Identification of the long stellar stream of the prototypical massive globular cluster ω Centauri

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Omega Centauri (ω Cen) is the Milky Way's most massive globular cluster, and has long been suspected of being the remnant core of an accreted dwarf galaxy. If this scenario is correct, ω Cen should be tidally limited and tidal debris should be spread along its orbit. Here we use _N_-body simulations to show that the recently discovered 'Fimbulthul' structure is the long-sought-for tidal stream of ω Cen, extending up to 28° from the cluster. Follow-up high-resolution spectroscopy of five stream stars shows that they are closely grouped in velocity, and have metallicities consistent with having originated in that cluster. Informed by our _N_-body simulations, we devise a selection filter that we apply to Gaia mission data to also uncover the stream in the highly contaminated and crowded field within 10° of ω Cen. Further modelling of the stream may help to constrain the dynamical history of the dwarf galaxy progenitor of this disrupting system and guide future searches for its remnant stars in the Milky Way.

T he massive globular cluster Omega Centauri (ω Cen) exhibits many peculiar properties in addition to its high mass[1]. In particular, it contains distinct multiple stellar populations, with a large spread in metallicity[2] and different kinematics as a function of light element abundance[3], implying that it formed over an extended period of time[4]. These observational conclusions have led to the suggestion that ω Cen is the remnant of the core of a satellite galaxy that merged onto the Milky Way[5,6]. Since the putative dwarf galaxy progenitor is not present as an obvious over-density surrounding ω Cen, the accreted satellite galaxy must now have been almost completely tidally stripped, leaving ω Cen as a tidally limited structure. This in turn implies that a stellar tidal stream should still be emanating from the system[7–10], albeit perhaps at a very low rate.

Stellar tidal streams represent the remnants of ancient accretion events into a galaxy that have remained spatially and kinematically coherent[11], and are thus extremely important as tracers of the galaxy formation process. They are generally long-lived features, as long as they do not stray too close to the dense inner regions of the host galaxy where dynamical times are short and the related precession and phase-mixing are very fast. It is now realized that these structures are extremely powerful astrophysical tools, as they are sensitive probes of the acceleration field they inhabit[12], allowing us to study the underlying distribution of dark matter[13–15], including the granularity or clumping of these dark materials[16–19].

The challenge now is to find a large sample of tidal streams that can be mapped with high-quality data, and measure their structural and kinematic properties. The recently released second data release (DR2) of the Gaia space mission[20,21] provides an unparalleled new dataset to attempt such an endeavour. With five-parameter astrometric solutions of approximately 1.3 billion stars, Gaia DR2 gives excellent proper motion measurements of stars, as well as parallax measurements.

We have developed a pragmatic, data-driven approach to the problem of searching for stream-like structures in datasets such as Gaia DR2. We search for features that are spatially and kinematically coherent, possessing a distribution on the sky that resembles

an orbit, together with distance properties and proper motion properties that are consistent with that orbit. Our algorithm[22,23], which we call the STREAMFINDER, works by examining every star in the Gaia survey in turn, sampling the possible orbits consistent with the observed photometry and kinematics, and finding the maximum-likelihood stream solution given a contamination model and a stream model. The adopted contamination model is an empirical model of the Milky Way in sky position, colour magnitude and proper motion space (that is six dimensions) constructed by smoothing the Gaia counts (here, on a 2° spatial scale), and building a Gaussian mixture model representation of the resulting smoothed Gaia data.

The adopted stream model is simple: we integrate to a given length along the sampled orbits (here 20°), and over this length the stream counts are assumed to have uniform probability. Perpendicular to the stream model, the properties of all observables are taken to be Gaussian, so the model has a Gaussian physical width, a Gaussian dispersion in both proper motion directions and a dispersion in distance modulus. The width and velocity dispersion parameters are chosen to be similar to the properties of known globular cluster streams. The algorithm returns the best-fit orbit for a given data point, the number of stars in the corresponding putative stream and the likelihood value relative to the model where the stream fraction is zero. By choosing those stars with stream solutions above a high significance level (8σ in the present case), one can immediately derive a map of stream structures.

Because the Gaia parallaxes are relatively poor at constraining the distances to the survey stars, we use stellar population models to convert the excellent Gaia photometry into trial line-of-sight distance values. To this end, we adopted the PARSEC isochrone models[24], and our resulting maps are valid for a particular choice of population age and metallicity. To date, the STREAMFINDER has allowed us to discover 14 new streams[22,25,26], although we have so far assumed only a relatively narrow range of template stellar population properties, due to the extremely high computational cost of the algorithm.

