A solar-type star polluted by calcium-rich supernova ejecta inside the supernova remnant RCW 86

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When a massive star in a binary system explodes as a supernova, its companion star may be polluted with heavy elements from the supernova ejecta. Such pollution has been detected in a handful of post-supernova binaries1, but none of them is associated with a supernova remnant. We report the discovery of a binary G star strongly polluted with calcium and other elements at the position of the candidate neutron star [GV2003]N within the young galactic supernova remnant RCW 86. Our discovery suggests that the progenitor of the supernova that produced RCW 86 could have been a moving star, which exploded near the edge of its wind bubble and lost most of its initial mass because of common-envelope evolution shortly before core collapse, and that the supernova explosion might belong to the class of calcium-rich supernovae — faint and fast transients3-12, the origin of which is strongly debated14-16.

Recently, it was recognized that a large fraction of massive stars reside in binary systems13,8 and that the evolution of the majority of massive stars is strongly affected by binary interaction, through mass transfer, common-envelope evolution or merger7. This suggests that most type Ib/c supernovae, which do not show hydrogen lines in their spectra, stem from progenitors that are stripped of their hydrogen envelopes by a companion star10,11. The low ejecta masses typical of such supernovae11 imply that a significant fraction of the post-supernova binaries remain bound. Only very few such binaries are known12,13 to be associated with supernova remnants (SNRs) because of the short lifetime (~0.1 yr) of the SNRs. Here we report the discovery of a post-supernova binary system within the young (few thousand years old)14 SNR RCW 86.

The pyriform appearance of RCW 86 (Fig. 1; see also Fig. 6 in ref. 15) can be explained as the result of a supernova explosion near the edge of a bubble blown by the wind of a moving massive star16 (Supplementary Information section 1). This interpretation implies that the supernova exploded near the centre of the hemispherical optical nebula in the southwest of RCW 86 (see Fig. 1) and that the stellar remnant should still be there. Motivated by these arguments, we looked for a possible compact X-ray source using archival Chandra data and discovered14 two sources in the expected position of the supernova progenitor (Fig. 1). One of them, [GV2003] S, has a clear optical counterpart with V = 14.4 mag, and its X-ray spectrum implies that this source is a foreground late-type active star.

For the second source, [GV2003] N, despite no optical counterpart being found in the Digital Sky Survey II to a limiting red-band magnitude of ~21, follow-up observations with the FORS2 optical instrument on the ESO Very Large Telescope (VLT) did detect a faint stellar object. An X-ray spectrum at the position of [GV2003] N suggests that this source might be a young pulsar14. Our deep follow-up observation with the Parkes radio telescope in 2002, however, failed to detect any radio emission from [GV2003] N, giving an upper limit on the flux of 35 µJy at 1.420 MHz (see Methods). This non-detection may be a consequence of beaming, or it could indicate that [GV2003] N may not be an active radio pulsar.

If [GV2003] N was a neutron star, its emission in the visual would be expected to be fainter than V ~28 mag. We therefore obtained a V-band image of the field around this source with the FORS2 instrument on the VLT in 2010. The FORS2 image, however, revealed a stellar-like object with V = 20.69 ± 0.02 mag just at the position of [GV2003] N (Fig. 1; Methods). To further constrain the nature of [GV2003] N, we obtained its g' r' i' z' JHK photometry with the seven-channel optical/near-infrared imager GROND in 2013 (Methods). With that, we fitted the spectral energy distribution (SED) of [GV2003] N and derived a temperature of ~5,200 K and a colour excess of E(B − V) ≈ 0.9 mag (Methods; Supplementary Fig. 1). These results exclude the possibility that [GV2003] N is an active galactic nucleus (as was proposed previously17) and strongly suggest that the optical emission originates from a G-type star at a distance comparable to that of RCW 86 of 2.3 ± 0.2 kpc (ref. 18). As the X-ray luminosity of [GV2003] N of ~1036 erg s−1 (refs 16,17) is far too high for a G star19, we arrived at the possibility that we were dealing with a binary system comprising a G star orbiting a neutron star.

Consequently, we searched for radial velocity variability and traces of the supernova ejecta in the spectrum of the optical counterpart of [GV2003] N. We obtained four spectra with the VLT/FORS2 in 2015. We found clear variations in radial velocity (Table 1; Methods), indicative of a binary system. Although the paucity of the radial velocity measurements did not allow us to firmly constrain parameters of the binary orbit, we carried out Keplerian fits to the existing data (Methods) and found that the period of the orbit is likely to be below 40 days (Fig. 2; Methods) and the eccentricity above 0.7 (Supplementary Information section 2).

