

A giant stream of metal-rich stars in the halo of the galaxy M31

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Recent observations have revealed streams of gas and stars in the halo of the Milky Way^{1–3} that are the debris from interactions between our Galaxy and some of its dwarf companion galaxies; the Sagittarius dwarf galaxy and the Magellanic clouds. Analysis of the material has shown that much of the halo is made up of cannibalized satellite galaxies^{2,4}, and that dark matter is distributed nearly spherically in the Milky Way. It remains unclear, however, whether cannibalized substructures are as common in the haloes of galaxies as predicted by galaxy-formation theory⁵. Here we report the discovery of a giant stream of metal-rich stars within the halo of the nearest large galaxy, M31 (the Andromeda galaxy). The source of this stream could be the dwarf galaxies M32 and NGC205, which are close companions of M31 and which may have lost a substantial number of stars owing to tidal interactions. The results demonstrate that the epoch of galaxy building still continues, albeit at a modest rate, and that tidal streams may be a generic feature of galaxy haloes.

Within the framework of hierarchical structure formation, large spiral galaxies like the Milky Way or Andromeda arose from the merger of many small galaxies and protogalaxies⁶. Later in their evolution, spiral galaxies become the dominant component in such mergers, cannibalizing smaller systems that fall within their sphere of influence. The complete destruction of the victim is usually progressive, and may take several orbits. However, the stellar debris from the destroyed dwarf galaxy follows a similar orbital trajectory to the progenitor, which is likely to have started life far away from the place of its final demise, and so the tidally disrupted matter tends to be deposited over a broad range in distance from the larger galaxy. Over time, with the accumulation of many such mergers, large galaxies develop an extensive stellar and dark-matter 'halo', the latter being by far the most massive component of the galaxy. Meanwhile, part of the (dissipative) gas component of the smaller galaxies feeds the growth of the disk of the larger galaxy. This is seen in numerical simulations of galaxy formation, which result in galactic haloes comprising clumps of dark matter⁵. If this prediction is correct, then haloes should possess significant substructure—in contrast to previous suggestions⁷, which predict the dark and luminous components of haloes to be distributed smoothly.

Most of the halo of the Milky Way is metal-poor and, to first order, smoothly distributed; but recent studies have shown that the halo contains non-negligible stellar substructure. Evidence for the phase-space clumping of halo stars has even been found in the solar neighbourhood, where about 10% of the stars may be associated with a single ancient accretion event⁴. The discovery that the Milky Way is surrounded by a giant rosette-like stream originating from the Sagittarius dwarf galaxy^{2,3} shows that—on the largest scales—the structure of the halo is substantially 'streamy': approximately half of the intermediate-age stars at distances beyond about 15 kpc belong to the Sagittarius stream. This also implies² that the last large accretion was that of the Sagittarius dwarf, and that the Milky Way

has not cannibalized many other small galaxies for about 7 Gyr. Unless there has been a continual accretion of highly dark-matter-dominated 'galaxies', or of galaxies containing exclusively old stars, the formation of the Galactic halo must have been essentially complete at a point in time less than half the age of the Universe.

We now consider whether the behaviour of the Milky Way is unusual. The only external galaxy in which halo substructure has been reported is NGC5907, which possesses a gigantic extraplanar stellar stream⁸, substantially brighter than similar structures in the Milky Way. However, this galaxy has long been known to be peculiar⁹, having a red, and luminous, flattened 'halo', probably the result of the strong interaction that deposited the stream. To understand whether stream-like substructure is the generic morphology of galaxy haloes, it is necessary to investigate other 'normal' galaxies like the Milky Way. The prime target for such a study is the Milky Way's 'sister' galaxy, M31—the Andromeda nebula, which at a distance of ~780 kpc is the closest large galaxy¹⁰.