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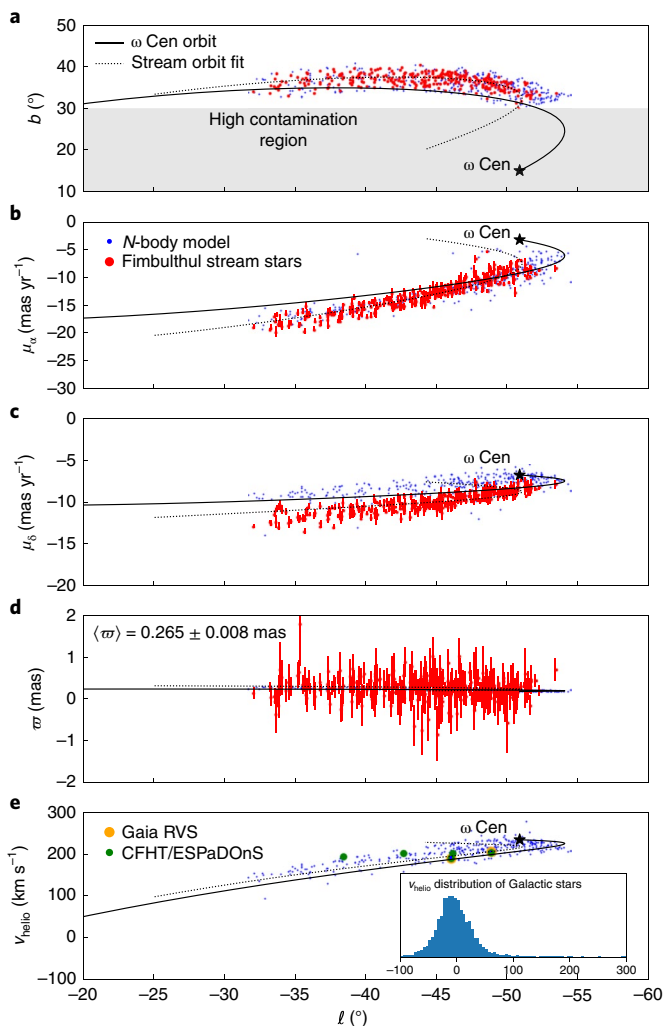
Fig. 1 | Physical properties of the Fimbulthul stream as a function of ℓ. The Gaia DR2 stars identified by the STREAMFINDER algorithm are shown in red in all panels (1σ error bars are shown), while the particles of the N-body simulation in the same region of sky are shown in blue. **a,** The sky distribution of the stars lies close to the backward-integrated orbit of ω Cen (continuous line). **b,** Proper motion μ_α along the right-ascension (α) direction. **c,** Proper motion μ_δ along the declination (δ) direction. (The measured proper motion[27] of ω Cen is $\mu_\alpha = -3.1925 \pm 0.0022$ mas yr^{-1}, $\mu_\delta = -6.7445 \pm 0.0019$ mas yr^{-1}). **d,** Although the Gaia parallaxes (ϖ) appear not to be very informative, the absence of stars with parallaxes strongly inconsistent with the model shows that the sample is not obviously dominated by nearby contaminants. The weighted mean parallax is $\langle\varpi\rangle = 0.265 \pm 0.008$ mas, although we caution the reader that this estimate does not account for any contamination that may be present in the sample. **e,** The heliocentric line-of-sight velocity v_{helio} from Gaia RVS (orange points) are shown, as well as the velocities from CFHT/ESPaDOnS (green points). The inset histogram shows the velocity distribution of the 5,631 Gaia RVS stars with colours in the range of the Fimbulthul sample listed in Supplementary Table 1 ($0.6 < G_{BP} - G_{RP} < 1.2$ mag, where G_{BP} and G_{RP} are magnitudes measured by the Gaia prism photometer) that are present in the region of sky where the Fimbulthul stream is found in **a**. Clearly, stars with radial velocities similar to those measured in the Fimbulthul stream are very rare. In all panels, the dotted line corresponds to a simple orbit model fit to the stream. All stars shown here are identified by the algorithm as being $>8\sigma$ stream candidates. This means that for each of these stars, the algorithm finds a stream model that passes through the location of the star, with proper motion and distance consistent with that of the star, that stands out at $>8\sigma$ confidence above a smooth model of the Galaxy. Note that this does not mean that the individual stars are stream members with 8σ confidence.

One of the structures we have identified in our stream map derived using a stellar population template of metallicity [Fe/H] $= -1.6$ and age 12.5 Gyr is the 'Fimbulthul' stream[22], an 18°-long feature, located at approximately Galactic latitude $b = 35°$ and following an arc between Galactic longitude $\ell = -52°$ and $\ell = -32°$ (Fig. 1a, red points). As the stream approaches $b = 30°$ its contrast over the Galactic contamination drops precipitously (grey region in Fig. 1a) and it becomes undetected by our algorithm. We display the proper motion and distance properties of these 309 stars in Fig. 1b–d (red points) and list them in Supplementary Table 1. Note that the stars still bound to ω Cen itself did not contribute in any way to the identification of this stream, as before running the detection software, we excised all stars from the input Gaia DR2 catalogue that lie within two tidal radii of all known globular clusters[1] (that is, those within 1.6° of ω Cen).

Fortunately, two of the candidate stream members identified by the STREAMFINDER (Fig. 1e, orange points) have their radial velocities measured by the Gaia Radial Velocity Spectrometer (RVS; these measurements are only available in Gaia DR2 for the very brightest stars with Gaia G-band magnitudes $G \lesssim 12.5$). We fitted the sky position, parallax, proper motion and radial velocity data of this sample of 309 stars using an orbit model (dotted line). Such a model is too simplistic if the progenitor of the stream is massive, because it does not take into account the large energy required to escape from a massive cluster (hence the escaping stars do not have the same orbital properties as their progenitor system). However, this nevertheless gives a first approximation of the orbital path and orbital properties of the stream. With the adopted Galactic mass model, the orbit fitted with a Markov chain Monte Carlo procedure[26] has a pericentre distance of 1.50 ± 0.01 kpc, an apocentre distance of 6.53 ± 0.01 kpc and has highly retrograde motion with z component of angular momentum $L_z = 490 \pm 1$ km s^{-1} kpc. We immediately noticed that these orbital properties are close to those recently deduced[27] for the massive globular cluster ω Cen (continuous line orbit in Fig. 1) from Gaia DR2 data.