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The spectrum of [GV2003] N (Fig. 3) clearly resembles that of a G-type star, confirming the results from theSED analysis. Owing to the moderate resolution of the FORS2 spectra and hence strong line blending, the spectrum of the G star was analysed through spectral synthesis (see Methods). This allowed us to disentangle the blends, derive the abundances of Si, Ca, Ti, V, Cr, Mn, Fe, Co, Ni and Ba, and to put an upper limit on the Li abundance. We stress that the line blending only limits the number of elements that we can measure, but did not affect our radial velocity measurements. Figure 4 shows that many elements are enhanced by a factor of about 3 with respect to the solar abundances, with silicon and iron being less than doubled. Calcium is particularly abundant, by a factor of ~6, which, to our knowledge, makes [GV2003] N the most Ca-rich late-type star yet known.

From the analysis of the Fe I lines (see Methods), we derived a stellar effective temperature of $T_{\text{eff}} = 5,100\pm200$ K. Using $V = 20.69$ mag, $E(B-V) = 0.9$ mag and assuming a ratio of total to selective extinction of $R_V = 3.1$, we estimated a visual extinction and absolute magnitude of $A_V = 2.79$ mag and $M_V = 6.09$ mag, respectively. With a bolometric correction of $-0.29$ mag (ref. 21), we obtained a bolometric luminosity of $\log(L/\,\text{L}_\odot) = -0.42\pm0.08$ (where $L_\odot$ is solar luminosity), taking into account the uncertainty on the distance. Using the Pisa stellar models, we estimated the mass of the optical star as $0.9\,M_\odot$, which for the given $T_{\text{eff}}$ and $L$ corresponds to a surface gravity of $\log g = 4.6\pm0.1$. Since the binary remains bound after the supernova explosion, and adopting the standard mass of a neutron star of $1.4\,M_\odot$, one finds that the mass of the supernova ejecta was less than $2.3\,M_\odot$ — provided that the supernova explosion was symmetric — and the mass of the exploding star was below $3.7\,M_\odot$. This in turn implies that the initial mass of the primary star was less than $13\,M_\odot$ (ref. 23). As such stars eject only small amounts of metals, their ejecta are dominated by He, and the supernova was probably of type Ib (compare Supplementary Information section 1).

The supernova ejecta captured by the G star are mixed with the material of its convective envelope. Adopting an envelope mass of $0.2\,M_\odot$ (ref. 23), we computed the mass accreted from the supernova ejecta for each element with measured abundances (Supplementary Table 2), which sums to $3.3\times10^{-5}\,M_\odot$. As the accreted mass of Fe of $\sim1.5\times10^{-4}\,M_\odot$ was most likely ejected in the form of $^{56}$Ni, an accreted fraction of the supernova ejecta of about 1% would lead to a total mass of radioactive Ni produced by the supernova of $0.015\,M_\odot$. These numbers seem consistent, as the explosion energy of supernovae of $\sim10\,M_\odot$ stars is thought to be low, with the consequence of a relatively low Ni mass and moderate ejecta velocities, allowing for a rather high accreted fraction of the supernova ejecta (Supplementary Information section 2).

The detection of the strongly polluted binary G star at the position of [GV2003] N supports the idea that this X-ray source is indeed a neutron star, substantiating that RCW 86 is the result of a core-collapse supernova explosion. This in turn supports the scenario for the origin of RCW 86 based on a supernova explosion near the edge of a wind bubble produced by a moving massive star (Supplementary Information section 1). An interesting consequence of this scenario is that after the supernova blast wave has completely overrun the dense material of the optical nebula in the southwest, RCW 86 will assume a two-shell form, with a newly formed shell attached to the existing one. This provides evidence that some of the known two-shell SNRs could originate from off-centred cavity supernova explosions and implies that their associated stellar remnants are located in the region where the shells overlap each other.

The inferred short orbital period of [GV2003] N means that this binary system will evolve into a low-mass X-ray binary (LMXB) within its nuclear timescale ($\sim10^{10}$ yr), providing the first example of a pre-LMXB located within a SNR. Before that, thermonuclear mixing is expected to dilute the accreted supernova material in the bulk of the mass of [GV2003] N on a timescale of $\sim10$ yr. Thereby, the enhanced abundances of the measured elements will be reduced by a factor of several, making them comparable to those found in most of the few main-component sequences of LMXBs for which pollution has been detected previously.