The Wide Field camera¹¹ on the 2.5-m Isaac Newton Telescope (INT WFC) is a four-chip charge-coupled device (CCD) mosaic camera imaging about 0.3 degree² per exposure. On the nights of 3–9 September 2000, this instrument was used to survey the southeastern half of the halo of the Andromeda galaxy. To tile this region out to a distance of 4° (~55 kpc in projection) from the centre of M31 required 58 contiguous fields. Images were taken in the equivalent of Johnson visual V and Gunn i bands under good atmospheric conditions, with 85% of fields taken in photometric conditions with seeing better than 1.2".

Previous imaging studies of the M31 halo and outer disk have either sampled the outer parts of M31 at only a few discrete locations^{12–14}, or have taken a panoramic, but much shallower, view^{15,16}. In contrast, our deep survey allows us to make an uninterrupted study of the spatial variations in stellar density as a function of magnitude and colour over a large fraction of the halo. The continuous nature of this survey enables us to distinguish local density enhancements from both the large-scale structure of the halo of M31 and the underlying foreground Galactic distribution of stars. The exposure time of 800–1,000 s per passband per field reaches i-band magnitude $i = 23.5$ and V-band magnitude $V = 24.5$ (with a signal-to-noise ratio of ~5) and allows detection of individual red-giant branch (RGB) stars to an absolute V-band magnitude $M_V = 0$ and main-sequence stars to $M_V = -1$ in the halo of M31.

The WFC pipeline processing provides internal cross-calibration for the four INT WFC CCDs (each of 4,096 × 2,048 pixels) at a level of about 1% within each pointing. Field-to-field variations in photometric zero points were calibrated and cross-checked using a combination of multiple nightly photometric standard sequence observations and the overlap regions between adjacent WFC pointings. The overall derived photometric zero-points for the whole survey are good to the level of 1–2% in both bands. (Details of the data processing and calibration will be presented elsewhere.) Objects were classified as noise artefacts, galaxies or stars according to their morphological structure on all the images.

Figure 1 presents a summary of the results of our survey. Visual inspection of the surface density of sources classified as star-like on the i-band images and with magnitudes and colours consistent with the known properties of RGB stars at the distance of M31, shows the presence of a stream-shaped over-density of sources in the halo close to, but distinct from, the minor axis of M31. The RGB stellar density in the halo increases on average by a factor of two in the on-stream regions, and is statistically significant at ~50σ level. For stars brighter than the tip of the RGB in M31, the spatial density of sources is smooth and shows no sign of the feature: the stream therefore cannot be a foreground Galactic population. The on-stream stars follow a similar colour–magnitude sequence to the RGB stars in the remainder of the halo of M31, but with evidence of an enhanced metallicity relative to the 'normal' M31 halo popula-

tion owing to their redder colours. The average V-band surface brightness of the stream is $\Sigma_V \approx 30 \pm 0.5 \text{ mag arcsec}^{-2}$, and the stream extends out to the current limit of our survey, at a projected distance of about 40 kpc.

The metallicity of the stream, deduced from the colour–magnitude diagrams displayed in Fig. 2, covers a broad range with a mean slightly more metal-rich than the Galactic globular cluster 47 Tucanae (whose metallicity, that is, whose ratio of iron to hydrogen compared to that of the Sun, is $[\text{Fe}/\text{H}] = -0.7$). We note that stars of near-solar metallicity are concentrated in the stream. Our survey reveals that such high-metallicity stars are also sparsely distributed throughout large parts of the halo of M31, consistent with the results of previous studies^{12,17}. This high metallicity, with a mean approximately 10 times greater than that of the Milky Way's halo, and the overly large stellar density of the halo—a factor of 10

greater¹⁴ than that of the Galactic halo—have until now been a puzzle.

What is this stream-like feature? The outer regions of galactic disks are metal-poor¹⁸, so the metallicity of the feature argues against a direct association with the outer disk of Andromeda. Furthermore, if it were a disk structure, it would be located at an impossible de-projected radial distance of about 140 kpc from the centre of the galaxy. This distance constraint is weakened if the feature is part of a pronounced disk warp, but that possibility is highly unlikely given the observed elongated structure. The only plausible explanation is that it is part of a large stellar stream within the halo. This stream lies along a line connecting the Andromeda satellites M32 and NGC205, and is aligned with the direction of elongation of the outer isophotes of NGC205, suggesting a relationship between the Andromeda stream and these two dwarf galaxies.

