

A 12.4-day periodicity in a close binary system after a supernova

<https://doi.org/10.1038/s41586-023-06787-x>

Received: 19 July 2023

Accepted: 26 October 2023

Published online: 10 January 2024

 Check for updates

Ping Chen^{1✉}, Avishay Gal-Yam¹, Jesper Sollerman², Steve Schulze³, Richard S. Post⁴, Chang Liu^{5,6}, Eran O. Ofek¹, Kaustav K. Das⁷, Christoffer Fremming^{8,9}, Assaf Horesh¹⁰, Boaz Katz¹, Doron Kushnir¹, Mansi M. Kasliwal⁷, Shri R. Kulkarni⁷, Dezi Liu¹¹, Xiangkun Liu¹¹, Adam A. Miller^{5,6}, Kovi Rose¹², Eli Waxman¹, Sheng Yang^{2,13}, Yuhan Yao⁷, Barak Zackay¹, Eric C. Bellm¹⁴, Richard Dekany⁸, Andrew J. Drake⁹, Yuan Fang¹¹, Johan P. U. Fynbo^{15,16}, Steven L. Groom¹⁷, George Helou¹⁷, Ido Irani¹, Theophile Jegou du Laz⁹, Xiaowei Liu¹¹, Paolo A. Mazzali^{18,19}, James D. Neill⁹, Yu-Jing Qin⁹, Reed L. Riddle⁸, Amir Sharon¹, Nora L. Strotjohann¹, Avery Wold¹⁷ & Lin Yan⁸

Neutron stars and stellar-mass black holes are the remnants of massive star explosions¹. Most massive stars reside in close binary systems², and the interplay between the companion star and the newly formed compact object has been theoretically explored³, but signatures for binarity or evidence for the formation of a compact object during a supernova explosion are still lacking. Here we report a stripped-envelope supernova, SN 2022jli, which shows 12.4-day periodic undulations during the declining light curve. Narrow H α emission is detected in late-time spectra with concordant periodic velocity shifts, probably arising from hydrogen gas stripped from a companion and accreted onto the compact remnant. A new Fermi-LAT γ -ray source is temporally and positionally consistent with SN 2022jli. The observed properties of SN 2022jli, including periodic undulations in the optical light curve, coherent H α emission shifting and evidence for association with a γ -ray source, point to the explosion of a massive star in a binary system leaving behind a bound compact remnant. Mass accretion from the companion star onto the compact object powers the light curve of the supernova and generates the γ -ray emission.

SN 2022jli was discovered by Libert Monard on 5 May 2022 (JD = 2459704.67) and was later confirmed by several surveys (see Methods section ‘Discovery of SN 2022jli’). It was classified as a type Ic supernova (SN Ic). The supernova explosion occurred in the spiral arm of a nearby galaxy, NGC 157 (Extended Data Fig. 1), at a redshift of $z = 0.0055$ with a peculiar-velocity-corrected Hubble flow distance of $D = 22.5$ megaparsecs (Mpc) (see section ‘Host galaxy and extinction’). The photospheric spectra of SN 2022jli match well with those of spectroscopically regular SNe Ic⁴. We measured an ejecta expansion velocity of around $8,200 \text{ km s}^{-1}$ from the absorption minima of prominent Fe II lines (Extended Data Fig. 2). The supernova brightens again around 1 month after discovery, which is unusual for SNe Ic. Since then, we obtained extensive follow-up photometry and spectroscopy data (see sections ‘Photometry’ and ‘Spectroscopy’).

The light curve of SN 2022jli (Fig. 1, inset) shows three distinct evolutionary phases: phase I, the first decline phase; phase II, the rebrightening and gradual decline phase; and phase III, the late-time fast-decline

phase. During the gradual decline in phase II starting around 2 months after discovery, SN 2022jli shows periodic undulations in the light curves (Fig. 1). These bumps appear in all the observed optical bands and last around 200 days until the onset of the late-time rapid decline. We performed a periodogram analysis of the multiband light curves and found a prominent peak at 12.4 days in the power spectrum (Fig. 2). The false-alarm probability for the detected periodicity is less than 10^{-9} (see section ‘Periodic undulation in the light curve’). We also performed a periodicity analysis on the individual-band light curves and found the same prominent period in each band around 12.4 days (Extended Data Fig. 3). The phase-folded light curve adopting $P = 12.4$ days (Fig. 2) shows a constant profile composed of a fast rise lasting about 3 days (around 0.25 phase) and a relatively slow decline. We divided the nearly 200-day undulating light curve into two halves with equal time spans and repeated the periodicity analysis performed for the whole dataset. We did not find significant differences in either the bump period or profile between the two parts. Individual bumps have been observed in

¹Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel. ²The Oskar Klein Centre, Department of Astronomy, Stockholm University, Stockholm, Sweden. ³The Oskar Klein Centre, Department of Physics, Stockholm University, Stockholm, Sweden. ⁴Post Observatory, Lexington, MA, USA. ⁵Department of Physics and Astronomy, Northwestern University, Evanston, IL, USA. ⁶Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL, USA. ⁷Cahill Center for Astrophysics, California Institute of Technology, Pasadena, CA, USA. ⁸Caltech Optical Observatories, California Institute of Technology, Pasadena, CA, USA. ⁹Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA, USA. ¹⁰Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel. ¹¹South-Western Institute for Astronomy Research, Yunnan University, Kunming, Yunnan Province, People's Republic of China. ¹²Sydney Institute for Astronomy, School of Physics, The University of Sydney, Sydney, New South Wales, Australia. ¹³Henan Academy of Sciences, Zhengzhou, People's Republic of China. ¹⁴DIRAC Institute, Department of Astronomy, University of Washington, Seattle, WA, USA. ¹⁵The Cosmic DAWN Center, Copenhagen, Denmark. ¹⁶Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. ¹⁷IPAC, California Institute of Technology, Pasadena, CA, USA. ¹⁸Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK. ¹⁹Max-Planck Institute for Astrophysics, Garching, Germany. ✉e-mail: chen.ping@weizmann.ac.il

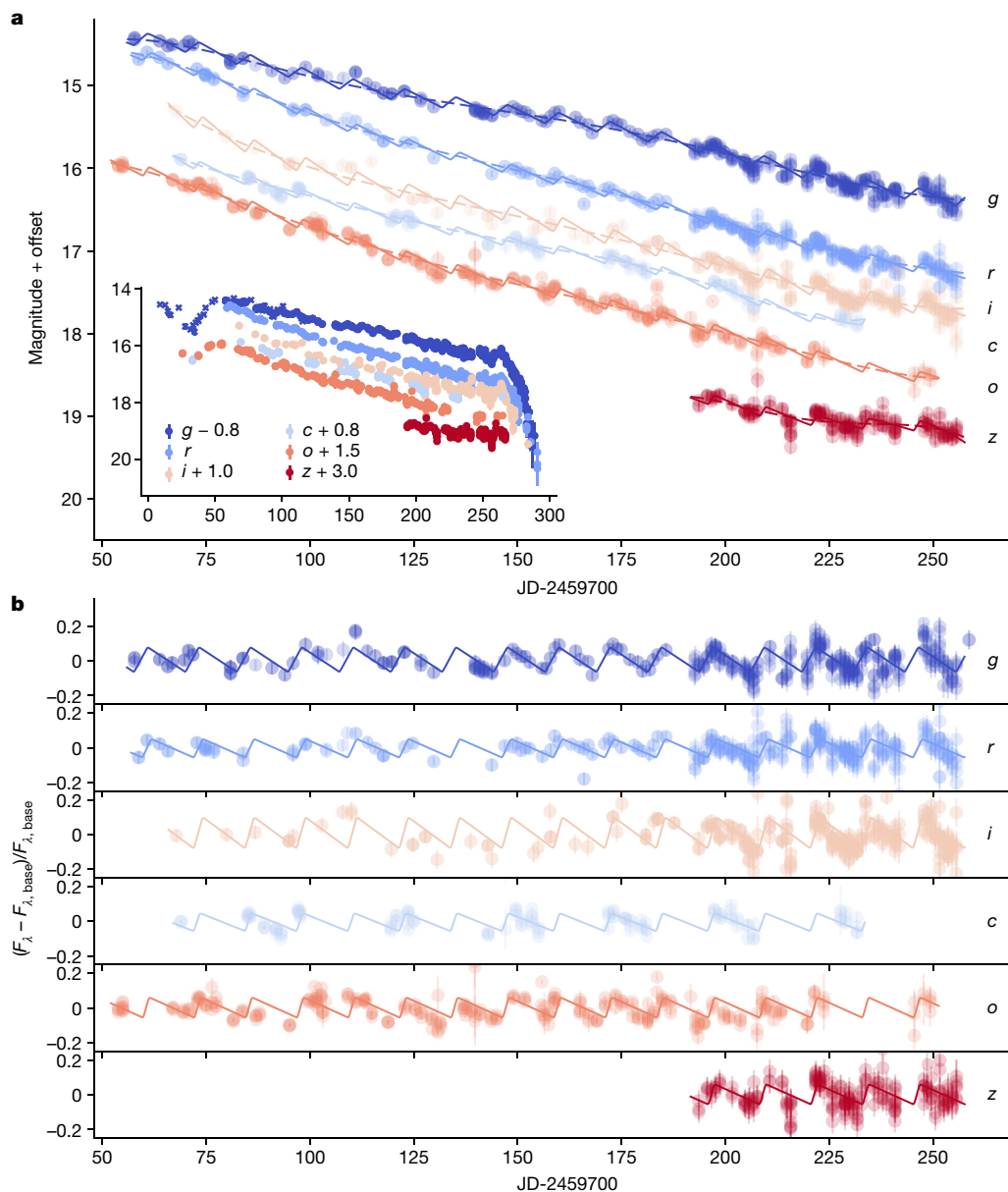


Fig. 1 | Multiband light curves of SN 2022jli showing periodic undulations. **a**, The *g*-, *r*-, *i*-, *z*-, *c*- and *o*-band light curves of SN 2022jli during phases between +50 days and +260 days after discovery. The dashed lines show the polynomial fit to the light curve, which serves as the baseline. An empirical model with a

12.4-day period is shown as a solid line for each band. Inset, the whole range of the multiband light curves. **b**, The relative undulations in the *g*-, *r*-, *i*-, *z*-, *c*- and *o*-band light curves. All the error bars of the data points are 1σ confidence intervals.

hydrogen-poor superluminous supernovae^{5–9}, and evidence for rapid variability in the optical light curve has also been found in type Ia SN 2014j¹⁰, but in this study around 20 bumps with such a strong periodic signal have been detected.

Figure 3 shows a selected sample of spectra between +139 days and +280 days after discovery. Before the rapid-decline phase ($\lesssim 270$ days), these spectra show multiple emission features as well as noticeable continuum emission. Compared with the nebular spectra of other stripped-envelope supernovae (SESNe), our spectra show stronger iron-group-element emission and many oxygen emission lines (Extended Data Figs. 2 and 4). The comparison shows that SN 2022jli resembles some hydrogen-poor superluminous supernovae^{5,11}, transients that might have an association with gamma-ray burst (GRB)^{12,13} and other peculiar long-lasting supernovae, such as SN 2012au¹⁴ and iPTF15dtg¹⁵, which are suggested to be powered by central engines. During the gradual decline phase, SN 2022jli shows unique emissions

around 6,500 Å with a relatively narrow feature superposed on a broad component. We attribute the narrow feature to hydrogen H α emission (see section ‘Hydrogen emission in the late-time spectra’). The H α lines show remarkable shifting around zero velocity in a repetitive pattern consistent with having a 12.4-day period (Fig. 3, bottom). SN 2022jli experiences significant spectroscopic evolution as it enters the fast-decline phase (Extended Data Fig. 5). One notable change is that the relatively narrow emissions, for example, the permitted O I lines with a full width at half maximum (FWHM) around 2,600 km s^{–1}, disappear, and broader [O I] λ 6300, 6363 with an FWHM around 5,500 km s^{–1} emerge (see section ‘Spectral analysis’).

