The remnant of a merger between two dwarf galaxies in Andromeda II

N. C. Amorisco1, N. W. Evans2 & G. van de Ven3

Driven by gravity, massive structures like galaxies and clusters of galaxies are believed to grow continuously through hierarchical merging and accretion of smaller systems. Observational evidence of accretion events is provided by the coherent stellar streams crossing the outer haloes of massive galaxies, such as the Milky Way4 or Andromeda5. At similar mass scales, around \(10^{10}\) solar masses in stars, further evidence of merging activity is also ample6,7. Mergers of lower-mass galaxies are expected within the hierarchical process of galaxy formation, but have hitherto not been seen for galaxies with less than about \(10^{10}\) solar masses in stars7,8. Here we report the kinematic detection of a stellar stream in one of the satellite galaxies of Andromeda, the dwarf spheroidal Andromeda II, which has a mass of only \(10^{10}\) solar masses in stars9. The properties of the stream show that we are observing the remnant of a merger between two dwarf galaxies. This had a drastic influence on the dynamics of the remnant, which is now rotating around its projected major axis10. The stellar stream in Andromeda II illustrates the scale-free character of the formation of galaxies, down to the lowest galactic mass scales.

Andromeda II is, in size, the second-largest dwarf spheroidal galaxy known in the Local Group, with a half-light radius\(^1\) of about \(1.2\) kpc (second only to Andromeda XIX\(^1\)). With a luminosity\(^*\) at visible wavelengths of \(L_V = 9.4 \times 10^8 L_\odot\), where \(L_\odot\) is the solar luminosity, it is at present \(185\) kpc from its host and at a heliocentric distance of about \(650\) kpc (ref. 13). Among the satellites of M31 (Andromeda), And II is one of the few for which a spectroscopic data set of hundreds of stars is available. These observations, made using the Deep Imaging Multi-Object Spectrograph (DEIMOS) on the Keck II telescope, revealed a strong and puzzling stellar rotation that is so far unique among the dwarf spheroidal galaxies of the Local Group\(^10\). The results presented here are based on a re-analysis of the latter spectroscopic observations, provided by N. Ho and M. Geha.

We assign reliable probabilities of membership to all spectroscopic targets, comprising more than \(700\) candidate red-giant-branch stars, by allowing for the presence of both foreground contaminants from the Milky Way and interlopers from the halo population of M31. Each of the three coexisting components (members, Milky Way halo contaminants and M31 halo contaminants) is described by a distinct spatial and kinematical distribution, the parameters of which are determined by a maximum-likelihood technique (Methods). A Bayesian approach then allows us to estimate a probability of membership for each available star: we count 632 high-probability members (\(P > 0.85\); Extended Data Fig. 1).

We study the kinematical properties of And II also by a maximum-likelihood method, fully taking into account the observational uncertainties in the line-of-sight velocity of each available giant star in the spectroscopic sample. We find that, within measurement errors (median value, \(6.5 \) km s\(^{-1}\)), there are no significant deviations from the strong rotation field of And II. However, despite such a smooth mean-velocity field and an otherwise flat velocity dispersion profile (Extended Data Fig. 2), we identify a drop and asymmetries in the velocity dispersion field, especially within the circular annulus \(0.9 \) kpc \(\lesssim R \lesssim 1.7\) kpc.

To quantify the significance of these kinematic anomalies, we isolate a group of stars that is defined based only on its spatially connected location. Figure 1a displays the giant stars identified as high-probability members in the spectroscopic data set, superimposed on a Subaru Prime Focus Camera (Suprime-Cam) image\(^1\) of And II. We select 134 stars over an annular, stream-like region covering an angle of \(270^\circ\) over the body of And II (blue points). These are compared with a control sample of 319 stars, comprising the remainder of the spectroscopic targets at comparable distances from the centre of And II (red points). Although sharing a compatible rotational field, the stream-like region is found to be kinematically colder (Fig. 1b, c). Figure 1b shows histograms of the line-of-sight velocity distribution of the available giant stars in both regions, and Fig. 1c shows the normalized generalized histograms obtained after subtracting the mean stellar rotation field. Figure 1d shows the probability distribution functions of the projected velocity dispersion, \(\sigma\). The blue dashed curves in Fig. 1b–d refer to the stream-like region, and the red curves are for the control sample. The probability that the velocities of the giant stars in the two described regions have been extracted from the same parent line-of-sight velocity distribution is negligible (\(P < 3 \times 10^{-6}\)). This shows that, together with the stellar population of And II, an additional kinematically colder component contributes a substantial fraction of the stars in the selected annulus.

