A Recurrent Nova Super-Remnant in the Andromeda Galaxy

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ABSTRACT

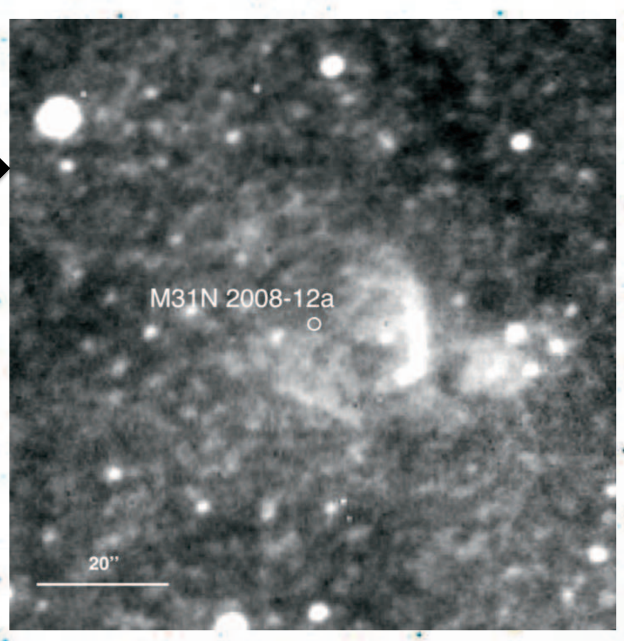
The accretion of hydrogen onto a white dwarf star ignites a thermonuclear runaway in the accumulated envelope, leading to luminosities up to 1 million times that of the Sun and a high-velocity mass ejection that produces a remnant shell – a classical nova eruption[1,2]. Close to the upper mass limit of a white dwarf[3] (1.4$M_{\odot}$), rapid accretion of hydrogen (~10-7$M_{\odot}$/yr) from a binary star companion leads to frequent eruptions on timescales of years[4,5] to decades[6]. Such systems are known as recurrent novae. The ejecta of recurrent novae, initially moving at up to 10,000km/s[(7)], must sweep-up the surrounding interstellar medium and evacuate cavities around the nova binary. No remnant larger than one parsec from any single classical or recurrent nova eruption is known[8,9,10], but thousands of successive recurrent nova eruptions should be capable of generating shells ~100-1,000 times this size.

