R-process enrichment from a single event in an ancient dwarf galaxy

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Elements heavier than zinc are synthesized through the rapid (r) and slow (s) neutron-capture processes1,2. The main site of production of the r-process elements (such as europium) has been debated for nearly 60 years2. Initial studies of trends in chemical abundances in old Milky Way halo stars suggested that these elements are produced continually, in sites such as core-collapse supernovae3,4. But evidence from the local Universe favours the idea that r-process production occurs mainly during rare events, such as neutron star mergers5,6. The appearance of a plateau of europium abundance in some dwarf spheroidal galaxies has been suggested as evidence for rare r-process enrichment in the early Universe7, but only under the assumption that no gas accretes into those dwarf galaxies; gas accretion favours continual r-process enrichment in these systems. Furthermore, the universal r-process pattern1,9 has not been clearly identified in dwarf spheroidals. The smaller, chemically simpler, and more ancient ultrafaint dwarf galaxies assembled shortly after the first stars formed, and are ideal systems with which to study nucleosynthesis events such as the r-process4,10,11. Reticulum II is one such galaxy12–14. The abundances of non-neutron-capture elements in this galaxy (and others like it) are similar to those in other old stars15. Here, we report that seven of the nine brightest stars in Reticulum II, observed with high-resolution spectroscopy, show strong enhancements in heavy neutron-capture elements, with abundances that follow the universal r-process pattern beyond barium. The enhancement seen in this ‘r-process galaxy’ is two to three orders of magnitude higher than that detected in any other ultrafaint dwarf galaxy11,16,17. This implies that a single, rare event produced the r-process material in Reticulum II. The r-process yield and event rate are incompatible with the source being ordinary core-collapse supernovae18, but consistent with other possible sources, such as neutron star mergers19.

Ultrafaint dwarfs (UFDs) are small galaxies that orbit the Milky Way and have been discovered by deep, wide-area sky surveys12,13. Although physically close to us, they are also relics from the era of the first stars and galaxies and thus an ideal place to investigate the first metal-enrichment events in the Universe10. Observations of UFDs provide evidence that they formed all of their stars within 1 to 3 gigayears (Gyr) of the Big Bang20, that their stars contain very small amounts of elements heavier than helium (‘metals’)21; and that they are enriched by the metal output of only a few generations of stars11,20. Analysis of the chemical abundances of light elements (those less heavy than iron) has suggested that core-collapse supernovae are the primary metal sources in these systems11,16,17. This conclusion is supported by the unusually low abundances of neutron-capture elements in UFDs—abundances that are consistent with a low production of such elements, and which are associated with massive star evolution14. Neutron star mergers might be the dominant source of r-process elements now22,23, but they have been thought to be irrelevant in the low-metallicity regime, including in UFDs. Specifically, the r-process yield from neutron star mergers was thought to be too high to be consistent with r-process abundances in low-metallicity stars2; the rate of occurrence of these binaries was too low to be found in typical UFDs2,7; and the long merging period precluded substantial contributions from neutron star mergers at early times4,22,23.

The UFD Reticulum II (Ret II) was recently discovered from Dark Energy Survey data12,13, and confirmed as one of the most metal-poor galaxies known14. On 1–4 October 2015, we obtained high-resolution spectra of the nine brightest member stars in Ret II (see Table 1 and Extended Data Fig. 1). The abundances of non-neutron-capture elements in all nine stars are consistent with the abundances in other UFD stars and Milky Way halo stars11,15,24. Surprisingly, however, only two of the two metal-poor stars show the deficiency in neutron-capture elements that is typically found in UFDs11,16; the remaining seven stars display extremely strong spectral lines for europium and other neutron-capture elements (Fig. 1). Our abundance analysis (see Methods) finds that these seven stars span a factor of ten in metallicity, centred at [Fe/H] = −2.5, and that all seven stars are substantially enhanced in neutron-capture elements. Their [Eu/Fe] abundances are the highest found in any dwarf galaxy so far2,16, and are comparable with those of