We were able to obtain spectroscopic observations (see Methods) of six candidate member stars of the Fimbulthul stream with the ESPaDOnS (Echelle SpectroPolarimetric Device for the Observation of Stars) high-resolution spectrograph on the Canada–France–Hawaii Telescope (CFHT). While one exposure was of insufficient signal-to-noise to yield a radial velocity measurement, all five others are found to be tightly grouped in radial velocity, confirming the reality of the Fimbulthul discovery. Four of the spectra are of sufficient quality to also allow metallicity measurements from the Ca II infrared triplet, and yield values between [Fe/H] $= -1.36 \pm 0.11$ and -1.80 ± 0.11, consistent with an intrinsic metallicity dispersion, as would be expected for members of a population that was tidally disrupted from ω Cen. The results of these follow-up observations are summarized in Table 1.

We ran a series of N-body simulations of the tidal disruption of a system similar to ω Cen (see Methods), trying to reproduce the observed structure. The cluster progenitor was modelled as an axisymmetric system including internal rotation[28]. There is very little freedom in the choice of orbit, given that even the line-of-sight distance to the cluster has recently been very well measured with RR Lyrae variable stars[29]. Figure 2 shows the end-point of the best simulation in the set. The blue points in Fig. 2b are the simulation particles that are spatially coincident with the Fimbulthul stars (also shown in blue in Fig. 1).

The measured proper motions of the Fimbulthul stars along the right-ascension direction μ_α^* ($\equiv \mu_\alpha \cos(\delta)$, but henceforth, for convenience, we will drop the asterisk superscript) and along the declination direction μ_δ, as a function of Galactic longitude ℓ match closely those of the N-body model (Fig. 1b,c, respectively). The heliocentric radial velocities of the stars measured by the Gaia RVS and with CFHT/ESPaDOnS also match the N-body model well (Fig. 1e). The correspondence between this N-body model of ω Cen and the detected stream provides strong evidence that the Fimbulthul stream is the long-searched for (trailing) tidal arm of ω Cen. As we

Table 1 | Fimbulthul stream candidate stars observed with CFHT/ESPaDOnS

RA J2000.0 (°)	Dec. J2000.0 (°)	G_0 (mag)	$(G_{BP} - G_{RP})_0$ (mag)	v_{helio} (km s^{-1})	[Fe/H]	CFHT odometer	Observation date	Exposure (s)	S/N pixel^{-1}
200.291401	−26.516432	12.167	1.182	205.52 ± 0.18	−1.36 ± 0.11	2372977	2019 January 24	600	41
202.470324	−24.439468	12.747	1.073	191.87 ± 0.27	−1.80 ± 0.11	2372978	2019 January 24	600	34
202.470611	−25.084004	13.425	1.018	202.72 ± 0.28	−1.47 ± 0.11	2373150	2019 January 25	600	19
205.597014	−25.009721	12.969	1.042	203.74 ± 0.29	−1.58 ± 0.11	2373151	2019 January 25	600	23
208.831549	−22.971256	15.323	0.903	194.74 ± 2.46	–	2373598	2019 January 28	900	1.5
202.505173	−25.937347	14.989	0.949	–	–	2373599	2019 January 28	600	1.2

The signal-to-noise (S/N) ratio listed is the value per 0.006 nm pixel at 860 nm.
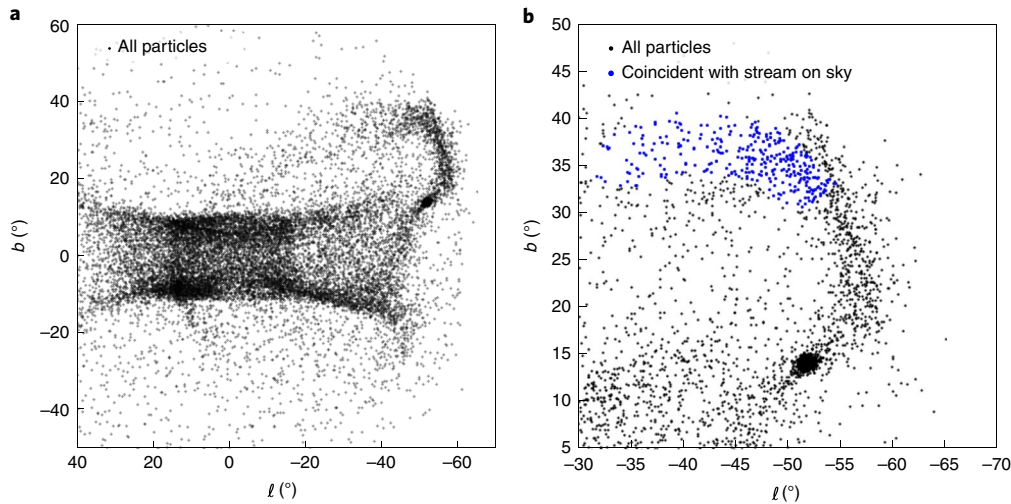
Fig. 2 | Present-day configuration of an *N*-body simulation of the disruption of a massive globular cluster on the orbit of ω Cen. a, The full simulation projected on Galactic coordinates. **b**, Zoom-in of the region of sky surrounding the cluster remnant. The blue particles were selected within a hand-drawn polygon to encompass the sky region containing the Fimbulthul stream stars in Fig. 1a.

show in Fig. 3a, the stellar population in the Fimbulthul stream is very similar to that of ω Cen, which provides further evidence for the link between these two structures.

