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

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Supplementary Information section 1. RCW 86 as the result of a SN explosion near the edge of a wind-blown bubble

RCW 86 (also G315.4–2.30, MSH 14–63) is a young Galactic shell-like SNR with an angular diameter of about $40'$, which – for a distance to the remnant of 2.3 kpc (ref.¹⁹) – corresponds to ≈ 26 pc. The almost complete shell of RCW 86, visible in X-ray⁵¹, optical¹⁶, radio¹⁵ and infrared⁵² wavelengths, has a bright peculiar protrusion to the south-west, what gives the SNR a pyriform appearance (see fig. 6 in ref.¹⁶). At optical wavelengths, the protrusion appears as a ragged arc-like nebula^{53,54} (Fig. 1) with a radius of about $2'$ (1.1 pc). Spectroscopic observations of the arc indicate that the SN blast wave expands with a velocity of $\sim 100 \text{ km s}^{-1}$ at this location. Deep imaging of RCW 86 revealed that almost the whole periphery of the SNR is encompassed by Balmer-dominated filaments¹⁶. Spectra of these filaments indicate shock velocities of $\approx 500 - 900 \text{ km s}^{-1}$ (ref.^{19,55}). Similar velocities of the SN blast wave were also inferred from observations of thermal X-ray emission in RCW 86⁵¹, while the detection of nonthermal X-ray emission in this SNR^{51,56,57} implies the existence of shocks with even higher speeds. Recent proper motion measurement of a nonthermal X-ray filament in the north-east rim of RCW 86 showed⁵⁸ that the blast wave expands there with a speed of $\approx 3000 \text{ km s}^{-1}$.

The striking asymmetry in expansion velocity of the SN blast wave was interpreted as an indication that the SN explosion has occurred within a low-density bubble created by the wind of the progenitor star⁵⁹, and that the actual SN explosion centre is closer to the south-west edge of the bubble because the ambient medium in this direction is denser than in the opposite (north-east) one⁶⁰. Correspondingly, it was suggested that the SN blast wave has already hit the nearest (south-west) edge of the bubble and slowed down its velocity to $\approx 600 \text{ km s}^{-1}$, while in the opposite direction it still freely expands within the bubble. This scenario is widely accepted in subsequent papers^{52,61} on RCW 86.

Gvaramadze & Vikhlinin¹⁷ supplemented the cavity explosion scenario by Vink et al.⁵⁹ by suggesting that the cavity was created by a moving star and that the SN explosion in RCW 86 has occurred near the edge of the cavity – in the centre of the south-west protrusion, which is similar to the model put forward by Wang et al.⁶² to explain the origin of large-scale structures (in particular the Napoleon's Hat) around the SN 1987A (cf. ref.⁶³). Including our results, we arrive at the following scenario. The SN progenitor was a $\sim 10 M_{\odot}$ star in a tight binary system with a low-mass companion and the SN explosion was of Type Ib. This means that before the SN explosion the binary system has lost a significant fraction of its initial mass, M_i , through a common-envelope ejection. The ejected mass is expected to be about $5 M_{\odot}$, since (single) $10 M_{\odot}$ stars lose only about 10% of M_i during their lives, and the pre-SN mass of the exploding star is constrained to $\leq 4 M_{\odot}$. After the common-envelope ejection, the stripped star could still be surrounded by a thin hydrogen envelope⁶⁴, which is blown off later on through a fast line-driven wind. This wind would sweep-up the material of the common-envelope ejecta in a dense shell, which we now observe as an arc-like nebula in the south-west corner of RCW 86.

From the expected ejection velocity of the common envelope of several tens of km s^{-1} and given the radius of the optical arc of ≈ 1.1 pc, one finds that the envelope ejection event occurred

a few 10^4 yr before the SN explosion. This time-scale is similar to the duration of the shell helium burning phase of $\sim 10 M_{\odot}$ stars⁶⁵, which implies that a case C Roche-lobe overflow initiated the common envelope evolution. Using the number density of the local interstellar medium of $\sim 0.5 \text{ cm}^{-3}$ (ref.⁵²), one finds that the common-envelope ejecta so far swept-up only $\sim 0.1 M_{\odot}$ of the ambient gas, which in turn implies that the arc should be composed mostly of the material lost by the binary system, and that it should therefore be overabundant in nitrogen by a factor of three or so⁶⁶. Optical spectroscopy of filaments at several positions in the optical arc revealed⁶⁷ a factor of two overabundance of nitrogen with respect to the value typical of old Galactic SNRs. Although this overabundance is slightly lower than what is expected from our scenario, we note that the observed spectra could be a superposition of spectra produced in regions with different physical conditions (e.g. because of the presence of shocks with different velocities along the same line-of-sight), which makes it difficult to determine the nitrogen and other chemical abundances with standard methods (cf. ref.⁶⁷).