Among the stars in the latter spatially connected stream-like region, we next use a Bayesian approach to identify those that are significantly better described by the properties of the control sample with a higher velocity dispersion, \(\sigma = 9.3 \pm 0.6\) km s\(^{-1}\). These are probably And II stars, and we find 14 such high-probability contaminants (\(P > 0.85\); Fig. 1a, blue points). If we exclude these, the remaining 120 stars (filled blue dots) are characterized by a much lower velocity dispersion (\(\sigma \lesssim 3\) km s\(^{-1}\)), the probability distribution of which is shown by the blue full curve in Fig. 1d. We identify these stars with a stream that extends coherently over a distance of 5 kpc, with an average thickness of \(0.3\) kpc.

The stellar stream contains at least one-tenth of the luminosity of And II, which allows us confidently to put a lower bound of \(L_V \gtrsim 10^6 L_\odot\) on the total luminosity of the progenitor. Furthermore, current photometric data do not suggest that the colour spread of the red-giant-branch population of the stream is dissimilar from the considerable spread of the And II population itself (Extended Data Fig. 3). Together, these point to the progenitor of the stream being a dwarf galaxy with a total mass not too different from that of And II. A progenitor with such properties is not unexpected: recent kinematic studies of members of the Local Group have identified analogue dwarf galaxies with comparably low velocity dispersions around both the Milky Way\(^11\) and M31\(^15\).

The merger had a substantial influence on the dynamics and structure of the remnant. The colder stream and warmer control sample do not show statistically significant differences in the properties of their rotation, which may seem somewhat odd within the merger context. However, it is very likely that the orbital angular momentum of the merging dwarfs was much larger than the intrinsic net angular momentum of the stars in either of the dwarfs. Combined with a mass ratio expected...
to be not too far from unity. This is most probably responsible for stars of the stream and control sample having the same rotation strength, as well as the puzzling orientation around the major axis—stellar rotation is nearly always around the minor axis, consistent with oblate axisymmetry (except for rotation around the major axis in some giant elliptical galaxies caused by triaxiality). At the same time, it is likely that more stars that once belonged to the stream’s progenitor are recorded in the galaxies caused by triaxiality. At the same time, it is likely that more stars that once belonged to the stream’s progenitor are recorded in the spectroscopic data set but cannot be clearly distinguished from the stellar population of And II because of their lower density contrast. The detection of such a stream also provides a natural explanation for the peculiar extended component of old stars in And II with an effectively constant rotation of such a stream also provides a natural explanation for the peculiar stars that once belonged to the stream’s progenitor are recorded in the galaxies caused by triaxiality. At the same time, it is likely that more stars that once belonged to the stream’s progenitor are recorded in the spectroscopic data set but cannot be clearly distinguished from the stellar population of And II because of their lower density contrast. The detection of such a stream also provides a natural explanation for the peculiar extended component of old stars in And II with an effectively constant density out to a large radius of about 1.9 kpc; the merger has dynamically heated the remnant’s stellar population. Although a particularly close tidal encounter with M31 may also have contributed to shaping the structure of And II, this remains very uncertain given the galaxy’s unknown proper motion and consequent degeneracy in the modelling.

We measure the line-of-sight velocity of the stream as well as its projected spatial position onto the body of And II, and use this information to constrain its approximate orbit. As Fig. 2 shows, a simple model of an orbit in a spherical potential is capable of describing the available velocity and position measurements. Although it is not possible to infer the detailed properties of the gravitational potential of And II, because the orbit is found to be almost circular, we are able to constrain the enclosed mass (stellar and dark matter) interior to the stream as follows: \( M(<1.5 \text{ kpc}) = 2.5^{+1.1}_{-0.5} \times 10^8 \text{M}_\odot \). This implies a mass-to-light ratio of \( 45^{+15}_{-10} \text{M}_\odot/L_\odot \), which is typical of dwarf spheroidal galaxies.

Even with a characteristic orbital velocity for the stream, dating the epoch of the And II merger remains challenging. The survival of cold kinematic clumps is strongly dependent on the properties of the gravitational potential in which they orbit. Nevertheless, the And II stream seems to lie on a nearly circular orbit and never passes close to the central regions of the galaxy, which allows it to retain coherence for a very long time. At the same time, dynamical friction can drag two mutually orbiting dwarf galaxies closer, causing a merger in just a fraction of the Hubble time. We estimate that this process requires \( \gtrsim 3 \text{ Gyr} \), which provides us with an approximate lower limit to associate with the merger of the And II system.