In our initial *N*-body explorations, we modelled the cluster progenitor with a simple (non-rotating) King model, which cannot account for the complex internal dynamics of ω Cen[3], which is rotating and significantly flattened. The resulting *N*-body stream was substantially wider than the observed Fimbulthul stream; this shows that it is important to model the internal dynamics of the progenitor correctly, but also that observations of the structure and kinematics of the stream may allow us to deduce the past internal properties of the progenitor.

Our aim with these simulations is to illustrate the discovery of the stream and its connection to ω Cen. The full modelling of the structure in such a way as to reproduce faithfully the observations is beyond the scope of this contribution. Such modelling is very challenging because the precise morphology of a stream depends sensitively on the Galactic potential, and on the dynamical properties of the progenitor, including complex details such as its original shape and rotation properties. It may also require modelling the effects of time-dependent substructures in the Galaxy, such as the bar[30] and spiral arms, as well as the effect of dynamical friction. We defer trying to obtain a good quantitative fit to the Fimbulthul stream to a future study.

We noticed that the kinematic behaviour of the particles in the *N*-body simulation that have just begun to leave ω Cen is very

simple: they share approximately the same μ_δ as the cluster, and display an approximately linear gradient in μ_α as a function of b (decreasing by approximately 0.125 mas yr^{-1} for every degree in Galactic latitude). Using this prediction, we selected stars from the Gaia DR2 catalogue with proper motion measurements within 1 mas yr^{-1} (that is, approximately 26 km s^{-1}) of these criteria (we additionally required the parallax uncertainty to be less than 1 mas, and for the parallax measurements to be consistent within 1σ with a distance in the range [4, 6] kpc). Stars obeying this selection function are shown in blue in Fig. 3, where we compare the colour–magnitude distribution (CMD) of stars within 0.5° of the cluster centre (Fig. 3a), with a nearby reference field (Fig. 3b). It can be seen that this selection filter has not biased us against selecting ω Cen stars. The difference between these two distributions motivated our choice to define the (green) CMD selection polygons, which are intended to filter out contaminants. The resulting map of stars that have both the kinematic properties of the expected stream near ω Cen and that pass the colour and magnitude selection criterion are shown in Fig. 4a. A clear narrow stream can be seen emanating from ω Cen, within ±10° of the cluster, approximately along the path expected from the *N*-body model (Fig. 2b). For comparison, Fig. 4b additionally marks the positions of the Fimbulthul stream stars (red) and of the best *N*-body simulation (black). The knee in the *N*-body stream at $\ell \approx -57°$, $b \approx 20°$ appears to be mirrored in the Gaia DR2 map, pointing towards the Fimbulthul stream, as expected from the *N*-body simulation.
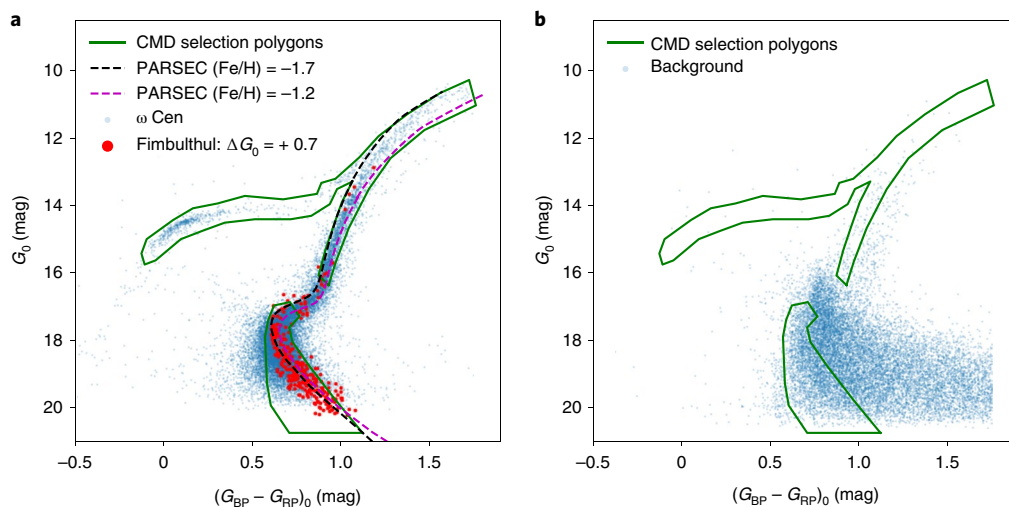
Fig. 3 | Comparison of the colour-magnitude diagram of ω Cen and Fimbulthul in the Gaia photometric system. a, The stars within 0.5° of the cluster centre region and with kinematics consistent with cluster membership are shown in blue. The Fimbulthul stars identified by the STREAMFINDER are displayed in red. These have been offset by 0.7 mag to make the two distributions match (implying that the Fimbulthul sample is approximately 1.5 kpc closer than ω Cen). PARSEC model isochrones of age 12.5 Gyr and metallicity −1.7 and −1.2 are shown for comparison, these [Fe/H] values are representative of the spectroscopically measured range of the cluster[51]. **b**, The CMD of a nearby background field (covering the sky area −70° < ℓ < −40°, 10° < b < 50°, but without those sources within a 10° radius circle of ω Cen). The green polygons in both panels show the two colour-magnitude selections chosen to select stars with properties similar to ω Cen, while minimizing the number of contaminants.
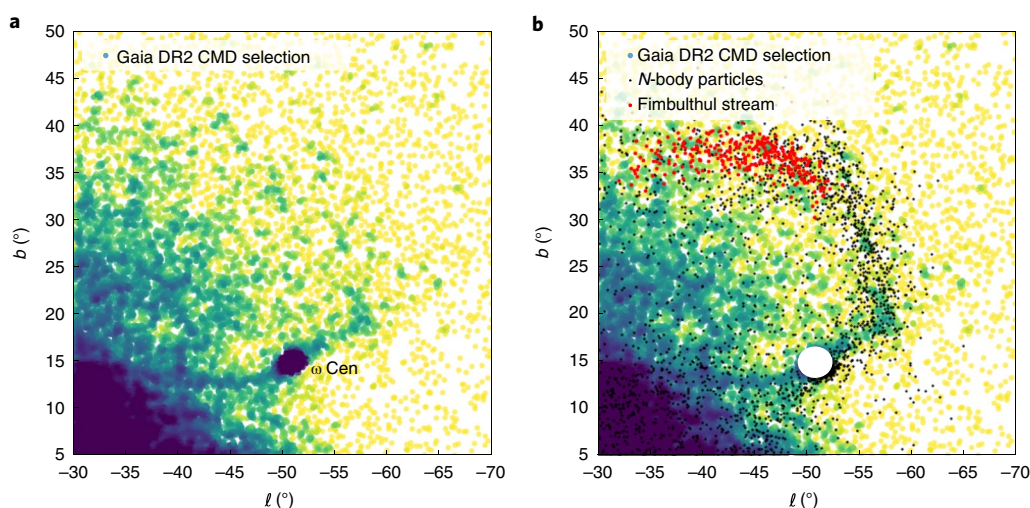
Fig. 4 | Stars with kinematic properties of the expected stream near ω Cen, fulfilling colour and magnitude selection criteria. a, Spatial distribution of stars within the CMD box of Fig. 3, and that have kinematics of the ω Cen stream within ±10° of the cluster as predicted by the N-body model of Fig. 2. Colour encodes local stellar density (on a logarithmic scale). **b**, The Fimbulthul population (red) and the N-body model (black) are overlaid on the map shown in **a**. The clear stream that is detected emanating from the cluster has similar spatial structure to the N-body model of Fig. 2b. The white region indicates the area within 1.6° of ω Cen.