Although there are no doubts that RCW 86 is the result of a cavity SN explosion, there is no consensus^{52,54,56,61} on whether the progenitor of the SN was a massive star or a white dwarf (WD). It was suggested that an accreting WD in a binary system might be a source of strong wind lasting $\sim 10^6$ yr before the WD will reach the Chandrasekhar limit and explode as a Type Ia SN⁶⁸, and that RCW 86 is the remnant of SN explosion within a bubble created by such a wind⁶⁹. Two often cited arguments in support of the Type Ia origin for RCW 86 are the lack of a compact remnant in RCW 86 and the non-detection of super-solar oxygen abundances anywhere in this SNR. Our findings indicate that RCW 86 stems from a core-collapse SN and naturally explain why searches for a compact remnant within RCW 86, based on the standard wisdom that it should be located near the geometric centre of the SNR, gave a null result^{70,71}. The lack of a significant amount of oxygen in the SN ejecta can also be naturally explained: the lowest mass progenitors of the core-collapse SNe eject a very small amount of this element⁷².

Supplementary Information section 2. Simulated effects of a SN explosion in a tight binary

We performed Monte Carlo calculations of 10 000 asymmetric SN explosions to simulate the resulting kinematics on the surviving binary system containing a NS and a $0.9 M_{\odot}$ G-dwarf, based on the equations of Tauris & Takens⁷³. The impact of the SN shell is modelled according to the three-dimensional hydrodynamical simulations results of Liu et al.⁷⁴, by applying their power-law fit (see their fig. 6) for a $0.9 M_{\odot}$ main-sequence companion star which experiences shell impact from a nearby, stripped exploding core of $3.0 M_{\odot}$.

The mass of the exploding star and the pre-SN orbital period are randomly drawn from the intervals $2.9 - 3.7 M_{\odot}$ and $0.28 - 1.0$ d. We only considered circular pre-SN orbits as the pre-SN binary evolved through a common envelope phase. The chosen mass interval corresponds to M_1 in the range $10 - 13 M_{\odot}$ (see main text). A minimum pre-SN orbital period of 0.28 d was adopted to prevent the $0.9 M_{\odot}$ star from filling its Roche lobe, which would most likely lead to a merger event. The upper limit of the orbital period is given by the strong pollution of the companion star with heavy elements from the SN ejecta, which means that the pre-SN orbit must have been tight. The momentum kicks are randomly drawn from the range of $0 - 500 \text{ km s}^{-1}$, assuming an isotropic

distribution of kick directions. We assume a NS with a mass of $1.4 M_{\odot}$ is formed, releasing a gravitational binding energy of $0.16 M_{\odot} c^2$ (ref.⁷⁵). Since we estimate a post-SN orbital period in the range of 10 – 40 d (Methods) we consider only cases where this is achieved.

Supplementary Fig. 2 (left panel) shows that the most likely obtained systemic velocities are of the order of 80 km s^{-1} , in agreement with observational constraints based on the location of the NS relative to the centre of the optical arc in the south-west of RCW 86. We found a minimum orbital eccentricity of 0.7. Liu et al.⁷⁴ obtained the mass of accreted SN ejecta by the companion star as function of E_{SN} and the pre-SN binary separation. We parameterized their results, and applied them to our calculations. Supplementary Fig. 2 (right panel) shows that using the canonical value of $E_{\text{SN}} = 10^{51} \text{ erg}$ results in very small accreted amounts of SN ejecta (blue histogram, left), but a five times smaller SN energy yields values (red histogram, right) which are well compatible with the enrichments seen in [GV2003]N (see main text). A smaller than canonical supernova energy is also consistent with our initial mass estimate of the SN progenitor of about $10 M_{\odot}$ (cf. ref.^{4,76}).