Finally, the large overabundance of Ca in the G star together with the modest enhancement of Si is in contrast to the predictions of classical core-collapse supernovae from single stars in the mass range from $11\,M_\odot$ to $25\,M_\odot$ (compare Supplementary Information section 3). This suggests that the supernova that produced RCW 86 might belong to the rare type of Ca-rich supernovae — the fast and faint transients, which show strong Ca lines in their spectra and are believed to be intrinsically Ca-rich (Supplementary Information section 4). Whereas observations indicate that many of the Ca-rich supernovae are produced by long-lived low-mass stars, our findings hint at the possibility that the lowest mass stars capable of producing neutron stars can produce similar explosions, if the progenitor is stripped of its envelope by a companion star. Indeed, from

**Table 1 | Radial velocity changes with time in the spectrum of [GV2003] N.**

| Date       | Radial velocity (km s$^{-1}$) | Heliocentric correction (km s$^{-1}$) |
|------------|------------------------------|--------------------------------------|
| 2015 April 14 | $-71\pm2$                   | 13.0                                 |
| 2015 April 21 | $-74\pm4$                   | 10.9                                 |
| 2015 May 13  | $-44\pm3$                   | 3.3                                  |
| 2015 May 16  | $-62\pm3$                   | 2.4                                  |

*Corrected for the heliocentric motion of the Earth. The uncertainties were calculated by adding in quadrature the uncertainties on the fit of the average line profiles and the uncertainties on the correction for systematic shifts derived from the telluric emission lines.
that Ca and Fe are overabundant. The observed spectrum (black dots connected by solid lines) shows a good match to the solar abundances (dashed red line) for the atmospheric parameters of the solar abundances (solid blue line). The main components of the atmosphere are

![Figure 2 | Keplerian fits to the measured radial velocities for different orbital periods and eccentricities.](image)

The values of the radial velocity are shown by open (red) circles, and the 1σ errors are indicated by vertical bars. The solid (black) line shows best-fitting Keplerian orbits (see Methods section ‘Keplerian fits to the radial velocity measurements’) with orbital periods in the ranges 0–10 days (top left), 10–20 days (top right), 20–30 days (middle left), 30–40 days (middle right), 40–50 days (bottom left) and 50–60 days (bottom right), and a maximum eccentricity of 0.5. The dashed (blue) lines in the bottom panels show the best-fitting orbits for an eccentricity that is free to vary between 0 and 0.999.

Methods

Radio observations of [GV2003] N. Observations were conducted in the L band at the Parkes radio telescope on 2002 October 13. The bandwidth was 256 MHz, with 512 spectral channels. We observed [GV2003] N for about 7.5 hours, with a time resolution of 0.4 ms. The recorded data were de-dispersed for 512 independent dispersion measures, uniformly spaced between zero and 275 pc cm$^{-1}$, beyond which the smearing of the signal in the individual spectral channels becomes greater than the sampling interval. We then searched for harmonically related peaks by the standard harmonic folding procedure, after performing a Fourier transform, for the time series corresponding to each dispersion measure. Details of statistically significant ‘candidates’ were stored and later used to produce coherently folded profiles for assessing the quality. The de-dispersion of the data was performed with Taylor’s tree algorithm, which assumes linearity of the dispersion delay as a function of frequency. In our case, the frequency was high enough for the error caused by this assumption to be negligible (~1.2%), and we did not need to apply further correction to the band.

Ultimately, we did not detect any reliable (pulsed) radio signal from [GV2003] N, although our search was very sensitive. In general, detection sensitivity for pulsars is difficult to quantify, mainly because of uncertainties introduced by unknown duty cycle of pulsars, interstellar scattering, and the details of the search procedure. The sensitivity of our observations was estimated as follows. The telescope gain, $G$, of Parkes is ~0.65 K Jy$^{-1}$. The system temperature, $T_{\text{sys}}$, in the L band is ~32 K, with a sky contribution of about 6 K. In general, one expects the intrinsic duty cycle of long-period pulsars to be ~4%. Interstellar scatter broadening and dispersion smearing will increase this width for high-dispersion-measure pulsars (these smears add in quadrature with the pulse width). The minimum detectable flux can be written as $S_{\text{min}} = \frac{AT_{\text{sys}}}{G} \left( \frac{N_{\beta} \beta T}{P-w} \right)^{1/2}$, with $A$ being detection threshold in terms of r.m.s. of the noise, $\beta$ the bandwidth, $N_{\beta}$ the number of independent polarization channels and $T$ the total observation time, respectively. With a bandwidth of 256 MHz and observing time of 7.46 h ($2^\circ$ samples at 0.4-ms intervals), this amounts to 35 mJy with a 10σ limit. In comparison, this is about 3 times as sensitive as the Parkes Multi-beam Pulsar Survey.