Although several surveys have detected clumps of stars at numerous locations around the sky[31–37] with angular momentum properties that would be expected from the tidal debris of the progenitor of ω Cen, here we identify the actual tidal arms of the globular cluster, beyond the central tidal distortion[38]. This confirms that ω Cen is the most massive tidally disrupting globular cluster in our Galaxy. The N-body models we have run suggest that the system has been disrupting for at least approximately 5 Gyr, as shorter disruption times did not produce a feature similar to Fimbulthul. The models also suggest that there should be a substantial amount of debris elsewhere in the Galaxy (Fig. 2a), which is mostly located at low Galactic latitude where it may be challenging to detect.

In future work it will be interesting to build on the findings reported here to devise a disruption model that can fully reproduce the tidal arms we have uncovered while simultaneously fitting accurately the remnant cluster. We expect that this may also require a more accurate model of the Galactic acceleration field (which this stream may contribute to constrain). With those additional constraints, it will be interesting to examine the possible progenitors of ω Cen, and determine whether it may have been accreted onto the Milky Way as part of a more massive system. The reasonably good correspondence of our N-body model with the observed stream structures suggests that what we have identified here is material stripped from the cluster, and probably not stars of the hypothetical

parent satellite galaxy that ω Cen was accreted with. Those stars, if they exist, may be searched for elsewhere, probably at larger Galactocentric radii where they would have been deposited during their catastrophic infall into our Galaxy.

Methods

Observational follow-up. The six Fimbulthul stream candidate stars listed in Table 1 were observed with the ESPaDOnS spectrograph at the CFHT by observatory staff on the nights of the 24, 25 and 28 January 2019. Two of these stars already had Gaia RVS velocity measurements, but were re-observed to obtain a more accurate radial velocity and to measure the chemical abundances of these stars. The targets were observed in 'star + sky' mode, yielding very highly resolved spectra ($R = 68,000$) from 369 to 1,048 nm. The Libre-ESpRIT pipeline[39] was used to reduce the data, resulting in extracted and wavelength-calibrated spectra, with a normalized continuum. We measured the velocities of the target stars by cross-correlating their spectra against a spectrum of the radial velocity standard star HD182572, using the `fxcor` command from the PyRAF package. Due to poor signal-to-noise, we were not able to measure the radial velocity of one of the stars (CFHT exposure number 2373599); however, all others show a tight velocity grouping ($\langle v_{helio} \rangle = 199.7$ km s^{-1} with root mean square scatter of 5.4 km s^{-1}). This confirms the stream discovery, and suggests that the sample of Fimbulthul stream candidates listed in Supplementary Table 1 is not substantially contaminated.

