A recurrent nova super-remnant in the Andromeda galaxy

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The accretion of hydrogen onto a white dwarf star ignites a classical nova eruption1–12—a thermonuclear runaway in the accumulated envelope of gas, leading to luminosities up to a million times that of the Sun and a high-velocity mass ejection that produces a remnant shell (mainly consisting of interstellar medium). Close to the upper mass limit of a white dwarf13 (1.4 solar masses), rapid accretion of hydrogen (about 10−7 solar masses per year) from a stellar companion leads to frequent eruptions on timescales of years4,14 to decades5. Such binary systems are known as recurrent novae. The ejecta of recurrent novae, initially moving at velocities of up to 10,000 kilometres per second5, must ‘sweep up’ the surrounding interstellar medium, creating cavities in space around the nova binary. No remnant larger than one parsec across from any single classical or recurrent nova eruption is known15–18, but thousands of successive recurrent nova eruptions should be capable of generating shells hundreds of parsecs across. Here we report that the most frequently recurring nova, M31N 2008-12a in the Andromeda galaxy (Messier 31 or NGC 224), which erupts annually11, is indeed surrounded by such a super-remnant with a projected size of at least 134 by 90 parsecs. Larger than almost all known remnants of even supernova explosions14, the existence of this shell demonstrates that the nova M31N 2008-12a has erupted with high frequency for millions of years.

Located within the disk of the Andromeda galaxy (Messier 31, M31), the rapidly recurring nova M31N 2008-12a (hereafter ‘12a’) has erupted annually since at least 200813. The eruptions of 12a exhibit the fastest optical evolution, the highest ejection velocities, the hottest X-ray source and the most rapid recurrence cycle of any known thermonuclear nova11. Combined, these observations imply the most massive white dwarf ever discovered14 (1.38M⊙, where M⊙ is the solar mass), accreting at the largest rate seen in any nova system15 (more than 10−7M⊙ per year). Hubble Space Telescope (HST) ultraviolet spectroscopy of the 2015 eruption uncovered no evidence for neon in the ejecta, which is consistent with—but not conclusive proof of—a carbon-oxygen white dwarf15, one which must have grown from an initial formation mass of at most17,18 1.1M⊙.

Pre-existing ground-based narrow-band Hα imaging shows a partially complete shell-like structure spatially coincident with the nova19,20. The full ring of this shell-like nebula surrounding 12a is clearly visible in our deep ground-based and HST observations (Fig. 1; see Methods) of the proposed nova super-remnant. The super-remnant is elliptical and brighter to the southwest than it is to the northeast. We measure the projected semi-major axes to the inner and outer edge of the bright super-remnant shell to be 52 pc and 67 pc, respectively, a shell thickness of 22%. If the super-remnant shell is dynamic in nature, the pre-existing interstellar medium (ISM) has been swept up and compressed by a factor of about 2. There is a sharply defined outer edge visible to the south and west. The well defined elliptical boundary of the super-remnant implies that it has not been substantially shaped by the ISM, but that such a geometry was imparted by the nova eruptions and has largely persisted. The high spatial resolution of the HST images reveals that the super-remnant’s outer shell is not smooth, as seen from the ground, but fragmented into knots and radially nested filaments, reminiscent of the handful of interacting nova shells seen around the Galactic recurrent nova T Pyxidis11,21.

Our deep spectroscopy of the super-remnant shell (see Fig. 2 and Methods) reveals strong and narrow emission lines from the hydrogen Balmer series with natural widths narrower than the instrumental resolution (about 180 km s−1 for Hα). The presence of the [O ii] (wavelengths 3,726 Å and 3,729 Å) and [S ii] (6,716 Å and 6,731 Å) doublets place an upper limit on the electron density of the emitting gas of around 3,000 cm−3 (ref. 22). The lack of [O i] emission lines indicates that there is no nearby source of ionizing radiation and that the material is of sufficient age to have cooled below the ionization temperature of O+. No [O i] lines are detected, suggesting minimal shock heating. Given that the [N ii] (6,548 Å and 6,584 Å) doublet is visible, but the [N i] (5,755 Å) line is not, we can place a 3σ limit on the electron temperature of less than 9,000 K (ref. 23). The [N ii]/Hα line-intensity ratio is 0.54 ± 0.02, the [S ii]/Hα ratio is 0.48 ± 0.04, and the [S ii] doublet ratio itself is 1.42 ± 0.05 and indicates an electron density of less than 100 cm−3 (ref. 23) within the bright outer shell of the super-remnant. With a compression factor of about 2, the pre-nova ISM density must have been less than 50 cm−3. This density and measurements of the super-remnant shell size (Fig. 1) indicate that the shell mass is less than 7 × 105M⊙ (see Methods).

A second spectrum contains emission from a bright ‘knot’ slightly within the outer shell to the east of 12a (see Figs. 1b, 2 and Methods). This is similar to, but fainter than, the emission of the outer shell. However, the knot spectrum contains strong [O iii] (4,959 Å and 5,007 Å) emission, indicating a more extreme temperature or radiation environment closer to the nova system. The lack of the [O i] (4,363 Å) line allows only a weak temperature constraint of less than 160,000 K, but the knot [N i] emission indicates temperature T < 18,000 K.

