The three dimensional structure of the giant stellar stream in Andromeda

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ABSTRACT
The wide-field CCD camera at the CFH telescope was used to survey the giant stellar stream in the Andromeda galaxy, resolving stars down the red giant branch in M31 to $I \approx 25$, a magnitude deeper than our previous INT survey of this galaxy and extending $1^\circ$ further out. The stream is seen to extend out to the south-east of M31 as far as we have surveyed (some $4.5^\circ$, corresponding to a projected distance $\sim 60$ kpc). It is a linear structure in projection, and the eastern edge of the stream presents a sharp boundary in star counts suggesting that it remains a coherent structure. By analysing the luminosity function of the metal rich component of the stream we find that, at the furthest extent of our survey, the stream is 100 kpc further away along the line of sight than M31. It can then be traced to a point on the north-western side of the galaxy where it is some 30 kpc in front of M31, at which point the stream turns away from our survey area.

Key words: Local Group - galaxies: interactions - galaxies: haloes - galaxies: evolution - galaxies: general - galaxies: stellar content

1 INTRODUCTION

Stellar streams are the remnants of structures that have become perturbed or disrupted due to the action of gravitational tides. In the hierarchical formation model of galaxy haloes, smaller systems merge first and form the larger galaxies we see today (White & Rees 1978). As such, these structures are expected to be common and examination of their properties gives valuable information about the galactic formation process. In the outer regions of haloes, dynamical times are sufficiently long to leave many structures detectable over much of the age of the universe (eg. Johnston, Hernquist & Bolte 1996) and so these streams can trace the left-overs of even ancient accretions. Indeed, under some favourable conditions the galaxy potential can leave massive streams essentially intact for all cosmic time.

Within our Local Group there is a lot of observational evidence that galaxy mergers are an on-going process. The discovery of the Sagitarius dwarf galaxy by Ibata, Gilmore & Irwin (1994) revealed that our own Galaxy is undergoing strong interactions with its companions. Further observations detected a tidal stream associated with this galaxy’s disruption (eg. Ibata et al. 2001a). Indeed, several of our Galaxy’s globular clusters have been found to have originally been associated with this dwarf galaxy (Ibata, Gilmore & Irwin 1994; Bellazzini, Ferraro & Ibata 2003). One of the most favoured explanations for the formation of the thick disk is that it is due to a violent merging event (eg. Quinn, Hernquist & Fullager 1993, Schwarzkopf & Dettmar 2000, Feltzing et al. 2003). Disentangling the merger history of galaxies is thus of prime importance and streams are ideal tracers of this process.

The discovery of a giant stellar stream in the outer regions of our neighbouring giant galaxy M31 was reported in two earlier contributions in this series (Ibata et al. 2001b, Ferguson et al. 2002). It is an apparently vast structure and our initial INT WFC survey did not go out far enough to find its true extent. Here we report on our findings from a deeper survey using the CFH12K camera that probes further out and to fainter magnitudes than we had previously surveyed.
2 OBSERVATIONS

During the nights of August 23, September 13-14 and September 17-18 2001, fourteen fields were observed with the 12k×8k CFH12K camera, at the prime focus of the Canada-France-Hawaii telescope. The observations were kindly taken by CFH Telescope staff, in service mode. Conditions were generally photometric, with good seeing of ≈ 0′′.8. Three sets of Mould V-band exposures and three Mould I-band exposures, each of 545s duration, were secured per field. A negligible colour correction is involved to convert these filters to the standard Johnson-Kron-Cousins system. The data were preprocessed by CFH staff with the CFH pipeline software, to correct for bias offset, flat-fielding and fringing. We then applied the same object detection, classification, photometry and catalog generation algorithms as we successfully used before on our INT-based survey (Irwin & Lewis 2001).

The fields were selected to lie along the previously detected region of the Andromeda stream, and we extrapolated along this stream in a straight line ~ 3 degrees further out to the south-east and to the north-west. The arrangement of the survey regions presented here is displayed in Figure 1 and the RA and Dec of fields 1–8 and 12–14 are listed in Table 1. The photometry of the three heavily-crowded fields 9–11, which lie close to the center of M31, will be presented elsewhere. Field 14 is used as a reference field, as no stream component was found there.