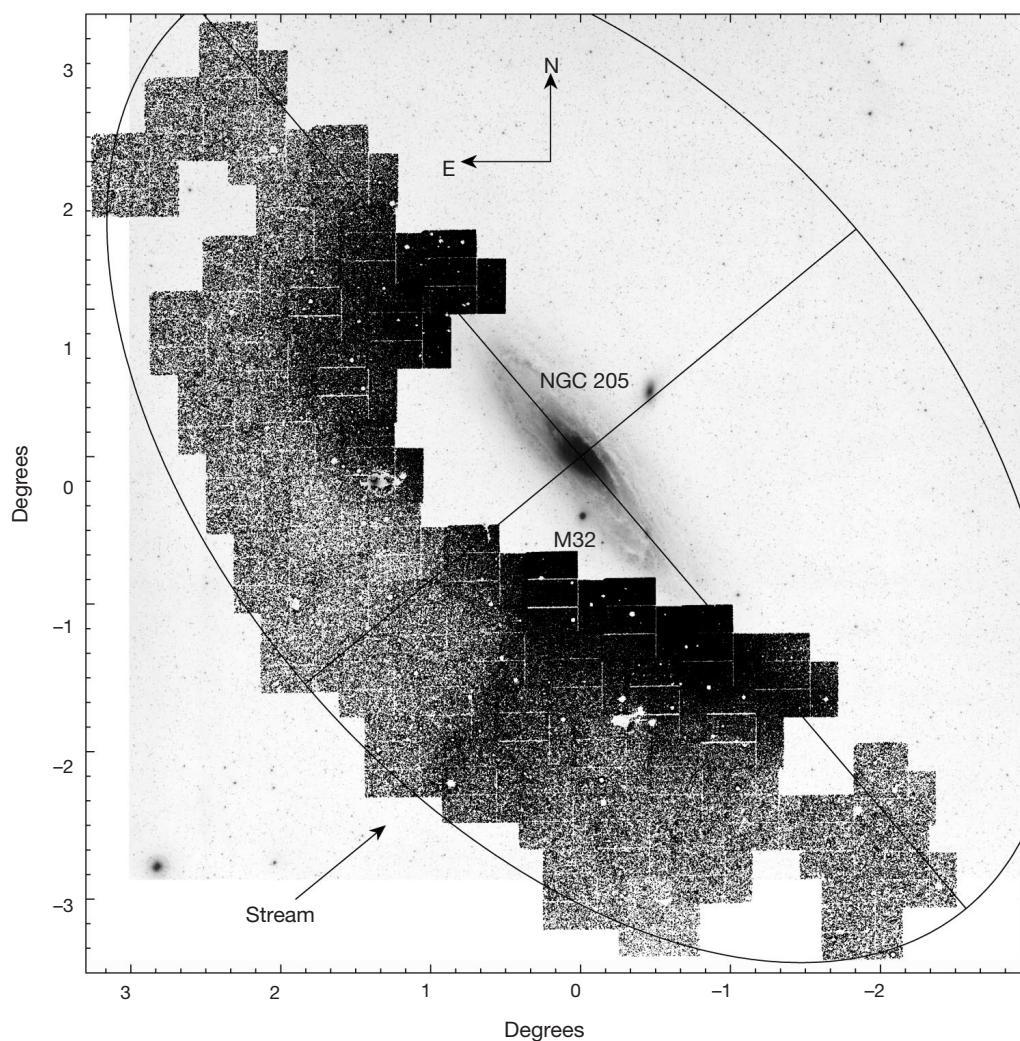


Figure 1 Surface density of red-giant branch (RGB) stars over the outer southeastern halo of M31. The surface-density maps produced by our survey are shown as 'tiles' overlaying an optical image centred on M31 (see below). The over-density of stars revealed in the present study is seen as a stream extending out of M31 close to its minor axis. The density of extended background galaxies (approximately 25,000 per degree² to $V < 24$ mag) becomes comparable to the stellar density at a projected distance of 20–25 kpc from the centre of M31 along the minor axis. A fraction of these galaxies are misclassified by the reduction algorithm, thereby contaminating the stellar sample. There is a further contamination from foreground Galactic disk dwarfs, which number $< 10\%$ of the M31 halo population over the survey region. However, the contribution of these contaminating sources to the number density maps is easily removed. Indeed, the stream can be

