CSIRO PUBLISHING
5th Workshop on Galactic Chemodynamics
www.publish.csiro.au/journals/pasa
Publications of the Astronomical Society of Australia, 2004, **21**, 203–206

The Andromeda Stream

G. F. Lewis[1,7], *R. A. Ibata*[2], *S. C. Chapman*[3], *A. M. N. Ferguson*[4], *A. W. McConnachie*[5], *M. J. Irwin*[5], *and N. Tanvir*[6]

[1] School of Physics, University of Sydney, Sydney NSW 2006, Australia
[2] Observatoire de Strasbourg, 67000 Strasbourg, France
[3] California Institute of Technology, Pasadena, CA 91125, USA
[4] Max-Planck-Institut für Astrophysik, 85741 Garching, Germany
[5] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
[6] Physical Sciences, University of Hertfordshire, Hatfield AL10 9AB, UK
[7] E-mail: gfl@physics.usyd.edu.au

Received 2003 October 17, accepted 2004 January 8

Abstract: The existence of a stream of tidally stripped stars from the Sagittarius dwarf galaxy demonstrates that the Milky Way is still in the process of accreting mass. More recently, an extensive stream of stars has been uncovered in the halo of the Andromeda galaxy (M31), revealing that it too is cannibalising a small companion. This paper reports the recent observations of this stream, determining its spatial and kinematic properties, and tracing its three-dimensional structure, as well as describing future observations and what we may learn about the Andromeda galaxy from this giant tidal stream.

Keywords: Galaxy: kinematics and dynamics — methods: N-body simulations

1 Introduction

ΛCDM has become the preferred model of cosmological structure formation, providing a convincing description of the large scale distribution of matter in the Universe. On galactic scales, however, this paradigm has proved somewhat unsatisfactory, predicting a myriad of satellite systems accompanying the Milky Way which do not appear to be there (Klypin et al. 1999). One clear prediction of this model, however, is that large galaxies like the Milky Way grew over time via the accretion of smaller systems.

Numerical simulations of such accretion events reveal that they leave long-lived *fossil* signatures within the halo of the cannibalising galaxy in the form of extensive tidal streams that can completely wrap the host (e.g. Johnston 1998). The detection and characterisation of this fossil record will unravel the recent accretion history of a galaxy. While there is some evidence that the Magellanic Clouds may represent a case of ongoing accretion, displaying an extensive gaseous tail, the first clear detection of current cannibalisation in the halo of the Milky Way came with the discovery of the Sagittarius dwarf galaxy in 1994 (Ibata et al. 1994). Since its initial detection, studies have revealed more and more stellar debris located farther and farther from the main body of the dwarf (e.g. Majewski et al. 1999). Ibata et al. (2001b) found a stream of carbon stars lying over a great circle on the sky which intersects with the current location of the Sagittarius dwarf. Furthermore, this stream is also aligned with Sagittarius's proper motion, clearly demonstrating that it represents material associated with the dwarf galaxy. Intriguingly, the collimated nature of the stream strongly suggests that the dark matter halo is spherical, at odds with theoretical expectations of a strongly flattened, triaxial distribution. These results were recently confirmed by Majewski et al. (2003) using a larger sample of stars drawn from the Two Micron All Sky Survey (2MASS).

While the study of Sagittarius has proved quite successful, our location within the Milky Way limits our observational prospects, with any tidal debris presenting an extremely low stellar density on the sky. Furthermore, it is very important to know if the situation of the Milky Way is unique or if its current appetite is representative of galaxies in general. We need, therefore, to turn our attention to the search for tidal features in external galaxies. While this increases the apparent stellar density of tidal debris, distance rapidly blurs individual stars into uniform surface brightness and dynamical measures become extremely time consuming. Hence, the search for tidal debris should be aimed at our nearest companions if we are to use their structural and kinematic properties in a fashion similar to that of the Sagittarius stream.