The pseudo-bolometric light curve of SN 2022jli (see section ‘Bolometric light curve’) shows an evolution similar to those of the individual bands. It shows two peaks (Fig. 4), making it a double-peaked SESN, although the rising part of the first peak is missing. The phase I light curve could be explained by the ⁵⁶Ni radioactive decay as in normal SNe Ic

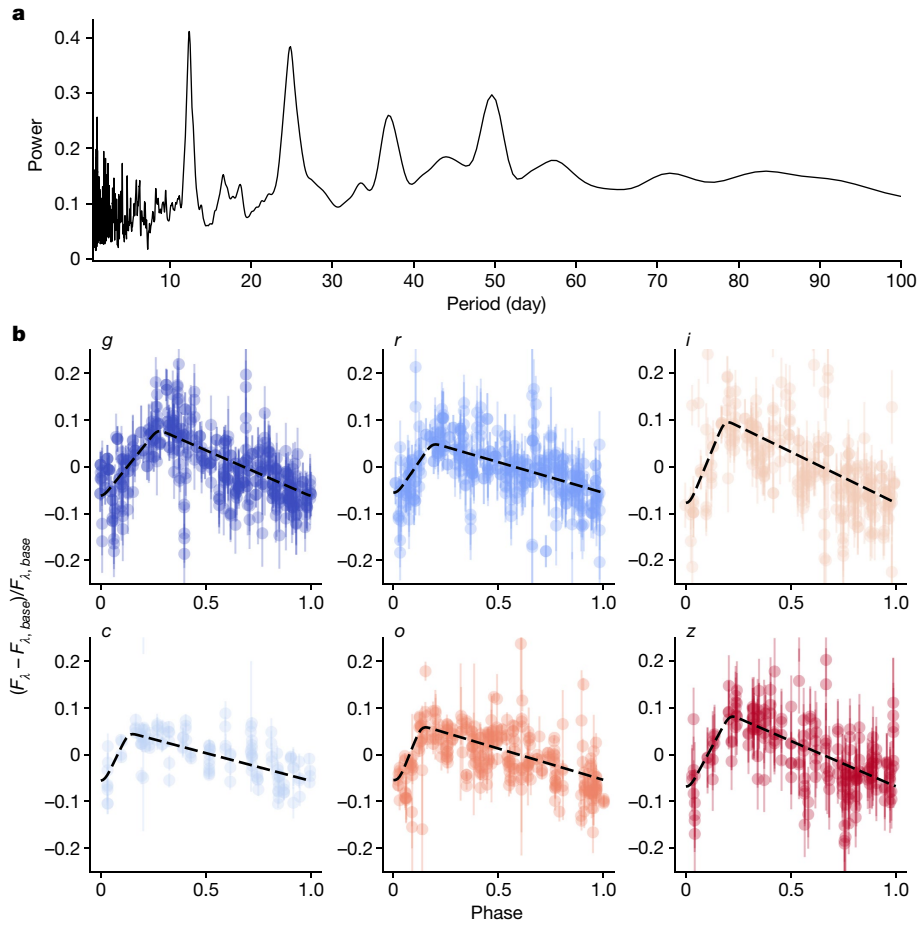


Fig. 2 | Multiband periodogram and the undulation profile of SN 2022jli. **a**, Power spectrum of the multiband light curve by joint fitting of the *g*-, *r*-, *i*-, *c*- and *o*-band light curves shown in Fig. 1. The power spectrum shows clear peaks at 12.4 days and its lower-frequency harmonic aliases at around 24.8 days, 37.2 days and 49.6 days. **b**, The folded undulation profile using the

period of 12.4 days. The black dashed lines show the best-fit empirical model (see Methods section ‘Periodic undulation in the light curve’) describing the undulation profile by a fast rise and a gradual decline. Error bars of the data points are 1 σ confidence intervals.

(see section ‘The energy source of the SN luminosity’ and the discussion below). The phase II light curve requires another energy source of around 2×10^{49} ergs, and the dramatic drop in phase III indicates a sudden shutoff of the extra energy input. To probe the properties of such a late-time energy source, we obtained two epochs of radio observation with the Australian Telescope Compact Array (ATCA) at +213 days and +228 days after the discovery, respectively. Neither epoch had a clear detection of SN 2022jli, and the second epoch with the longer exposure time gave 5 σ limits of less than 0.074 millijansky (mJy) per beam and less than 0.055 mJy per beam at central wavelengths of 5.5 GHz and 9.0 GHz, respectively. We also performed X-ray observations of SN 2022jli with NuSTAR (+227 days to +237 days after discovery) and the Chandra X-ray Observatory (+257 days to +266 days after discovery), but did not detect any emission in soft or hard X-rays (see section ‘X-ray and radio observations’) with upper limits of $L_{30-60 \text{ KeV}} < 2.5 \times 10^{40} \text{ erg s}^{-1}$ and $L_{0.5-7 \text{ KeV}} < 1.3 \times 10^{38} \text{ erg s}^{-1}$.

We searched for high-energy γ -ray emission using data from Large Area Telescope on board the Fermi Gamma-ray Space Telescope (Fermi-LAT) and found a γ -ray source in the direction of SN 2022jli (see section ‘Fermi-LAT detection of γ -ray emission from the direction of SN 2022jli’). The γ -ray source is detected after the supernova explosion, and there was no detection, to our knowledge, in the past 13.5 years of archival data before the supernova explosion (Extended Data Fig. 7). SN 2022jli is within the 68% confidence localization area of the detected source, and the detection time of the γ -ray photons

from the source shows evidence for a correlation with the 12.4-day optical flux undulation (Extended Data Fig. 8). The temporal and spatial coincidence, together with potential periodicity, suggests an association of the γ -ray emission with SN 2022jli. The source is most significantly detected in the 1–3 GeV energy band with $L_{1-3 \text{ GeV}} = 3.1 \times 10^{41} \text{ erg s}^{-1}$ in November and December 2022, and the whole γ -ray light curve is shown in Fig. 4. We suggest the γ -ray emission was only detected several months after the supernova explosion because of high pair-production opacities to γ -ray photons at early time^{16,17}. The observed γ -ray emission falls below the Fermi-LAT sensitivity at the end of December 2022, which is 1 month before the fast drop in optical flux.

Below we discuss the energy source that powers the unique light curves of SN 2022jli. Owing to the photometric and spectroscopic resemblance to normal SESNe in phase I (Extended Data Figs. 2 and 9), it is natural to attribute the first peak to the same origin as in normal SESNe, a ^{56}Ni -decay powered peak. It is more intriguing to think about the energy source of the second peak and the powering mechanism of the undulations. Supernova ejecta interaction with hydrogen-poor circumstellar medium (CSM) has been commonly adopted to explain the observed bumps in the light curves of SESNe^{8,9,18–20}. It is appealing to connect the periodic bumps to ejecta–CSM interaction (ECI) with a CSM having density fluctuation, such as the nested dust shells surrounding the Wolf–Rayet binary WR 140²¹, and a late-time drop in the light curve is also expected after the ejecta sweeps through the confined

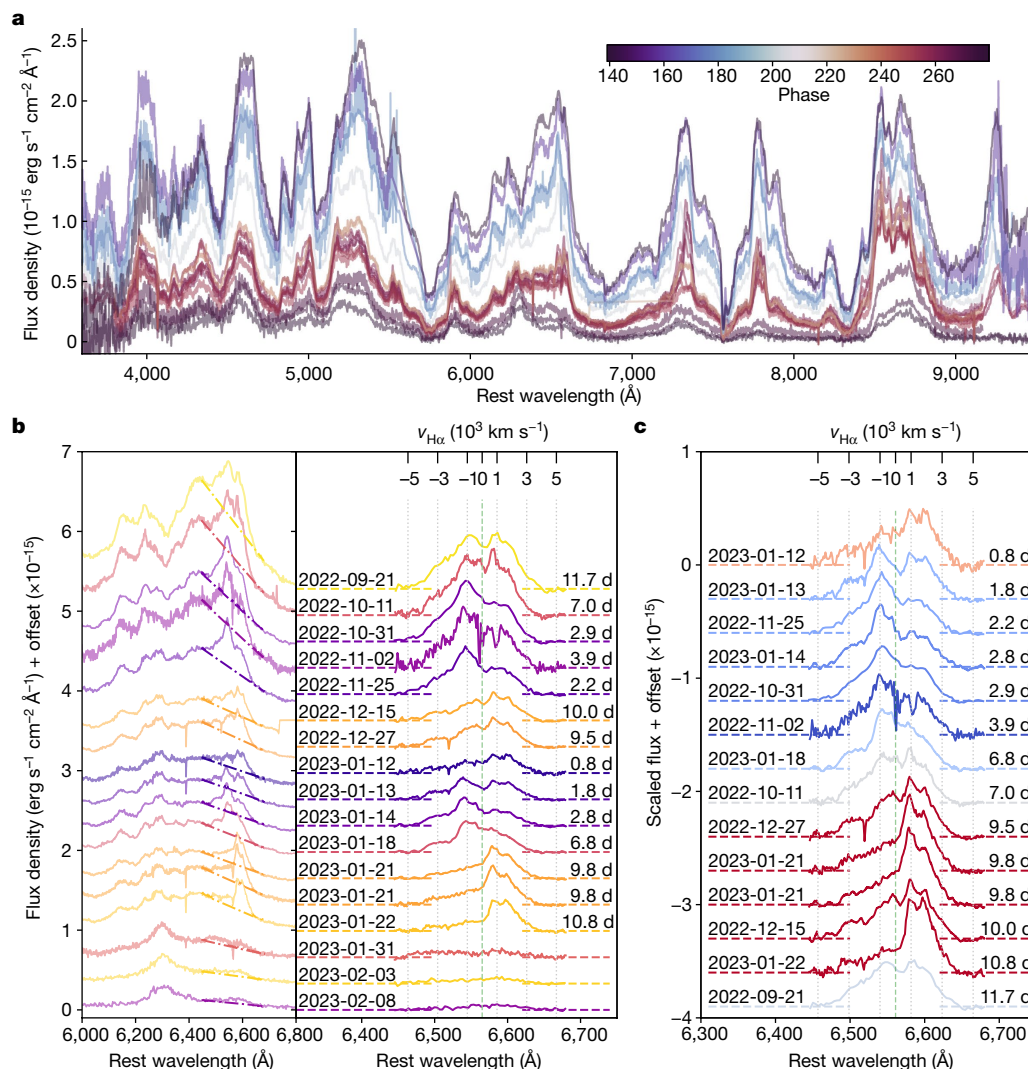


Fig. 3 | The spectral evolution of SN 2022jli between +139 days and +280 days after discovery. **a**, Flux-calibrated optical spectra of SN 2022jli. The spectral phase in days relative to the discovery time is shown with the colour bar. **b**, The evolution of H α emission. Left, magnified view around 6,000–6,800 Å. Right, the narrow H α after subtracting the pseudo-continuum (dash-dotted line in the left). For each spectrum, the observation date is shown on the left, and the

phase relative to the minimum of the bump profile is shown on the right. The H α velocity is shown at the top. **c**, The same as the right panel of **b**, but the flux of each spectrum has been scaled to have the same integrated flux within 6,430–6,680 Å, and the spectra are sorted by the phase relative to the minimum of the bump profile.

dense CSM^{22,23}. However, the persistence and short period of the bumps, especially the short-time scale of around 3 days for the rising part, put tight constraints on the feasibility of the ECI scenario to explain the observed properties. For example, consider a CSM composed of nested spherical shells. In that case, the light travel time difference between the near and far sides of the ECI is $\Delta t \approx \frac{R}{c} = 10 \times \frac{v_{ej}}{10^4 \text{ km s}^{-1}} \frac{t}{300 \text{ days}}$ days, where v_{ej} is the effective ejecta expansion velocity and t is the time from the explosion. For the observed ejecta velocity of 8,200 km s⁻¹, at 260 days, the light travel time difference is around 7 days, which would smear out any periodic signal from ECI because of CSM density fluctuation. Moreover, the light travel time difference is phase dependent as the ejecta expand and interact with CSM at different radii. The observed periodic bumps span around 200 days, showing no significant evolution, arguing against the ECI explanation for the periodic undulations.

The observed bumps have a short time scale, a constant profile and a constant ratio to the continuum flux—that is, the fluctuating light is not being diluted even when the ejecta expands. This requires an emitting region that covers a constant fraction of the expanding ejecta and that

behaves coherently. The corresponding power source must reside in a spatially confined region to remain coherent and be located close to or at the centre of the ejecta. In particular, the quick rise of the bump profile requires that the diffusion time of optical photons through the ejecta is short (<3 days).