Table 1 | Properties of the nine observed Reticulum II stars

| RA       | Dec.   | \(v_{hel}\) | g | Teff (K) | log g (dex) | \(v_t\) (km s\(^{-1}\)) | [Fe/H] | [Eu/Fe] |
|----------|--------|-------------|---|----------|-------------|------------------------|--------|---------|
| 3 h 35 min 23.85 s | −54° 04′ 07.50″ | 66.8 | 16.45 | 4,608 | 1.00 | 2.40 | −3.01 | 0.79 | 1.68 |
| 3 h 36 min 07.75 s | −54° 02′ 35.56″ | 62.7 | 17.43 | 4,833 | 1.55 | 2.15 | −2.97 | 0.91 | 1.74 |
| 3 h 34 min 47.94 s | −54° 05′ 25.01″ | 62.0 | 17.52 | 4,900 | 1.70 | 1.90 | −2.91 | 1.08 | 1.87 |
| 3 h 35 min 31.14 s | −54° 01′ 48.25″ | 60.9 | 17.64 | 4,925 | 1.90 | 1.80 | −3.34 | <−0.80 | <−1.50 |
| 3 h 34 min 48.04 s | −54° 03′ 49.82″ | 61.9 | 18.27 | 5,125 | 2.35 | 1.75 | −2.19 | 0.36 | 0.95 |
| 3 h 35 min 37.06 s | −54° 04′ 01.24″ | 63.5 | 18.57 | 5,170 | 2.45 | 1.55 | −2.73 | 1.40 | 1.70 |
| 3 h 35 min 56.28 s | −54° 03′ 16.27″ | 62.7 | 18.85 | 5,305 | 2.95 | 1.65 | −3.54 | <−0.10 | <−2.40 |
| 3 h 34 min 57.57 s | −54° 05′ 31.42″ | 61.9 | 18.94 | 5,328 | 2.85 | 1.50 | −2.08 | 1.36 | 1.77 |
| 3 h 35 min 54.24 s | −54° 05′ 58.02″ | 71.6 | 18.95 | 5,395 | 3.10 | 1.35 | −2.77 | 1.40 | 2.11 |

Right ascension (RA) and declination (Dec.) indicate star coordinates. \(v_{hel}\) is the heliocentric radial velocity of the star in km s\(^{-1}\), g is the star’s magnitude. Stellar parameters are effective temperature \(T_{eff}\), surface gravity \(\log g\), and microturbulence \(v_t\). The notation \([A/B]\) = \(\log[N_A]/N_B]_{\odot}\) − \(\log[N_A]/N_B]_{\odot}\), which quantifies the logarithmic number ratio between two elements A and B relative to the solar ratio.1

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the most europium-enhanced halo stars known\textsuperscript{24} (Fig. 2a, b). Surface accretion of neutron-capture elements from the interstellar medium is at least 1,000 times too small to account for this level of enhancement\textsuperscript{25}, and binary mass transfer is unlikely to enrich multiple stars in this galaxy. Thus, these stars must have formed from gas that was heavily pre-enriched with neutron-capture elements.

From our spectra of the four brightest neutron-capture-rich stars, we measure two to eight additional abundances of rare-earth elements. The relative abundances of elements with atomic numbers greater than 55 unambiguously match the scaled solar r-process pattern\textsuperscript{1,9} (Fig. 2c). The [Eu/Ba] ratios of the three fainter neutron-capture-rich stars also point to an r-process origin. Ret II thus appears to be an ‘r-process galaxy’, with 78\% of observed stars being highly enriched in r-process elements. In comparison, the frequency of metal-poor stars in the Milky Way halo that show similar r-process enhancement is less than 5\% (ref. 24). Furthermore, all stars in the nine other UFDs with high-resolution neutron-capture abundances have [Ba/Fe] and [Eu/Fe] values at least 100 times lower than those of the stars in Ret II (although, for some of these UFDs, there are as yet few stars for which such measurements have been made)\textsuperscript{11,16,17}. It is thus extremely likely that the neutron-capture material in Ret II was produced by just one r-process event. If each UFD were equally likely to host an r-process event, then the probability that N r-process events occurred in Ret II, but zero r-process events occurred in the other nine UFDs, is (1/10)\textsuperscript{N}. There is thus only about a 1\% chance that two or more events contributed to the r-process material in Ret II. Although gas accretion could potentially hide a prolific r-process event in one of the other UFDs, accreting enough gas to decrease the neutron-capture abundance by over two orders of magnitude, while leaving no stars with intermediate r-process enhancements, is implausible.