2 The Andromeda Stream

2.1 Wide Field Photometry

M31, being our extragalactic neighbour, has been the target of numerous observational programs. With the advent of CCDs earlier work focussed on deep pencil-beam studies which indicated a complex metallicity mix

© Astronomical Society of Australia 2004
10.1071/AS04003 1323-3580/04/02203

https://doi.org/10.1071/AS04003 Published online by Cambridge University Press

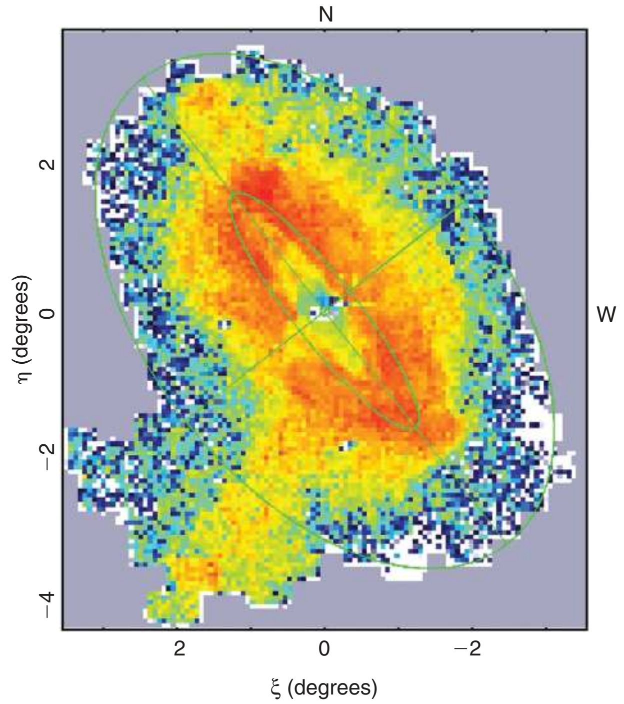

Figure 1 RGB stars as derived from the INT WFC survey. The Andromeda stream of stars is clearly visible extending to the south.

in M31's halo. In contrast, this present study employed the Wide Field Camera (WFC) on the Isaac Newton Telescope (INT) to obtain a deep but panoramic survey of the stellar populations in the halo of M31. Covering 0.3 deg^2 per pointing, the initial survey in the year 2000 tiled a region out to 4° (55 kpc) of the southern portion of the halo of M31, covering an area of $\sim$10 deg^2 to $i = 23.5$ and $V = 24.5$ (Ibata et al. 2001a).

An examination of the halo stellar density by eye clearly reveals that it is not smooth, showing significant substructure, particularly an apparent stream of stars stretching to the south of the main body of Andromeda. This feature is significantly enhanced if a selection is made of metal rich red giant branch (RGB) stars (see Figure 1; note, this Figure contains further observations with the INT WFC, mapping out the northern sector of the halo also). As well as the prominent tidal stream, these data also reveal complex structure in the halo of M31, including the northern spur and a significant overdensity of stars in the vicinity of the giant globular cluster G1 (Ferguson et al. 2002). The extensive substructure suggests that M31 may have undergone more recent accretion events, resulting in the rather complex metallicity distribution within its halo.

2.2 *The Distance to the Stream*

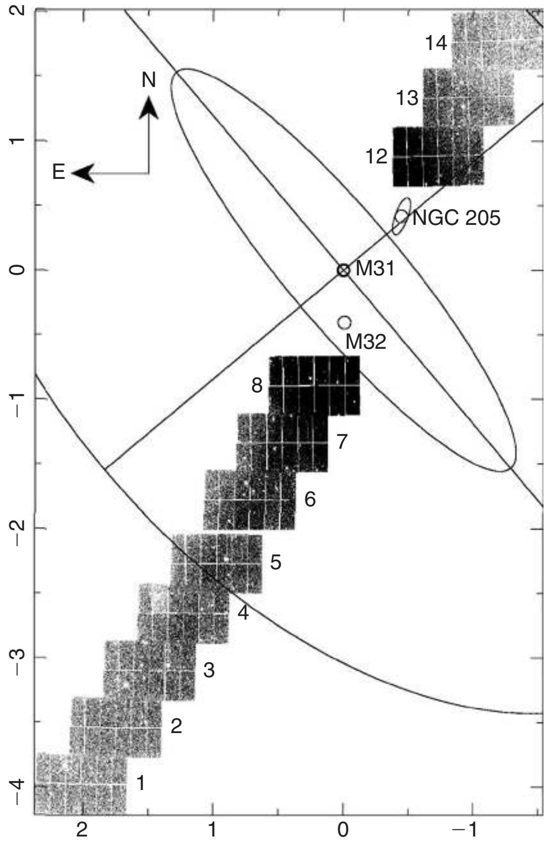

Figure 2 The location of the CFHT 12K fields relative to the central regions of M31. Three fields crossing the plane of M31 have been removed as they were not employed in the analysis of McConnachie et al. (2003) due to severe crowding issues.