Using existing ground-based imaging and serendipitous spectroscopy, the origin of the nebulous could not be confirmed19. Possible sources of an elliptical nebular shell could include a supernova remnant, a ‘superbubble’, or photoionization phenomena such as a ‘fossil’ H II region.
The $[\text{S} \, \text{II}]/\text{H}\alpha$ ratio is marginally consistent with the lower cutoff (more than 0.5) that is required to suggest a ‘forbidden line’ supernova remnant candidate, but the lack of $[\text{O} \, \text{II}]$ and $[\text{O} \, \text{I}]$ emission strongly suggests that the outer shell is not a supernova remnant. Moreover, there are no known radio sources close to 12a and its surrounding super-remnant.

Fig. 1 | 12a and its surrounding super-remnant. a, Liverpool Telescope narrow-band H$\alpha$ + $[\text{N} \, \text{II}]$ continuum-subtracted (see Methods) image of the region surrounding 12a. The majority of stellar sources have been removed, but the four dark-blue sources indicate field stars detected only in continuum light. The closed nebula is seen within the white dashed ellipse, as is its asymmetry and varying luminosity around the outer ‘shell’. The position of 12a is marked and the offset from the geometric centre is indicated by the black line. b, HST H$\alpha$ + $[\text{N} \, \text{II}]$ continuum-subtracted (see Methods) image of the same region; all stellar sources have been removed via the subtraction process. The high spatial resolution of this image reveals that the nebulosity is not smooth, as imaged from the ground, but fragmented and filamentary in nature, reminiscent of the ejecta of the Galactic recurrent nova T Pyxidis. The red squares mark the locations of the two regions discussed in the text; the large square shows the bright western shell, and the small square the eastern ‘knot’. c, Zoomed-in HST H$\alpha$ + $[\text{N} \, \text{II}]$ image showing the region within the large red box in b. At the top of this panel three long ‘nested’ filaments are discernible, separated by only 5 pc and 12 pc.

Superbubbles, caused by the winds of massive stars and supernovae, are typically observed surrounding O–B star associations. HST observations of the region reveal no such associations within the super-remnant (see Methods) and no nearby supernova remnants have been identified. Known Galactic fossil H II regions are typically much smaller than the super-remnant. Although 12a has probably undergone eruptions for a long period, the luminosity of the eruptions is not high enough to grow a photoionized region to the observed size of the super-remnant (see Methods).

To demonstrate the viability of multiple recurrent nova eruptions producing a vast super-remnant, we performed a series of one-dimensional hydrodynamic simulations of the ejecta, their self-interaction, and their interaction with the surrounding environment. Results of our simulations of up to 100,000 separate but interacting ejecta are presented in Fig. 3. The simulations (Fig. 3a–c) illustrate how repeated nova eruptions create a vast, evacuated cavity around the system, by continually sweeping up the ISM and piling it up within a shell at the edge of the growing super-remnant (Fig. 3d). In Fig. 3e, the observed super-remnant radial profile is compared to the simulations (scaled to the size of the nebula), demonstrating striking similarity at scales above 10 pc. These profiles are consistent with a shell rather than a ring (see Methods).

Such repeated eruptions sweep up 17 M$_\odot$ of ISM after 100,000 eruptions (see Methods), about 3,000 times the mass ejected by the nova over this period. Therefore, super-remnants must comprise almost exclusively swept-up material and will have an ISM-like, not nova-like, composition; the super-remnant He i/H$\alpha$ line-strength ratio of less than 0.04 is consistent with the ratios observed in warm diffuse ISM. The He i/H$\alpha$ ratio of the 12a ejecta has been repeatedly measured and varies from 0.16 to 0.48, driven by the high helium abundance of nova ejecta.

The super-remnant contains three distinct regions, as marked in Fig. 3b (also see Methods): the inner cavity (where recent ejecta effectively undergo free, high-velocity expansion while cooling adiabatically); the ejecta pile-up (where the ejecta from successive eruptions eventually collide as preceding eruptions are slowed by interaction with the ISM, with high-velocity inter-ejecta shocks driving substantial heating and deceleration of this gas); and the super-remnant shell (which consists almost entirely of swept-up ISM that is slowly driven outward by the multiple-ejecta pile-up culminating at its inner edge). The radii of the outer and inner edges of the super-remnant increase with a power-law-like time dependence (Fig. 3d), maintaining a shell thickness of about 22%, consistent with the observations. Once established, the peak shell over-density remains at four times the ISM density (Fig. 3a–c).
The computational intensity limited simulations to 100,000 eruptions; continued growth of the super-remnant has been explored by extrapolation to later times (see Methods). Our models show that the 12a super-remnant has been built up by annual nova eruptions sweeping up the surrounding ISM over $6 \times 10^6$ years (Fig. 3d). Over that time, the outer shell of the super-remnant has cooled sufficiently below $10^4$ K to explain the observed spectrum (Fig. 3f). Throughout the evolution, the high temperature of the pile-up region is, however, maintained by the continual arrival of high-velocity ejecta, a possible explanation of the inner knot spectrum. The predicted X-ray luminosity of the super-remnant is orders of magnitude below current detection capabilities (see Methods). The simulations show that the total mass swept up by the eruptions is about $3 \times 10^3 M_\odot$, consistent with the upper limit derived from the observations. The size and mass of this super-remnant demonstrate that 12a has not just been erupting frequently for a decade as observed, but for millions of years.