The magnitude of the kick imparted onto a newborn NS is, in general, poorly known. The commonly used kick velocity distribution of Hobbs et al.⁷⁷ is based on isolated radio pulsars and suffers from selection effects such that slow moving radio pulsars, for which no proper motions have been measured yet, are not included in the sample. In addition, there is ample evidence that the kick velocities added onto newborn NSs depend on whether the exploding star was stripped prior to its SN explosion. It has been demonstrated⁷⁸ that kick velocities of the order $400 - 500 \text{ km s}^{-1}$ (similar to typical velocities from the Hobbs et al. distribution) cannot reproduce the observed transverse velocities of binary millisecond pulsars (typically $\sim 80 \text{ km s}^{-1}$). Similarly, an analysis of the distribution and the peculiar velocities of high-mass X-ray binaries⁷⁹ (often being only $\sim 10 - 20 \text{ km s}^{-1}$) also support the hypothesis that exploding stars generally produce smaller kicks if they have lost (at least) their hydrogen-rich envelope via mass transfer prior to the SN. Finally, it is known that the kick produced in the second SN in the production of double NS systems is often less than 50 km s^{-1} (ref.⁷⁶ and references therein).

If the kicks applied in our simulations are instead chosen in the range of $300 - 500 \text{ km s}^{-1}$ or $0 - 200 \text{ km s}^{-1}$, the number of surviving binaries decreases (increases) by 57% (42%), respectively, compared to our default range of $0 - 500 \text{ km s}^{-1}$. However, using the large kick velocity interval always results in systemic velocities of the surviving binaries in excess of 210 km s^{-1} , in contradiction with observational constraints for the NS binary in RCW 86.

Supplementary Information section 3. Chemical abundances in LMXBs

Heavy element enrichment due to an exploding binary companion have been measured in a handful of stars^{1,80–82}, all in active X-ray binaries, where the X-rays produced by mass transfer from a low mass main sequence star to a compact companion prove the physical connection of both components. Except for one object (Nova Scorpius), the pollution of the low mass star with SN products is rather mild, i.e., some metal abundances are typically enhanced by a factor of two, with an oxygen enhancement of ten in Nova Scorpius as the record holder⁸⁰. Remarkably, the

Ca overabundances of all objects so far are small, i.e. $[\text{Ca}/\text{H}] \approx 0.2 \pm 0.2$ including that in Nova Scorpius (see table 5 in ref.¹), and further on their enhancement in silicon is larger than that in calcium. This is to be contrasted with the Ca enhancement of $[\text{Ca}/\text{H}] \approx 0.8 \pm 0.05$ in [GV2003] N, which exceeds its Si enhancement by a factor of ≈ 4 . We stress that the Ca overabundance is not caused by non-LTE (NLTE) effects. Mashonkina et al.⁸³ showed that for a star like the one analysed in this work the NLTE effects for the measured Ca I lines are smaller (in modulus) than -0.02 dex, too small to compensate for the measured overabundance.

More importantly, in the known post-SN binaries Si is more overabundant than Ca¹. This is consistent with studies^{72,84} of explosive yields from (single) stars with $M_i \geq 11 M_\odot$, which show that Si is generally produced in larger amounts than Ca (see Supplementary Fig. 3). A possible explanation of the observed abundance pattern in [GV2003] N is that the element distribution in the SN ejecta was highly asymmetric because of 3D instabilities in the core collapse and that the Ca-rich clumps (observed in a number of young SNRs^{29,30}) were ejected by chance mostly towards the G-star. Another possibility is that the elevated overabundance of Ca with respect to Si is intrinsic to the SN ejecta as a whole, which implies that RCW 86 might be the result of a Ca-rich SN explosion (see Supplementary Information section 4).

Supplementary Information section 4. Calcium-rich SNe

Ca-rich SNe are a recently defined class of transients with peak absolute magnitudes of $M_R \geq -16$, intermediate between Type Ia SNe and novae^{2,3,85}, whose observational properties appear challenging to explain. While at maximum light, the optical spectra resemble those of Type Ib SNe, thus showing lines of helium but not of hydrogen³, these objects evolve very quickly to the optically thin nebular phase (at ~ 2 months). Their nebular phase spectra are dominated by [Ca II], with lines from oxygen or other intermediate mass elements being weak or absent.

