcmin of our stream field, but their spheroid fields are significantly further from the M31 nucleus. The shelf is an apparent fan of stars in the northeast quadrant of M31. Ferguson et al. (2005) note that their shelf fields are 0.14 mag brighter than their stream fields, and we concur. Ferguson et al. (2005) make no comparison between those fields and their spheroid fields, but we find that their spheroid fields agree with our spheroid field at the ≲0.03 mag level, while their stream fields agree with our stream field at the ≲0.02 mag level. These comparisons also imply that McConnachie et al. (2003) overestimate the distance of the stream from Andromeda, at least at a point 1.5′′ from the nucleus.

Our 0.014 mag shift to the blue is well within the calibration and reddening uncertainties; comparisons at the HB and RGB imply the shift is not due to intrinsic age and metallicity differences. The HB and RGB are sensitive to metallicity and age, but not in the same sense. As [Fe/H] increases, more stars populate the HB redward of the RR Lyrae gap, and RGB stars become redder. As age increases, more stars populate the HB blueward of the RR Lyrae gap, but the RGB stars again become redder. Our small color shift creates perfect agreement across the entire HB and the lower RGB. The upper RGBs are also similar, but the comparison is hampered by foreground contamination and the scarcity of stars.

The RGB in both fields is broad, indicating wide and similar metallicity distributions; the RGB luminosity functions are also remarkably similar. The HB is dominated by a red clump, with a minority population (≲10%) of blue HB stars due to old, metal-poor stars. Distinct multiple turnoffs, as might be expected from star formation pulses due to interaction of the stream with Andromeda, are not seen. As noted by Ferguson et al. (2005), the stream RGB “bump” is well-defined, and extends well below the HB. However, such a prominent bump does not necessarily indicate a narrow age distribution, as suggested by Ferguson et al. (2005). Brown et al. (2003) noted a similar RGB bump in their CMD of the spheroid – a population with broad distributions in both age and metallicity. This feature can be seen clearly in both of our fields (Figures 1c and 1d). In globular clusters, the bump becomes fainter (relative to the HB) as metallicity increases; here, the bump in both the stream and spheroid slopes from a blue point near the HB to a red point about 0.5 mag below the HB, again indicating similarly broad distributions in metallicity for both fields. Such similar metallicity distributions do not necessarily contradict the results of Guhathakurta et al. (2005a), who find that the stream is slightly more metal-rich (by ≈0.3 dex) than the surrounding spheroid; their fields are further out, where the metallicity gradient in the spheroid would enhance the contrast with the stream.

There is a subtle difference between the stream and spheroid luminosity functions at the SGB (Figure 1h). The luminosity offset between the HB and SGB is a standard age indicator; a 1
Gyr decrease in age decreases this offset by ~0.1 mag for ages near 10 Gyr. When we force the HB luminosities to agree (Figure 1g), the stream SGB is ~0.04 mag brighter than that of the spheroid, suggesting that the stream population, is, on average, ~300 Myr younger; this would have a negligible effect on the RGB and HB.

4. SUMMARY AND DISCUSSION

The stream CMD presents a challenge for the hypothesis that the progenitor is a disrupted dwarf galaxy on an early passage close to M31. The dwarf apparently stopped forming stars at least 6 Gyr ago (<5% of the stars in the stream field are less than 4 Gyr old). Orbit models (e.g., Font et al. 2005) imply that the progenitor of the stream only recently (~1 Gyr ago) approached within 100 kpc of M31. Those models do not explain why star formation stopped long before the interaction started.

The relatively high metallicity of the stream implies that the progenitor had a stellar mass of ~10^9 M⊙ if it followed the scaling relation for Local Group dwarfs found by Dekel & Woo (2003). However, according to their correlations, a dwarf galaxy with σ_v ~ 15 km s^{-1} (observed for the stream) would have a stellar mass of only ~10^8 M⊙. Font et al. (2005) claim that σ_v can vary significantly over the orbit, and could be much lower than that in the progenitor; it remains to be seen if this explanation can account for the large mass discrepancy. We note in this context that the only known systems that are kinematically cold and metal rich are disks. Thus a disk galaxy may be a more attractive candidate for the progenitor of the stream than a pressure-supported dwarf.