The 12a white dwarf has an accretion rate of about $1.6 \times 10^{-7} M_\odot$ per year$^{14}$ and a current accretion efficiency (the proportion of accreted material retained by the white dwarf post-eruption)$^{14, 15}$ that exceeds 60%. Assuming a white dwarf formation mass of about $1 M_\odot$, an average efficiency of just 40% over the lifetime of the remnant is required to grow the white dwarf to the maximum mass permissible before collapse ensues$^3$ ($1.4 M_\odot$; the Chandrasekhar limit). This is consistent with predictions of increasing accretion efficiency as the white dwarf mass grows$^5$.

The discovery of additional super-remnants around other accreting white dwarfs will point to systems undergoing regular eruptions over long periods of time. Our simulations show that this super-remnant—to our knowledge, the first extragalactic nova shell observed—is not static and will continue to grow at least as long as nova eruptions continue in the system. Any nova super-remnants around accreting carbon-oxygen white dwarfs will ultimately be destroyed by the explosion of their parent system in a type Ia supernova. 12a is predicted to pass the Chandrasekhar limit in less than 40,000 years$^{15}$.

At that point, the underlying composition of the white dwarf$^{16}$ will be revealed incontrovertibly when either a type Ia supernova$^{29}$ or an accretion-induced collapse of the white dwarf to a neutron star$^{30}$ is observed.

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Fig. 3 Results of hydrodynamic simulations of the interacting ejecta of multiple recurrent nova eruptions. a–c, The radial density profile around 12a. The solid lines illustrate the simulated density profiles for 2 to 100,000 eruptions (see keys). The lower and upper dotted lines show the ISM and outer-shell peak densities, respectively. d, The upper solid line illustrates the growth of the outer edge of the super-remnant shell over 100,000 eruptions; the lower solid line shows the inner-edge growth. The diagonal dotted lines are extrapolations of the radial growth curves to further eruptions. The upper and lower grey lines indicate the growth of the outer edge for lower and higher ISM densities, respectively. The horizontal dotted line is the maximum projected radius of the 12a super-remnant (67 pc; the 45-pc semi-minor axis is also shown). e, The radial Hα + [N II] flux from the Liverpool Telescope (grey) and HST (red) imaging compared to the simulated super-remnant hydrogen column (black). The simulation has been rescaled from 100,000 eruptions to the observed size of the remnant. f, The super-remnant temperature evolution. The solid black line indicates simulations of 100,000 eruptions; the red and green lines show the effects of a lower and higher ISM density, respectively. An extrapolation to further eruptions is shown by the diagonal black dotted line, with the currently predicted shell temperature of around 1,200 K indicated to the lower right (cross). The solid blue line indicates the evolution of the mean electron temperature within the ejecta pile-up region. The horizontal lines indicate the upper limit of the electron temperature of the shell of the nova super-remnant (NSR) as required by the spectroscopy, and the ionization temperatures of O$^+$ and N$^+$, required to observe [O III] or [N III] lines in the spectra.

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Online content
Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0825-4.

Received: 12 December 2017; Accepted: 8 November 2018; Published online 9 January 2019.