The periodic undulation first appears around the second peak, requiring that the diffusion time of the ejecta is already short at this time. This means that the phase II light curve could not be powered by ⁵⁶Ni decay because the diffusion time would be similar to the rise time to peak (tens of days), which is inconsistent with powering the much shorter bumps. This argument applies to any other energy source that was produced during the explosion (such as a magnetar) with a decreasing or constant energy output after the explosion. A possible mechanism that could provide extra energy to power the later evolution of this supernova is accretion onto a newly formed compact object^{24–29}, which we propose to explain the observed light curves of SN 2022jli (see section ‘The energy source of the SN luminosity’). In this model, the deferred onset of the energy input could be because of the time it takes to form an accretion disk, whereas the abrupt luminosity drop-off

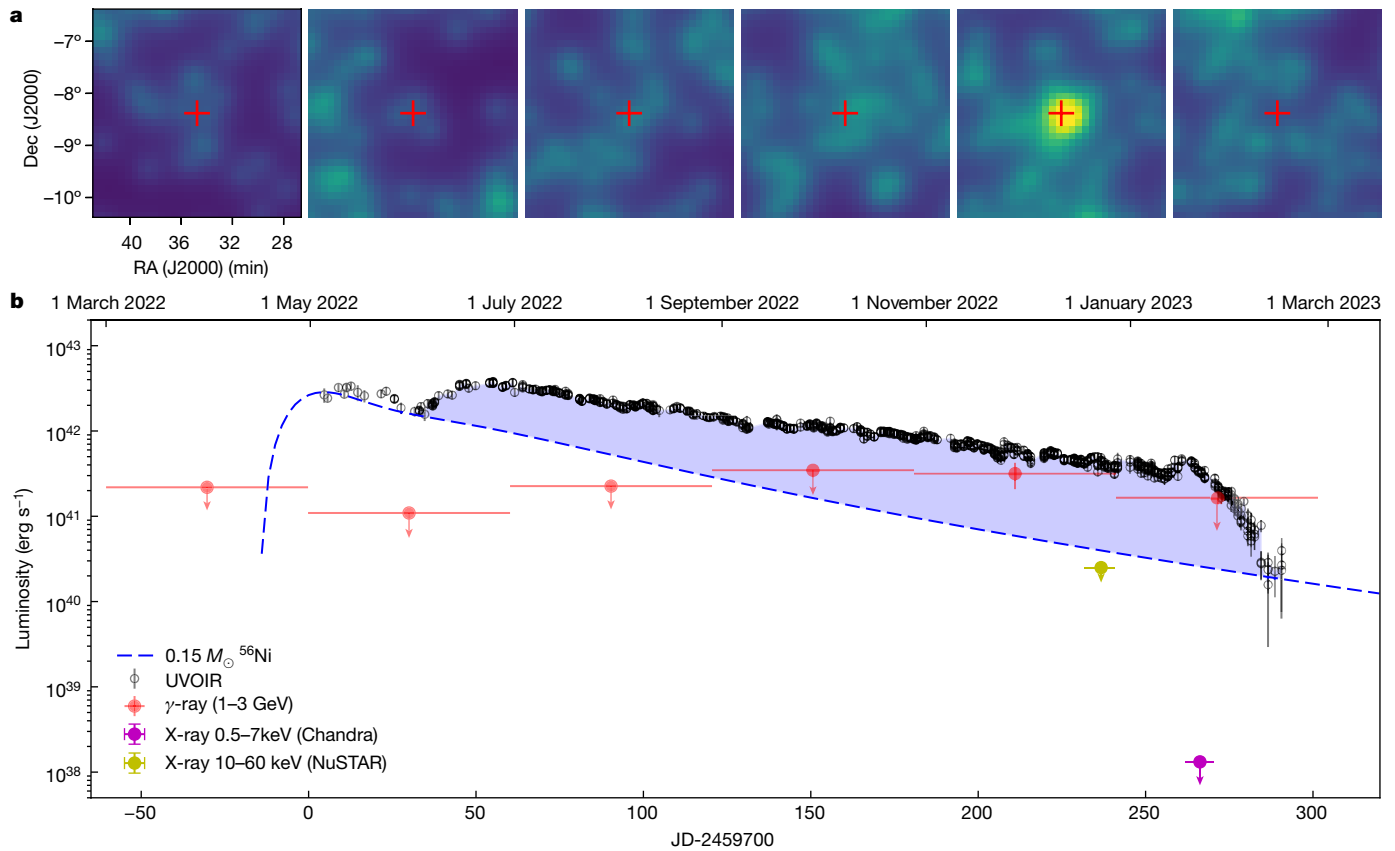


Fig. 4 | The pseudo-bolometric light curve and multi-frequency data of SN 2022jli. **a**, The γ -ray source-detection map generated with bimonthly Fermi-LAT observation in the energy band of 1–3 GeV using the Poisson-noise-matched filter method (see section ‘Fermi-LAT detection of γ -ray emission from the direction of SN 2022jli’). The red plus symbol indicates the position of SN 2022jli. A clear γ -ray source is detected in the 1 November 2022 to 1 January 2023 bin. **b**, The multi-frequency light curve of SN 2022jli. The black points

show the pseudo-bolometric light curve from 3,750 Å to 25,000 Å. The blue line shows the radioactive decay model with $0.15 M_{\odot} {}^{56}\text{Ni}$. The light curve of high-energy (1–3 GeV) γ -ray emission associated with SN 2022jli is shown with red points. Two epochs of X-ray observations with NuSTAR (yellow) and Chandra (magenta) around 250 days resulted in non-detections. All the error bars are 1σ uncertainties. All the non-detections are shown as 3σ upper limits.

at the late time is accounted for by the central object running out of infalling gas to fuel the accretion.

Given the periodic signals observed in three different aspects of the supernova, the undulation in the optical light curve, the shifting H α emission and the high-energy γ -ray photons, the most viable explanations seem to inevitably involve a binary system to provide the clocking mechanism. The luminosity of the narrow H α emission closely follows the evolution of the bolometric luminosity (Extended Data Fig. 10), even during the transition phase when the supernova luminosity shows an enhancement before diving down. This means the H α emission shares the same origin as the excess luminosity of the supernova, implying the H α also comes from the central region of the system. Therefore, a companion star with a hydrogen-rich envelope is necessary to provide the hydrogen, which corroborates the existence of a binary system. Such a binary system provides direct evidence supporting the binary origins of some SESNe.

We suggest that the compact supernova remnant and the companion star remain bound in a binary system after the supernova explosion. One plausible idea to power the supernova is through the accretion from the bloated companion star onto the compact object, forming an accretion disk. An eccentric orbit is expected (see section ‘Supernova explosion in a binary system’), which modulates the accretion rate generating the observed undulation. With $L = \epsilon \dot{M} c^2$, and adopting the optical-NIR pseudo-bolometric luminosity for the accretion luminosity L , we calculated a peak accretion rate $\dot{M}$ around $4 \times 10^{-3} \left(\frac{\epsilon}{0.01}\right)^{-1} M_{\odot} \text{ yr}^{-1}$ and a total mass to account for the

accretion-powered energy around $10^{-3} \left(\frac{\epsilon}{0.01}\right)^{-1} M_{\odot}$, where ϵ is the radiative efficiency of accretion. This extreme accretion rate could give rise to an extreme outflow of wind and/or a jet. The generation of a jet and/or wind favours the idea that the detected γ -ray emission of SN 2022jli shares a similar origin to that seen in black hole X-ray binary systems³⁰. Jets have been predicted in several supernova explosion scenarios^{31,32}.

The unprecedented properties of SN 2022jli indicate that whatever happens in the system should be a rare phenomenon, which might be explained by the rarity of a bound binary system surviving a supernova explosion^{33,34}. SN 2022jli provides direct observational evidence for the survival of this binary system after a supernova explosion. SN 2022jli builds a direct link between the supernova explosion and the formation of a compact object. It highlights the importance of the interplay between the companion star and the newly formed compact object in shaping the appearance of a core-collapse supernova.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-023-06787-x>.

1. Heger, A., Fryer, C. L., Woosley, S. E., Langer, N. & Hartmann, D. H. How massive single stars end their life. *Astrophys. J.* **591**, 288–300 (2003).
2. Sana, H. et al. Binary interaction dominates the evolution of massive stars. *Science* **337**, 444–446 (2012).
3. Hirai, R. & Podsiadlowski, P. Neutron stars colliding with binary companions: formation of hypervelocity stars, pulsar planets, bumpy superluminous supernovae and Thorne–Zytkov objects. *Mon. Not. R. Astron. Soc.* **517**, 4544–4556 (2022).
4. Gal-Yam, A. in *Handbook of Supernovae* (eds Alsabti, A. W. & Murdin, P.) 195–237 (Springer, 2017).
5. Nicholl, M. et al. SN 2015BN: a detailed multi-wavelength view of a nearby superluminous supernova. *Astrophys. J.* **826**, 39 (2016).
6. Yan, L. et al. Hydrogen-poor superluminous supernovae with late-time H α emission: three events from the Intermediate Palomar Transient Factory. *Astrophys. J.* **848**, 6 (2017).
7. Hosseinzadeh, G. et al. Bumpy declining light curves are common in hydrogen-poor superluminous supernovae. *Astrophys. J.* **933**, 14 (2022).
8. West, S. L. et al. SN 2020qlb: a hydrogen-poor superluminous supernova with well-characterized light curve undulations. *Astron. Astrophys.* **670**, A7 (2023).
9. Chen, Z. H. et al. The hydrogen-poor superluminous supernovae from the Zwicky Transient Facility Phase I Survey. II. Light-curve modeling and characterization of undulations. *Astrophys. J.* **943**, 42 (2023).
10. Bonanos, A. Z. & Boumis, P. Evidence for rapid variability in the optical light curve of the Type Ia SN 2014J. *Astron. Astrophys.* **585**, A19 (2016).
11. Gal-Yam, A. et al. Supernova 2007bi as a pair-instability explosion. *Nature* **462**, 624–627 (2009).
12. Matheson, T., Filippenko, A. V., Li, W., Leonard, D. C. & Shields, J. C. Optical spectroscopy of type Ib/c supernovae. *Astron. J.* **121**, 1648–1675 (2001).
13. Mazzali, P. A. et al. Properties of two hypernovae entering the nebular phase: SN 1997ef and SN 1997dq. *Astrophys. J.* **614**, 858–863 (2004).
14. Milisavljevic, D. et al. SN 2012au: a golden link between superluminous supernovae and their lower-luminosity counterparts. *Astrophys. J. Lett.* **770**, L38 (2013).
15. Taddia, F. et al. The luminous late-time emission of the type-Ic supernova iPTF15dtg - evidence for powering from a magnetar? *Astron. Astrophys.* **621**, A64 (2019).
16. Zdziarski, A. A. & Svensson, R. Absorption of X-rays and gamma rays at cosmological distances. *Astrophys. J.* **344**, 551–566 (1989).
17. Acharyya, A. et al. VERITAS and Fermi-LAT constraints on the gamma-ray emission from superluminous supernovae SN2015bn and SN2017egm. *Astrophys. J.* **945**, 30 (2023).
18. Chatzopoulos, E. & Wheeler, J. C. Hydrogen-poor circumstellar shells from pulsational pair-instability supernovae with rapidly rotating progenitors. *Astrophys. J.* **760**, 154 (2012).
19. Chevalier, R. A. & Fransson, C. in *Handbook of Supernovae* (eds Alsabti, A. W. & Murdin, P.) 875–937 (Springer, 2017).
20. Chen, T. W. et al. The evolution of superluminous supernova LSQ14mo and its interacting host galaxy system. *Astron. Astrophys.* **602**, A9 (2017).
21. Lau, R. M. et al. Nested dust shells around the Wolf–Rayet binary WR 140 observed with JWST. *Nat. Astron.* **6**, 1308–1316 (2022).
22. Ofek, E. O. et al. SN 2010jl: optical to hard X-ray observations reveal an explosion embedded in a ten solar mass cocoon. *Astrophys. J.* **781**, 42 (2014).
23. Zhu, J. et al. SN 2017egm: A helium-rich superluminous supernova with multiple bumps in the light curves. *Astrophys. J.* **949**, 23 (2023).
24. Michel, F. C. Neutron star disk formation from supernova fall-back and possible observational consequences. *Nature* **333**, 644–645 (1988).
25. Chevalier, R. A. Neutron star accretion in a supernova. *Astrophys. J.* **346**, 847 (1989).
26. Zhang, W., Woosley, S. E. & Heger, A. Fallback and black hole production in massive stars. *Astrophys. J.* **679**, 639–654 (2008).
27. Dexter, J. & Kasen, D. Supernova light curves powered by fallback accretion. *Astrophys. J.* **772**, 30 (2013).
28. Moriya, T. J., Nicholl, M. & Guillochon, J. Systematic investigation of the fallback accretion-powered model for hydrogen-poor superluminous supernovae. *Astrophys. J.* **867**, 113 (2018).
29. Moriya, T. J., Müller, B., Chan, C., Heger, A. & Blinnikov, S. I. Fallback accretion-powered supernova light curves based on a neutrino-driven explosion simulation of a 40 $M_{\odot}$ star. *Astrophys. J.* **880**, 21 (2019).
30. Zanin, R. et al. Gamma rays detected from Cygnus X-1 with likely jet origin. *Astron. Astrophys.* **596**, A55 (2016).
31. Akashi, M. & Soker, N. Simulating jets from a neutron star companion hours after a core-collapse supernova. *Astrophys. J.* **901**, 53 (2020).
32. Hober, O., Bear, E. & Soker, N. Feeding post-core collapse supernova explosion jets with an inflated main sequence companion. *Mon. Not. R. Astron. Soc.* **516**, 1846–1854 (2022).
33. Renzo, M. et al. Massive runaway and walkaway stars. A study of the kinematical imprints of the physical processes governing the evolution and explosion of their binary progenitors. *Astron. Astrophys.* **624**, A66 (2019).
34. Chrimes, A. A. et al. Where are the magnetar binary companions? Candidates from a comparison with binary population synthesis predictions. *Mon. Not. R. Astron. Soc.* **513**, 3550–3563 (2022).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© The Author(s), under exclusive licence to Springer Nature Limited 2024

