The Andromeda Stream

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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

$\Lambda$CDM 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.

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...
in M31’s halo. In contrast, this present study employed
the Wide Field Camera (WFC) on the Isaac Newton Tele-
scope (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 $4^\circ$ (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 substruc-
ture, 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 com-
plex 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

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). Cover-
ing a total of $\sim 3$ deg$^2$, 14 fields were obtained, start-
ing $\sim 5$ degrees below the plane of M31, and ending
$\sim 2.5$ degrees above the plane (Figure 2). An examina-
tion 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 sur-
vey. The situation is, however, different in the north where
the signature of the stream quickly peters out, disappear-
ing in the northernmost field; this reflects the structure
seen in the INT imaging survey described previously.

The superb quality of the CFH12K data, however, pro-
vided 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 dis-
tance (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.
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 ~100 spectra over a 16′ × 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 $M_{tot} = 6.5 \pm 1.6 \times 10^{11}$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).

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 ~2 × 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.
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.

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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, Nat, 370, 194

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

Ibata, R., Lewis, G. F., Irwin, M., Totten, E., & Quinn, T. 2001b, ApJ, 555, 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, 499, 297

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

Majewski, S. R., Sobeckie, 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

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