The metallicities of the stars were derived from the equivalent widths of the Ca II triplet lines. The calibration we used[40] requires knowledge of the V-band magnitude of the targets with respect to the horizontal branch. To this end, we assumed that the absolute magnitude of the horizontal branch[41] is $V_{HB} = 0.60$ mag, and used colour transformations[42] to convert magnitudes in the Gaia photometric bands to the V-band. For two stars (CFHT exposures 2373598 and 2373599), the spectra were of insufficient quality to allow a metallicity measurement. The other four spectra have excellent signal-to-noise, however, and result in metallicity measurements where the dominant source of uncertainty comes from the poorly constrained distance. The metallicity values listed in Table 1 were derived assuming a mean distance to these stars of 4.1 kpc, as predicted by the STREAMFINDER algorithm (using the stellar populations template with a metallicity of [Fe/H] $= -1.6$ and an age of 12.5 Gyr). If instead we assume a common distance of 3.4 kpc (corresponding to the mean parallax derived above, but which as we mentioned, may be affected by contamination), the metallicities change by +0.11 dex. This difference provides a plausible level of uncertainty on these metallicity measurements.

Simulation details. The N-body model constructed here was simulated using the NEMO software package[43]. A realistic Galactic potential model was used throughout this work ('model 1' of Dehnen and Binney[44]), which consists of a disk, a thick disk, an interstellar medium, a bulge and a halo component. To perform the coordinate transformations between the models and observations, we assumed that the Sun is located 8.122 kpc from the Galactic Centre[45] and 17 pc above the Galactic mid-plane[46]. We take the circular velocity at the solar neighbourhood to be 220.0 km s^{-1} and correct for the peculiar velocity of the Sun[47].

To model the progenitor cluster of ω Cen, we used a distribution function model that was fit to the present-day structure and kinematics of the cluster, and that is also able to fit the observed strong rotation in the system. This family of rotating models[48] has been specifically designed to describe the internal dynamics of axisymmetric systems, characterized by internal differential rotation and pressure anisotropy, and therefore it constitutes a significant improvement to the simple spherical King models. The best model has initial mass $M = (2.471 \pm 0.02) \times 10^6 M_\odot$, concentration parameter $C = 1.27 \pm 0.01$ and core radius $R_c = 127.8'' \pm 1.1$. On the plane of the sky, the rotation axis of this model is inclined 12° east of north (in equatorial coordinates), with the (right-handed) north pole of the model inclined 45° towards us along the line of sight, as recently measured from Gaia DR2 proper motions[49]. A total of 10^5 particles were simulated. This model was advanced forward in time using the gyrfalcON N-body integrator[50] using a softening length for gravitational forces of 1 pc and a minimum time step of 2^{-18} Gyr.

The radial velocity and proper motion of ω Cen are now extremely well measured[27], and the distance to the cluster ($d = 5,630 \pm 100$ pc) is also reasonably well constrained[29]. We first used these values to integrate an orbit backwards in time to find a first approximation to the starting position and velocity that could be used to initialize the N-body model to allow us to integrate it forwards in time to the present day. However, due to self-gravity, the dynamics of a stellar stream is nonlinear, and so it can be challenging to find good initial conditions of a model that will reproduce an observed stream and remnant. Finding such initial conditions becomes harder as the total disruption time increases. The approach we took was to search for the minimum disruption time (that is the integration time, in increments of 0.5 Gyr) consistent with the formation of the Fimbulthul structure. For each chosen total integration time, we surveyed many dozens of phase-space starting points in our efforts to recover a cluster with the observed present-day radial velocity, proper motion and distance as ω Cen. The comparisons between the models and the observations were performed

visually, attempting to find the best positional and kinematic match of the N-body stream at the sky position of ω Cen and the Fimbulthul structure.

In our best simulation, the material that makes up the Fimbulthul stream was removed from the cluster relatively recently (~0.4 Gyr ago). However, we found that we require the gravitational influence of the stream particles disrupted at earlier times to reproduce the morphology and kinematics of a trailing arm resembling the Fimbulthul stream (that is the self-gravity of the stream appears to be important). With the N-body model used here, this required a minimum disruption time of approximately 5 Gyr. The best model was started (5 Gyr ago) from an initial position $(x, y, z) = (3.3, -5.6, 2.0)$ kpc, and with velocity $(v_x, v_y, v_z) = (98.3, 20.0, -47.2)$ km s^{-1}; this Galactic Cartesian coordinate system is defined so that z points perpendicular to the Galactic Disk with the Sun located at $(x, y, z) = (-8.122, 0.0, 0.017)$ kpc. In this model, the final bound structure has a mass of $2.03 \times 10^6 M_\odot$, close to the initial mass of the system. We checked for convergence by re-running the model that best fits the stream with 10^6 particles, which showed a qualitatively identical distribution of stream stars as the 10^5 particle simulation. We stress that this modelling effort is exploratory and is intended to show that the Fimbulthul stream is very likely the tidal stream of ω Cen; it is not a comprehensive quantitative survey of the dynamics of this system.