VLT/FORS2 imaging of [GV2003] N. [GV2003] N was observed with the Focal Reducer and Low-Dispersion Spectrograph (FORS2) camera at the ESO VLT in the V band on 2010 April 10–12. With the FORS2 resolution of 0.25 arcsec per pixel, we obtained high-quality images from a total of 45 exposures of 300 s each under dark time and photometric conditions with seeing of ~0.25 arcsec. We created master bias and master normalized flat-field images. A detector bad-pixel map was constructed from the ratio of low and high-count rate flats. These calibration products were used to process each individual V-band exposure. Single images were registered to a reference frame with the smallest airmass. Geometric transformation solutions were estimated with GEOMAP and GEOTRAN procedures using over 1,500 reference stars in common. The final average combined image (combined using the CCDCLIP algorithm) was obtained from all images brought to the same zero (sky) level as the reference using the mode value of a 25 pixel x 25 pixel statistics region. The large number of single exposures and the nine-point observing dither pattern allowed us to create a final average combined image with high signal-to-noise ratio, clean of remaining detector

![Figure 3 | Portion of the VLT/FORS2 spectrum of the optical counterpart of [GV2003] N.](image)

The observed spectrum (black dots connected by solid black line) is compared with synthetic spectra calculated from the derived atmospheric parameters for the solar abundances (dashed red line) and final estimated abundances (solid blue line). The main components of each spectral feature are labelled. One can see that the solar abundances are not a good match to the observed spectrum, and that Ca and Fe are overabundant.

![Figure 4 | Elemental abundances of the optical counterpart of [GV2003] N.](image)

The blue dashed line corresponds to solar abundance values. The smaller black error bars indicate the statistical uncertainties, and the larger red ones show the maximum systematic uncertainties. The real uncertainties lie in between. For the Li abundance, we give only an upper limit. Note that there is a very high overabundance of Ca.
cosmetics (bad pixels and rows/columns) and cosmic-ray hits. The full-width at half-maximum (FWHM) of this image is 2.1 pixels; that is, 0.53 arcsec.

We performed point spread function (PSF) photometry on all sources in the final combined image. For this, we created a PSF model using 168 isolated stars (no contaminating sources within a radius of 3 FWHM). Best photometry was obtained from a second-order variable PSF model dependent on the position on the detector, resulting in negligible (<1% in flux) residuals. The aperture and PSF photometric residuals were found to be <3 FWHM, where there were few to few objects was estimated locally from an annulus with a width of 5 pixels. Aperture correction to the PSF magnitudes was estimated from comparison between the PSF and aperture magnitudes of the isolated PSF stars used to build the PSF model. We perform PSF fitting photometry to all sources with detection threshold of 4σ above the background. The photopair counterpart to [GV2003] N was readily detected (see Fig. 1).

Photometric Stetson standard star fields of NGC 2437 and ES (with 53 and 75 stars, respectively) were taken at the beginning and end of each night. These were used to obtain the photometric zeropoint ($V_p = 28.1563 ± 0.0013$ mag) and airmass coefficients ($X_0 = 0.1996 ± 0.0014$ mag) to convert from instrumental to standard magnitudes. The aperture-corrected instrumental PSF magnitudes were calibrated using these coefficients at an airmass of 1.269. We found an apparent V-band magnitude of [GV2003] N to be 20.688 ± 0.024.