Methods

Discovery of SN 2022jli

SN 2022jli was first discovered and reported to the Transient Name Server (TNS; <https://www.wis-tns.org/object/2022jli>) by Libert Monard³⁵ on 5 May 2022. It was later recovered by wide-field transient surveys, including the Asteroid Terrestrial-impact Last Alert System (ATLAS³⁶; ATLAS22oat), the Gaia transient survey³⁷ (Gaia22cbu), the Panoramic Survey Telescope and Rapid Response System (PanSTARRS³⁸; PS22gwo), and the Zwicky Transient Facility (ZTF^{39,40}; ZTF22aapubuy). The transient was discovered as it was rising in the morning sky. Solar conjunction before the discovery of SN 2022jli hindered any direct constraint on the explosion time, so we set the discovery epoch as the reference time for phase definition whenever the reference epoch is not explicitly specified throughout this paper. The Gaia detection gives a transient coordinate of right ascension $\alpha = 00^{\text{h}}34^{\text{m}}45.690^{\text{s}}$ and declination $\delta = -08^{\circ}23'12.16''$ (J2000.0). The Galactic extinction in the direction of SN 2022jli is $E(B - V)_{\text{MW}} = 0.039$ mag. The latest non-detection was on 6 February 2022, from Gaia, 87.5 days before the discovery. Therefore, owing to the large seasonal gap, we do not have any constraint on the explosion time of SN 2022jli.

Host galaxy and extinction

SN 2022jli is located on a spiral arm of NGC 157 (Extended Data Fig. 1). NGC 157 has a large number of H II regions, resulting in a complex background with strong nebular emission from the host galaxy, which commonly causes over-subtraction of host galaxy lines. The distance to NGC 157 is uncertain. The peculiar-velocity-corrected Hubble flow distance gives D (Virgo + GA + Shapley) = 22.5 ± 1.6 Mpc ($\mu = 31.76$ mag)⁴¹ using a standard Λ CDM cosmology⁴² with $\Omega_{\text{M}} = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0 = 73$ km s⁻¹ Mpc⁻¹ (ref. 43). The Tully–Fisher method gives smaller values of 12–13 Mpc (refs. 44–46). In this work, we adopt the distance of 22.5 Mpc for our analysis, but it is to be noted that distance-related quantities are subject to large uncertainties.

We detected prominent sodium absorption from the host galaxy in the supernova spectra, distinguished as a doublet in our medium-resolution spectra taken with IMACS and X-Shooter (Extended Data Fig. 1). We measured a sodium absorption equivalent width $\text{EW}(\text{Na I D1 + D2}) = 1.07 \pm 0.11$ Å, which converts to $E(B - V)_{\text{host}} = 0.25^{+0.11}_{-0.07}$ mag (ref. 47). We did not detect marked sodium absorption from the Milky Way, consistent with the low Galactic reddening. We also detected narrow diffusion interstellar band (DIB) absorption at 6,283 Å (Extended Data Fig. 1), from which we measured an equivalent width of $\text{EW}(\text{DIB6283}) = 0.27 \pm 0.03$ Å, which converts to $E(B - V)_{\text{host}} = 0.25 \pm 0.03$ mag (ref. 48) or $E(B - V)_{\text{host}} = 0.28 \pm 0.04$ mag (ref. 49). The extinction uncertainty derived from DIB absorption includes only the uncertainty of the equivalent width measurement but not the uncertainty from the conversion. In this work, we adopted $E(B - V)_{\text{host}} = 0.25$ mag and the conservative uncertainty obtained from sodium absorption for the analysis.

Photometry

SN 2022jli was detected by ZTF starting from 27 June 2022. ZTF *gri* photometry obtained with the ZTF survey⁵⁰ camera was processed with the ZTF image reduction pipeline⁵¹ using the ZOGY image-subtraction method⁵². We obtained additional *gri* images with the robotic 60-inch telescope at Palomar (P60⁵³), using the Spectral Energy Distribution Machine (SEDM⁵⁴). FPIPE⁵⁵ was used to extract PSF photometry from image subtraction against Sloan Digital Sky Survey (SDSS) templates. ZTF and SEDM photometry were obtained and reduced in real-time mode and streamed to the Fritz SkyPortal^{56,57} to aid further follow-up observations. The SEDM photometry obtained above with FPIPE was considered preliminary and was refined as described below.

We included photometry data reported to TNS by Libert Monard at the Kleinkaroo Observatory (KKO), which were taken on 5, 6, 11 and

22 May 2022. We obtained All-Sky Automated Survey for Supernovae (ASAS-SN) *g*-band photometry⁵⁸ from the ASAS-SN Sky Patrol⁵⁹. We adopted the option of ‘Image Subtraction (No reference flux added)’ for the photometry method, which performs aperture photometry on the co-added-image-subtracted data for each epoch but does not add the flux of the source on the reference image to the light curve. We noted a constant offset between ASAS-SN *g*-band and ZTF *g*-band photometry in flux. We added a constant flux of 360 mJy to the measured flux in the ASAS-SN data to minimize the difference between the ASAS-SN and ZTF in the overlapping time range. We extracted ATLAS-*c* and ATLAS-*o*-band light curve data from ATLAS forced photometry server (<https://fallingstar-data.com/forcedphot/>)^{36,60}. We also used three epochs of Gaia-*G* band photometry obtained by Gaia transient survey³⁷ through the Gaia Alert service (<http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia22cbu/>).

After discovering the periodic bumps, we started more follow-up observations with the 0.8-m RC32 telescope operated by the Post Observatory. We performed aperture photometry on the reference-subtracted images and calibrated them with the SDSS standard catalogue. For image subtraction, we built template images from SDSS images (<https://dr12.sdss.org/mosaics>). The FPIPE pipeline did not successfully reduce all P60 SEDM images. We performed the same photometry for SEDM images with some manual assistance. The detailed photometry procedures are described in ref. 61.

We also observed SN 2022jli with the Multi-channel Photometric Survey Telescope (Mephisto^{62,63}) during the telescope commissioning phase from 10 December 2022 to 6 February 2023. The observations were done in *uv* and *iz* bands. We conducted image subtraction and then performed PSF photometry on the subtracted images. The images taken on the night of 6 February 2023 were used as template images. We obtained the flux of SN 2022jli with PSF photometry from the template images and added to the flux obtained from the difference images.

Supplementary Fig. 1 shows the observed light curves and all photometry is listed in Supplementary Table 1.

Spectroscopy

We obtained 46 low-to-medium resolution ($R \approx 100$ –6,000) spectra of SN 2022jli, taken with the instruments listed in Supplementary Table 2. The spectra are shown in Supplementary Figs. 2–4. All spectra will be made publicly available through the Weizmann Interactive Supernova Data Repository (WiSeREP; <http://wiserep.weizmann.ac.il/>)⁶⁴. Detailed information on the spectroscopic observations and data reduction is listed below.

P60/SEDM. The Spectral Energy Distribution Machine (SEDM^{54,65}) is an integral field unit (IFU) spectrograph mounted on the 60-inch robotic telescope (P60⁵³) at the Palomar Observatory. We conducted 25 epochs of spectroscopy observation with the SEDM between 29 June 2022 and 2 February 2023. The SEDM has a very low resolution ($R \approx 100$) covering the wavelength range from 3,650 Å to 10,000 Å. All SEDM IFU data were reduced using the pipeline described in ref. 66, and new modules for the SEDMachine described in ref. 67 were used to remove the contamination from cosmic rays and non-target light.

NOT/ALFOSC. The Alhambra Faint Object Spectrograph and Camera (ALFOSC) is mounted on the 2.56-m Nordic Optical Telescope (NOT). We acquired six epochs of low-resolution spectra with NOT/ALFOSC between 6 August 2022 and 8 February 2023. The spectra were obtained with a slit width of either 1.0'' or 1.3'' depending on the seeing and using grism 4. The data were reduced using the pipeline foscgui (<http://sngroup.oapd.inaf.it/foscgui.html>). The reduction includes cosmic-ray rejection, bias corrections, flat fielding and wavelength calibration using HeNe arc lamps imaged immediately after the target. The relative flux calibration was done with spectrophotometric standard stars observed on the same night or nights before the observation.

Article

P200/DBSP. The Double Beam SPectrograph (DBSP⁶⁸) is mounted on the 200-inch Hale telescope at Palomar Observatory (P200). The DBSP uses a dichroic (at 5,500 Å for the used D55 dichroic) to split the light into separate red and blue channels (sides), observed simultaneously. We obtained three epochs of spectroscopy of SN 2022jli with DBSP. The observations were taken using a blue grating with 600 lines per mm blazed at 4,000 Å, a red grating with 316 lines per mm blazed at 7,500 Å, and a 1.5" wide slit on 20 August 2022 and 2 November 2022, and a 1.0" wide slit on 11 October 2022. The data are reduced using the Python package DBSP_DRP (https://github.com/finagle29/dbsp_drp) that is primarily based on Pypelt^{69,70}.

MMT/Binospec. We obtained five spectra of SN 2022jli between 27 December 2022 and 31 January 2023 with Binospec⁷¹ on the MMT Observatory 6.5-m telescope. All data were acquired with a grating of 270 lines per mm and a 1.0" slit mask. The Binospec spectra have a wavelength coverage of 3,900–9,240 Å. The basic data processing (bias subtraction, flat fielding) is done using the Binospec pipeline⁷². The processed images are downloaded from the MMT queue observation data archive. All the spectra are reduced with IRAF, including cosmic-ray removal, wavelength calibration (using arc lamp frames taken immediately after the target observation) and relative flux calibration with archived spectroscopic standards observation.

Magellan/IMACS and FIRE. We observed SN 2022jli with the Folded-port InfraRed Echellette (FIRE⁷³) spectrograph on 25 August 2022, and with both the FIRE and the Inamori-Magellan Areal Camera and Spectrograph (IMACS⁷⁴) on 14 December 2022. Both FIRE and IMACS are mounted on the 6.5-m Magellan Baade telescope. The first epoch of the FIRE spectrum was taken with the long-slit mode and the second with the echelle mode. The long-slit mode FIRE spectrum was reduced with the IDL pipeline firehose⁷⁵. The echelle FIRE spectrum was reduced with Pypelt^{69,70}. The IMACS spectrum was taken with a grating of 1,200 lines per mm at two different tilt angles, covering 5,130–6,780 Å and 7,290–8,920 Å. The IMACS spectrum was reduced with IRAF in the same way as for the Binospec spectra.

VLT/X-shooter. We obtained three intermediate resolution spectra with the X-shooter echelle spectrograph⁷⁶ on 14, 18 and 21 January 2023 through a DDT program (program ID 110.25A6, principal investigator P. Chen). These data were executed in target-of-opportunity mode to spectroscopically monitor the supernova during the different phases of the light curve undulations. All observations were performed in nodding mode and with 1.3", 1.2" and 1.2" wide slits (UVB, VIS and NIR). The observations covered the entire spectral range of the X-shooter spectrograph from 3,000 Å to 24,800 Å. We first removed cosmic rays with the tool astrocrappy (<https://github.com/astropy/astrocrappy>), which is based on the cosmic-ray removal algorithm in ref. 76. Then the data were processed with the X-shooter pipeline v.3.3.5, and the ESO workflow engine ESOReflex^{77–79}. All data from three arms were reduced in nodding mode. The nodding mode reduction is important for NIR data to ensure a good sky-line subtraction. The spectra of the individual arms were stitched by averaging the overlap regions. The atmospheric absorption in the VIS and NIR arms was corrected with the software tool molefit⁸⁰ (v.4.2.3).