M31N 2008-12a

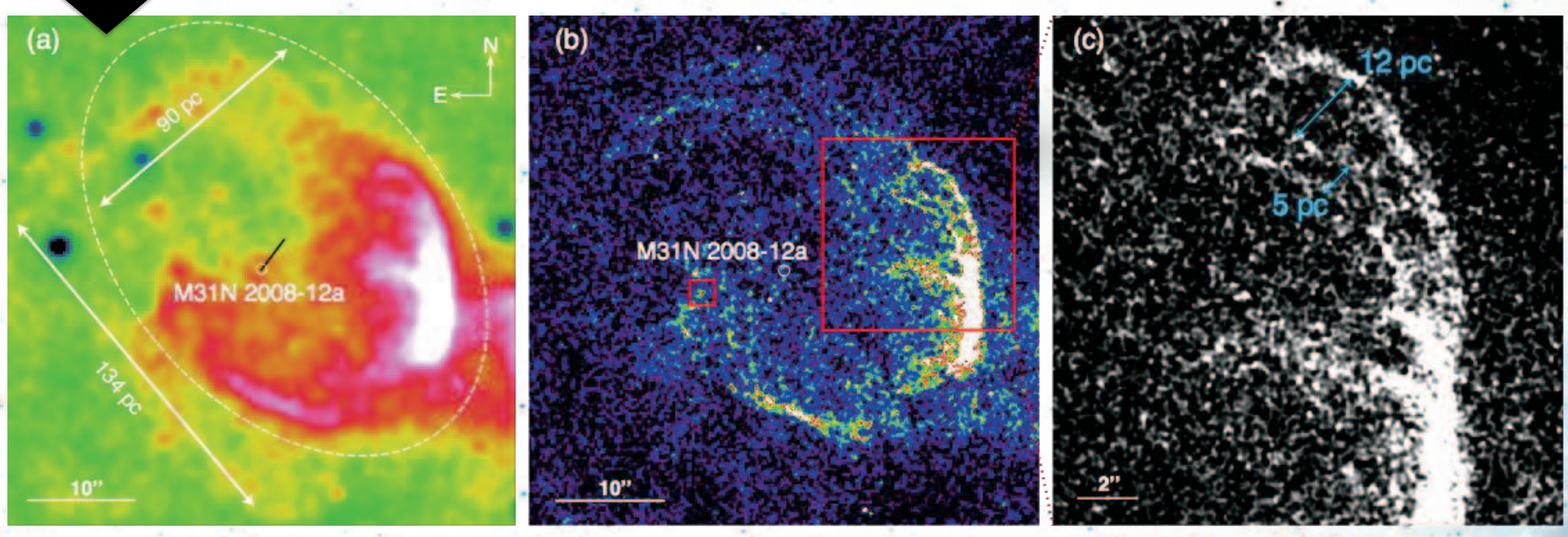
M31N 2008-12a is the most rapidly recurring nova, erupting annually[11]. The recurrent nova progenitor is surrounded by a nova super-remnant with a projected size of at least 134 by 90 parsecs. Larger than almost all known remnants of supernova explosions[12], this enormous shell demonstrates that M31N 2008-12a has erupted with high frequency for millions of years.