The question which progenitors can produce Ca-rich SNe is not settled. A significant fraction of these SNe (8/13)⁸⁶ occurs in early-type galaxies and many of them (6/13) are found at large (> 10 kpc) galactocentric distances^{3,86,87}. This points towards relatively large progenitor lifetimes (from tens to hundreds of Myr) and/or high (up to $\sim 1000 \text{ km s}^{-1}$) space velocities⁸⁶, which in turn implies low-mass SN progenitor stars. However, four Ca-rich SNe are found within (at least in projection) or close to the disks of late type galaxies, and nearly all (11/13) of the Ca-rich SNe host galaxies show signs of galaxy-galaxy interaction or merger^{86,88}. This implies that recent star formation might occur in the host galaxies of some Ca-rich SNe (as indeed is evidenced by the *Hubble Space Telescope* observations of the host galaxy of the Ca-rich SN 2003H⁸⁷), allowing for the possibility that these objects originate from massive stars^{4,6} (though see ref.⁸⁹ for the case of SN 2005cz).

Thermonuclear events involving WDs^{2,5,90–92} and core-collapse events produced from stripped⁴ (and ultra-stripped⁶) lowest mass ($M_i \sim 10 M_\odot$) massive stars have been proposed to explain Ca-rich SNe. In both cases, explosive helium burning is expected to occur. Whereas SN simulations of stripped stars are available only for stars with rather large M_i (e.g. ref.⁹³ and references therein), Waldman et al.⁵ found in simulations of helium shell detonations on CO WDs that Ca

may be the most abundant product in such events, together with large amounts of unburnt helium.

In parameterized explosive helium burning conditions, Hashimoto et al.⁹⁴ find Ca to be the main product for a peak temperature of $\approx 1.3 \times 10^9$ K. Assuming the core radius of a white dwarf of $r = 0.01 R_\odot$ and adopting the SN post-shock temperature $T_{\text{ps}} = [3E_{\text{SN}}/(4\pi r^3 a)]^{1/4}$ from ref.⁹⁵, with E_{SN} being the SN kinetic energy and $a = 7.57 \times 10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4}$ being the radiation constant, one finds that T_{ps} would reach the above value if $E_{\text{SN}} = 3 \times 10^{49} \text{ erg}$. Weaver & Woosley⁹⁵ argue for a shock-induced production of Ca at somewhat higher temperature of $T_{\text{ps}} \approx 3.5 \times 10^9$ K, which would require $E_{\text{SN}} \sim 10^{51} \text{ erg}$.

In any case, we emphasize that the chemical structure, and thus the expected nucleosynthesis in the lowest mass core-collapse SNe is different in single stars compared to stripped envelope stars. While in both cases, the metal core mass is close to the Chandrasekhar mass and therefore the mass of the mantle of intermediate mass elements surrounding the innermost strongly electron-degenerate core is very small^{65,96}, the second dredge-up largely diminishes the mass of the helium shell in single stars, while this does not happen in the stripped stars⁹⁷. The stripped stars thus possess a massive helium shell, whose lower boundary is located at a very small radius and can therefore be exposed to very high temperatures when the SN shock wave passes through. It thus appears possible, but remains to be shown with detailed models, that SNe from stripped stars of relatively low M_i produce fast and faint transients with Ca- and helium-rich ejecta.