detected at signal-to-noise ratio > 5 over tiny individual regions of area $> 0.01 \text{ degree}^2$. The gaps to the northeast and southwest of the map correspond to fields taken in poor seeing conditions where the image quality criteria of the survey were not attained. The surface density maps are superimposed upon a photographic Palomar Sky Survey image of M31; clearly visible are the two companion galaxies M32 and NGC 205. The major and minor axes of M31 are displayed, and an ellipse denoting the size of a flattened ellipsoid (aspect ratio 3:5) of semi-major axis length 55 kpc has been superimposed to show the spatial extent of the survey. The location of the Andromeda stream is labelled. The overall shape of the M31 halo revealed by our observations appears rather boxy, with indications of other possible substructures—but these results require further study to confirm their reality.

The total absolute magnitude of the stellar stream is $M_V \approx -14$, which we estimate from the differential luminosity function between equivalent on- and off-stream fields (plausible assumptions were made to allow for fainter stream stars, the incompleteness of the survey and the uniformity of the stream). This luminosity is a factor of about 10 lower than that of either M32 and NGC205, consistent with the possibility that the stream is the debris stripped from one (or both) of these two dwarf galaxies during a recent interaction with M31.

M32 and NGC205 are both unusual dwarf elliptical galaxies which lie at projected distances of, respectively, only 5 kpc and 9 kpc from the centre of M31. NGC205 is still active in forming stars, and has had a varied and complex star-formation history¹⁹. The central regions are also known to contain dust, H I gas and molecular gas²⁰, and there is substantial morphological²¹ and kinematic²² evidence that indicates that NGC205 is being tidally distorted and potentially disrupted. The H I distribution shows a well defined velocity gradient (unlike the stars), and is less extended than the overall stellar content of the galaxy^{20,23}. The clear inconsistency between the gas and stars suggests that the gas may have recently been captured, possibly from the disk of M31.

M32, on the other hand, does not appear to be substantially distorted, yet it does seem to have a significant population of intermediate-age stars in addition to a classical old stellar component^{24,25}. There is also clear evidence of a large metallicity spread in the giant branch, with a mean just below solar, supporting a prolonged star-forming epoch²⁶.

The broad agreement of the metallicity distributions of the stream stars and these two dwarf satellites, together with their alignment and physical proximity to M31, point to a common origin. Furthermore, the unusual properties of most of the rest of the halo of M31 is also consistent with its relatively recent tidal

origin. It seems quite likely that the apparently peculiar properties of M31's halo are simply the result of a prolonged, aggressive bout of tidal stripping from either one, or both, of its two nearest neighbour satellite galaxies.

If this interpretation is correct, the stream (and possibly most of the stellar halo) has to be the result of previous interactions with M31, as there is otherwise not enough time to spatially separate if from either of the two dwarf galaxies. Furthermore, by comparison with numerical models of the Sagittarius stream^{27,28}, there will be a similar stream (either leading or trailing the progenitor dwarf(s), depending on the sense of their orbit) on the opposite side of M31.

During disk-crossing episodes, gas in the disk of M31 and in these dwarf galaxies is shocked, leading to episodic bursts of star formation, and gas exchange. In the dwarf galaxies, this gas may either be recycled from earlier generations of stars or accreted from the M31 disk. These complex interactions may explain the unusual star-formation history of the dwarf galaxies and the Andromeda stream. In turn, the regular impacts perturb the disk of M31, possibly enough to induce its warped shape²⁹ (it is plausible that a similar process is responsible for the warp in the disk of the Milky Way³⁰).