The r-process yield of a typical core-collapse supernova cannot explain the high r-process abundances found in this galaxy. Using europium as the representative r-process element, we found that five of the r-process stars in Ret II have [Eu/H] abundances of –1 to –1.3, suggesting that these stars formed in an environment in which the europium mass ratio (M\textsubscript{Eu}/M\textsubscript{H}) was 10\textsuperscript{–4.3} to 10\textsuperscript{–4.6} solar masses. The two faintest r-process stars have higher [Eu/H] values, but their larger abundance uncertainties place them within 1–2σ of [Eu/H] = –1. In a UFD, metals are typically diluted into roughly 10\textsuperscript{8} solar masses of hydrogen by turbulent mixing during galaxy assembly\textsuperscript{10,26,27}, with low and high limits of 10\textsuperscript{7}–10\textsuperscript{8} solar masses (see Methods). The europium yield from this r-process event would then be 10\textsuperscript{–10} to 10\textsuperscript{–9.5} solar masses—1,000 times higher than the yields that are typical of core-collapse supernovae (M\textsubscript{Eu} \approx 10\textsuperscript{–7.5} solar masses\textsuperscript{17}; brown vertical bar in Fig. 2a, b). Extreme supernova europium yields of about 10\textsuperscript{–9} solar masses have been invoked to aid in chemical evolution models\textsuperscript{4}, but even combining these with the minimum possible dilution mass results in [Eu/H] values that are too low to match the stellar abundances in Ret II.

Although there are several candidate sites for rare and prolific r-processes, neutron star mergers are thought to be one of the most likely\textsuperscript{5,6,23,25–28}. Typical europium yields from neutron star mergers are M\textsubscript{Eu} = \approx 10\textsuperscript{–4.5} solar masses\textsuperscript{15}, resulting in [Eu/H] values compatible with those observed in Ret II (orange vertical bar in Fig. 2a, b). The rate of the Ret II r-process event also appears consistent with a neutron star merger, although both the observed and the expected rates are uncertain (see Methods). Given that only one prolific r-process event has occurred in the ten UFDs observed so far, combining the present-day stellar masses of these ten UFDs allows an estimate of how many supernovae must explode for every neutron star merger. Using a standard initial mass function, we find that about 2,000 supernovae contributed...
Figure 2 | Chemical abundances of stars in Reticulum II. a, [Ba/H] and [Fe/H] abundances in stars from Ret II (red points), in halo stars24 (grey points), and in other UFDs (coloured points; see references within refs 16, 17). The orange and brown vertical bars indicate the abundance ranges that would be expected following a neutron star merger and in a core-collapse supernova, respectively. The dotted black lines show constant [Ba/Fe] abundances. Arrows denote upper limits. Error bars represent 1σ (see Extended Data Table 1 and Methods). b, As in a, but for [Eu/H] abundances. c, Abundance patterns beyond barium for the four brightest europium-enhanced stars in Ret II (black dots; see Extended Data Table 2), compared with the solar r-process and s-process patterns4 (purple and yellow lines, respectively). Solar patterns are scaled to stellar barium abundance. Stars are offset from each other by multiples of five.