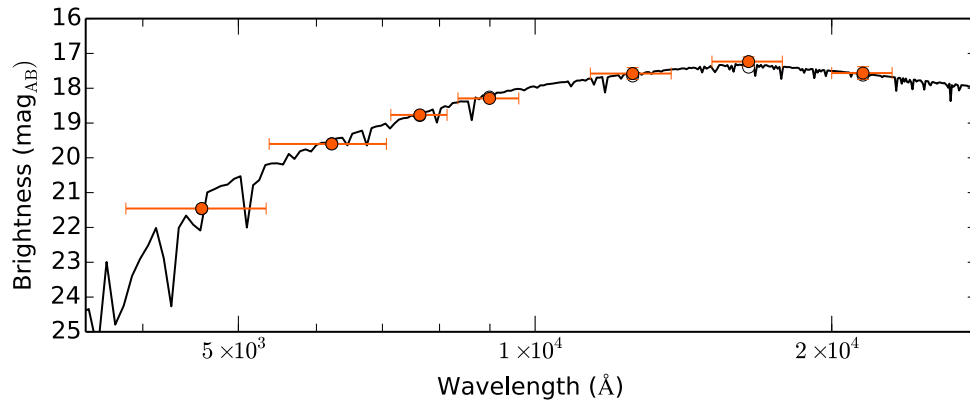
References

51. Borkowski, K. J., Lyerly, W. J. & Reynolds, S. P. Supernova remnants in the Sedov expansion phase: Thermal X-Ray emission. *Astrophys. J.* **548**, 820–835 (2001).
52. Williams, B.J. *et al.* RCW 86: A type Ia supernova in a wind-blown bubble. *Astrophys. J.* **741**, 96 (2011).
53. Rodgers, A. W., Campbell, C. T. & Whiteoak, J. B. A catalogue of H α -emission regions in the southern Milky Way. *Mon. Not. R. Astron. Soc.* **121**, 103–110 (1960).
54. Rosado, M., Ambrocio-Cruz, P., Le Coarer, E. & Marcelin, M. Kinematics of the galactic supernova remnants RCW 86, MSH 15-56 and MSH 11-61A. *Astron. Astrophys.* **315**, 243–252 (1996).
55. Long, K. S. & Blair, W. P. The identification of Balmer-dominated filaments in RCW 86. *Astrophys. J.* **358**, L13–L16 (1990).
56. Bamba, A., Koyama, K. & Tomida, H. Discovery of non-thermal X-rays from the shell of RCW 86. *Publ. Astron. Soc. Japan* **52**, 1157–1163 (2000).
57. Rho, J., Dyer, K., Borkowski, K. J. & Reynolds, S. P. X-Ray synchrotron-emitting Fe-rich ejecta in supernova remnant RCW 86. *Astrophys. J.* **581**, 1116–1131 (2002).

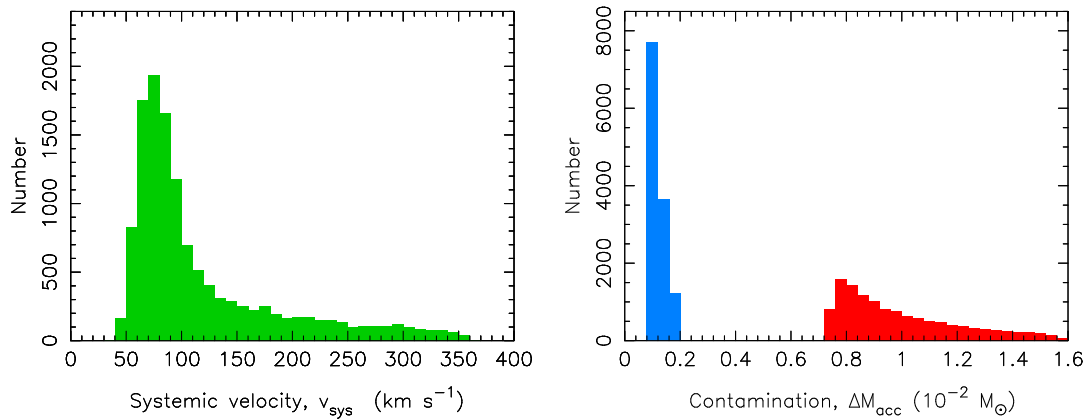
58. Yamaguchi, H. *et al.* The refined shock velocity of the X-Ray filaments in the RCW 86 north-east rim. *Astrophys. J.* **820**, L3 (2016).
59. Vink, J., Kaastra, J. S. & Bleeker, J. A. M. X-ray spectroscopy of the supernova remnant RCW 86. A new challenge for modeling the emission from supernova remnants. *Astron. Astrophys.* **328**, 628–633 (1997).
60. Vink, J., Bocchino, F., Damiani, F., & Kaastra, J. S. An unresolved X-ray source inside the supernova remnant RCW 86. *Astron. Astrophys.* **362**, 711–714 (2000).
61. Broersen, S., Chiotellis, A., Vink, J. & Bamba, A. The many sides of RCW 86: a Type Ia supernova remnant evolving in its progenitor's wind bubble. *Mon. Not. R. Astron. Soc.* **441**, 3040–3054 (2014).
62. Wang, L., Dyson, J. E. & Kahn, F. D. The nature of the Napoleon's Hat nebula of SN 1987A. *Mon. Not. R. Astron. Soc.* **261**, 391–395 (1993).
63. Meyer, D. M.-A., Langer, N., Mackey, J., Velázquez, P. F. & Gusdorf, A. Asymmetric supernova remnants generated by Galactic, massive runaway stars. *Mon. Not. R. Astron. Soc.* **450**, 3080–3100 (2015).
64. Yoon, S.-C., Woosley, S. E. & Langer, N. Type Ib/c supernovae in binary systems. I. Evolution and properties of the progenitor stars. *Astrophys. J.* **725**, 940–954 (2010).
65. Jones, S. *et al.* Advanced burning stages and fate of 8 – 10 $M_{\odot}$ stars. *Astrophys. J.* **772**, 150 (2013).
66. Brott, I. *et al.* Rotating massive main-sequence stars. I. Grids of evolutionary models and isochrones. *Astron. Astrophys.* **530**, A115 (2011).
67. Ruiz, M. T. Spectroscopy of RCW 86 - A young supernova remnant. *Astrophys. J.* **243**, 814–816 (1981).
68. Hachisu, I., Kato, M. & Nomoto, K. A new model for progenitor systems of Type Ia supernovae. *Astrophys. J.* **470**, L97–L100 (1996).
69. Badenes, C., Hughes, J. P., Bravo, E. & Langer, N. Are the models for Type Ia supernova progenitors consistent with the properties of supernova remnants? *Astrophys. J.* **662**, 472–486 (2007).
70. Fesen, R. A., Kirshner, R. P. & Winkler, P. F. A search for stellar remnants of supernovae. *Astrophys. J.* **234**, 174–181 (1979).
71. Kaplan, D.L. *et al.* An X-Ray search for compact central sources in supernova remnants. I. SNRs G093.3+6.9, G315.4–2.3, G084.2+0.8, and G127.1+0.5. *Astrophys. J. Sup.* **153**, 269–315 (2004).