In unravelling the history of the stream, it is important to determine its three-dimensional structure. To this end, the stream was targeted with the 12K camera on the Canada–France–Hawaii Telescope (CFH12K). Covering a total of $\sim$3 deg^2, 14 fields were obtained, starting $\sim$5 degrees below the plane of M31, and ending $\sim$2.5 degrees above the plane (Figure 2). An examination of colour–magnitude diagrams of the CFH12K fields clearly reveals the presence of the tidal stream of stars as a distinct feature to the very southern extremity of the survey. The situation is, however, different in the north where the signature of the stream quickly peters out, disappearing in the northernmost field; this reflects the structure seen in the INT imaging survey described previously.

The superb quality of the CFH12K data, however, provided an opportunity to measure the distance to the stream at various locations along its length. This was achieved by first determining the location of the tip of the red giant branch (TRGB) in the main body of M31 at a range of metallicities. By comparing the location of the TRGB in the fields along the stream with the main body of M31, the position of each field relative to M31 could be measured via a cross-correlation of the stellar luminosity functions, as any offsets would primarily be due to a difference in distance (McConnachie et al. 2003). The results of this study are presented in Figure 3, revealing that the Andromeda stream curves away from us below the disk of M31. The most southern extremity of the survey lies at a distance of $\sim$900 kpc from us, 120 kpc farther than M31 itself. In the north, the fields are actually in front of M31, but are curving away from us northwards.

https://doi.org/10.1071/AS04003 Published online by Cambridge University Press

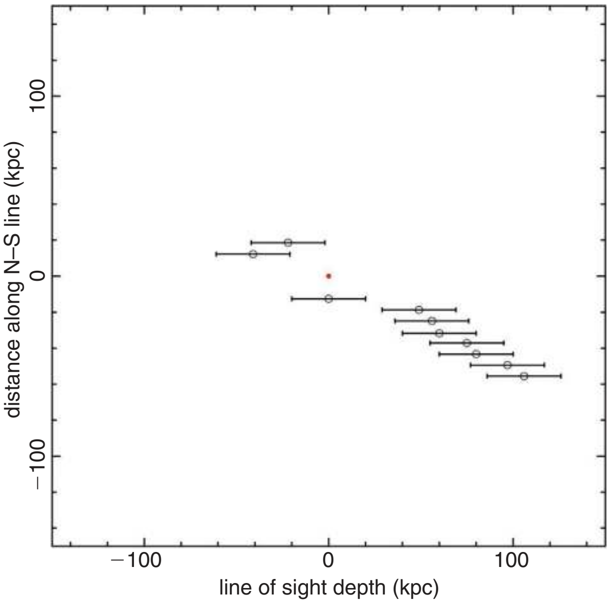

Figure 3 The distance to the Andromeda stream as determined from calibrating the tip of the red giant branch and cross-correlating the luminosity function of stars along the Andromeda stream.

2.3 Stellar Velocities

While the spatial structure of the Andromeda stream reveals important clues to its origin and evolution, fully unravelling its dynamical history requires a measurement of the stellar kinematics. As the wide-field imaging has resolved the stream into individual stars the determination of stellar velocities is possible with 8-m class telescopes. To this end, a series of observations was undertaken using the DEIMOS spectrograph on the 10-m Keck2 telescope. Employing multislit masks, resulting in $\sim$100 spectra over a $16' \times 5'$ region, four fields along the stream were targeted. The RGB sources possessed $20.5 < i < 22.0$, resulting in a velocity accuracy of 5–10 km s^{-1}.

These observations revealed a strong velocity gradient along the stream, with the southernmost region of the stream travelling towards us at the systemic velocity of M31, while in the vicinity of M31 it is approaching at 300 km s^{-1} with respect to M31 (Ibata et al. 2004). Coupled with the distance determinations outlined above, these kinematics provide strong constraints on the orbital properties of the stream; Figure 4 presents two preliminary orbit fits to the extant kinematic and spatial data of stars in the stream.

2.4 Interpretation

The stream orbits allow us constrain the mass distribution in the M31 halo. A full analysis will require N-body simulations to be carried out in different halo potentials, with the resulting stellar stream compared to the observed position, distance, and velocity data. However, a good approximation can be obtained by simply comparing the locus and velocity profile of test particle orbits, a task which is computationally much cheaper. For this approximation to work, the dwarf galaxy progenitor of the stream must be of relatively low mass, $<10^9 M_\odot$, for the self-gravity of the stream to be unimportant. By comparing the best-fit orbit to the data as a function of halo potential, the most likely value of the total mass of M31 is $M_{\rm tot} = 6.5 \pm 1.6 \times 10^{11} M_\odot$ out to 145 kpc. With this, Andromeda has a very similar halo mass to the Milky Way. However, this result is somewhat uncertain; using only the southern data to constrain the form of the potential reduces the halo mass by a factor of about four (see Ibata et al. 2004 for more details).