1. Starrfield, S., Truran, J. W., Sparks, W. M. & Kutter, G. S. CNO abundances and hydrodynamic models of the nova outburst. Astron. Astrophys. 176, 169–176 (1982).
2. Pravdin, D., Shara, M. M. & Shaviv, G. The evolution of a slow nova model with a Z = 0.003 envelope from pre-explosion to extinction. Astron. Astrophys. 62, 339–348 (1978).
3. Chandrasekhar, S. The maximum mass of ideal white dwarfs. Astrophys. J. 74, 81–82 (1931).
4. Kato, M., Sato, H., Hachisu, I. & Nomoto, K. Shortest recurrence periods of novae. Astrophys. J. 793, 136 (2014).
5. Hillman, Y., Pravdin, D., Kovetz, A. & Shara, M. M. Growing white dwarfs to the Chandrasekhar limit: the parameter space of the single degenerate SN channel. Astrophys. J. 819, 168 (2016).
6. Schaefer, B. Comprehensive photometric histories of all known Galactic recurrent novae. Astrophys. J. Suppl. Ser. 187, 275–373 (2010).
7. Munari, U. et al. The 1999 outburst of the eclipsing and recurrent nova U Scorp. Astron. Astrophys. 347, L93–L94 (1999).
8. Bode, M. F., O’Brien, T. J. & Simpson, M. Echoes of an explosive past: solving the mystery of the first superluminal source. Astrophys. J. 600, L63–L66 (2004).
9. Shara, M. M., Martin, C. D., Seibert, M., Rich, R. M. & Salim, S. An ancient nova shell around the dwarf nova Z Camelopardalis. Nature 456, 159–162 (2009).
10. Shara, M. M. et al. AT Cnc: a second dwarf nova with a classical nova shell. Astrophys. J. 758, 121 (2012).
11. Darnley, M. J. et al. M31N 2008–12a—the remarkable recurrent nova in M31: panchromatic observations of the 2015 eruption. Astrophys. J. 833, 149 (2016).
12. Stil, J. M. & Irwin, J. A. GSH 138–01–94: an old supernova remnant in the far outer Galaxy. Astrophys. J. 563, 816–827 (2001).
13. Henze, M. et al. Breaking the habit—the peculiar 2016 eruption of the unique recurrent nova M31N 2008–12a. Astrophys. J. 857, 68 (2018).
14. Kato, M., Sato, H. & Hachisu, I. Multi-wavelength light curve model of the one year recurrence period nova M31N 2008–12a. Astrophys. J. 808, 52 (2015).
15. Darnley, M. J. et al. Inflows, outflows, and a giant donor in the remarkable recurrent nova M31N 2008–12a—Hubble Space Telescope photometry of the 2015 eruption. Astrophys. J. 849, 96 (2017).
16. Darnley, M. J. et al. No neon, but jets in the remarkable recurrent nova M31N 2008–12a?—Hubble Space Telescope spectroscopy of the 2015 eruption. Astrophys. J. 847, 35 (2017).
17. Toonen, S., Voss, R. & Knigge, C. The influence of mass-transfer variability on the growth of white dwarfs, and the implications for type la supernova rates. Mon. Not. R. Astron. Soc. 441, 354–363 (2014).
18. Ritossa, C., Garcia-Berro, E. & Iben, I. On the evolution of stars that form electron-degenerate cores processed by carbon burning. II. Isotope abundances and thermal pulses in a 10 M⊙ model with an ONe core and accretion-induced collapse. Astrophys. J. 460, 489–505 (1996).
19. Darnley, M. J. et al. A remarkable recurrent nova in M31: discovery and optical/UV observations of the predicted 2014 eruption. Astron. Astrophys. 580, A45 (2015).
20. Walterbos, R. A. M. & Braun, R. The interstellar medium of M31: III. Narrow-line emission in Hα and [NII]. Astron. Astrophys. Suppl. Ser. 92, 625–682 (1992).
21. Shara, M. M., Zurek, D. R., Williams, R. E., Pravdin, D., Gilmozzi, R. & Moffat, A. F. J. HST imagery of the nova super-remnant, I. A. Steele for assistance with the Liverpool Telescope spectra. K. L. Page for assistance with XSPEC, K. A. Misselt and D. Baer for assistance with the Steward 2.3-m observations, also M. Link and C. Proffitt, and W. Eck and K. Long, the programme coordinators and contact scientists for HST GO:14125 and GO:14651, respectively. M.J.D. and M.W.H. acknowledge financial support and a PhD scholarship, respectively, from the STFC. N.M.H.V. acknowledges support from the European Commission through the Horizon 2020 Marie Skłodowska-Curie Actions Individual Fellowship 2014 programme (grant agreement number 659706). V.A.R.M.R. acknowledges financial support from the Fundação para a Ciência e a Tecnologia in the form of an exploratory project (reference IF/00498/2015), from the Center for Research and Development Mathematics and Applications (strategic project UID/MAT/04106/2013), and from Enabling Green E-science for the Square Kilometer Array Research Infrastructure (ENGAGE SKA), POCI-01-0145-FEDER-022217 funded by Programa Operacional Competitividade e Internacionalização (COMPETE 2020) and the Fundação para a Ciência e a Tecnologia, Portugal.

Reviewer information
Nature thanks S. Shore and J. Sokoloski for their contribution to the peer review of this work.

Author contributions All authors contributed to the discussion, proposing and planning of observations, data interpretation and writing of the manuscript. M.J.D. and S.C.W. led the Liverpool Telescope observations. M.J.D. and R.H. wrote the proposals and led the HST observations and resulting analysis. P.R.-G. and M.J.D. proposed and led the GTC observations and R.G.-R. assisted with their analysis. R.C. and B.D.D. obtained the HET spectrum. A.W.S. acquired the Steward 2.3-m Bok Telescope data. M.H. analysed the archival X-ray data. M.J.D., M.W.H. and S.C.W. undertook the photoionization analysis. M.J.D., T.J.O’B. and T.W. undertook the X-ray and UV observations of the predicted 2014 eruption. R.G.-R. assisted with their analysis. R.C. and B.D.D. obtained the HET spectrum. A.W.S. acquired the Steward 2.3-m Bok Telescope data. M.H. analysed the archival X-ray data. M.J.D., M.W.H. and S.C.W. undertook the photoionization analysis. M.J.D., T.J.O’B. and N.M.H.V. led the hydrodynamic simulations. M.J.D. and N.M.H.V. produced the synthetic X-ray spectra.

Competing interests The authors declare no competing interests.

Additional information
Extended data is available for this paper at https://doi.org/10.1038/s41586-018-0825-4.

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M31N 2008–12a. The recurrent nova 12a is located in the northeastern part of the outer disk of M31 with equatorial coordinates 0 h 45 min 28.89 s +41° 54′ 10.2′′ (J2000)32. Eruptions have been detected in each year from 2008 to 2018 and recovered from archival X-ray observations taken in 1992, 1993 and 200132. The 2013–2017 eruptions have been studied extensively in the X-ray, far- and near-ultraviolet and optical parts of the spectrum. The mean recurrence period of the system is 347 ± 10 days3, although an alias of 174 ± 10 days3 cannot yet be entirely excluded. The mass donor has been identified as a ‘red clump’ star14, but on the basis of Galactic recurrent nova systems3 is most likely to be a low-luminosity red giant, with accretion driven either by Roche lobe overflow or by the red giant wind. Spectroscopy of the 2012–2017 eruptions has shown strong evidence for the deceleration of the 12a ejecta over the first 5 days post-eruption as they interact with and shock circumbinary material, which must be replenished between each eruption1,3,11. The most likely source of this material is from a donor wind, although an accretion disk wind has also been proposed13.