72. Woosley, S. E. & Weaver, T. A. The evolution and explosion of massive stars. II. Explosive hydrodynamics and nucleosynthesis. *Astrophys. J. Supp.* **101**, 181–235 (1995).
73. Tauris, T. M. & Takens, R. J. Runaway velocities of stellar components originating from disrupted binaries via asymmetric supernova explosions. *Astron. Astrophys.* **330**, 1047–1059 (1998).
74. Liu Z.-W. *et al.* The interaction of core-collapse supernova ejecta with a companion star. *Astron. Astrophys.* **584**, A11 (2015).
75. Lattimer, J. M. & Yahil, A. Analysis of the neutrino events from supernova 1987A., *Astrophys. J.* **340**, 426–434 (1989).
76. Tauris, T. M., Langer, N. & Podsiadlowski, P. Ultra-stripped supernovae: progenitors and fate. *Mon. Not. R. Astron. Soc.* **451**, 2123–2144 (2015).
77. Hobbs G., Lorimer, D. R., Lyne, A. G., & Kramer, M. A statistical study of 233 pulsar proper motions. *Mon. Not. R. Astron. Soc.* **360**, 974–992 (2005).
78. Tauris, T. M. & Bailes, M. The origin of millisecond pulsar velocities. *Astron. Astrophys.* **315**, 453–462 (1996).
79. Coleiro, A. & Chaty, S. Distribution of high-mass X-ray binaries in the Milky Way. *Astrophys. J.* **764**, 185–198 (2013).
80. Israelian, G., Rebolo, R., Basri, G., Casares, J. & Martin, E. L. Evidence of a supernova origin for the black hole in the system GRO J1655–40. *Nature* **401**, 142–144 (1999).
81. González Hernández, J. I. *et al.* Chemical abundances in the secondary star of the neutron star binary Centaurus X-4. *Astrophys. J.* **630**, 495–505 (2005).
82. Suárez-Andrés, L., González Hernández, J. I., Israelian, G., Casares, J. & Rebolo, R. Chemical abundances of the secondary star in the neutron star X-ray binary Cygnus X-2. *Mon. Not. R. Astron. Soc.* **447**, 2261–2273 (2015).
83. Mashonkina, L., Korn, A. J., & Przybilla, N. A non-LTE study of neutral and singly-ionized calcium in late-type stars. *Astron. & Astrophys.* **461**, 261–275 (2007).
84. Rauscher, T., Heger, A., Hoffman, R. D., Woosley, S. E. Nucleosynthesis in massive stars with improved nuclear and stellar physics. *Astrophys. J.* **576**, 323–348 (2002).
85. Filippenko, A. V. *et al.* Supernovae 2001co, 2003H, 2003dg, and 2003dr. *IAU Circ.* **8159**, 2 (2003).
86. Foley, R. J. Kinematics and host-galaxy properties suggest a nuclear origin for calcium-rich supernova progenitors. *Mon. Not. R. Astron. Soc.* **452**, 2463–2478 (2015).