Periodic undulation in the light curve

Multiband periodicity analysis. We adopt the multiband periodogram method⁸¹, a general extension of the well-known Lomb–Scargle approach^{82–84}, to quantitatively detect the periodic signal in the multiband light curves of SN 2022jli. The light curves in each band are modelled as arbitrary truncated Fourier series with the period and/or phase shared across all bands. The model contains two parts: (1) an N_{band} -term-truncated Fourier series that models the shared

variability among all six bands, that is, the base model; and (2) a set of N_{band} -term-truncated Fourier series for an individual band, which models the residual from the base model. The model can be described as follows

$$y_k(t|\omega, \theta) = \theta_0 + \sum_{n=1}^{N_{\text{base}}} [\theta_{2n-1} \sin(n\omega t) + \theta_{2n} \cos(n\omega t)] + \theta_0^{(k)} + \sum_{n=1}^{N_{\text{band}}} [\theta_{2n-1}^{(k)} \sin(n\omega t) + \theta_{2n}^{(k)} \cos(n\omega t)]$$

where θ_0 is the constant offset of the base model, $\theta_0^{(k)}$ is the residual component of each filter k , and $[\theta_{2n-1} \text{ (or } \theta_{2n-1}^{(k)}), \theta_{2n} \text{ (or } \theta_{2n}^{(k)})] = [A \cos\phi, A \sin\phi]$ describes the amplitude and phase, respectively, of the single-component sinusoidal model of $d(t) = A \sin(\omega t + \phi)$. We used the gatspy (<http://www.astroml.org/gatspy/>) tool to fit the g -, r -, i -, z -, c - and o -band light curve observed between +50 days and +250 days after discovery. In practice, the light curves have been detrended and normalized in flux before periodicity analysis. We first subtracted fluxes in each band, F_{λ} , with the mean flux light curve and then normalized the residual flux by the mean flux. The mean flux in each band was modelled with a polynomial baseline, $F_{\lambda, \text{base}}$. The detrending and normalization procedure can be described as $\psi = (F_{\lambda} - F_{\lambda, \text{base}})/F_{\lambda, \text{base}}$. The adopted polynomial orders for the baseline model in each band depend on the length and smoothness of the baseline. As a result, polynomial orders of 6, 6, 4, 4, 6 and 5 have been used for the g -, r -, i -, z -, c -, and o bands, respectively. We adopted $N_{\text{base}} = 4$ and $N_{\text{band}} = 2$ in our fitting and obtained a significant peak in the power spectrum corresponding to 12.4 days, which is accompanied by three low-frequency harmonic aliases. We applied the bootstrap method to study the significance of the detected periodicity by shuffling the data points and calculating the power spectrum as done for the original data. We performed 10^9 experiments, and none of them showed any similar peaks in the power spectrum, which means the false-alarm probability (FAP) of the 12.4-day period is smaller than 10^{-9} . To test whether there is a significant phase-dependent periodicity evolution, we divided the above data into two parts to perform the same analysis on each part as done for the whole data. We obtained a best-fit period of 12.23 ± 0.10 days for the first-half data and a best-fit period of 12.40 ± 0.08 days for the second-half data. The 3σ uncertainties are reported. No significant period change was detected in our data.

Empirical model of the undulation profile. The relative undulation of SN 2022jli (Fig. 2) shows characteristic profiles consisting of a fast rise and then a gradual decline. We constructed an empirical model for the undulation profile to more quantitatively characterize its features. The basis of the empirical model is a piecewise function with two linear components:

$$\psi(t) = \begin{cases} \frac{A}{t_{\text{rise}}} t + C, & 0 \leq t < t_{\text{rise}} \\ \frac{-A}{P - t_{\text{rise}}} (t - P) + C, & t_{\text{rise}} \leq t < P \end{cases} \quad (1)$$

where t_{rise} is the time for the rising phase, A is the whole amplitude from the lowest to the highest point, P is the period and C is a constant. The empirical model is defined within the range of one period $t \in [0, P]$, which starts from the point with the lowest value of ψ . To smooth the model, we convolved the above function with a narrow Gaussian kernel ($\sigma = 0.2$ days). We applied the above empirical model to fit the phase-folded undulation profile in each band and obtained a rising phase duration of 3.5 ± 0.2 , 2.5 ± 0.2 , 2.5 ± 0.2 , 2.7 ± 0.3 , 1.9 ± 0.2 , and 1.9 ± 0.2 days for the g -, r -, i -, z -, c -, and o bands, respectively. The best-fit empirical models are shown in Fig. 2 (black dashed lines) and are also used in Fig. 1.

Individual-band periodicity analysis. We also performed periodicity analysis with the Lomb–Scargle method^{82–84} in individual bands. Extended Data Fig. 3 (left) shows the Lomb–Scargle power spectrum for each $g, r, i, c, o,$ and z band with blue lines. We also compute the power spectrum of the window function shown with yellow lines. The diurnal peaks of the window power are pronounced, which is typical for ground-based data with nightly observations. The strong diurnal component from the window function causes each frequency signature f_0 to be partially aliased at $f_0 + n\delta f$, for integers n and $\delta f = 1$ cycle per day. A notable peak of around 12.4 days is detected in each band (Extended Data Fig. 3, inset), in which the period corresponding to the peak power is given by $P_g = 12.5$ days, $P_r = 12.4$ days, $P_i = 12.4$ days, $P_c = 12.8$ days, $P_o = 12.2$ days and $P_z = 12.2$ days. All the detected peaks have FAP smaller than 10^{-9} . The power spectra of the observational window functions do not show any notable peaks around the detected periods, confirming the authenticity of the periodicity. Extended Data Fig. 3 (right) shows the phase-folded light curves after detrending and normalization.

Bolometric light curve

We built the pseudo-bolometric light curve with the photometry data (see section ‘Photometry’) and spectral sequence (see section ‘Spectroscopy’) of SN 2022jli. We first get the integrated flux in the wavelength range of 3,750–9,150 Å, which most of our optical spectra cover. This wavelength range corresponds roughly to the BVRI bands, and we denote the luminosity obtained from this wavelength range as L_{BVRI} . Then we derive the fraction of NIR contribution (9,150–25,000 Å) to the bolometric luminosity which is defined as $f_{\text{NIR}} = \frac{L_{\text{NIR}}}{L_{\text{BVRI}} + L_{\text{NIR}}}$, and apply the correction to get $L_{\text{bol}} = L_{\text{BVRI}} + L_{\text{NIR}}$. The U -band contribution to the bolometric luminosity is not considered, but is known to be small for SESNe, around 10% around peak light and then quickly declining to less than 5% (ref. 85). To get the integrated optical flux, for each epoch of photometry, the closest spectrum was used as the spectral energy distribution template and scaled by a constant value to match the observed flux, then the scaled spectrum was corrected for the Milky Way foreground extinction with $E(B - V)_{\text{MW}} = 0.039$ mag (ref. 86) and host extinction with $E(B - V)_{\text{host}} = 0.25$ mag (see section ‘Host galaxy and extinction’) with the CCM extinction law adopting $R_V = 3.1$ (ref. 87). For the NIR fractional contribution, we got $f_{+107\text{days}} = 0.28$ and $f_{+224\text{days}} = 0.29$ for SN 2022jli. We derived the same ratios for two epochs of spectra of the SESN SN 2013ge and found $f_{\text{SN2013ge},+9\text{days}} = 0.24$ and $f_{\text{SN2013ge},+20\text{days}} = 0.36$. Finally, we used a uniform fraction of 0.3 for the NIR contribution and added a 10% uncertainty to account for the variation. The distance uncertainty was not included in the uncertainty budget. The resulting bolometric light curve is shown in Fig. 4 and Extended Data Fig. 6.

The pseudo-bolometric light curve of SN 2022jli shows clear undulations as seen in the individual optical light curves. We constructed the empirical undulation profile in the same way as done in the section ‘Periodic undulation in the light curve’ by adopting a sixth-order polynomial for the baseline. We notice an enhancement in the pseudo-bolometric luminosity during the last bump before the rapid decline (Extended Data Fig. 6b,c). If we assume the last bump followed the evolution as the previous undulations, the integrated luminosity of the extrapolation in the last bump would be about 3.0×10^{47} ergs, whereas the integrated luminosity of observed data in the last bump is about 3.9×10^{47} ergs. In the accretion-powered scenario (see next section), the excess radiation in the last bump converts to an accretion mass of $M_{\text{excess}} = 5 \times 10^{-6} \left(\frac{\epsilon}{0.01} \right)^{-1} M_{\odot}$, where ϵ is the radiative efficiency of accretion. The undulation profile of the last bump is markedly different from the previous undulations, with a peak time delayed by around 4 days.

The energy source of the supernova luminosity

In the standard model of SNe Ic, the supernova luminosity is dominantly powered by the radioactive decay of unstable isotopes, in particular

^{56}Ni , and its daughter element ^{56}Co , with some contribution from previously stored kinetic energy in the early time through shock cooling emission. During the first month after discovery, SN 2022jli looks like a normal type Ic supernova both in terms of the spectral evolution (Extended Data Fig. 2) and from the light curve evolution (Extended Data Fig. 9). Owing to the spectral and photometric similarities, it is natural to attribute the first decline phase to ^{56}Ni decay as in normal SNe Ic. We found that around $0.15 M_{\odot}$ ^{56}Ni produced in the explosion combined with a characteristic diffusion time scale of around 17.5 days and a γ -ray escape time scale of around 100 days can explain the first peak of SN 2022jli (Fig. 4). The γ -ray escape time scale is adopted arbitrarily with a typical value for SNe Ib/c (ref. 88). The characteristic diffusion time is a function of ejecta mass, velocity and opacity. Owing to the limited amount of data around the first peak, we do not attempt to constrain the ejecta properties by modelling the light curve.

After the first decline phase, SN 2022jli brightens again around +20 days after discovery and reaches the second peak around +50 days after discovery. This makes SN 2022jli a double-peaked SESN. After the second peak, the luminosity of SN 2022jli declines around 10 times from +70 days to +270 days. After subtracting the underlying radioactive decay emission from $0.15 M_{\odot}$ ^{56}Ni , the integrated energy is 2×10^{49} erg, which requires an additional energy source. Double-peaked light curves have been observed in other SESNe, for example, SN 2005bf (ref. 89), PTF11mnb (ref. 90), SN 2019cad (ref. 91), SN 2019stc (refs. 92,93), SN 2021uvy (ref. 94), SN 2022xxf (ref. 95) and a sample of these objects in ref. 96. The morphology of these double-peaked light curves shows a large diversity. Except SN 2021uvy, all of them do not have a long-lasting gradual decline phase after the second peak as seen in SN 2022jli (Extended Data Fig. 9). The popular explanation for the double-peaked light curves of SESNe includes interaction between the ejecta and either extended material at the outskirts of the progenitor⁹⁷ or detached circumstellar material surrounding the progenitor⁹⁸; double-peaked distribution of radioactive ^{56}Ni (refs. 89,99); and enhanced magnetar power⁹³. Below we discuss the possible origins of the second peak of SN 2022jli and test whether they can explain the undulations observed after the second peak.

The light curve of SN 2022jli after the second peak declines at a rate similar to that of light curves powered by fully trapped γ -ray from the decay of ^{56}Co , that is, around 0.01 mag per day. It is appealing to attribute the double-peaked light curves to the result of the double-peaked distribution of ^{56}Ni . In this scenario, the first peak is powered by ^{56}Ni carried out by a jet-like phenomenon and deposited in the outer layers of the ejecta¹⁰⁰, and the second peak is powered by ^{56}Ni residing in the deep layers of the ejecta. One problem with the ^{56}Ni explanation is the plummet of luminosity at very late times. The luminosity declined by one order of magnitude during around 20 days, which can not be explained by, for example, γ -ray photon leakage or the formation of cold dust in the ejecta. Another issue with ^{56}Ni comes when considering the diffusion time scale. The timescale of the ^{56}Ni -powered peak is determined by the time it takes for the emission to diffuse through the ejecta. The long time before the second peak means that there must be a large ejecta mass, causing a long diffusion time. This long diffusion time will smear out short time scale signals generated from the centre of the ejecta (see section ‘Light travel time and diffusion time’). The other possibility for the energy source is the spin-down energy of the newborn magnetar. Similarly, the magnetar model also has problems with the late-time drop of the supernova flux and with the diffusion time.

The interaction between the ejecta and the CSM could explain the rise and fall of the second peak if the CSM is distributed in a confined distance range from the progenitor. The interaction could generate periodic energy input if the CSM has evenly distributed density fluctuation. However, such periodic energy fails to produce the observed bumps in the light curves of SN 2022jli because of the light travel time difference (see section ‘Light travel time and diffusion time’).