Our observations are also consistent with other rare and prolific r-process events. In particular, magnetorotationally driven supernovae synthesize as much as some 10⁻⁵ solar masses of europium on a supernova timescale and at a rate more frequent than that of neutron star mergers32. These particular supernovae and neutron star mergers are similar enough in their r-process yields and rates that Ret II cannot yet be used to distinguish firmly between them. If future theoretical work finds that these two sites differ in other ways—for example, in the abundance of neutron-capture elements around the first r-process peaks15—then the stellar abundances in Ret II might eventually be used to differentiate between them.

Previous evidence for the occurrence of rare, prolific r-process events in more luminous dwarf spheroidals relied on interpreting a flat [Eu/H] trend with respect to [Fe/H]₁⁷. However, the existence of this plateau favours a rare r-process event only if gas accretion is unimportant in the galaxy. Invoking gas accretion actually lowers the [Eu/H] plateau value as metallicity increases—in which case the observed plateau requires continual europium production from core-collapse supernovae, rather than a single r-process event. We note that hierarchical structure formation predicts substantial gas accretion into these larger dwarf galaxies, and that extra gas is needed to reproduce their overall metallicity-distribution functions⁸.

In contrast, our evidence for a single event in Ret II is based on large [Ba/Fe] and [Ba/Fe] enhancements relative to those measured in stars in the other UFDs. The europium and barium trends within Ret II can then be used to understand the star-formation, gas-accretion, and metal-mixing history of this galaxy. As an illustration, the star with the highest [Fe/H] abundance might reveal the presence of inhomogeneous metal mixing, as it has a similar [Eu/Fe] abundance to those of the stars with lower [Fe/H] abundances3⁰ (although we caution that the present data give statistically insignificant abundance trends; see Methods). Thus, the stellar abundances in Ret II not only show that rare and prolific r-process events occurred in the early Universe; they also hold the key to understanding the formation of this relic from the era of the first galaxies.
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METHODS

Observations and abundance analysis. We selected for observation the brightest known red-giant members of Ret II from published medium-resolution spectroscopic surveys of Ret II\(^{33,32}\) (Extended Data Fig. 1). On 1–4 October 2015, we obtained high-resolution spectra with the MIKE spectrograph\(^{93}\) on the Magellan Clay telescope, using a 1.0-arcsec slit and covering 3,500 Å to 9,000 Å. This provides a spectral resolution of \(\sim 22,000\) and \(\sim 28,000\) at redder and bluer wavelengths, respectively. Stars were each observed for 1 to 4 hours, resulting in signal-to-noise ratio per pixel of \(\sim 8–12\) at 4,250 Å and \(\sim 5\) at 6,000 Å (Extended Data Table 1). We used the Carnegie–Python pipeline to reduce the spectra\(^{39}\). Separate echelle orders were normalized and summed with the semi-automated code SMH\(^{35}\), which was also used for the abundance analysis. Radial velocities were determined by cross-correlation of the magnesium triplet lines near 5,150 Å against a high signal-to-noise spectrum of the metal–poor star HD140283.

We determined stellar parameters and abundances with standard spectroscopic methods\(^{36,37}\), which we summarize briefly here. Equivalent widths of iron lines were determined by fitting Gaussian profiles. We rejected iron lines whose reduced equivalent width is larger than \(\sim 4.5\), because these lines are probably past the linear regime of the curve of growth. We used the Castelli–Kurucz stellar atmospheres with enhanced alpha-abundances\(^{37}\) and the abundance-analysis code MOOG\(^{38}\) to determine the abundances of these lines. The effective temperature was found by requiring no iron abundance trend with respect to excitation potential. The surface gravity was found by requiring the Fe i lines to have the same abundance as the Fe ii lines. For the seventh and ninth stars in Table 1, we used an isochrone\(^{39}\) to determine the surface gravity, as no Fe ii lines were detectable. We found the microturbulence by requiring no trend between abundance and reduced equivalent width. After determining the stellar parameters spectroscopically, we applied an effective temperature correction\(^{38}\) and re-determined the surface gravity and microturbulence. This correction increases the effective temperatures and results in increased metallicities. We estimated statistical uncertainties in the effective temperature and microturbulence by varying the parameters to match the standard deviation of the fitted slopes. Uncertainty in the surface gravity was estimated by varying the parameter to match the standard error of the Fe i and Fe ii abundance. We adopt systematic slopes. Uncertainty in the surface gravity was estimated by varying the parameter uncertainties. The latter uncertainty typically dominates (see Extended Data Table 1). The stellar parameter uncertainties typically correspond to a total uncertainty in iron abundance of \(\sim 0.2–0.3\) dex, which is dominated by the uncertainty in the effective temperature. The abundances of the brightest four stars have been confirmed by observations with higher signal-to-noise ratios\(^{15}\).