Short recurrence times are driven by the combination of a high-mass white dwarf and a high mass accretion rate3. Among Galactic systems, U Scorpii exhibits the shortest recurrence period of around ten years6, although recently a number of other short-period (less than ten years, but more than one year) systems have been discovered in M3114.

Ground-based imaging observations. Nebulosity in the region around 12a had first been identified as a ‘ring’-like structure in a narrow-band scan of M31 undertaken in 198720, 21 years before the first optical eruption was discovered. Following the 2015 eruption of 12a, an inspection of Hα data collected using the STScI calwfc pipeline38, and Drizzlpac39 was used to align defects and cosmic ray rejection. The dither pattern of each visit was further offset in Fig. 2 indicates the FWHM of the F645N filter, confirming that it is not affected of the Wide Field Camera 3 instrument. The total exposure time for each F675N observations were conducted on 2016 December 7, 8, 9, 10, 11 and 17. By chance, HST observations.

Ten orbits of cycle 24 HST time were used to obtain Hα + [N II] imaging of the nebulosity around 12a (programme GO:14651). These images were processed and combined in a similar fashion to the narrow-band Hα + [N II] images. A sample of these images is shown in Extended Data Fig. 1b–d. Consistent with the ground-based spectra, there is no evidence for any continuum emission from any part of the super-remnant in these images, nor any strong ultraviolet sources (besides 12a).

Ground-based spectroscopic observations. Five 30-min spectra spanning the wavelength range from 3,670 Å to 7,870 Å were taken with the OSIRIS instrument on the GTC on 2017 January 16. We used a slit width of 0.6″ oriented east–west and the ‘R1000B’ grism, achieving a spectral resolution of 5.3 Å (about 250 km s−1 for Hα). After image reduction, cosmic ray and two-dimensional sky background removal using IRAF, the five spectra were co-added, and the one-dimensional spectra of the super-remnant shell and eastern ‘knot’ were optimally extracted using PAMELA (part of the Starlink software package40).

On 2018 January 12, the super-remnant was observed for 2 × 757 s through 2.2″ seeing with the blue feed of the new integral-field unit low-resolution spectrograph (LR2S-B) on the Hobby–Eberly Telescope (HET). This double-armed instrument surveys a 12″ × 6″ area on the sky using an array of 22 × 13 lenslet-coupled fibres, and produces an image scale of 0.59″ per fibre. The ‘blue arm’ of LR2S-B covers the wavelength range 3,700–4,700 Å at R = 1,910 resolution, while the ‘orange arm’ simultaneously records the region 4,600–7,000 Å at R = 1,140. We note that because LR2S-B employs lenslets, there are no dead spots between the fibres, so that many of the problems associated with faint-object spectrophotometry—such as atmospheric dispersion, slit losses and lack of data acquisition due to imprecise astrometry—are mitigated. The HET data were reduced using the procedures described in ref. 41; flux calibration was achieved via comparison to the tertiary spectroscopic standard star HD 289002 (ref. 12). By comparing the emission line fluxes between the outer-shell spectra from HET (flux-calibrated) and GTC, an approximate flux calibration was applied to both the GTC spectra.

In Fig. 2, the flux-calibrated GTC spectroscopy of the super-remnant outer shell (black) and the inner eastern knot (grey) are presented. In Extended Data Fig. 2 we show the HET spectrum of the outer shell. In addition to hydrogen Balmer series lines, the GTC spectrum of the outer shell included emission lines from the resolved [N II] (6,548 Å and 6,584 Å) and [S II] (6,716 Å and 6,731 Å) doublets, and the unresolved [O II] (3,726 Å and 3,729 Å) doublet can be seen, all on top of a negligible continuum flux. The HET spectrum, with its higher spectral resolution, but lower signal-to-noise ratio, resolved the [O I] doublet (see inset to Extended Data Fig. 2), which has a FWHM of 100 Å and therefore contains Hα emission in the knot that is [O I] Å is 1.5 ± 0.3, consistent with the outer-shell density limit of < 100 cm−3 (ref. 23), as derived from the [S II] doublet. There is little evidence for any other species, including the forbidden lines of O I or O II—if seen, both would be indicative of shock heating. No He lines are observed.

While the inner ‘knot’ spectrum is broadly similar to that of the super-remnant shell it is much fainter (Fig. 2). The [O I] emission in the knot has been joined by strong [O III] (4,959 Å and 5,007 Å) emission. The knot [O II] (5,007 Å) line intensity surpasses that of Hα, and the [N II] (6,548 Å) line is as strong as Hα. The [O III] (4,633 Å) line and again the [N II] (5,755 Å) line are not observed. The [O III]/Hα ratio in the knot is 1.23 ± 0.08, and [S II]/Hα = 1.54 ± 0.09, the [S II] doublet ratio (that is, [S II] 6,717 Å/6,731 Å) is 1.41 ± 0.07, and the [O III]/Hβ ratio is 1.8 ± 0.5. The line ratios in the knot spectrum indicate a similar density upper limit to the super-remnant shell. However, these ratios also point towards the inner knot containing much more strongly ionized gas.

Given its location within the super-remnant, it is plausible that the knot spectrum contains contributions from both the outer shell (giving rise to the Balmer and [O II] emission, and a contribution to the [N II] and [S II]) and the hotter transition region between the outer shell and the ejecta pile-up region (leading to the [O III] and enhanced [N II] and [S II] emission).