Imaging observations

The Steward 2.3m Bok Telescope H? image that allowed the association between the nebulosity and M31N 2008-12a to be made. North is up and East to the left.



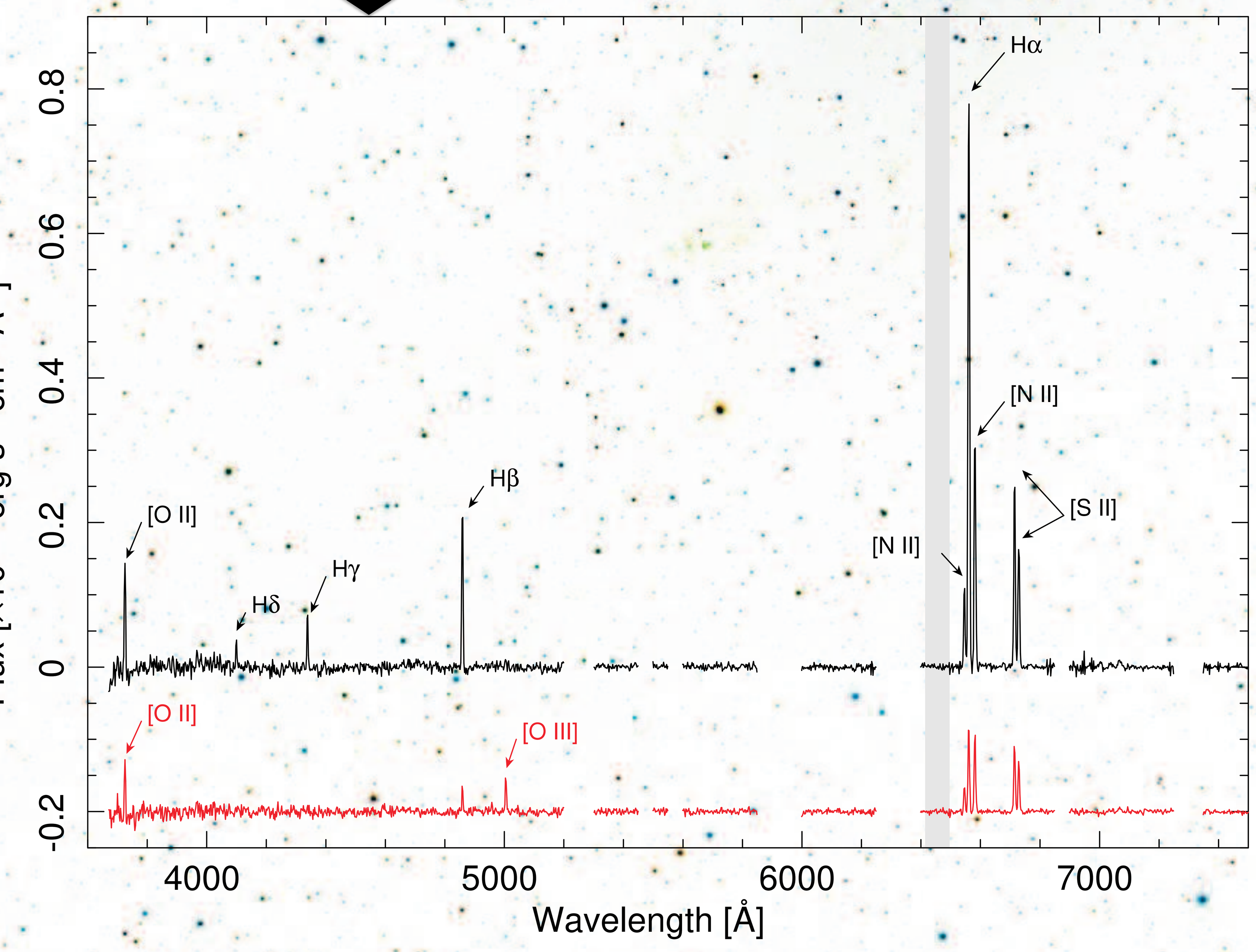
[a] Liverpool Telescope narrow-band Hα + [N II] continuum-subtracted
[b] HST Hα + [N II] continuum-subtracted
[c] Zoomed-in HST Hα + [N II] image showing the region within the large red box in [b]