Accretion onto the supernova remnant has been proposed as another energy source to power supernova light curves, and most of the models consider the fallback ejecta as the fuel^{25–27,29}. Accretion power could provide the extra energy of SN 2022jli. In light of the existence of a bloated companion star in a close orbit (see section ‘Supernova explosion in a binary system’) and the requirement of the hydrogen-rich material to explain the observed H α emission (see section ‘Hydrogen emission in the late-time spectra’), we propose that the companion star with hydrogen-rich envelope is the donor to fuel the accretion. The accreted mass required to account for the extra 2×10^{49} erg is $M_{\text{acc}} = 10^{-3} \left(\frac{\epsilon}{0.01} \right)^{-1} M_{\odot}$, where ϵ is the radiative efficiency of accretion. In the accretion scenario, an extremely high Eddington luminosity ratio is inevitable to explain the observed light curve. For a $1.4 M_{\odot}$ neutron star, the Eddington luminosity ratio is around 10^4 . For a $10 M_{\odot}$ black hole, the Eddington luminosity ratio decreases to around 10^3 , alleviating the super-Eddington tension. Many ultraluminous X-ray sources^{101,102} have been observed to have Eddington luminosity ratios above 100, but the mechanism of super-Eddington accretion still remains an open question¹⁰³. If the accretion origin is valid for SN 2022jli, it provides a new environment and opportunity to study super-Eddington accretion.

Under the scenario that accretion powers the excess emission of SN 2022jli, it is intriguing to consider the possibility of one pre-existing accreting compact object in the system. Regardless of the origin of the compact object, one strong constraint on the accretion is that we need hydrogen-rich material to fuel the accretion to explain the hydrogen emission and its evolution in the late-time spectra (see sections ‘Hydrogen emission in the late-time spectra’ and ‘Evolution of the accretion-powered H α emission’). However, the non-detection of hydrogen lines in the photospheric spectra (see next section) indicates hydrogen-poor ejecta, which excludes the supernova ejecta as the main fuel for accretion. This means that accretion of the supernova ejecta onto a pre-existing compact companion to the progenitor star cannot explain the spectroscopic properties of SN 2022jli. Therefore, we suggest a newly formed compact object in the supernova explosion and a companion star with a hydrogen-rich envelope is the most likely binary system.

Spectral analysis

Photospheric spectra. Two spectra taken on 11 May 2022 (+6.0 days after discovery) and 24 May 2022 (+19.2 days after discovery) were used to classify SN 2022jli^{104,105}; these spectra are available on TNS. We estimated an ejecta velocity of around $8,200 \text{ km s}^{-1}$ from the absorption minimum of the identified absorption lines. We compared the +19.2-day spectrum of SN 2022jli to other supernovae (Extended Data Fig. 2) and found that SN 2022jli resembles normal SNe Ib/c well, and it is a good match to the SE SN 2013ge. Helium absorption was found in the early-time spectra of SN 2013ge through careful analysis of both the optical and NIR spectral sequence, which probably results from a thin layer of helium remaining at the time of core collapse¹⁰⁶. Actually, a complete stripping of the He layer from the progenitor stars of SNe Ic is not expected in many models, and the contribution of the remaining helium layer to the spectra of SNe Ic has been long debated^{107–109}. Helium absorption might also exist in early-time spectra of SN 2022jli, but we do not have an extensive enough early-time spectral sequence to explore this fully. We point out that the absorption signature of helium was indeed reported in the NIR spectra of SN 2022jli presented in ref. 110.

Nebular spectra. Normal SNe Ib/c starts to enter the nebular phase some months after the explosion, during which the supernova ejecta become optically thin, and emission lines with little continuum emission dominate the spectra. The spectra of SN 2022jli are well sampled at late times during the long-lasting gradual decline phase and the fast-decline phase. The late-time spectra of SN 2022jli show significant differences with those of normal SNe Ib/c, for example, SN 2013ge in

Supplementary Fig. 5. Before the fast-decline phase, the spectra of SN 2022jli are good matches to the other two long-lasting SESNe (SN 2012au and iPTF15dtg), showing prominent permitted oxygen emission and iron plateau, and they look more similar to some SLSNe, GRB-SNe than normal SNe Ib/c (Extended data Fig. 2). We identify the emission lines in Extended data Fig. 4. Besides the aforementioned iron plateau and oxygen emission, the other elements contributing to the plethora of emission lines in SN 2023jli spectra can be identified as Ca, Mg, C and Na. The O I $\lambda 7774$ line seems to have two different components manifesting as a relatively narrow feature on a broader base. The O I $\lambda 9263$ line appears to be an isolated line without significant blending from other emissions. We measured the width of the O I $\lambda 9263$ line by fitting a simple Gaussian profile and obtained the velocities as follows: $v_{\text{FWHM}}(\text{O I } \lambda 9263, +203.8 \text{ days}) = 2,660 \pm 90 \text{ km s}^{-1}$, and $v_{\text{FWHM}}(\text{O I } \lambda 9263, +260.9 \text{ days}) = 2,720 \pm 50 \text{ km s}^{-1}$. We also measured the width of the narrow component of the O I $\lambda 7774$ line, and obtained $v_{\text{FWHM}}(\text{O I } \lambda 7774, +203.8 \text{ days}) = 2,580 \pm 200 \text{ km s}^{-1}$, and $v_{\text{FWHM}}(\text{O I } \lambda 7774, +260.9 \text{ days}) = 2,480 \pm 30 \text{ km s}^{-1}$. Before transitioning to the fast-decline phase ($\lesssim +270$ days), SN 2022jli shows prominent emission around $6,500 \text{ \AA}$, which differs from all the other comparison objects (see section ‘Hydrogen emission in the late-time spectra’ for discussion on this feature).

Accompanying the fast photometric evolution of SN 2022jli from the gradual decline to the rapid drop in luminosity, significant spectral evolution was also noticed (Extended Data Fig. 5). One conspicuous change is the disappearance of those narrow oxygen lines, including O I $\lambda 6158$, O I $\lambda 7774$, O I $\lambda 8446$ and O I $\lambda 9263$, and probably also [O II] $\lambda 7320$, 7330 after the supernova enters the fast-declining phase (>270 days after discovery). The narrow features of the Ca II NIR triplets also disappeared. In the meantime, the [O I] $\lambda 6300$, 6363 lines emerge. We measured an [O I] $\lambda 6300$ line width of $v_{\text{FWHM}}(+280 \text{ days}) = 5,520 \pm 190 \text{ km s}^{-1}$. Theoretically, the fast change of O I emission from permitted emission to forbidden emission indicates a dramatic change of density or temperature in the ejecta. In the case of SN 2022jli, the transition happened rather quickly, during which the ejecta density is not expected to change much. Therefore, the most plausible explanation for the spectral change is a decrease in temperature because of the quenching of the central energy source, which is consistent with the contemporary fast decline of the light curve. The narrower widths of the disappearing lines corroborate the idea that they were emitted from the inner parts of the ejecta with lower velocities.

Theoretical calculations of nebular phase spectra of SESNe powered by both nickel decay and a central engine are rare^{111,112}. Detailed modelling of SN 2022jli spectra considering both energy sources and their temporal evolution might shed more light on the explosion mechanism but is beyond the scope of this paper.

Hydrogen emission in the late-time spectra

The spectra of SN 2022jli show unique strong emission around $6,500 \text{ \AA}$ (Extended Data Fig. 2). The emission seems to have two components, with one narrow feature sitting on top of a broad component. The wavelength range of interest in the supernova spectrum is contaminated by host galaxy emission from nearby H II regions, but we confirm that the narrow feature does not come from any artefact because of host galaxy line contamination (Supplementary Fig. 6). We attribute the narrow emission feature to H α emission, and the co-evolution with the emission at the wavelength of H β supports this identification (Supplementary Fig. 7). The narrow feature shows back-and-forth shifts in wavelength—that is, moving to shorter and longer wavelengths around the rest wavelength of H α (Fig. 3, bottom left). The shifting behaviour shows a cyclical pattern, consistent with the 12.4-day period as derived for the undulation period in the optical light curves. The luminosity of the narrow H α line closely follows the total luminosity of the supernova as $L_{\text{H}\alpha} = 0.004 \times L_{\text{bol}}$ (Extended Data Fig. 10). There is a transition phase in the bolometric luminosity, an overshooting before

it drops, during which the H α luminosity also follows the bolometric luminosity closely. The narrow feature disappears after the SN enters the fast-decline phase (Extended Data Fig. 5). The tight connection between the narrow H α feature and the light curve of the supernova, both the periodicity and the luminosity, implies that the energy that powers the extra emission of the supernova is also responsible for the H α emission.

The region producing the periodic undulation in the light curve has been limited to a relatively small size in the centre of the ejecta, which implies the emission of H α also comes from the centre of the ejecta. The hydrogen material that gives rise to the narrow H α and H β emission probably comes from the envelope of the companion star that is accreted onto the newly formed compact object. H α and H β emission lines have been commonly observed in binary systems with accretion disks^{113–115}, which could serve as an analogy in the low accretion rate regime to understand the emission mechanism and structure of the H α in SN 2022jli.

After the narrow H α emission vanishes, there is still a prominent emission around 6,500 Å (Extended Data Fig. 5). Similar emission has been observed in other SESNe^{116–118}, mainly SNe IIB or Ib. The origin of such emissions has been debated. For example, the emission has been explained as either [N II] $\lambda\lambda 6548, 6583$ (refs. 119,120) or H α (refs. 121,122). In SNe IIB, the hydrogen could be leftovers in the outer layer, and the ejecta–wind interaction could be a possible power source for the ionization. However, a previous study (ref. 123) shows that the hydrogen envelopes of type IIB SNe are too small and dilute to produce any noticeable H α emission or absorption after about 150 days. We performed spectral decomposition of the spectra around 6,400 Å. The spectra can be well decomposed into four Gaussian emission profiles, among which two are emission lines of [O I] $\lambda\lambda 6300, 6363$ (Supplementary Fig. 8), but the derived velocities for the different lines are not consistent for [O I] and the [N II] or H α components. We get $v_{[\text{OI}]} = -890 \text{ km s}^{-1}$ (+271 days), $v_{[\text{OI}]} = -480 \text{ km s}^{-1}$ (+275 days), $v_{[\text{OI}]} = -310 \text{ km s}^{-1}$ (+280 days); $v_{[\text{NII}]} = -3,770 \text{ km s}^{-1}$ (+271 days), $v_{[\text{NII}]} = -2,690 \text{ km s}^{-1}$ (+275 days), $v_{[\text{NII}]} = -2,200 \text{ km s}^{-1}$ (+280 days); and $v_{\text{H}\alpha} = -3,260 \text{ km s}^{-1}$ (+271 days), $v_{\text{H}\alpha} = -2,170 \text{ km s}^{-1}$ (+275 days) and $v_{\text{H}\alpha} = -1,680 \text{ km s}^{-1}$ (+280 days). It is difficult to explain the velocity difference if the emission is dominated by [N II]. Another possible origin of the emission could be hydrogen stripped from the companion star by the supernova ejecta^{124–126}. Late-time H α emission with the potential origin of stripped hydrogen from the companion star has been observed in several type Ia supernovae^{127–129}. However, the observed H α profiles in those SN Ia spectra have much narrower line widths around 1,000 km s⁻¹, whereas the component on the red side of [O I] $\lambda\lambda 6300, 6363$ in SN 2022jli has a FWHM width of about 10,000 km s⁻¹, which is twice the width of the [O I] $\lambda 6300$ line. The hydrogen origin from the companion star has also been proposed to explain the nebular H α emission in the type Ic SLSN iPTF13he^{130,131}, for which other works argue for a hydrogen origin from hydrogen-rich CSM produced in mass loss before the supernova explosion^{6,130}.

Evolution of the accretion-powered H α emission

In the accretion-powered supernova scenario, the compact remnant and the companion star are bound in an eccentric orbit, in which the hydrogen-rich material is accreted from the envelope of the companion star to the newborn compact remnant every time the compact remnant passes through the pericenter of the orbit. Now we consider whether the orbital motion of this eccentric orbit can explain the observed velocity shift. The light-of-sight velocity of the compact remnant can be written as

$$V_r = V_z + K(\cos(w+f) + e \cos(w)), \quad (2)$$

where V_z is the proper motion velocity of the binary system barycenter, K is the characteristic velocity amplitude, w is the argument of periapee, f is the true anomaly and e is the orbital eccentricity. We adopted the

same nomenclature for the orbital elements as in ref. 132. The velocity amplitude can be written as

$$K = \frac{m_2}{m_c + m_2} \frac{na \sin i}{\sqrt{1-e^2}} \quad (3)$$

$$= 214 \left(\frac{m_2}{15M_\odot} \right)^2 \left(\frac{m_c + m_2}{1.4M_\odot + 15M_\odot} \right)^{-\frac{2}{3}} \frac{\sin i}{\sqrt{1-e^2}} \text{ km s}^{-1},$$

where m_c is the compact remnant mass, m_2 is the companion star mass, $n = \frac{2\pi}{P}$, a is the semimajor axis of the elliptical orbit and i is the inclination of the orbit. We can see the velocity amplitude is highly degenerate with respect to the binary masses and the orbital eccentricity.