The shell mass, luminosity and motion of 12a. The upper limit on the shell mass of the super-remnant was estimated from the imaging and spectroscopy. Based on studies of Galactic nova shells44 we assumed a bi-axial geometry (either prolate or oblate). We used the projected semi-major and semi-minor axes of 67 pc and 45 pc, respectively, a shell thickness of 22%, and the [S II] electron density upper limit of 100 cm−3. We note that the measured shell thickness ratio is invariant to projection effects. We derive shell mass upper limits of 7 × 105 M⊙ and 106 M⊙ for the prolate and oblate geometries, respectively. We also note that the [S II] doublet is not a sensitive probe of densities below 100 cm−3 (ref. 23).

Using the HST continuum-subtracted Hα + [N II] image (Fig. 1b) we computed the integrated Hα + [N II] flux from the super-remnant to be 7 × 10−17 W m−2.
When accounting for the distance \( d \) to M31 of 770 ± 19 kpc, we find that the total H\( \alpha \) + [N \( \alpha \)] luminosity alone from the super-remnant is \( (1,300 \pm 200) L_\odot \) (bolometric), where \( L_\odot \) is the solar luminosity.

In Fig. 1 we show that 12a is offset from the geometric centre of the super-remnant by 13 pc. The geometric centre was determined by the best-fitting ellipse to the optical imaging (see Fig. 1a). To attain such a displacement over 6 × 10^6 years a transverse velocity of 2.1 km s\(^{-1}\) is required. All the spectra of 12a in eruption show no evidence for a significant \( 3\sigma \), exceeding 100 km s\(^{-1}\) \( \rightarrow \) radial component to the system velocity\(^{11,13,19,31}\).

**Hydrodynamic modelling.** The hydrodynamic simulations were performed with the Morpheus program, an MPI-OpenMP Eulerian second-order Godunov simulation code with options of Cartesian, spherical and cylindrical coordinates, which includes radiative cooling and gravity. Morpheus combines well established one-dimensional (Asphere\(^{46}\)), two-dimensional (Novarot\(^{47}\)) and three-dimensional (CubepMF\(^{48}\)) codes written by the Manchester-LJMU astrophysics groups into a single framework. For the purposes of these simulations we assumed one-dimensional spherical symmetry.

From observations of 12a and theoretical modelling of the eruptions\(^{11,14,15,39}\), we assumed the following model for the system. We assumed that the mass donor is a red giant with a wind mass loss rate (after any accretion onto the white dwarf) of \( 2.6 \times 10^{-5} M_\odot \) yr\(^{-1}\), that the terminal velocity of the red giant wind is 20 km s\(^{-1}\) (compare with RS Ophiuchi\(^{39}\)), and that this wind blows continuously, except during the eruption period. The mass loss from the white dwarf, via nova eruptions, is modelled as a wind with a constant mass-loss rate and velocity, which has a simple top-hat function on for 7 consecutive days in every 350 days (the nova recurrence period). The total mass ejected by each nova eruption is \( 5 \times 10^{-5} M_\odot \), and the ejecta have a terminal velocity of 3,000 km s\(^{-1}\). By injecting mass with terminal velocity, we can neglect gravity. As the spatial resolution of the larger simulations is smaller than the expected orbital separation, both the donor star and the white dwarf are assumed to be spatially coincident at the origin and there is assumed to be no interaction between the ejecta and the donor or the accretion disk. Mass injection via a wind or nova ejecta is effected by means of a boundary condition at the inner boundary of the simulation grid. The energy of the injected mass is dominated by kinetic energy. The grid is uniformly spaced and the maximum domain size is predetermined to contain the outer edge of the super-remnant. All simulations have sufficient spatial resolution to resolve and follow each separate eruption until they merge in the pile-up region. For computational efficiency, the domain is actually resized as the super-remnant grows by the addition of new cells.

Simulations were conducted as follows. An initial run, following 20 eruptions, with a spatial resolution of 0.02 astronomical units (au) per cell and maximum domain size \( 10^7 \) cm (6,667 au) was conducted to ‘benchmark’ the lower-resolution simulations. This was followed by a simulation of 100 eruptions with 0.2 au per cell and maximum domain size \( 3 \times 10^7 \) cm, 1,000 eruptions at 0.4 au per cell and maximum domain size \( 10^8 \) cm, 10,000 eruptions with a resolution of 1 au per cell and maximum domain size \( 4.4 \times 10^{13} \) cm (1.43 pc), and finally, 100,000 eruptions with 4 au per cell resolution and domain size \( 1.8 \times 10^{19} \) cm (5.8 pc). All of these simulations prepopulated the domain with a low-pressure, cold (90 K), uniform ISM density of one hydrogen atom per cubic centimetre, and did not invoke radiative cooling. Prepopulating the domain with a red giant wind did not result in any large differences after about ten eruptions. Extended Data Fig. 3 illustrates the consistency between the models at all resolutions, particularly within the outer dense shell of the super-remnant.