Although the stream and spheroid populations have very different kinematic and spatial distributions, their CMDs are strikingly similar, implying nearly identical age and metallicity distributions. A subtle difference between the CMDs is a slightly brighter (~0.04 mag) SGB in the stream, suggesting a slightly younger mean age (~300 Myr). Could the similarity of the CMDs be explained by the stream passing through the spheroid field, as suggested by some orbital models (e.g., Ibata et al. 2004)? The stream dominates by a 3:1 ratio in our stream CMD (Figure 1a; Kalirai et al. 2005). Thus the stream would have to similarly dominate in the spheroid field, yet show no clear morphological signature in the Ferguson et al. (2002) maps, and exhibit the kinematics shown in Figure 1b (a broad distribution at the M31 systemic velocity; Rich et al. 2005, in prep.); this seems implausible given the current orbital models. Thus, if there is ”contamination” from the stream in the spheroid field, it is likely to be much more complex and extended over a much wider region than that suggested by models where the infalling object has only completed one or two orbits.

Perhaps the stars in the spheroid came from a different dwarf galaxy (or galaxies) that merged with M31 earlier. This hypothesis can help explain why other locations in the spheroid (Ferguson et al. 2005) show RGB and HB morphologies similar to our spheroid field (Brown et al. 2003). However, it then becomes mere coincidence that the star-formation histories in the stream and the spheroid look nearly identical.

Perhaps the spheroid is a disrupted disk – either the M31 disk itself (Brown et al. 2003), or the remnants of a disk galaxy that merged with M31. The star formation history in the spheroid might be naturally explained if the disruption occurred 6–8 Gyr ago. We are still left invoking coincidence to explain the similar CMDs – unless the stream is also part of the disrupted disk.

It would be interesting to explore a wider range of dynamical simulations than those considered previously, to see whether the stream might nor be a dwarf galaxy that has encountered M31 in the last 1 Gyr, but instead a remnant of a merged disk galaxy or a plume of stars disrupted from the M31 disk. It is unclear if this interpretation can be reconciled with the stream’s structure and kinematics. Compared to a dwarf, a disk population might better explain the extended star formation history and high metallicity present in the stream and spheroid. Measurements of the formation history at multiple locations in the stream and distorted spheroid of M31 are undoubtedly going to be critical for sorting out what happened. Guhathakurta et al. (2005b) and Irwin et al. (2005) find that the minor-axis surface-brightness profile changes from a de Vaucouleurs r^{-1/4} law to an r^{-2.3} power law beyond ~30 kpc; exploration of this region might yield important constraints on the ”primordial” halo unaffected by Andromeda’s violent merger history.