Data availability

References

1. Harris, W. E. A catalog of parameters for globular clusters in the Milky Way. *Astron. J.* **112**, 1487–1488 (1996).
2. Johnson, C. I. & Pilachowski, C. A. Chemical abundances for 855 giants in the globular cluster Omega Centauri (NGC 5139). *Astrophys. J.* **722**, 1373–1410 (2010).
3. Bellini, A. et al. The HST large programme on Omega Centauri. II. Internal kinematics. *Astrophys. J.* **853**, 86 (2018).
4. Marino, A. F. et al. The C+N+O abundance of Omega Centauri giant stars: implications for the chemical-enrichment scenario and the relative ages of different stellar populations. *Astrophys. J.* **746**, 14 (2012).
5. Zinnecker, H., Keable, C. J., Dunlop, J. S., Cannon, R. D. & Griffiths, W. K. In *The Harlow Shapley Symposium on Globular Cluster Systems in Galaxies* (eds Grindlay, J. E. & Davis Philip, A. G.) 603–604 (IAU, 1988).
6. Majewski, S. R. et al. In *Proc. 35th Liege International Astrophysical Colloquia, The Galactic Halo: From Globular Cluster to Field Stars* (eds Noels, A. et al.) 619–622 (Institut d'Astrophysique et de Geophysique, 2000).
7. Bekki, K. & Freeman, K. C. Formation of Omega Centauri from an ancient nucleated dwarf galaxy in the young Galactic Disc. *Mon. Not. R. Astron. Soc.* **346**, L11–L15 (2003).
8. Mizutani, A., Chiba, M. & Sakamoto, T. Kinematics of tidal debris from Omega Centauri's progenitor galaxy. *Astrophys. J.* **589**, L89–L92 (2003).
9. Ideta, M. & Makino, J. Formation of Omega Centauri by tidal stripping of a dwarf galaxy. *Astrophys. J.* **616**, L107–L110 (2004).
10. Tsuchiya, T., Korchagin, V. I. & Dinescu, D. I. Disruption of a dwarf galaxy under strong shocking: the origin of Omega Centauri. *Mon. Not. R. Astron. Soc.* **350**, 1141–1151 (2004).
11. Johnston, K. V., Hernquist, L. & Bolte, M. Fossil signatures of ancient accretion events in the halo. *Astrophys. J.* **465**, 278–287 (1996).
12. Johnston, K. V., Zhao, H., Spergel, D. N. & Hernquist, L. Tidal streams as probes of the Galactic potential. *Astrophys. J.* **512**, L109–L112 (1999).
13. Ibata, R., Lewis, G. F., Irwin, M., Totten, E. & Quinn, T. Great circle tidal streams: evidence for a nearly spherical massive dark halo around the Milky Way. *Astrophys. J.* **551**, 294–311 (2001).
14. Law, D. R. & Majewski, S. R. The Sagittarius dwarf galaxy: a model for evolution in a triaxial Milky Way halo. *Astrophys. J.* **714**, 229–254 (2010).
15. Küpper, A. H. W. et al. Globular cluster streams as Galactic high-precision scales—the poster child palomar 5. *Astrophys. J.* **803**, 80 (2015).
16. Ibata, R. A., Lewis, G. F., Irwin, M. J. & Quinn, T. Uncovering cold dark matter halo substructure with tidal streams. *Mon. Not. R. Astron. Soc.* **332**, 915–920 (2002).
17. Johnston, K. V., Spergel, D. N. & Haydn, C. How lumpy is the Milky Way's dark matter halo? *Astrophys. J.* **570**, 656–664 (2002).
18. Carlberg, R. G. Dark matter sub-halo counts via star stream crossings. *Astrophys. J.* **748**, 20 (2012).
19. Erkal, D., Belokurov, V., Bovy, J. & Sanders, J. L. The number and size of subhalo-induced gaps in stellar streams. *Mon. Not. R. Astron. Soc.* **463**, 102–119 (2016).
20. Gaia Collaboration Gaia data release 2. Summary of the contents and survey properties. *Astron. Astrophys.* **616**, A1 (2018).