Streams of disrupted and engulfed galaxies are abundant in the halo of the Milky Way, as memorably shown in the Sloan Digital Sky Survey’s ‘Field of Streams’ and by the disrupting Sagittarius galaxy. However, the frequency and role of accretion onto low-mass galaxies, and in particular of dwarf–dwarf mergers, remains unclear, given the extremely limited observational evidence. Stellar overdensities similar to those of shells have been discovered in the Fornax dwarf spheroidal galaxy, suggesting a late merger origin. Irregular isophotes and a kinematically cold spot indicate that Ursa Minor has suffered recent disturbance, most probably the accretion of a lower-mass stellar system in the form of a stellar cluster. In this respect, And II represents a compelling case of a dwarf–dwarf merger.

Mergers between low-mass galaxies are predicted within the hierarchical framework of galaxy formation, but they are rare at present times. This is particularly true for dwarf satellite galaxies: after accretion onto their host, in this case M31, the cross-section for encounters between previously unrelated dwarf galaxies is very low, implying that subsequent merging activity is essentially limited to galaxies that were closely associated before infall. This makes the discovery of a tidal stream, originating from the engulfment of one dwarf satellite by another, particularly remarkable. As for merger events preceding infall, it is estimated that one in two dark matter haloes with a virial mass of \( 10^{10} \text{M}_\odot \) have experienced a major merger (mass ratio \( \gtrsim 1/3 \)) between redshift 4 and 1, but data to confirm these figures are exceedingly scarce.
Andromeda II provides direct evidence for the importance of merging events even for the smallest and least luminous of galaxies. Just as for the largest giant ellipticals, merging and accretion were dominant processes in the formation of the dwarf galaxies we see today.

METHODS SUMMARY
Spectroscopic targets that belong to the red-giant-branch population of And II are separated from Milky Way dwarf stars in the foreground and interlopers from the stellar halo of Andromeda by using maximum-likelihood and Bayesian techniques. The three distinct populations have different spatial and kinematical distributions, the properties of which are determined by the maximum-likelihood method. The extraction of the kinematics of the member stars is also obtained using a maximum-likelihood technique. This includes a full treatment of the individual observational uncertainties in the line-of-sight velocity of each spectroscopic target and allows for the subsequent kinematic detection and characterization of the stream.

The luminosity estimate of the identified kinematically cold structure and inferred constraints on its progenitors are obtained by using the detailed surface density profile of And II, together with the projected region where the density contrast of the stream is highest.

Figure 2 | The stream reproduced by an orbit in a spherical potential. a, Spectroscopic targets belonging to the stream, colour-coded using a smoothed velocity field for comparison with the best-fitting orbit. b, c, Line-of-sight velocity (b) and distance from the centre of And II (c) of the stars belonging to the stream, reproduced using a simple model of an orbit in a spherical potential. These data provide a direct comparison between the observables (each data point was obtained from a subset of ten stream stars; centre values, average; errors, s.d.) and the corresponding 68% confidence region obtained from the model.
METHODS

Membership selection. To address the kinematical properties of And II, we need to separate the spectroscopic targets that belong to the red-giant-branch population of the dwarf galaxy from any contaminants. Contamination has two different origins: dwarf stars in the foreground belonging to the Milky Way and interlopers from the stellar halo of Andromeda. To disentangle these three distinct components reliably, we model the spectroscopic data set as a superposition of multiple independent stellar populations, within the framework of a maximum-likelihood technique\textsuperscript{23–25}:

\[
L(\Theta) = \prod_j \left( \sum_i f_j P(\chi_j; \Theta_j) \right) \times \frac{p_{\text{kin}}(v_j; \Theta_{\text{kin}})}{p_{\text{sys}}(v_j; \Theta_{\text{sys}})}
\]

The index \(j\) runs over the spectroscopic targets, and \(i\) indicates the three populations of the model, each containing a fraction of stars \(f_i\) with the constraint \(\sum_i f_i = 1\). The probability function \(P(\chi_j; \Theta_j)\), parameterized by the set of parameters \(\Theta_j\), describes the spatial distribution of the members of the component \(i\) on the plane of the sky. Given the limited angular size of And II, we can adopt a constant surface density distribution for both populations of contaminants, and use a Plummer density profile with elliptical isophotes to describe the population of And II itself. Analogously, the three components have different probability distributions for their kinematics, which are respectively described by the functions \(p_{\text{kin}}\) and the parameters \(\Theta_{\text{kin}}\). Given the significant separation of the contaminants from And II in terms of systematic velocity\textsuperscript{4}, we can describe both the Milky Way and the Andromeda halo population with a simple Gaussian line-of-sight velocity distribution. The observational uncertainty in the measurement of the line-of-sight velocity of each single spectroscopic target, \(\delta v\), is fully included in the analysis by formal convolution; hence, for the contaminants, we have

\[
p_{\text{kin}}(v_j; v_0, \sigma) = \frac{1}{\sqrt{2\pi} \sigma} \exp\left( -\frac{(v_j - v_0)^2}{2\sigma^2} \right)
\]

where Milky Way and Andromeda contaminants have their own systematic velocity, \(v_0\), and intrinsic velocity dispersion, \(\sigma\). The velocity distribution of And II is also normally distributed, but has a rotating mean velocity field, with frequency \(\Omega\):

\[
p_{\text{And II}}(v_j; v_0, \sigma, \Omega) = \frac{1}{\sqrt{2\pi} (\sigma^2 + \delta^2)} \exp\left( -\frac{(v_j - v_0 - \Omega X)^2}{2(\sigma^2 + \delta^2)} \right)
\]