3 STELLAR POPULATIONS OF THE STREAM

A typical field from our survey (field 6) that illustrates the quality of the CFHT data is shown in Figure 1. This field is one of several that overlaps the INT survey region, although the CFHT data extends a full magnitude deeper than our previous survey. The overlap enables us to make an external comparison of the photometric systems and calibration. The internal overlaps between (most) CFH fields and their external overlap with some of the INT data allowed us to update the calibration of two CFH fields (2,3) that were taken under slightly non-photometric conditions. After these adjustments the photometric calibration systematic errors are at the level of ≈ ±2% over the entire region surveyed. Overlaid on the colour-magnitude diagram are four well-studied globular cluster sequences (NGC6397, NGC1851, 47Tuc and NGC6553) from Da Costa & Armandroff (1990) and Sagar et al. (1999) that span a range of different metallicities (left panel), and also four evolutionary tracks (for α-enhanced 0.8 M⊙ stars) from VandenBerg et al. (2000) (right panel). A wide range of stellar populations are evident in this field spanning the full range of metallicities represented by the fiducial sequences (−0.2 ≥ [Fe/H] ≥ −1.9). Inspection of a sequence of these diagrams shows evidence for a metal-poor halo population with a metallicity spanning roughly [Fe/H] ∼ −2 to [Fe/H] ∼ −0.7 and, in addition to this, a more metal-rich population is evident in the majority of the fields. Using the fiducial sequences to define the metallicity distribution function we can attribute a mean metallicity of [Fe/H] ≈ −0.5 to this component, with a dispersion of ≈ −0.5dex. This population is clearly seen to extend out to field 1 in our CFH survey data, where it still remains a numerous component: around 1000 stream stars are detected in field 1 to I = 23.5. This is in contrast to the metal poor halo component that virtually disappears by this galactocentric distance (~ 4′).

The evolutionary tracks we have selected correspond to [α/Fe] = 0.3 since CNO and other α-process elements, which dominate the heavy element composition, are thought to be enhanced relative to solar for Galactic halo stars (eg. Wheeler, Sneden & Truran 1989, Carretta, Gratton & Sneden 2000). These tracks are seen to be in good agreement with the globular cluster sequences and our data. In particular, the I magnitude of the tip of the red giant branch (TRGB) of the tracks appear to match up well as a function of metallicity. We will make use of this property in Section 4 in order to determine the relative distance of the metal-rich population to the bulk of the stellar population of M31.

4 THREE DIMENSIONAL STRUCTURE OF THE ANDROMEDA STREAM

4.1 Stellar profile across the stream

In the INT data, the stream appeared as a fairly straight structure pointing away to the SE from the center of the galaxy. With our extra CFH data we are now in a position to better constrain the projected profile of the stream on the sky. A reference line was chosen that follows a path parallel to the direction of the CFH survey fields and that passes through the centre of M31. The density of sources perpendicular to this line satisfying 20.5 < I < 22.5 and V − I > 2, for fields 1 to 8, is displayed as a solid line in Figure 3. This figure demonstrates that there is a rapid rise in number counts from the NE side of the stream towards the SW side, with the density of sources increasing by a factor

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1 http://www.cfht.hawaii.edu
The Andromeda Stream

Figure 2. Colour-magnitude diagrams of field 6. Error bars show typical uncertainties in the photometry at $I = 21.0, 21.5$ and $22.0$. On the panel on the left we have overlayed 4 well studied globular clusters sequences of different metallicities. From left to right, these are NGC6397 ([$Fe/H$] = $-1.9$), NGC1851 ([$Fe/H$] = $-1.3$), 47Tuc ([$Fe/H$] = $-0.7$) and NGC6553 ([$Fe/H$] = $-0.2$). In the panel on the right are 4 VandenBerg tracks for a 0.8 M$_\odot$ star with $[\alpha/Fe] = 0.3$. The metallicities that these correspond to, from left to right, are $[Fe/H] = -1.8, [Fe/H] = -1.3, [Fe/H] = -0.7$ and $[Fe/H] = -0.4$. For all the overlays, we have assumed a distance modulus of 24.47 and an average reddening of $E(B-V) = 0.07$ (following Schlegel et al. 1998).

of $\sim 2$ over 0.5$^\circ$. However, after the peak, the distribution is almost flat up to the SW edge of our survey area. This is consistent with the sharp edge to the stream seen in the INT survey, although at this time we cannot constrain the behaviour of the SW edge of the stream. To investigate the radial dependency we divided the CFH survey data into 4 bins (dotted lines). In Figure 3, the shallowest histogram is for fields 1 – 3, next is for fields 4–5, then 6–7 and finally 8. The distribution of sources in each of these bins can be observed to have a similar shape and, in particular, we find that the position of the peak of the distribution varies by less than 0.2$^\circ$ over the 4$^\circ$ line between fields 1 and 8. However, the spatial profile of the stream beyond $d = 2.4^\circ$ is broader, showing that the stream of width $\sim 0.5^\circ$ appears to fan out into a wider distribution in the outer regions.

Likewise, by separating the stars in Figure 4 with $d < 0.9^\circ$, we find that there is no significant difference in the shape of the histograms with that for $d > 0.9^\circ$. We had expected that for $d < 0.9^\circ$ the contribution of the stream would be small compared to the halo, and so the histograms would be flatter in appearance. Instead, it would appear that the stream contamination is still significant in the $d < 0.9^\circ$ region.