Abundances of neutron-capture elements were determined with a line list compiled from several sources (refs 40, 41, and references within refs 42, 43). We used spectrum synthesis to derive abundances of barium, lanthanum, praseodymium and europium. Abundances of other neutron-capture elements were determined using equivalent widths of unblended lines. The abundances are tabulated in Extended Data Table 2. Abundance uncertainties indicate the larger of: (1) the standard deviation of abundances derived from individual lines, accounting for small-number statistics\(^{44}\); and (2) the total [Fe/H] uncertainty, including stellar parameter uncertainties. The latter uncertainty typically dominates (see Extended Data Table 1). Abundances are quoted relative to solar abundances\(^{41}\). We determined conservative upper limits by synthesizing a line with amplitude two times larger than the typical continuum uncertainty.

The strong 4,554 Å and 4,934 Å barium lines are affected by the isotope ratios\(^{22}\). The strong 4,554 Å and 4,934 Å barium lines are affected by the isotope ratios\(^{22}\). The isotope ratios\(^{22}\), which can eject the binary from its host galaxy and further reduce the expected event rate for the event than calculated here, because r-process elements synthesized by neutron star mergers occurring after star formation finished cannot be preserved in a galaxy’s chemical abundances. Some UFDs may contain r-process-enhanced neutron star mergers\(^{27}\). For the event than calculated here, because r-process elements synthesized by neutron star mergers occurring after star formation finished cannot be preserved in a galaxy’s chemical abundances. Some UFDs may contain r-process-enhanced neutron star mergers\(^{27}\). 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Extended Data Figure 1 | Properties of Reticulum II member stars.

a, Coordinates of member stars, in right ascension (RA) and declination (DEC) at the standard epoch (J2000)\textsuperscript{14}. Stars selected for observation with high-resolution spectroscopy are highlighted with large coloured circles, while other members are shown in black. b, Colour–magnitude diagram based on Dark Energy Survey photometry\textsuperscript{14}; $g$ and $r$ are the stars’ magnitudes in two different filters.
| Star | S/N 4250Å | N Fe i Lines | S/N | N Fe i Lines | Stellar-parameter uncertainties | Total Uncertainty | [Fe/H] | Ba error | Eu error |
|------|-----------|-------------|-----|-------------|-------------------------------|-------------------|--------|----------|----------|
|      |           |             |     |            | Statistical Uncertainty      | Total Uncertainty | total error | s.d. (N) | s.d. (N) |
| 1    | 22        | 128         | 46  | 0.02       | 0.21                          | 157   | 0.30     | 0.29     | 0.23     | 0.06     | 0.13     |
| 2    | 12        | 103         | 71  | 0.16       | 0.19                          | 166   | 0.34     | 0.28     | 0.21     | 0.17     | 0.22     |
| 3    | 11        | 104         | 81  | 0.08       | 0.20                          | 170   | 0.31     | 0.28     | 0.23     | 0.30     | 0.06     |
| 4    | 16        | 80          | 63  | 0.19       | 0.20                          | 163   | 0.36     | 0.28     | 0.23     |          |          |
| 5    | 12        | 124         | 62  | 0.12       | 0.20                          | 162   | 0.32     | 0.28     | 0.22     | 0.11     | 0.27     |
| 6    | 10        | 51          | 134 | 0.21       | 0.30                          | 201   | 0.37     | 0.36     | 0.31     | 0.30     | 0.00     |
| 7    | 11        | 33          | 210 | N/A        | 0.35                          | 258   | 0.40     | 0.40     | 0.37     |          |          |
| 8    | 8         | 67          | 104 | 0.11       | 0.23                          | 183   | 0.32     | 0.30     | 0.26     | 0.04     | 0.35     |
| 9    | 7         | 31          | 199 | N/A        | 0.37                          | 249   | 0.40     | 0.42     | 0.36     | 0.24     | 0.00     |