(1)

The parameter space is explored by means of a suite of Monte Carlo chains, constructed using the Metropolis–Hastings algorithm\textsuperscript{29}. Once the best-fitting model is constructed using the Metropolis–Hastings algorithm\textsuperscript{29}. Once the best-fitting model is properly marginalized against uncertainties in all other parameters of the model.

Stream luminosity and progenitor. Our kinematical analysis identifies \(N_{\text{str}} = 120\) red giant stars as high-probability members of the kinematically cold stream, in a pool of \(N_{\text{mm}} = 632\) members of And II. Although indicative of the significant luminosity of this structure, it is not entirely correct to use simply the ratio \(N_{\text{str}}/N_{\text{mm}}\) to derive an estimate of the luminosity of the stream itself. This is because the stream covers a limited area over the body of And II and the spectroscopic coverage is neither uniform over the body of the dwarf nor proportional to its surface brightness profile.

We can instead obtain more accurate insight into the luminosity of the stream by restricting ourselves to the projected region it covers. This has been identified in Fig. 1a as an approximately annular region, centred around \(R = 1.35\) kpc and covering an angle of \(\sim 270^\circ\). By using the detailed surface density profile\textsuperscript{1} of And II, obtained by using deep Suprime-Cam data, we calculate that the projected area contains \(\sim 15\%\) of the total luminosity of the dwarf. In turn, we find only 14 high-probability contaminants in this region, that is, stars that are significantly more likely to belong to the And II population than to the kinematically cold stream. This implies a luminosity estimate for the stream of

\[
L_{\text{str},V} = 0.15 \times \frac{120}{134} L_{\text{And II},V} = 0.13 L_{\text{And II},V} = 1.3 \times 10^7 L_{\odot}
\]

(2)

It is worth mentioning that, on the basis of kinematical data alone, we are inevitably capable of identifying only those parts of the stream that have a sufficiently high density contrast relative to the And II population, and whose kinematics in the stream’s progenitor were cold enough to stand out against the average present properties of And II. In particular, as a result of the merger, it is plausible that any stellar components that were originally more diffuse in the stream’s progenitor are now dispersed in And II, eluding purely kinematical detection. This implies that the above 13\% (equation (2)) should be regarded as a lower limit for the luminosity of the progenitor itself.

Whereas the resulting luminosity already makes a stellar cluster origin unlikely, this can be excluded further by considering the properties of the distribution of the stream’s members in the colour–magnitude diagram. Extended Data Fig. 3 follows the same stream versus control sample labelling as in Fig. 1a, to allow for the comparison of the properties of the stream’s member stars with those of the And II population. We find that this data suggest little difference in the distribution of such two populations in the colour–magnitude diagram, highlighting the fact that the stream also has a significant colour spread.

28. Walker, M. G. & Peñarrubia, J. A method for measuring (slopes of) the mass profiles of dwarf spheroidal galaxies. Astrophys. J. 742, 20 (2011).

29. Metropolis, N., Rosenbluth, A. W., Rosenbluth, M. N., Teller, A. H. & Teller, E. Equation of state calculations by fast computing machines. J. Chem. Phys. 21, 1087–1092 (1959).
Extended Data Figure 1 | Membership selection. The spectroscopic data set in the plane ($v_{\text{los}}, R$), shaded according to the probability of each target belonging to the stellar population of And II. Non-member targets with velocities higher than the systematic velocity of And II, $v_{\text{sys}} = -191.4 \pm 0.4$, are foreground contaminants from the Milky Way, whereas non-member targets at lower negative velocities are interlopers from the Andromeda halo.
Extended Data Figure 2 | Velocity dispersion profile. Andromeda II has an approximately flat velocity dispersion profile, except for a significant dip near the average projected radius of the stellar stream. Points of different sizes and shading depths refer to different circular annuli sizes (as in the key), and error bars display 68% confidence levels around the most likely central value.
Extended Data Figure 3 | Colour–magnitude diagram. The distribution of the stars belonging to the stream (blue points) and stars in the control sample (red points) in V-band magnitude versus V – I colour.