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REFERENCES

Brown, T.M., et al. 2005, AJ, 130, 1693
Brown, T.M., Ferguson, H.C., Smith, E., Kimble, R.A., Sweigart, A.V., Renzini, A., & Rich, R.M. 2004a, AJ, 127, 2738
Brown, T.M., Ferguson, H.C., Smith, E., Kimble, R.A., Sweigart, A.V., Renzini, A., Rich, R.M., & VandenBerg, D.A. 2003, ApJ, 592, L17
Brown, T.M., Ferguson, H.C., Smith, E., Kimble, R.A., Sweigart, A.V., Renzini, A., Rich, R.M., & VandenBerg, D.A. 2004b, ApJ, 613, L125
Bullock, J.S., Kravtsov, A.V., & Weinberg, D.H. 2000, ApJ, 539, 517
Dekel, A., & Woo, J. 2003, MNRAS, 344, 1131
Durrell, P.R., Harris, W.E., & Pritchet, C.J. 2001, AJ, 121, 2557
Ferguson, A.M.N., Irwin, M.J., Ibata, R.A., Lewis, G.F., & Tanvir, N.R. 2002, AJ, 124, 1452
Ferguson, A.M.N., Johnson, R.A., Faria, D.C., Irwin, M.J., Ibata, R.A., Johnston, K.V., Lewis, G.F., & Tanvir, N.R. 2005, ApJ, 622, L109
Font, A.S., Johnston, K.V., Guhathakurta, P., Majewski, S.R., & Rich, R.M. 2005, AJ, accepted astro-ph/0501468
Ford, H.C., et al. 1998, Proc. SPIE, 3350, 234
Freedman, W.L., & Madore, B.F. 1990, ApJ, 365, 186
Fruchter, A.S., & Hook, R.N. 2002, PASP, 114, 144
Galleti, S., Federici, L., Bellazzini, M., Fusi Pecci, F., & Macrina, S. 2004, A&A, 416, 917
Guhathakurta, P., et al. 2005a, AJ, submitted astro-ph/0504061
Guhathakurta, P., et al. 2005b, Nature, submitted astro-ph/0509236
Ibata, R., Chapman, S., Ferguson, A.M.N., Irwin, M., Lewis, G., & McConnachie, A. 2004, MNRAS, 351, 117
Ibata, R., Chapman, S., Ferguson, A.M.N., Lewis, G., & McConnachie, A. 2004, MNRAS, 351, 117
Ibata, R., Chapman, S., Ferguson, A.M.N., Lewis, G., Irwin, M., & Tanvir, N. 2005, ApJ, submitted astro-ph/0504164
Ibata, R.A., Gilmore, G., & Irwin M.J. 1994, Nature, 370, 194
Ibata, R.A., Irwin, M., Lewis, G., Ferguson, A.M.N., & Tanvir, N. 2001, Nature, 412, 49
Irwin, M.J., Ferguson, A.M.N., Ibata, R.A., Lewis, G.F., & Tanvir, N.R. 2005, 628, L108
Kalirai, J.S., Guhathakurta, P., Gilbert, K.M., Reitzel, D.B., Majewski, S.R., Rich, R.M., & Cooper, M.C. 2005, ApJ, in press
McConnachie, A.W., Irwin, M.J., Ibata, R.A., Ferguson, A.M.N., Lewis, G.F., & Tanvir, N. 2003, MNRAS, 343, 1335
Mould, J., & Kristian, J. 1986, ApJ, 305, 591
Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525
Stetson, P. 1987, PASP, 99, 191
Fig. 1 – (a) The velocity histogram for RGB stars at our stream position (Kalirai et al. 2005), showing two cold peaks due to the stream, and a minority spheroid component ($\approx 23\%$). (b) The velocity histogram (Rich et al. 2005, in prep.) for RGB stars at our original spheroid position (Brown et al. 2003). Note that Ibata et al. (2005) recently found a cold ($\sigma_v \approx 30$ km s$^{-1}$), slowly-rotating, disk-like structure extending to 40 kpc in the disk plane; it seems unlikely that this structure contributes significantly here, at 50 kpc in the disk plane, given the much broader dispersion. (c) The CMD of our stream field, shown as a Hess diagram with a logarithmic stretch. Cuts across the CMD (red boxes) are used to highlight comparisons with the spheroid. The ridge line for NGC 104 (Brown et al. 2005) is shown for comparison. (d) The CMD of the spheroid, from a subset of the images chosen to match the stream depth and a subset of the resulting catalog chosen to match the number of stream stars. Cuts across the CMD (blue boxes) highlight the remarkable similarities to the stream. Cut labels correspond to the subsequent panels in this figure. The spheroid has been shifted 0.03 mag fainter and 0.014 mag to the blue (see text). (e) Histograms for stars along the RGB color cut for the stream (red) and spheroid (blue). (f) Histograms along the HB color cut for the stream (red) and spheroid (blue). (g) Histograms along the HB luminosity cut for the stream (red) and spheroid (blue). (h) Histograms along the SGB luminosity cut for the stream (red) and spheroid (blue).