We extracted the accretion-powered H α by simply subtracting the emission by a pseudo-continuum. The continuum model is constructed by fitting a linear model to the arbitrarily selected continuum region on both sides of the emission feature. We estimated the H α velocities by measuring the flux-weighted centroid of the emission feature without considering the nontrivial velocity structure. We estimated the uncertainties in the velocity by considering both the flux uncertainty and the systematic uncertainty because of the different choices on the continuum region. The uncertainty budget did not include the systematic uncertainty that would be introduced by the unknown nature of the underlying baseline for the H α feature. The result is shown in Extended Data Fig. 10. Only the last bump period was well sampled with decent spectral resolutions. We caution the unusual rebrightening of the last bump (see section ‘Bolometric light curve’), which might introduce other contributions to H α velocity besides the orbital motion. The Keplerian orbit with high eccentricity can roughly account for the velocity evolution trend, as shown by the four models with representative parameters. In this exercise, we simply subtracted one arbitrarily chosen linear continuum to get the H α emission without considering the potential contamination from other lines. The spectral data analysed here span more than 120 days, and the spectral evolution could cause problems when we combine data from different periods with notable separation in time. This might explain the obvious outlier in the earliest spectrum.

In this heuristic experiment, we assume the orbital velocity is the main component. We need to point out that other possible kinematic processes may complicate the velocity evolution. These complications include the velocity structure of the accretion disk, the mass flow from the companion star to the compact object and the outflow of winds. The potential eclipse of the accretion disk by the companion star and the emission from the companion envelope could also complicate the velocity structure of the H α emission line. We stress that the velocity measurement with the current method under simplified assumptions is helpful in understanding the property of the binary system qualitatively. We caution the readers to refrain from deriving the exact orbital parameters from the current analysis.

X-ray and radio observations

Chandra. We obtained three epochs of X-ray observation with the Advanced CCD Imaging Spectrometer (ACIS) of the Chandra X-ray Observatory from 17 January 2023 to 25 January 2023 (+257.4 days, +261.8 days and +265.8 days after discovery) under an approved Director Discretionary Time Proposal (principal investigator Chen). Each epoch has an exposure time of 10.06 ks. The Chandra ACIS-S data were reduced with the CIAO¹³³ software package (v.4.14) and relevant calibration files (CALDB v.4.10.2), applying standard filtering criteria. SN 2022jli was not detected in any of the three epochs. We measured the count rate within a 5'' radius aperture at the supernova position and obtained absorbed flux upper limits in 95% confidence interval of $5.27 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ (+257.4 days), $5.32 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ (+261.8 days), and $5.27 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ (+265.8 days). We merged

Article

the three epochs and obtained an absorbed flux upper limit of f_{ul} (0.5–7 keV; 95%) = $1.77 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$.

The Galactic neutral hydrogen column density in the direction of the supernova is $N_{\text{H,gal}} = 3.49 \times 10^{20} \text{ cm}^{-2}$ (ref. 134). From our optical spectra, we estimate $E(B - V)_{\text{host}} = 0.25 \text{ mag}$. Assuming a Galactic dust-to-gas ratio¹³⁵, $N_{\text{H}}(\text{cm}^{-2}) = 2.21 \times 10^{21} A_V(\text{mag})$, the extinction value corresponds to an intrinsic neutral hydrogen column density of $N_{\text{H,host}} \approx 1.7 \times 10^{21} \text{ cm}^{-2}$. For an assumed simple power-law spectral model with spectral photon index $\Gamma = 2$, we find an unabsorbed flux limit in 95% confidence interval of $2.18 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ (0.5–7 keV). At the distance of 22.5 Mpc, this flux translates into a luminosity of $1.32 \times 10^{38} \text{ erg s}^{-1}$.

The supernova ejecta may be optically thick to soft X-rays for decades. The opacities of X-ray flux absorption are dominantly because of photoelectric absorption (photon ionization and photon excitation) below around 100 keV. The X-ray optical depth at a given epoch can be described as $\tau(E) \approx \frac{3\kappa_{\text{bf}} M_{\text{ej}}}{4\pi(\nu_{\text{ej}} t)^2}$, where M_{ej} is the supernova ejecta mass, ν_{ej} is the ejecta velocity and κ_{bf} is the bound-free opacity that is largely determined by the ejecta abundance. A previous study¹³⁶ calculated a typical optical depth of $\tau(t, E) \approx 100 t_4^{-2} E^{-2}$ for core-collapse supernovae, where t_4 is the time since the explosion in units of 10,000 days, and E is the energy in units of keV. In the case of SN 2022jli, we have $\tau(+250 \text{ days}, 1 \text{ keV}) = 1.6 \times 10^5$, $\tau(+250 \text{ days}, 10 \text{ keV}) = 1.6 \times 10^3$. The supernova progenitor in their calculation has an ejecta mass of around $10 M_{\odot}$. Even if SN 2022jli has a smaller ejecta mass, the X-ray optical depth in the Chandra energy band is still very high.

In the context of interacting supernovae, our upper limits constrain the X-ray luminosity to be more than three orders of magnitude lower than the optical and NIR luminosity at the same epoch. This ratio of X-ray to optical and NIR luminosity puts a strong constraint on the interaction contribution to the bolometric luminosity. Higher X-ray to optical and NIR luminosity have been observed in supernovae with strong interaction, for example, type II_n SN 2010jl^{22,137}, type Ib_n SN 2006jc¹³⁸ and type II_n SN 2006jd^{139,140}, in which strong X-ray emission from ejecta–CSM interaction is detected by the Chandra observatory.

NuSTAR. SN 2022jli was also observed with the Nuclear Spectroscopic Telescope Array (NuSTAR¹⁴¹). NuSTAR has two coaligned X-ray telescopes, with corresponding focal plane modules FPMA and FPMB. The observations were conducted in three epochs spanning from +227 days to +237 days after discovery. The first epoch (ID 90801535002) was on 18 December 2022, with an effective exposure time of 20,353 s (FPMA) and 20,142 s (FPMB). The second epoch (ID 90801535004) was on 23 December 2022, with an effective exposure time of 20,231 s (FPMA) and 20,008 s (FPMB). The third epoch (ID 90801535006) was on 27 December 2022, with an exposure time of 20,257 s (FPMA) and 20,036 s (FPMB). The data were reduced using HEASoft v.6.31 and the NuSTAR Data Analysis Software (NuSTARDAS) v.2.1.2, in particular the nupipeline (v.0.4.9) and nuproducts routines. No source was detected at the supernova position. We focused our analysis in the 30–60 keV energy range because the probability of detecting the supernova is higher in the hard X-ray energy range with lower optical depth. We estimated an upper limit of $4.5 \times 10^{-4} \text{ counts s}^{-1}$ by calculating $3 \times \sqrt{B_{\text{tot}}}/t_{\text{exp}}$, where B_{tot} is the total count in a circular aperture with 50'' radius at the position of SN 2022jli from both epochs and both instruments and $t_{\text{exp}} = 121 \text{ ks}$ is the total effective exposure time. Assuming a power-law model with photon index $\Gamma = 2$, the above count rate upper limit corresponds to an unabsorbed flux of f_{ul} (30–60 keV) = $4.1 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ or an upper limit of $2.5 \times 10^{40} \text{ erg s}^{-1}$ at a luminosity distance of 22.5 Mpc.

ATCA. We observed SN 2022jli with the Australian Telescope Compact Array (ATCA¹⁴²) in the C/X-band (3.9–11.0 GHz) on MJD 59916 for 2 h and on MJD 59931 for 5 h using the extended 6C array configuration (CX517). For both observations, we used the ATCA calibrator source

PKS 1934–638 as the primary flux calibrator and the calibrator source PKS 0003–066 for phase calibration scans. We used the Miriad software¹⁴³ to reduce and image the data from these observations. We used mfclean with Briggs weighting and a robust parameter of 0.0, with multifrequency synthesis (mfs) deconvolution.

Neither observation resulted in a clear detection of SN 2022jli in the observed frequency range. We use imfit in C-band (5.5 GHz) to extract 5 σ non-detection limits of less than 0.176 mJy per beam and less than 0.074 mJy per beam, respectively, on MJD 59916 and MJD 59931. At the X-band 9.0 GHz central observing frequency, we obtain 5 σ limits of less than 0.057 mJy per beam and less than 0.055 mJy per beam, respectively, on MJD 59916 and MJD 59931.

Light travel time and diffusion time

We can use the time scale of the 12.4-day period and the time scale of around 3 days in the rising part of the undulation profile to constrain the size and location of the varying energy source. If the process that generates the energy powering the periodically undulating light curve happens outside of the supernova ejecta, for example, the ejecta and CSM interaction (ECI), the finite size of the ejecta can cause different light travel time from different parts of the ejecta—that is, the emission from the closer side to the observer arrive earlier. In the case of ECI, if we consider a simple model in which the optically thin ejecta expand homologously and the CSM has a spherical shell-like structure, the light travel time difference between the earliest and the latest arrival of emission from the same sphere is $\Delta t - \frac{R}{c} = 10 \times \frac{v}{10^4 \text{ km s}^{-1}} \frac{t}{300 \text{ day}}$ days. This phase-dependent light travel time difference will smear out any potential periodic signals.

If the energy source is located inside the ejecta, any sudden change in the input luminosity is subject to delay and smear effects by the ejecta that the emission goes through before reaching the observer. The short rising time of around 3 days of the bump requires the diffusion time to be less than that. The diffusion time through spherical ejecta with opacity κ from a radius r to the outer edge R is

$$t_{\text{diff}}(r, R) = \frac{\kappa}{c} \int_r^R \rho(r) r dr. \quad (4)$$

If adopting ejecta density profile $\rho(r) = \frac{M}{2\pi R^2 r}$ (ref. 144), we get

$$t_{\text{diff}}(r, R) = \frac{M\kappa}{2\pi c R} \left(1 - \frac{r}{R}\right). \quad (5)$$

For ejecta in homologous expansion, we have $R = vt$, where v is the velocity of the outer edge of the ejecta and t is the time since the supernova explosion. We get the diffusion time from the centre of the ejecta

$$t_{\text{diff}}(0, vt) = 2 \times \frac{M}{M_{\odot}} \frac{\kappa}{0.07 \text{ cm}^2 \text{ g}^{-1}} \left(\frac{v}{10^4 \text{ km s}^{-1}}\right)^{-1} \left(\frac{t}{50 \text{ day}}\right)^{-1} \text{ day}. \quad (6)$$

If we assume the discovery time of SN 2022jli is around the first peak and assume a typical rising time of 15 days for SNe Ic, the second peak is around 70 days after the explosion. We note that the discovery time could be later than the first peak because we missed the rising part of the first peak. Therefore, at the second peak, adopting ejecta velocity of 8,200 km s^{−1}, the requirement of diffusion time less than 3 days is roughly consistent with the energy source residing in the centre of the ejecta if the ejecta mass $M_{\text{ej}} \lesssim 1.7 M_{\odot}$.

Supernova explosion in a binary system

Two mainstream scenarios, the stellar-wind origin and the binary interaction origin, have been proposed to explain envelope stripping for the progenitor of SESNe. Observational evidence has been found in both directions^{145,146}. A supernova explosion in a compact binary system, that is, a binary system with a small separation between two stars,

markedly affects the companion star and the further evolution of the binary system¹⁴⁷. The existence of the companion star, in return, might have profound effects on the manifestation of the observed supernova.

Assuming the mass loss in the supernova explosion is instantaneous, the equations relating the pre-explosion and post-explosion orbital parameters (in an instantaneous reference frame centred on the companion star right at the time of explosion) are¹⁴⁷

$$\mu_f \frac{V_f^2}{2} - \frac{GM_c M_2}{a_i} = - \frac{GM_c M_2}{2a_f} \quad (7)$$

and

$$\mu_f a_i \sqrt{w_z^2 + (V_i + w_y)^2} = \mu_f \sqrt{G(M_c + M_2) a_f (1 - e^2)} \quad (8)$$

where M_2 is the companion mass, M_c is compact remnant mass, $\mu_f = M_c M_2 / (M_c + M_2)$ is the reduced mass of the system after explosion, V_i is the relative velocity before explosion, V_f is the relative velocity after explosion, a_i is the semimajor radius of the orbit before explosion, a_f is the semimajor radius of the orbit after explosion and $\mathbf{w} = w_x, w_y, w_z$ is the kick velocity.