The discovery of the Andromeda stream in the first deep, panoramic survey of the Milky Way's nearest large companion suggests that halo substructure in the form of giant tidal streams may be a generic property of large spiral galaxies, and that the formation of galaxies continues at a moderate pace up to the present day. Although the dwarf galaxies M32 and NGC205 may be the source of this material, we cannot rule out the alternative possibility that the stream may be the fossil remnant of a third cannibalized system, found at a stage intermediate to those seen within the Milky Way^{2,4}.

To understand more fully the origin and evolution of the

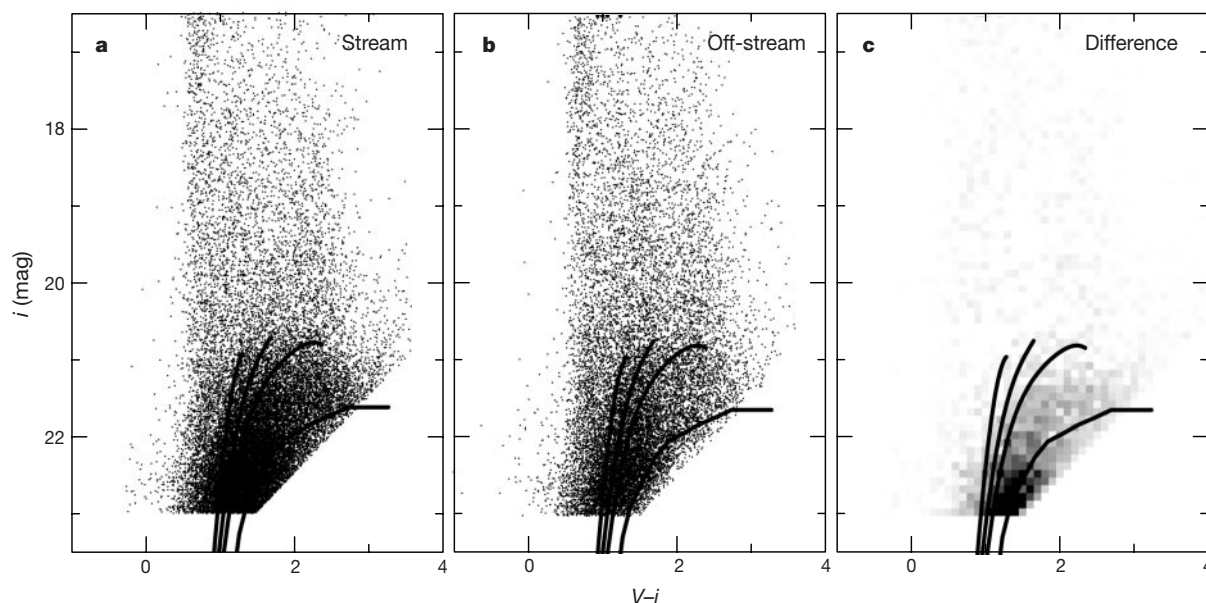


Figure 2 The relation between $V-i$ colour and i -band magnitude. Data are shown for a stream field (**a**), and an off-stream field (**b**). **a** and **b** both cover 0.3 degree^2 of sky, and were taken in similar observing conditions ($0.97''$ in i and $0.93''$ in V for the stream field, and $1.08''$ for both i and V for the off-stream field). **a** and **b** are also at a similar distance ($\sim 2''$) from the centre of M31, with the off-stream field almost exactly on the minor axis of the galaxy. The red-giant branch (RGB) stars of M31 are seen at magnitudes fainter than $i = 20.5$. To guide the interpretation of these diagrams, we have superimposed on each panel the RGB tracks (shifted to the distance of M31 and corrected for extinction) of four well-studied galactic globular clusters of different metallicity ($[\text{Fe}/\text{H}]$); these are, from left to right, NGC6397 ($[\text{Fe}/\text{H}] = -1.91$), NGC1851 ($[\text{Fe}/\text{H}] = -1.29$), 47 Tuc