GROND photometry and SED fitting. [GV2003] N was observed on 2013 August 8 simultaneously in four optical ($g, r, i, z$) and three near-infrared ($J, H, K$) bands with the GROND instrument on the 2.2-m MPG telescope at the ESO La Silla Observatory. (Chopper wheel exposures were taken for a range of 41 min in the optical bands and 53 min in the near-infrared bands. Observing conditions were good with a medium seeing of 1 arcsec and an average airmass of 1.2. The data reduction was performed using standard IRAF tasks. The $g' , r' , i' , z'$ photometry was obtained using PSF fitting, whereas, owing to the undersampled PSF in near-infrared bands, $J, H, K$, photometry was measured using sets of line profiles, with sizes corresponding to the FWHM of field stars. The results of this photometry were obtained using an observation of a Sloan Digital Sky Survey field. Photometric calibration of the near-infrared bands was achieved against selected 2MASS stars in the field of the target. The resulting AB magnitudes are: $g' = 19.60 ± 0.05$ mag, $r' = 18.77 ± 0.08$ mag, $i' = 18.29 ± 0.06$ mag, $z' = 17.60 ± 0.17$ mag, $H = 17.24 ± 0.14$ mag and $K_s = 17.57 ± 0.18$ mag. Using the LePHARE simulation program and the NextGen model atmosphere grid, and leaving the foreground reddening towards the target as a free parameter, we found that the best-fitting SED ($\chi^2 = 2.0$; Supplementary Table 1) is that of a star with an effective temperature of $T_e ≈ 5,200$ K and a colour excess of $E(B − V) ≈ 0.9$ mag.

VLT/FORS2 spectroscopy of [GV2003] N. [GV2003] N was observed once on each of 2003 April 14, 21, May 13 and 16 with the VLT/FORS2 instrument. The observations were conducted using a long slit with 1.0 arcsec width centred on the target. We used the 1200R grating with a (1:1) prism to obtain a prism coverage of the wavelength range 5,870–7,370 Å with a average spectral resolution, measured using the emission lines of the wavelength calibration lamps, of Δλ/λ ≈ 2,900. Each exposure was 2,700 s long. For the parameter determination and abundance analysis, the four spectra were co-added, yielding a signal to noise ratio of 91–8,800 Å. The spectra were divided into a set of ten bias and ten flat-field images collected on the morning following each observing night. Each spectrum was extracted by using an aperture of 12 pixels and applying background subtraction. The spectra were wavelength-calibrated using a wavelength-calibration lamp obtained on the morning following each observing night. We further refined the absolute wavelength calibration using the sky Na I emission lines at 5,890 and 5,896 Å, with a typical correction of ~2 km s$^{-1}$.

To derive an accurate radial velocity from each spectrum of the star, we co-added the spectral lines using the least-squares deconvolution technique (LSD), which is also effective with FORS spectra obtained with the 1200 grisms. The LSD technique$^4$ combines line profiles centered at the position of the individual lines in the considered spectral range using a convolution kernel that is defined as the average profile obtained by combining about 300 lines, yielding a strong increase in signal to noise ratio, therefore improving the precision of the radial velocity measurements. We prepared the line mask used by the LSD code, adopting the stellar temperature derived from the GROND SED, a surface gravity of log g = 4.5 typical of main-sequence solar-like stars, and solar abundances$^5$. We note that the FORS2 spectra do not cover strong enough ionization stages of the same element to infer the surface gravity spectroscopically. We extracted the line parameters from the Vienna Atomic Line Database (VALD)$^{10}$ using all lines stronger than 20% of the continuum, avoiding hydrogen lines and lines in spectral regions affected by the presence of telluric and nebular features. The radial velocity values, obtained by fitting each line to each LSD profile, are listed in Table 1. The results show the presence of clear radial velocity variations, indicative of a binary system.

Keplerian fits to the radial velocity measurements. We used the rvfit code$^{11}$ to analyse the FORS2 radial velocity measurements. The code fits non-precessing Keplerian radial velocity curves for double- and single-line binary systems. It fits a simple Keplerian model to the measured radial velocity values and computes the seven parameters (six for a single-line system, as in this case) from the model. For our analysis, the fitted parameters are the orbital period $P$, the time of periastron passage $T_p$, the eccentricity $e$, the argument of the periastron $ω$, the gamma velocity of the system $γ$, and the semi-amplitude of the radial velocity variation for the optical component $K_1$. The code allows one to constrain each parameter within values provided by the user. The fit is done using an adaptive simulated annealing algorithm optimized for this specific task (see ref.$^{12}$ for more details).

We find that for $P < 40$ days, it is also possible to obtain stable solutions for $e > 0.5$, whereas, for 20 < $P$ ≤ 40, there are unstable solutions and the code fails to converge. We therefore explore a range of possible orbital periods as follows. We look for the best-fitting orbital period with the period spaced between the shorter allowed period and leads to a large, and very unlikely, eccentricity. Both Fig. 2 and Supplementary Table 1 also show that for $P > 40$ days, the quality of the fit decreases significantly compared with the other cases. We therefore conclude that the measured radial velocity values can indeed be fitted by a Keplerian orbit with a most likely period of about 30 days, and that they do not exclude a rather large eccentricity (such as $e > 0.7$) suggested by our Monte Carlo calculations of asymmetric supernova explosions (Supplementary Information section 2).