Simulations of 100 eruptions were also conducted, as above, to explore the effect of different ISM densities on the super-remnant. This effect is shown in Fig. 3d. As any energy lost due to radiative cooling can affect the dynamics of a system, a simulation of 1,000 eruptions, again as above, was also conducted while using the radiative cooling module of Morpheus with a suitable cooling curve\(^{46}\). The results of this simulation are presented in Extended Data Fig. 4 and are compared to the uncooled version. Again, although the details of the freely expanding nova ejecta are slightly altered, the gross structure of the super-remnant shell is consistent. We also note that radiative cooling is inefficient above \( 10^8 \) K and for low densities, which is the case for all the material in the remnant shell and the ejecta pile-up regions. Therefore, for computational ease, we moved on to simulate greater numbers of eruptions while ignoring radiative cooling effects. Figure 3f shows that eventually the super-remnant shell will cool sufficiently that radiative cooling may be important; however, the efficiency of such cooling also depends on the square of the density, that is, as the shell cools further, below \( 10^7 \) K, cooling becomes inefficient once more, so we do not expect cooling to affect the results greatly at later times. As the addition of the Morpheus radiative cooling module had negligible effect on the results of the simulations, we can conclude that radiative losses must be minimal and do not affect the dynamics of the system. The remnant mass (Extended Data Fig. 5a) was computed by integrating over the super-remnant shell, defined as the outer region whose density is above that of the ISM (see Fig. 3a–c). Extrapolation of the simulations to greater timescales was performed by fitting the super-remnant growth curves, as shown in Fig. 3d and Extended Data Fig. 5a, with power laws.

The predicted radial profile of the simulated super-remnant (Fig. 3e) was produced by integrating the computed density profile over a sphere and then generating a collapsed two-dimensional image. The resultant image was smoothed to match the point-spread function of HST and annular photometry was performed on this image in-line with the radial profiles of the Liverpool Telescope and HST data. Simulated data have been truncated at 10 pc of the sky. The simulations indicate that the outer edge of the super-remnant has a power-law deceleration (Extended Data Fig. 5b), \( r^{-3/4} \), the predicted present expansion velocity of the super-remnant is \( 5 \) km s\(^{-1}\).
Super-remnant X-ray luminosity. To compute the present-day X-ray luminosity of the super-remnant we again employed the hydrodynamic simulations to compute a time series of synthetic X-ray spectra, following the procedure given in refs 55,56. The cells of the simulation were grouped into 30 logarithmically distributed temperature bins between 10^4 K and 10^8 K (see top panel of Extended Data Fig. 7). The contribution from each bin was determined by its emission measure. The resulting 30-temperature-component plasma was used as an input to XSPEC (v12.10.0c), which computed the X-ray spectra using the MEKAL model. We assumed that the material had solar composition and the spectrum included effects of emission from C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe and Ni, and free–free, free–bound, and two-electron emission processes. Synthetic X-ray spectra, covering 0.3–10 keV, were produced for all time steps in the 100,000-eruption model (see bottom panel of Extended Data Fig. 7), and the evolution of the predicted X-ray luminosity is shown in Extended Data Fig. 5c.

This emission modelling shows that at all times, the majority of the super-remnant emission arises from the super-remnant outer shell—the piled-up ISM. Other regions of the structure are far too low in density (and the ejecta pile-up region too hot) to contribute substantially to the emission. Again, this supports the finding of negligible radiative cooling from the multiple ejecta, and that radiation losses do not affect the dynamics of the super-remnant.

The evolution of the emission measure (Extended Data Fig. 7, top) indicates that the luminosity of the super-remnant grows with time. However, the X-ray luminosity peaks at about 1,000 eruptions as the peak of the emission measure distribution continually shifts to longer wavelengths with time. As is illustrated in Extended Data Fig. 5c, the initial peak emission occurs in the hard X-ray (1–10 keV), before shifting to softer X-ray energies after about 1,000 eruptions due to the peak emission moving into, first, the extreme ultraviolet (10–124 eV; 10,000 eruptions), and then the ultraviolet (100,000 eruptions). By simple logarithmic extrapolation, the expected current emission peak will be in the infrared region (around 12–13 μm)—a potential target for follow-up observations by the James Webb Space Telescope.

The X-ray luminosity of the super-remnant peaks after approximately 1,000 eruptions at about 6 × 10^{34} erg s^-1, before fading to < 10^{34} erg s^-1 after 100,000 eruptions. Using a power-law extrapolation, the expected present-day X-ray luminosity is 3 × 10^{32} erg s^-1. At all times (see below), the X-ray luminosity of the super-remnant lies well below current detection capabilities.

Archival X-ray observations. To constrain the X-ray emission of the proposed nova-super-remnant, we examined the archival X-ray data for the two most sensitive (and relevant) telescopes, XMM-Newton and Chandra. In the case of Chandra, there are only three archival observations that contain the nova position, but at the very edge of their fields of view: observation identification numbers ObsID 17012 (50 ks nominal exposure), 17013 (45 ks) and 17637 (10 ks). In all three, the super-remnant is located partly off the edge of the detector and so far off-axis that we are not able to benefit from the superior (on-axis) spatial resolution of Chandra. Therefore, these data are much less useful for our objective than the XMM-Newton observations and we do not consider them in the following analysis.

In the case of XMM-Newton, there exist four archival observations with a total of 211 ks effective exposure; that is, after considering dead time and exposure mask vignetting. Owing to the superior collecting area of XMM-Newton this exposure results in substantially more photons than Chandra would have collected in the same time. The observations were taken in the following years: 2002 (ObsID 0109270301, 2007) (ObsID 0402561501, 2015) (ObsID 0763120301), and 2016 (ObsID 0763120401). The 2002 and 2007 observations were employed to produce one of the X-ray catalogues used to rule out a supernova-remnant origin for the super-remnant. The inclusion of the 2015 and 2016 X-ray data results in more than a tripling of the effective exposure time.