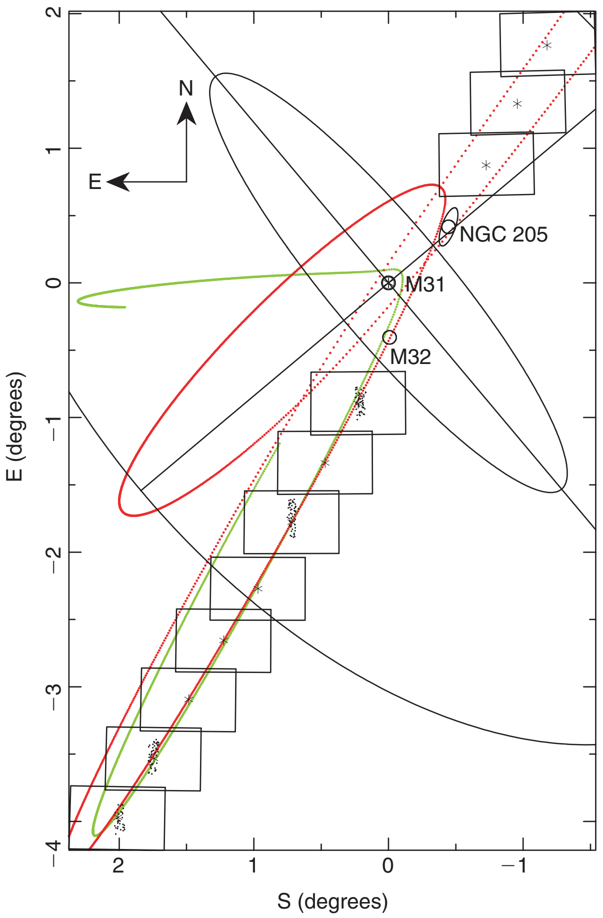

Figure 4 Two preliminary fits to the orbit of the Andromeda stream. The green model utilises only the southern data; the overall fit to the kinematic and spatial data is good but the resulting orbit is strongly radial. The red model, incorporating the entire dataset, is a poor representation of the data, but its orbit is similar to the rosette orbit of the Sagittarius dwarf.

3 Future Observations

In September 2003, further DEIMOS spectroscopy was undertaken at Keck2. To increase the observational multiplexing to roughly 1000 stars per mask, a narrow-band filter was employed to capture only the region of the CaII NIR triplet. In this manner we targeted a total of $\sim 2 \times 10^4$ stars. These data will be supplemented with a CFHT/MEGACAM survey of the southern quadrant of M31, covering a total of almost 80 deg^2, calibrating the entire extent of the tidal stream and allowing us to probe the halo between M31 and M33.

https://doi.org/10.1071/AS04003 Published online by Cambridge University Press

This extensive dataset will allow a more complete determination of the orbital properties of the Andromeda stream and characterise its dynamical evolution and ultimate demise. As with the studies of the Sagittarius tidal stream (e.g. Ibata et al. 2001b), this approach will reveal the form of the dark matter halo of M31.

Acknowledgments

G.F.L. thanks Swinburne University's Astronomy Group for hosting a fun and informative meeting, although Sydney would have been warmer.

References

Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2002, AJ, 124, 1452

Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Natur, 370, 194

Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001a, Natur, 412, 49

Ibata, R., Lewis, G. F., Irwin, M., Totten, E., & Quinn, T. 2001b, ApJ, 551, 294

Ibata, R. A., Chapman, S., Ferguson, A. M. N., Irwin, M., Lewis, G. F., & McConnachie, A. 2004, MNRAS, accepted, astro-ph/0403068

Johnston, K. V. 1998, ApJ, 495, 297

Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82

Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, ApJ, 599, 1082

Majewski, S. R., Siegel, M. H., Kunkel, W. E., Reid, I. N., Johnston, K. V., Thompson, I. B., Landolt, A. U., & Palma, C. 1999, AJ, 118, 1709

McConnachie, A. W., Irwin, M. J., Ibata, R. A., Ferguson, A. M. N., Lewis, G. F., & Tanvir, N. 2003, MNRAS, 343, 1335

https://doi.org/10.1071/AS04003 Published online by Cambridge University Press