Figure 4 shows how the number density of these stars varies along the path defined above (fields 9, 10 and 11 have not been used due to crowding problems). As expected, the star counts increase as we approach the centre of M31. However, there is an excess of stars clearly visible for $d < 1.5^\circ$, which is highlighted in Figure 4 by comparison with the profile for $d > 0^\circ$ (its reflection about $d = 0^\circ$ is shown as a dot-dashed line). The CFH fields were selected to highlight the stream which is clearly delineated in azimuth (Ferguson et al. 2002) thus we attribute this excess to the stream. Although we believe stream to be present at $d > 0^\circ$ (Section 4.3), its stellar density by this point is much smaller compared to other M31 components.

4.2 Stream distance relative to M31

The I band magnitude of the tip of the red giant branch (TRGB) is now recognised as a good standard candle for
Figure 5. On the left is an inner field from our M31 INT WFC survey, converted to V and I using the transformation equations given in the text. The location of the tip of the red giant branch (TRGB) is readily seen. Overlaid is the behaviour of the tip as a function of metallicity as given by the evolutionary tracks of Vanden Berg et al. (2000). Detailed inspection shows that the tracks are in good agreement with the data. On the right is field 8 from our CFH12K survey. By calibrating the accuracy of the Vandenberg tracks in predicting the magnitude of the TRGB in our M31 field on the left, we can measure the distance variation between the stream-dominated component $(V - I > 2.2)$ and the M31-dominated component $(V - I < 2.2)$ in the field on the right. This places the stream component in field 8 approximately at the same distance as the bulk of M31.

Figure 4. The distribution of stars along the path of the stream, as defined in the previous figure. The dotted line is a mirrored version of the data from fields 12 and 13, to illustrate the large excess of stars due to the stellar stream obvious in fields 1-8 for a distance $<-1.5^\circ$. The dip at $-2^\circ$ is due to the gap between fields 5 and 6.

metal poor ($[Fe/H] < -0.7$) old ($> 2$ Gyr) stellar populations (eg. Salaris & Cassisi 1997). However, as we go to redder, more metal rich populations, the luminosity decreases due to the effect of increased opacity in the stellar atmosphere. This is clearly observed in our colour magnitude diagrams. As such, in order to gain a distance estimate of the stream relative to M31, we need to calibrate the redder $(V - I > 2.2)$, metal-rich stream to the bluer $(V - I < 2.2)$ M31 component and therefore need to know how the TRGB behaves a function of colour.

Vanden Berg et al. (2000) present evolutionary tracks for a range of stellar masses ($0.5 \leq M_\odot \leq 1.0$), with a range of metallicities ($-2.31 \leq [Fe/H] \leq -0.30$). A selection of these tracks are shown in Figure 2. In the left panel of Figure 5 we show the predicted location of the TRGB for $0.8 M_\odot$ stars with $[\alpha/Fe] = 0.3$ as a function of metallicity for these tracks. This is overlaid on one of our INT WFC survey fields (#76 located at $\xi = -1.068^\circ, \eta = -0.386^\circ$) from a central region of M31 with a similar colour spread on the red giant branch. Evidently there is good agreement between these theoretical evolutionary tracks and our M31 data. The INT passbands have been converted to V and I using $I = i' - 0.101 \times (V - I)$ and $V = V' + 0.005 \times (V - I)$. These transformations have been derived by comparison with observations of several Landolt standard fields $^2$.

In order to calibrate this model to the data, we adjust every I magnitude for stars in the M31 field using the differential model TRGB magnitudes with respect to a fiducial colour of $V - I = 1.6$. We then construct luminosity functions in the ranges $1.4 < V - I < 2.2$ and $2.2 < V - I < 2.8$ to represent the metal poor and metal rich components respectively. Using a data adaptive least-squares technique (McConnachie et al. in preparation), we measure the relative locations of the two TRGBs. The model-corrected metal-rich TRGB is systematically $\approx 0.1$ mags brighter than the metal-poor TRGB and defines an empirical correction to the model-corrected TRGB magnitude.

We now apply this metallicity correction to field 8 in our

$^2$ http://www.ast.cam.ac.uk/~wfcsur/colours.php
CFH data, as it is both the closest field to M31 and has the highest signal. The colour magnitude diagram of this field is shown in the right panel of Figure 5. By applying the magnitude transformation on the stars and by taking into account the 0.1 mag difference between the redder and bluer TRGBs that we would expect were the components all at one distance, we conclude that in field 8 there is no significant difference between the distance of the stream component and that of the bulk of M31.