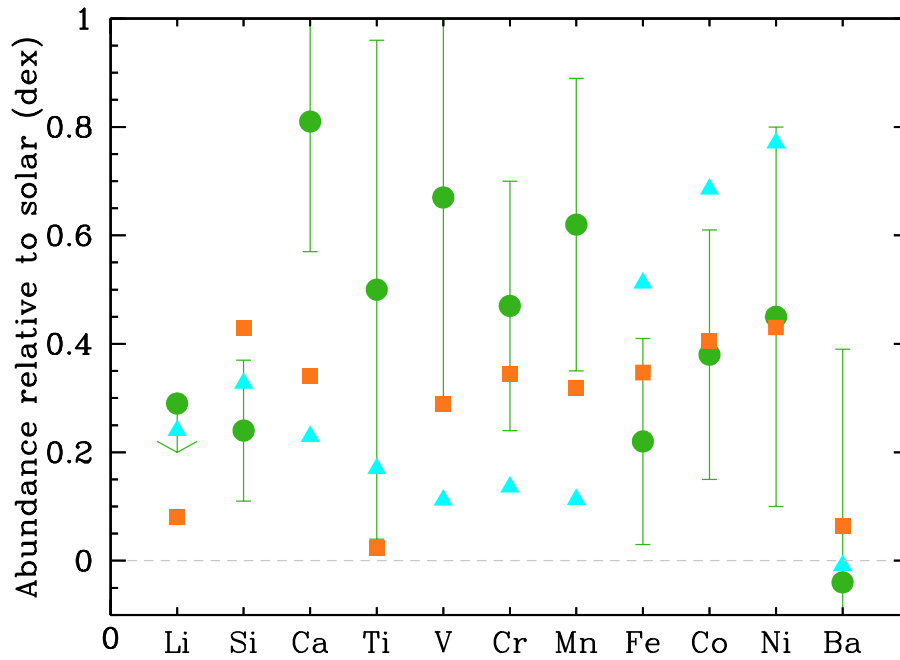
87. Lyman, J. D., Levan, A. J., Church, R. P., Davies, M. B. & Tanvir, N. R. The progenitors of calcium-rich transients are not formed in situ. *Mon. Not. R. Astron. Soc.* **444**, 2157–2166 (2014).
88. Lyman, J. D. *et al.* Hubble Space Telescope observations of the host galaxies and environments of calcium-rich supernovae. *Mon. Not. R. Astron. Soc.* **458**, 1768–1777 (2016).
89. Perets, H. B. *et al.* The old environment of the faint calcium-rich supernova SN 2005cz. *Astrophys. J.* **728**, L36 (2011).
90. Shen, K. J., Kasen, D., Weinberg, N. N., Bildsten, L. & Scannapieco, E. Thermonuclear .Ia supernovae from helium shell detonations: Explosion models and observables. *Astrophys. J.* **715**, 767–774 (2010).
91. Sell, P. H., Maccarone, T. J., Kotak, R., Knigge, C. & Sand, D. J. Calcium-rich gap transients: tidal detonations of white dwarfs? *Mon. Not. R. Astron. Soc.* **450**, 4198–4206 (2015).
92. Metzger, B. D. Nuclear-dominated accretion and subluminal supernovae from the merger of a white dwarf with a neutron star or black hole. *Mon. Not. R. Astron. Soc.* **419**, 827–840 (2012).
93. Dessart, L. *et al.* Inferring supernova IIb/Ib/Ic ejecta properties from light curves and spectra: correlations from radiative-transfer models. *Mon. Not. R. Astron. Soc.* **458**, 1618–1635 (2016).
94. Hashimoto, M.-A., Hanawa, T. & Sugimoto, D. Explosive helium burning at constant pressures. *Publ. Astron. Soc. Japan* **35**, 1–15 (1983).
95. Weaver, T. A. & Woosley, S. E. Evolution and explosion of massive stars. *Annals of the New York Academy of Sciences* **336**, 335–357 (1980).
96. Wanajo, S., Nomoto, K., Janka, H.-T., Kitaura, F. S. & Müller, B. Nucleosynthesis in electron capture supernovae of asymptotic giant branch stars. *Astrophys. J.* **695**, 208–220 (2009).
97. Podsiadlowski, P. *et al.* The effects of binary evolution on the dynamics of core collapse and neutron star kicks. *Astrophys. J.* **612**, 1044–1051 (2004).