21. Gaia Collaboration Gaia data release 2. The astrometric solution. *Astron. Astrophys.* **616**, A2 (2018).
22. Ibata, R., Malhan, K. & Martin, N. The streams of the gaping abyss: a population of entangled stellar streams surrounding the inner galaxy. *Astrophys. J.* **872**, 152 (2019).
23. Malhan, K. & Ibata, R. A. STREAMFINDER—I. A new algorithm for detecting stellar streams. *Mon. Not. R. Astron. Soc.* **477**, 4063–4076 (2018).
24. Bressan, A. et al. PARSEC: stellar tracks and isochrones with the PAdova and TRieste stellar evolution code. *Mon. Not. R. Astron. Soc.* **427**, 127–145 (2012).
25. Malhan, K., Ibata, R. A. & Martin, N. F. Ghostly tributaries to the Milky Way: charting the halo's stellar streams with the Gaia DR2 catalogue. *Mon. Not. R. Astron. Soc.* **481**, 3442–3455 (2018).
26. Ibata, R. A., Malhan, K., Martin, N. F. & Starkenburg, E. Phlegethon, a nearby 75 degree-long retrograde stellar stream. *Astrophys. J.* **865**, 85 (2018).
27. Gaia Collaboration Gaia data release 2. Kinematics of globular clusters and dwarf galaxies around the Milky Way. *Astron. Astrophys.* **616**, A12 (2018).
28. Bianchini, P., Varri, A. L., Bertin, G. & Zocchi, A. Rotating globular clusters. *Astrophys. J.* **772**, 67 (2013).
29. Braga, V. F. et al. On the RR Lyrae stars in globulars. V. The complete near-infrared (JHK$_s$) census of Omega Centauri RR Lyrae variables. *Astron. J.* **155**, 137 (2018).
30. Fernandez-Trincado, J. G. et al. RAVE stars tidally stripped or ejected from the Omega Centauri globular cluster. *Astron. Astrophys.* **583**, A76 (2015).
31. Gilmore, G., Wyse, R. F. G. & Norris, J. E. Deciphering the last major invasion of the Milky Way. *Astrophys. J.* **574**, L39–L42 (2002).
32. Meza, A., Navarro, J. F., Abadi, M. G. & Steinmetz, M. Accretion relics in the solar neighbourhood: debris from omega Cen's parent galaxy. *Mon. Not. R. Astron. Soc.* **359**, 93–103 (2005).
33. Altmann, M., Catelan, M. & Zoccali, M. Searching for merger debris in the Galactic halo: chemodynamical evidence based on local blue HB stars. *Astron. Astrophys.* **439**, L5–L8 (2005).
34. Majewski, S. R. et al. Exploring halo substructure with giant stars: substructure in the local halo as seen in the grid giant star survey including extended tidal debris from Omega Centauri. *Astrophys. J.* **747**, L37 (2012).
35. Helmi, A., Veljanoski, J., Breddels, M. A., Tian, H. & Sales, L. V. A box full of chocolates: the rich structure of the nearby stellar halo revealed by Gaia and RAVE. *Astron. Astrophys.* **598**, A58 (2017).
36. Koppelman, H., Helmi, A. & Veljanoski, J. One large blob and many streams frosting the nearby stellar halo in Gaia DR2. *Astrophys. J.* **860**, L11 (2018).
37. Myeong, G. C., Evans, N. W., Belokurov, V., Sanders, J. L. & Koposov, S. E. Discovery of new retrograde substructures: the shards of Omega Centauri? *Mon. Not. R. Astron. Soc.* **478**, 5449–5459 (2018).
38. Leon, S., Meylan, G. & Combes, F. Tidal tails around 20 Galactic globular clusters. Observational evidence for gravitational disk/bulge shocking. *Astron. Astrophys.* **359**, 907–931 (2000).
39. Donati, J. F., Semel, M., Carter, B. D., Rees, D. E. & Collier Cameron, A. Spectropolarimetric observations of active stars. *Mon. Not. R. Astron. Soc.* **291**, 658–682 (1997).
40. Starkenburg, E. et al. The NIR Ca II triplet at low metallicity. Searching for extremely low-metallicity stars in classical dwarf galaxies. *Astron. Astrophys.* **513**, 34 (2010).
41. Gratton, R. G. The absolute magnitude of field metal-poor horizontal branch stars. *Mon. Not. R. Astron. Soc.* **296**, 739–745 (1998).
42. Jordi, C. et al. Gaia broad band photometry. *Astron. Astrophys.* **523**, A48 (2010).
43. Teuben, P. The stellar dynamics toolbox NEMO. In *ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV* (eds Shaw, R. A., Payne, H. E. & Hayes, J. J. E.) 398–401 (ASP, 1995).
44. Dehnen, W. & Binney, J. Mass models of the Milky Way. *Mon. Not. R. Astron. Soc.* **294**, 429–438 (1998).
45. Gravity Collaboration Detection of the gravitational redshift in the orbit of the star S2 near the Galactic Centre massive black hole. *Astron. Astrophys.* **615**, L15 (2018).
46. Karim, M. T. & Mamajek, E. E. Revised geometric estimates of the north Galactic pole and the Sun's height above the Galactic mid-plane. *Mon. Not. R. Astron. Soc.* **465**, 472–481 (2017).
47. Schönrich, R., Binney, J. & Dehnen, W. Local kinematics and the local standard of rest. *Mon. Not. R. Astron. Soc.* **403**, 1829–1833 (2010).
48. Varri, A. L. & Bertin, G. Self-consistent models of quasi-relaxed rotating stellar systems. *Astron. Astrophys.* **540**, A94 (2012).
49. Bianchini, P. et al. The internal rotation of globular clusters revealed by Gaia DR2. *Mon. Not. R. Astron. Soc.* **481**, 2125–2139 (2018).
50. Dehnen, W. A hierarchical O(*N*) force calculation algorithm. *J. Comput. Phys.* **179**, 27–42 (2002).
51. Gratton, R. G., Johnson, C. I., Lucatello, S., D'Orazi, V. & Pilachowski, C. Multiple populations in Omega Centauri: a cluster analysis of spectroscopic data. *Astron. Astrophys.* **534**, A72 (2011).

Author contributions

All authors assisted in the development, analysis and writing of the paper. R.A.I., K.M. and N.M. devised the STREAMFINDER software that detected the Fimbulthul stream. M.B. analysed the Gaia mission data to reveal the presence of the stream close to ω Cen. The spectroscopic measurements were performed by R.A.I. The initial conditions for the dynamical model of ω Cen were developed by P.B.

Competing interests

The authors declare no competing interests.

Additional information

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