($[\text{Fe}/\text{H}] = -1.71$) and NGC6553 ($[\text{Fe}/\text{H}] = -0.2$). The difference between the stellar populations in **a** and **b** is displayed in **c** in the form of a binned colour-magnitude diagram. With much of the contamination removed in this way, we see that the stream contains a broad range of stellar populations, from metallicities similar to that of NGC1851 through to solar abundance, with a mean metallicity slightly higher than that of 47 Tuc. It is particularly difficult to constrain the distance to the stream owing to this metallicity spread; to within an uncertainty of possibly as much as 0.5 mag the stream RGB appears at the same position as the M31 RGB, which suggests a distance of $d \approx 800 \pm 200 \text{ kpc}$. (The photometric uncertainties are approximately 0.2 mag at the faint limit of the data in the diagrams; 0.1 mag uncertainties occur at $V = 23.7 \text{ mag}$, $i = 22.5 \text{ mag}$).

Andromeda stream, a number of follow-up observational programmes are required, including an extension of the panoramic survey not only to the northern regions of the halo of M31, but also out to larger radii, as it is evident in the present data that the stream extends beyond the 40-kpc limits of the survey. The proximity of M31 also provides us with an opportunity to undertake a spectroscopic survey of individual stars within the stream, allowing us to map its kinematic and chemical properties. As with the tidal material detected in the halo of our own Galaxy, studies of the Andromeda stream would allow us to map the distribution of dark matter within the halo of our nearest neighbouring galaxy, as well as furthering our understanding of the process of galaxy formation. □

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Dynamical tunnelling of ultracold atoms

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The divergence of quantum and classical descriptions of particle motion is clearly apparent in quantum tunnelling^{1,2} between two regions of classically stable motion. An archetype of such non-classical motion is tunnelling through an energy barrier. In the 1980s, a new process, ‘dynamical’ tunnelling^{1–3}, was predicted, involving no potential energy barrier; however, a constant of the motion (other than energy) still forbids classically the quantum-allowed motion. This process should occur, for example, in periodically driven, nonlinear hamiltonian systems with one degree of freedom^{4–6}. Such systems may be chaotic, consisting of regions in phase space of stable, regular motion embedded in a sea of chaos. Previous studies predicted⁴ dynamical tunnelling between these stable regions. Here we observe dynamical tunnelling of ultracold atoms from a Bose–Einstein condensate in an amplitude-modulated optical standing wave. Atoms coherently tunnel back and forth between their initial state of oscillatory motion (corresponding to an island of regular motion) and the state oscillating 180° out of phase with the initial state.

Tunnelling between discrete states is coherent and reversible—that is, the particle oscillates between the states, which is the process we describe here. Coherent tunnelling oscillations are especially significant, as the system must pass through states corresponding to superpositions of distinct classical motions. It has been suggested⁷ that such states are strongly suppressed by decoherence, a subject of central importance to quantum information. Our system should

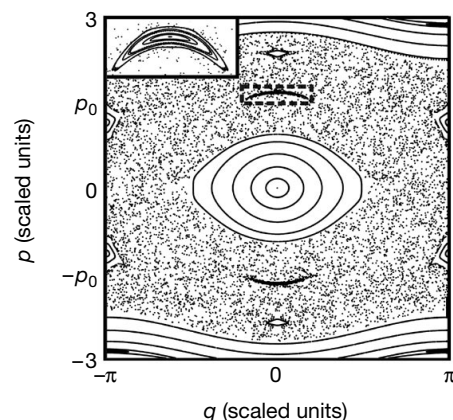


Figure 1 Poincaré section for position p and momentum q of a classical particle in an amplitude-modulated optical lattice. Data are shown for $\kappa = 1.66$ and $\epsilon = 0.29$, showing a mixed phase space. The central region consists of small-amplitude stable motion. Chaos separates this region from two period-one resonances located above and below the centre along $q = 0$. Further out in momentum are two stable regions of motion known as librations, which have a period of twice the modulation period. At the edges are bands of regular motion corresponding to above-barrier motion. The inset is a magnified view of the dashed rectangle.