Spectral analysis. Because of the moderate resolution and hence strong line blending, the spectrum of [GV2003] N could be analysed using a combination of the NextGen and the Model Stellar Atmospheres with Microturbulence (MESA), which also incorporates line broadening due to microturbulence. We calculated synthetic spectra with the synth3 code$^{13}$ on the basis of line lists extracted from the VALD database and of model atmospheres calculated with the LMD models stellar model atmosphere code$^{14}$. For all calculations, we assumed local thermodynamic equilibrium, plane-parallel geometry and a microturbulence velocity of 1.0 km s$^{-1}$, typical of solar-like stars$^{15}$. For the effective temperature of solar-like stars can be estimated using the wings of hydrogen lines, Hα in particular, which is fully covered by the FORS2 spectrum. Unfortunately, the intensity of the nebular Hα emission varies strongly in the region around [GV2003] N, preventing a reliable background subtraction at the wavelengths covered by the Hα line. We therefore derived $T_e$ from the analysis of the Fe I lines. We selected a set of 15 strong and weakly blended Fe I lines from which we derived the Fe abundance$^{16}$. By using the same continuum line abundance and excitation energy, and taking into account the results obtained from the SED, we estimated an effective temperature of 5,100 ± 200 K. The broadening of the spectral lines is dominated by the instrumental resolution; this sets an upper limit on the stellar projected rotational velocity $v\sin i$ of about 80 km s$^{-1}$. Because of the lack of data on the surface gravity, we adopted the stellar surface gravity obtained from comparing the position of the star in the Hertzsprung–Russell diagram with evolutionary tracks, as described in the main text.

On the basis of the derived stellar parameters, we derived the abundances of Si, Ca, Ti, V, Cr, Mn, Fe, Co, Ni and Ba (Fig. 4). Because of the rather large overabundances, we followed the same procedure typically adopted for a self-consistent analysis of magnetic chemically peculiar stars: re-calculting a new grid of model atmosphere, atmospheric parameters and abundances each time the abundances changed significantly from the previous iteration. This was possible because the model atmosphere code allows the use of individualized abundance patterns.

The derived statistical uncertainty for each element (that is, the standard deviation from the average abundance given a set of two or more lines), and the maximum systematic uncertainty, which takes into account the error bars on the atmospheric parameters: 0.08 K for $T_e$, 0.1 dex for log g, and 0.5 km s$^{-1}$ for the microturbulence velocity. The uncertainty value takes uncertainties for uncertainties in the placement of the continuum and in the atomic data. For the elements for which we derived the abundance from one line, we assumed that the statistical uncertainty was equal to that of Fe. The true uncertainty lies in between the statistical and maximum systematic uncertainties$^{16}$.

The spectrum does not show the presence of the Li I line at 6,708Å; we could therefore derive an upper limit on the Li abundance. The Mn and Ba abundances were derived taking into account hyperfine structure. The resulting abundances for all considered elements are listed in Supplementary Table 2.

Data availability. The data that support the plots within this paper are available from the corresponding authors upon request. The VLT/FORS2 spectra of the optical counterpart to [GV2003] N are publicly available in the European Southern Observatory (ESO) archive.
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Author contributions

V.V.G. and N.L. led the project and the manuscript writing. V.V.G., N.L., L.F. and D.C.-J. wrote the telescope proposals. L.F. reduced the VLT/FORS2 spectra, performed the spectral analysis and analysed the radial velocity measurements. S.J. and D.C.-J. performed and analysed the radio observations. L.V.G. performed the PSF photometry. J.G. and A.R. performed the GROND observations and the Sed fitting. N.C. performed part of the absolute wavelength calibration of the VLT/FORS2 spectra and worked on the removal of the spatially variable Hz emission. T.M.T. performed the Monte Carlo simulations of supernova explosions in binary systems. Figures were prepared by V.V.G., N.L., L.F. and T.M.T. All authors contributed to the interpretation of the data and commented on the manuscript.

Additional information

Supplementary information is available for this paper. Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to V.V.G. or N.L.

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Competing interests

The authors declare no competing financial interests.