S/N is the signal-to-noise ratio per pixel near 4,250 Å. $T_{\text{eff}}$ is in K, log g in dex, and $v_t$ in km s$^{-1}$. The number of lines used to determine the barium and europium abundances is given in parentheses. The adopted abundance error is the larger of the standard deviations between lines and the [Fe/H] error. Stars are numbered from brightest to faintest, from Star 1 to Star 9 in this order: DES J033523–540407, DES J033607–540235, DES J033447–540525, DES J033531–540148, DES J033548–540349, DES J033537–540401, DES J033556–540316, DES J033457–540531, DES J033454–540558. © 2016 Macmillan Publishers Limited. All rights reserved.
Extended Data Table 2  | Abundances of neutron-capture elements

| Element | Star 1 | Star 2 | Star 3 | Star 4 | Star 5 | Star 6 | Star 7 | Star 8 | Star 9 |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| log ε(Ba) | -0.04  | 0.12   | 0.35   | <=-1.96| 0.35   | 0.85   | <=-1.26| 1.46   | 0.81   |
| [Ba/Fe]  | 0.79   | 0.91   | 1.08   | <=-0.80| 0.36   | 1.40   | <0.10  | 1.36   | 1.40   |
| log ε(La) | -0.81  | -0.64  | -0.51  |        |        |        |        |        |        |
| [La/Fe]  | 1.10   | 1.23   | 1.30   |        |        |        |        |        |        |
| log ε(Ce) | -0.51  | -0.16  | -0.02  |        |        |        |        | 0.75   |        |
| [Ce/Fe]  | 0.92   | 1.23   | 1.31   |        |        |        |        | 1.25   |        |
| log ε(Pr) | -1.09  | -0.67  | -0.79  |        |        |        |        |        |        |
| [Pr/Fe]  | 1.20   | 1.58   | 1.40   |        |        |        |        |        |        |
| log ε(Nd) | -0.21  | -0.01  | 0.25   | 0.35   |        |        |        | 1.18   |        |
| [Nd/Fe]  | 1.38   | 1.54   | 1.74   |        |        |        |        | 1.84   |        |
| log ε(Sm) | -0.65  | -0.28  | -0.05  |        |        |        |        |        |        |
| [Sm/Fe]  | 1.40   | 1.73   | 1.90   |        |        |        |        |        |        |
| log ε(Eu) | -0.81  | -0.71  | -0.52  | <=-1.32| -0.72  | -0.51  | <=-0.62| 0.21   | -0.14  |
| [Eu/Fe]  | 1.68   | 1.74   | 1.87   | <=1.50 | 0.95   | 1.70   | <=2.40 | 1.77   | 2.11   |
| log ε(Gd) | -0.47  | -0.14  |        |        |        |        |        |        |        |
| [Gd/Fe]  | 1.47   | 1.76   |        |        |        |        |        |        |        |
| log ε(Dy) | -0.29  | -0.15  | 0.20   |        | 0.15   | 0.16   |        |        | 1.22   |
| [Dy/Fe]  | 1.62   | 1.72   | 2.01   |        | 1.24   | 1.79   |        |        | 2.20   |

Stars are numbered from brightest to faintest, from star 1 to star 9, as in Extended Data Table 1.