After conducting substantial testing, we decided to use an ellipsoidal source count extraction region, rather than an annulus, to study the super-remnant emission. The main reason for this is the relatively large XMM-Newton point-spread function, which, at the relatively small size of the super-remnant, would not give us an annulus shape for a detectable source. Fortunately, there are no known X-ray (point) sources near 12a in quiescence. We note that with an estimated quiescent X-ray luminosity of 10^{32} L_⊙ (ref. 58), 12a is yet to be detected in X-rays outside of its eruptive state. We thus use the EPICpn detector because of its higher response at lower energies.

Combining all XMM-Newton observations, we detect no significant X-ray emission from the nova super-remnant. We derive a count-rate upper limit of 6.7 × 10^-4 counts per second at the 3σ confidence level, using a Bayesian approach. Assuming a simple 1-keV plasma with solar abundance and foreground absorption, as expected from a young supernova remnant, this rate corresponds to an unabsorbed luminosity of < 9 × 10^{34} erg s^-1 at the M31 distance of 770 kpc. This limit is five orders of magnitude greater than the expected present-day X-ray luminosity of the super-remnant.

Code availability. The Morpheus code is freely available at http://www.nbi.dk/~nvaytet/morpheus.html.
Extended Data Fig. 1 | Additional multi-wavelength imaging of the super-remnant region. a, The Steward 2.3-m Bok Telescope Hα image that allowed the association between the nebulosity and 12a to be made. Image orientation is as in Fig. 1 but the image is 80″ × 80″. b–d, HST Wide Field Camera 3 broad-band filter images of the region around 12a. Image sizes are 40″ × 40″. These three panels show the F275W (ultraviolet) (b), F475W (optical) (c), and F814W (optical) (d) filters. The white contours in c show iso-flux regions as derived from the ground-based Hα + [N II] image. As b–d were taken towards the end of the 2015 eruption, the nova can be seen in the images. The F275W image clearly illustrates the lack of bright ultraviolet sources within the super-remnant. The white dashed ellipse indicates the extent of the super-remnant; the red dotted lines indicate the position of 12a.
Extended Data Fig. 2 | HET flux-calibrated spectrum of the super-remnant outer-shell. As with the GTC spectrum of the same region (Fig. 2), there is negligible continuum and hydrogen Balmer emission lines and nebular lines of [N II], [O II] and [S II]. The mean spectral resolution for the ‘blue arm’ is 1.68 Å and for the ‘orange arm’ is 4.04 Å (see Methods). Gaps in the spectrum indicate areas where skyline subtraction residuals remained.
Extended Data Fig. 3 | Comparison of results from the hydrodynamic modelling using a range of spatial resolutions. The blue and green lines indicate simulations of 20 eruptions with spatial resolutions of 0.02 au and 0.2 au, respectively, while the red and black lines indicate simulations of 100 eruptions with resolution 0.2 au and 0.4 au, respectively. a, Gas density radial distribution; the lower black dotted horizontal line indicates the ISM density, with the upper dotted line showing the consistent peak density of the super-remnant shell. b, Gas pressure radial distribution. c, Gas velocity radial distribution. d, Gas temperature radial distribution.
Extended Data Fig. 4 | The effect of radiative cooling on the super-remnant dynamics. a–d, Panels as in Extended Data Fig. 3. The close match between the results of simulations of 1,000 eruptions without radiative cooling (black) and with radiative cooling (blue).
Extended Data Fig. 5 | Additional results of the hydrodynamic simulations of the interacting ejecta of multiple recurrent nova eruptions. a. The mass growth of the super-remnant outer shell for up to 100,000 eruptions (see key). The diagonal dotted line illustrates a power-law extrapolation of the outer-shell mass to further eruptions. The upper and lower solid grey lines indicate the growth of the outer-shell mass for higher and lower ISM densities, respectively. The horizontal dotted line marks the predicted outer-shell mass at the current extent of the super-remnant. b. The evolution of the expansion velocity of the outer shell (black) compared to the mean velocity within the ejecta pile-up region (red). The diagonal dotted lines indicate power-law extrapolations, the horizontal line the initial injection velocity, and the vertical line the predicted current epoch. c. The evolution of the X-ray (0.3–10 keV) luminosity of the super-remnant (black), the hard (1–10 keV; red) and soft (0.3–1 keV; blue) components are shown for information along with the hardness ratio HR (hard/soft; right-hand axis) evolution; for each, the dotted line indicates a power-law extrapolation to later times. The horizontal dotted black line indicates the 3σ upper limit from the XMM-Newton observations.

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Extended Data Fig. 6 | The full (uncooled) simulations of 100,000 eruptions. a–d, Panels as in Extended Data Fig. 4.
Extended Data Fig. 7 | Super-remnant X-ray emission modelling. In both panels the cyan, blue, green, red and black lines indicate simulations of 10, 100, 1,000, 10,000 and 100,000 eruptions, respectively. The top panel shows the contribution to the super-remnant emission as a function of photon energy (in units of $kT$). The vertical dotted line indicates the lower-limit (0.08 keV) cut-off for input into XSPEC. The bottom panel shows the resultant synthetic X-ray spectra of the super-remnant (0.3–10 keV).