Supplementary Figure 1 | Observed spectral energy distribution of [GV2003] N. Data points (filled red circles) show the GROND $g'r'i'z'JHK_s$ magnitudes. The horizontal error bars represent the full-width at half maximum of the GROND filters. The quadratic sum of the statistical uncertainties and the systematic uncertainties of the brightness measurement are shown as vertical error bars (in most cases they are within the size of the data points). The best fitting spectral energy distribution (solid line) is that of a star with an effective temperature of ≈ 5200 K and the colour excess of $E(B - V) = 0.9$ mag.



Supplementary Figure 2 | Results of simulations of 10 000 asymmetric SNe in tight binary systems. The binary systems were assumed to be composed of an exploding $2.9 - 3.7 M_{\odot}$ core and a $0.9 M_{\odot}$ main sequence star with an orbital period between 0.28 and 1.0 d. Kick velocities were chosen randomly in the range from 0 to 500 km s^{-1} . The left panel shows the resulting systemic velocities of the post-SN binaries. The right panel gives the amount of SN ejecta accreted by the main sequence star, calculated for two values of the SN kinetic energy: $E_{SN} = 10^{51}$ erg (blue histogram, left) and $E_{SN} = 2 \times 10^{50}$ erg (red histogram, right).



Supplementary Figure 3 | Comparison of the measured atmospheric abundances of [GV2003] N (green dots with error bars, replicated from Fig. 4), with predicted supernova yields from the 11 M_⊙ model of Woosley & Weaver (ref.⁷²; blue triangles) and the 15 M_⊙ model of Rauscher et al. (ref.⁸⁴; orange squares). For the supernova models we assumed that all the predicted metals plus 0.2 M_⊙ of helium were ejected and well mixed, of which 0.01 M_⊙ were accreted and then diluted in a convective envelope of 0.2 M_⊙ (see main text).

Supplementary Table 1 | Results of the Keplerian fit to the measured radial velocity. The first and second columns give the considered range of periods and the maximum allowed eccentricity. Columns three, four, and five list the obtained best fitting period, eccentricity, and semi-amplitude of the radial velocity variation. The last column gives the χ^2 of the fit.

Period range (d)	$e_{\max}$	P (d)	e	K_1 (km s ⁻¹)	χ^2
0–10	0.5	3	0.2	78	10^{-7}
10–20	0.5	11	0.0	96	10^{-7}
20–30	0.5	26	0.0	77	10^{-9}
30–40	0.5	35	0.4	52	10^{-6}
40–50	0.5	40	0.5	25	0.8
40–50	0.999	40	0.9	41	10^{-4}
50–60	0.5	50	0.5	25	2.6
50–60	0.999	50	0.99	63	0.1

Supplementary Table 2 | Surface element abundances of [GV2003]N. Abundances for elements are $X/H = \log[N(X)/N(H)]_{\text{star}} - \log[N(X)/N(H)]_{\odot}$, where $N(X)$ is number density of atoms. For the Li abundance only an upper limit is derived (see Methods). The uncertainties quoted for the abundances are statistical and maximum systematic (in brackets). The true uncertainties lie in between. In the third column we provide the implied amount of accreted mass per element assuming dilution in a convective envelope of $0.2 M_{\odot}$.

Element	X/H	$M_{\text{acc}}/(10^{-5} M_{\odot})$
Li	<0.29	–
Si	$0.24 \pm 0.10(0.13)$	8
Ca	$0.81 \pm 0.05(0.24)$	7
Ti	$0.50 \pm 0.18(0.46)$	0.09
V	$0.67 \pm 0.01(0.37)$	0.028
Cr	$0.47 \pm 0.10(0.23)$	0.6
Mn	$0.62 \pm 0.18(0.27)$	0.8
Fe	$0.22 \pm 0.10(0.19)$	15
Co	$0.38 \pm 0.04(0.23)$	0.09
Ni	$0.45 \pm 0.33(0.35)$	1.8
Ba	$-0.04 \pm 0.10(0.43)$	0