4.3 Relative distance change along the stream

With a link between the stream distance and the distance of M31 in field 8, it is now possible to examine how this distance changes with respect to M31 as a function of stream position. To do this we cross-correlate the stream-dominated I-band luminosity function (2.5 < V − I < 3.5) in each field with the equivalent luminosity function in field 8. Any shift measured is a direct indicator of the stream distance. Examples are shown in Figure 6. In all cases field 14 is used as a reference field and a scaled (smoothed) version of its luminosity function is subtracted from each field analysed to account for varying foreground Galactic contamination. The luminosity functions are constructed using only objects classified as stellar sources in both the V and I filters. Although for the redder objects significant incompleteness due to the V-band sets in at I ≈ 22, this is sufficiently beyond the peak of the red star luminosity function to not affect the cross-correlation, even with slight variations in field-to-field depths. Further tests using I-band only stellar detections satisfying V − I > 2.5 support this conclusion.

The results of the cross-correlation are shown in Figure 6 and are tabulated in Table 1. The main contributors to the errors in the TRGB distance determinations are: the rms errors in the least-squares fit and cross-correlations which average about ±0.03 magnitudes; the photometric calibration error of around ±0.02 magnitudes; and model-dependent systematics from the various fits of order ≃ ±0.03. This leads to a total error of around ±20 kpc in the distances.

The projection on the sky and the distance variation along the stream point to an almost linear structure in the south-east region, aligned at roughly 60 degrees to the line of sight and extending out to distances well beyond 100 kpc from the centre of M31. No stream component is detected in field 8, although there is a clear signal in the inner half of field 13. The stream must therefore be wrapping around the south-east region, aligned at roughly 60 degrees to the line of sight. Additionally, by analysing the stellar profile across the stream we find that it remains a coherent structure, at least on the north-eastern edge. Its stellar distribution also appears to be fairly constant with increasing galactocentric distance. However, more observations are required in order to determine the true extent of this vast object.

5 CONCLUSIONS

The tidal stream discovered by our survey of M31 (Ibata et al. 2001) extends linearly over at least 6° of the sky. In fact, we still have not surveyed out far enough to find the far south-eastern end. By analysing the metal rich red giant branch luminosity function in the I band and comparing them to VandenBerg et al’s (2000) evolutionary tracks, we are able to measure a radial distance change of order 140 kpc between the two ends of our survey, with the stream extending from approximately 100 kpc behind to 40 kpc in front of M31. We also see evidence that the stream then proceeds to wrap itself around M31. This information confirms that the Andromeda stream is a gigantic structure, angled at approximately 60° to our line of sight. Additionally, by analysing the stellar profile across the stream we find that it remains a coherent structure, at least on the north-eastern edge. Its stellar distribution also appears to be fairly constant with increasing galactocentric distance. However, more observations are required in order to determine the true extent of this vast object.

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Figure 7. The distance variation along the tidal stream, measured by cross correlating the I-band luminosity function of field 8 with the other fields. The x-axis is the distance in degrees of the centre of each field from the intersection of the line with the semi-major axis of M31.

Table 1. The Depth Change Along the Stream.

| J2000 RA  | Dec    | $\xi^a$ | $\eta^a$ | Distance Along Stream$^b$ (°) | Distance to Stream$^c$ (kpc) |
|----------|--------|---------|----------|-------------------------------|-------------------------------|
| Field 1  | 0 52 50.36 | 37 17 01.6 | 2.015 | -3.965 | 4.37 | 886 ± 20 |
| Field 2  | 0 51 32.82 | 37 43 40.9 | 1.745 | -3.525 | 3.86 | 877 ± 20 |
| Field 3  | 0 50 16.28 | 38 10 12.8 | 1.483 | -3.087 | 3.35 | 860 ± 20 |
| Field 4  | 0 49 00.39 | 38 36 27.3 | 1.226 | -2.653 | 2.84 | 855 ± 20 |
| Field 5  | 0 47 43.24 | 38 59 59.5 | 0.969 | -2.204 | 2.38 | 840 ± 20 |
| Field 6  | 0 46 27.22 | 39 29 51.3 | 0.717 | -1.768 | 1.82 | 836 ± 20 |
| Field 7  | 0 45 10.35 | 39 56 27.1 | 0.467 | -1.327 | 1.32 | 829 ± 20 |
| Field 8  | 0 43 53.23 | 40 22 58.1 | 0.219 | -0.886 | 0.81 | 780 ± 20 |
| Field 12 | 0 38 47.83 | 42 09 18.6 | -0.731 | 0.891 | -1.20 | 739 ± 20 |
| Field 13 | 0 37 30.49 | 42 36 10.6 | -0.963 | 1.342 | -1.71 | 758 ± 20 |
| Field 14 | 0 36 14.95 | 43 02 15.5 | -1.186 | 1.781 | — | — |

$^a$ Standard coordinates measured in degrees from the centre of M31.

$^b$ Distance between the centre of the field and the point of intersection of the resulting line with the semi-major axis of M31.

$^c$ Measured relative to M31, assumed to be at a distance of 780kpc.

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