Ground-based spectroscopic observations

Our deep spectroscopy of the super-remnant shell 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. 13). The lack of [O III] 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 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 II] (5,755 Å) line is not, we can place a 3σ limit on the electron temperature of less than 9,000 K

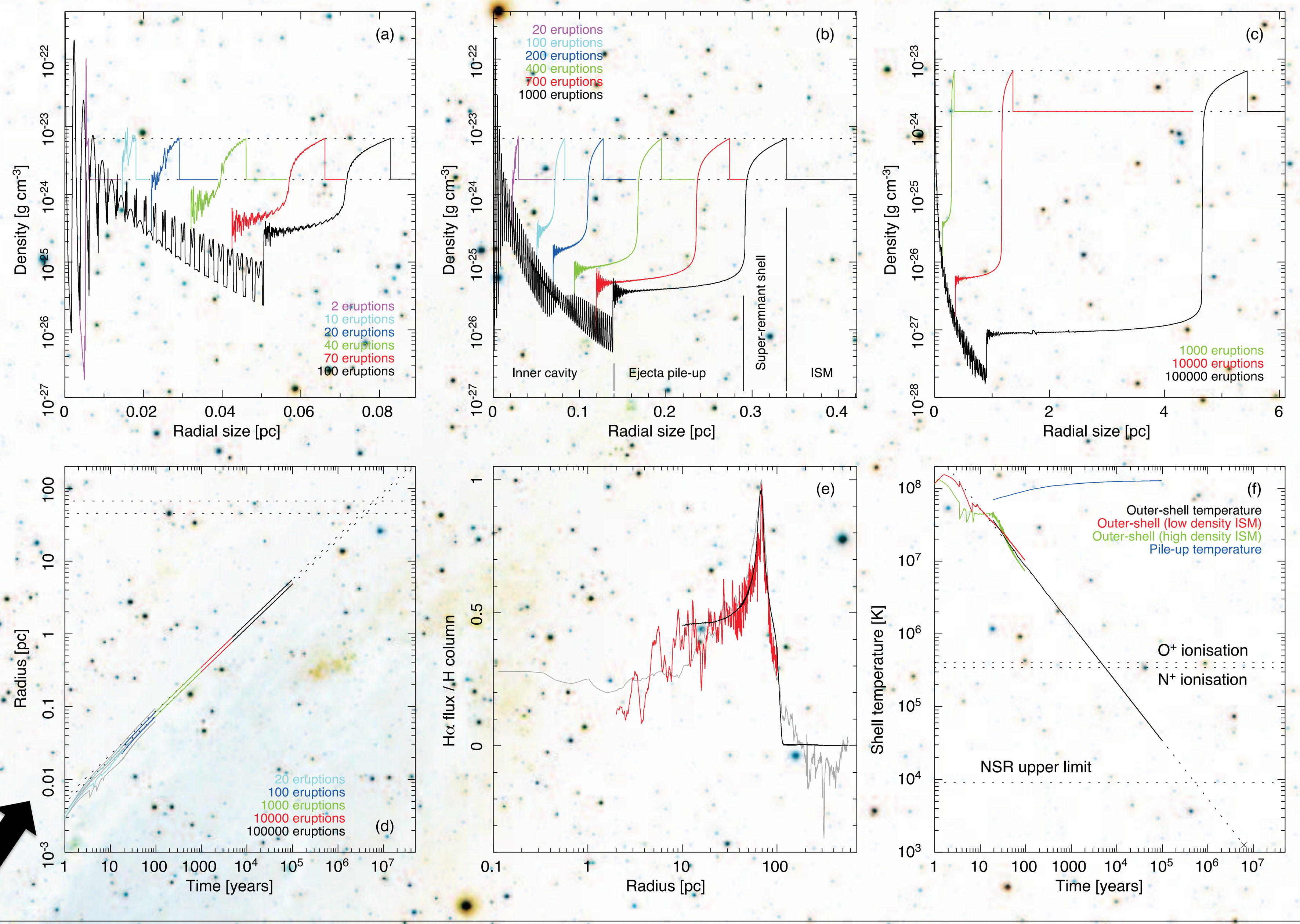
The top spectrum (black) is the Gran Telescopio Canarias (GTC) spectrum of the bright western part of the nova super-remnant shell. The lower spectrum (grey) is that of the inner eastern knot



The shell mass, luminosity, and the motion of M31N 2008-12a

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. 13) 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 indicate that the shell mass is less than 7 × 10^{5}$M_{\odot}$
The lack of the [O III] (4,363 Å line allows only a weak temperature constraint of less than 160,000 K,but the knot [N II] emission indicates temperature T < 18,000 K.
Using the HST continuum-subtracted Hα + [N II] image we computed the integrated Hα + [N II] flux from the super-remnant to be 7 × 10–17 Wm^{-2} .When accounting for the distance[45] to M31 of 770 ± 19 kpc, we find that the total Hα + [N ii] luminosity alone from the super-remnant is (1,300 ± 200)$L_{\odot}$ (bolometric).

Hydrodynamic modelling



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 as required by the spectroscopy, and the ionization temperatures of O+ and N+, required to observe [O III] or [N III]

Conclusions

The 12a white dwarf has an accretion rate of about 1.6 × 10^{-7}MΘ per year[15] and a current accretion efficiency (the proportion of accreted material retained by the white dwarf post-eruption)[15,16] that exceeds 60%. Assuming a white dwarf formation mass of about 1MΘ, 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 ensues3 (1.4MΘ; 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[16]. At that point, the underlying composition of the white dwarf16 will be revealed incontrovertibly when either a type Ia supernova[17] or an accretion-induced collapse of the white dwarf to a neutron star[18] is seen.

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