The above equations result in the following evolution of orbital parameters:

$$\frac{a_f}{a_i} = \left[2 - \chi \left(\frac{w_x^2 + w_z^2 + (V_i + w_y)^2}{V_i^2} \right) \right]^{-1} \quad (9)$$

and

$$1 - e^2 = \chi \frac{a_i}{a_f} \left(\frac{w_z^2 + (V_i + w_y)^2}{V_i^2} \right) \quad (10)$$

where $\chi = (M_1 + M_2) / (M_c + M_2) > 1$. M_1 is the mass of the primary star that exploded. When the explosion is spherically symmetric, the compact remnant gains no kick velocity, that is, $V_0 = V_i$. If the binary system remains bound, we get the simplified results of the orbital parameters of

$$\frac{a_f}{a_i} = \frac{1}{2 - \chi} \quad (11)$$

and

$$e = \frac{M_1 - M_c}{M_c + M_2} \quad (12)$$

The above results tell that the supernova explosion will widen the binary orbit and introduce eccentricity to the system even when the explosion is symmetric.

In the case of SN 2022jli, the post-explosion binary system has

$$a_f = \left[\frac{G(M_2 + M_c) P^2}{4\pi^2} \right]^{1/3}, \quad (13)$$

where $P = 12.4$ days. Before the supernova explosion, the separation between the primary and secondary stars is smaller, which can easily achieve $\frac{a_i}{R_2} < 10$, where R_2 is the radius of the companion star, for a large parameter space of M_1 , M_2 and M_c , in which regime the ejecta impact has a significant influence on the companion^{125,148,149}. The momentum transfer and energy injection will result in an impact velocity to the companion, strip material from the companion and bloat the envelope of the companion. The amount of removed stellar mass, the resulting impact velocity and the reaction of the companion to the impact in radius, temperature and luminosity strongly depend on the binary separation and explosion energy. For a main-sequence

companion star, the radius can easily increase by one or two orders of magnitude^{125,149} for a typical explosion energy of 10^{51} erg and $\frac{a}{R_2} \lesssim 10$. The fluffy material of the bloated envelope makes it easier to get accreted onto the supernova remnant, which could form an accretion disk and provide extra energy to power the supernova³². The accretion rate is not expected to be constant because the companion radius evolves. Once the deposited energy fully radiates away, the companion starts to contract by releasing its gravitational energy and eventually resumes its original state before the SN explosion.

Owing to the accretion from the companion star to the compact remnant with likely wind and jet production in the meantime, the evolution of the surviving binary system is subject to the mass loss and mass transfer process. The detailed orbital evolution of the binary system is beyond the scope of this work. But we can argue qualitatively if any significant orbital evolution is expected during the approximately 300-day evolution of SN 2022jli. If we assume non-conservative mass, that is, $\dot{M}, \dot{J}_{\text{orb}} \neq 0$, where $\dot{M}$ is the total mass change of the system and $\dot{J}_{\text{orb}}$ is the orbital angular momentum, delta-function mass loss or transfer through Roche Lobe Overflow (RLOF), the secular relative change of the orbital semimajor axis has $\left\langle \frac{da}{a} \right\rangle \approx - \frac{dM_2}{M_1}$ with an order-of-magnitude estimate¹⁵⁰, where M_2 is the mass of the accretor and M_1 is the mass of the donor. With $dM_2 \approx M_{\text{acc}} = 10^{-3} \left(\frac{\epsilon}{0.01} \right)^{-1} M_{\odot}$ for SN 2022jli (see section ‘The energy source of the supernova luminosity’), and assuming $M_1 = 5M_{\odot}$, we can say that the relative change of semimajor axis during the first about 300 days of SN 2022jli is very small, which is consistent with what we found in the section ‘Periodic undulation in the light curve’.

A surviving companion star has been important evidence for the binary origin of some SESNe. These companion stars might have been observed in SN 1993J¹⁵¹ (SN Iib), SN 2001ig¹⁵² (SN Iib), SN 2006jc^{153,154} (SN Ibn) and SN 2011dh^{155,156} (SN Iib). SN 2022jli provides a good candidate to search for the surviving companion star of a type Ib/c supernova.

Detailed numerical simulations have shown that a supernova explosion can often unbind the secondary star in the binary system^{157,158}. A previous study³³ found that around 90% of the pre-explosion binary systems become unbound after the core-collapse explosion, and the rarity of a bound binary system surviving a supernova explosion has been observationally confirmed by dedicated searches for the companion star of the compact remnant in young supernova remnants^{159,160} and the search for companion stars of magnetars³⁴. This may be the reason why we did not observe similar properties of SN 2022jli in other SESNe.

Possible explanations for the late-time rapid decline

An interesting phenomenon of SN 2022jli is the rapid decline around 260 days after the discovery. A possible explanation is that the rapid decline happens when the accretion rate drops notably after the bloated envelope of the companion star shrinks back (see section ‘Supernova explosion in a binary system’). The other possible explanations involve a dramatic change in the binary orbit, for example, the compact object plunges into the companion star³, which prevents further mass accretion. For the latter scenario to happen, the compact object is expected to penetrate the envelope of the companion star and lose significant angular momentum and mechanical energy to shrink the distance to the companion star at periape. For an eccentric orbit, the periape distance is $r_{\text{peri}} = a(1 - e)$. The period of the binary system in SN 2022jli; therefore, the semimajor axis did not show any significant evolution before the rapid decline (see section ‘Periodic undulation in the light curve’). The mechanical energy of a binary system is $E = - \frac{GM_1 M_2}{2a}$ and the absolute value of the orbital momentum is $J_{\text{orb}} = \mu \sqrt{GMa(1 - e^2)}$, where $M = M_1 + M_2$ and $\mu = \frac{M_1 M_2}{M}$. If we simply assume an external force working on the compact object to slow the velocity instantaneously at the periape, the mechanical energy of the binary system is more susceptible to the external force than the angular momentum. It is unlikely that the orbital eccentricity changes significantly when the semimajor axis remains constant. In

the first explanation, the binary orbital parameter undergoes secular evolution, which hardly changes in the comparatively short duration of the supernova. The accretion rate suffers a fast drop, but the periodicity of the orbital undulation shall persist if the compact object continues to accrete mass from the companion. We inspect the late-time evolution of the pseudo-bolometric light curve of SN 2022jli to see if the 12.4-day periodicity continues. During the fast-decline phase, there is a hint of a small bump in the light curve as indicated by the vertical dashed line in Extended Data Fig. 6b, which is consistent with 12.4-day separation to the peak of the last clear bump before the rapid decline. This might be a hint of evidence for the continuous accretion. The prominent accretion rate variation before the rapid-decline phase might markedly change the disk properties. We suspect this could trigger some disk instability¹⁶¹, which might be responsible for the enhanced luminosity before the rapid-decline phase, as reported in the section ‘Bolometric light curve’.

Fermi-LAT detection of γ -ray emission from the direction of SN 2022jli

The Large Area Telescope (LAT) on the Fermi Gamma-Ray Space Telescope¹⁶² has been surveying the entire sky since 2008. LAT has a large field of view of 60°, enabling it to scan the sky in about 3 h. We queried LAT data within a 10° radius of SN 2022jli with photon energies between 100 MeV and 300 GeV observed in the past 14.5 years between 1 September 2008 and 1 March 2023 using the Fermi Science Support Center data server (<https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>). We filtered the photons using source-type events (evclass=128) with the most stringent cuts on the data quality (DATA_QUAL==1 && LAT_CONFIG==1), reconstructed both in the front and the back of the detector (evtype=3) and with a maximum zenith angle of 90°.

Previously unknown γ -ray source detection. We used the standard binned likelihood analysis method *glike* to analyse the data. The sources in the incremental Fermi Large Area Telescope Fourth Source Catalog (4FGL-DR3¹⁶³), together with the diffuse Galactic and isotropic backgrounds (<https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>) *gll_iem_v07.fits* and *iso_P8R3_SOURCE_V3_v1.txt* are included in the model. We tried different binning strategies in time and energy to search for new γ -ray sources. A previously unknown source was detected in the data observed after the supernova explosion from 1 May 2022 to 1 March 2023, as shown in the test statistic (TS) map in Extended Data Fig. 7 (top left). The energy light curve of the source in the 100 MeV to 300 GeV energy band is shown in Extended Data Fig. 7 (bottom left). The source was detected in two bins corresponding to September and October 2022 (TS = 20.0) and November and December 2022 (TS = 29.6). We got the spectral energy distribution of the γ -ray source in three different time windows: September and October 2022 (Supplementary Fig. 9, top left); November and December 2022 (Supplementary Fig. 9, top right), and the above two combined (Supplementary Fig. 9, bottom panel). The source is most notably detected in the 1–3 GeV energy band. We also extracted the 1–3 GeV light curve at the supernova position, and the result is shown in Extended Data Fig. 7 (bottom right).

We performed likelihood modelling with the 1–3 GeV data observed from 1 November 2022 to 1 January 2023. The test statistic map is shown in Extended Data Fig. 7 (top right), and the localization of the source from the above modelling is shown in Extended Data Fig. 8. The best localization of the γ -ray source is right ascension (RA) = 8.620 (± 0.084)°, declination (Dec) = $-8.425 (\pm 0.077)^\circ$ with uncertainty given by the 68% confidence interval. The Fermi-LAT source 4FGL J0035.8-0837 at RA = 8.958 (± 0.060)°, Dec = $-8.632 (\pm 0.048)^\circ$ is 0.33° East, 0.21° South to the detected source. They are two different sources spatially separated from each other, but we note that they could contaminate each other when measuring their fluxes.

Poisson-noise-matched filter method. We also used the Poisson-noise-matched filter to corroborate the detection of the GeV photons associated with SN 2022jli. As we are dealing with the problem of detecting sources embedded in low-number-count Poisson noise, the optimal matched filter presented in ref. 164 was used. We built the Poisson-noise optimal filter as

$$P_{\text{poi}} = \ln \left(1 + \frac{F}{B} P \right), \quad (14)$$

where B is the expectancy for the background level, F is the unknown flux of the source we would like to detect and P is the PSF of LAT (the observed photon distribution of a point source with LAT). We divided the 14.5-year data into two-month bins, and we then divided the photons into seven energy bands (0.1–0.3 GeV, 0.3–1.0 GeV, 1–3 GeV, 3–10 GeV, 10–30 GeV, 30–100 GeV and 100–300 GeV) in each temporal bin. We generated count maps for each temporal and energy bin. Following the method in ref. 164, the log-likelihood difference image used to detect the source is

$$S = M \otimes \overleftarrow{P_{\text{poi}}} \quad (15)$$

where M denotes the measured data, that is, the count map, $\otimes$ denotes convolution, $\overleftarrow{}$ denotes coordinates reversal. The PSF of Fermi-LAT observation is a function of an incident photon energy, the inclination angle and the event class. In practice, we built the PSF by generating energy-dependent PSF data with *gtpsf* for the 2-month observation and then simply averaged the PSF of different energies.

The result shows a notable source detection at the supernova position in the 1–3 GeV band in November and December 2022, as shown in Supplementary Fig. 11, which is consistent with the result obtained with *glike*. The other Fermi-LAT source near SN 2022jli, 4FGL J0035.8-0837 has also been shown in the 1–3 GeV band in March and April 2020 (Supplementary Fig. 11), and also in the 3–10 GeV band in March and April 2020, and July and August 2020 (Supplementary Fig. 15). Emission of 4FGL J0035.8-0837 might also contribute to the photons seen in July and August 2013 (Supplementary Fig. 14).

Evidence for periodicity of the detected γ -ray source. We studied the temporal distribution of the photons associated with the detected γ -ray source. There are eleven 1–3 GeV photons within the half containment radius of the averaged PSF from 1 September 2022 to 1 January 2023. The estimated number of background photons within the above temporal and spatial range is two. As shown in Extended Data Fig. 8, there is a large avoidance region (50%) in the phase space after folding the γ -ray photon light curve with a 12.4-day period, as shown by the shaded grey area. This hints at a correlation between the γ -ray photon arrival time and the optical light-curve bump phase. We performed a simple simulation by drawing N photons randomly distributed in 4 months, assuming there is no preference for when the photons arrive with respect to the bump phase. In 98.9% (98.0%, 96.5%) of the experiments, the maximum separation is less than 0.5 for any two photons in the phase space for $N = 11$ ($N = 10$, $N = 9$). We checked and found that the correlation of γ -ray photons with the 12.4-day period could not be caused by the telescope survey profile (Supplementary Fig. 16).

Association between SN 2022jli and the detected γ -ray source. The detected Fermi-LAT γ -ray source is positionally and temporally consistent with SN 2022jli, which suggests that the γ -ray source is associated with the supernova explosion. The correlation between the γ -ray photon detection time and the 12.4-day periodic undulation of the optical light curve provides further evidence that the detected γ -ray source and SN 2022jli share the same origin.

Owing to the potential periodicity detected in the γ -ray source, the probability of it coming from some other contamination source, such as a blazar, within the localization area is low. However, we inspected any potential sources within the 99% localization confidence area that might emit γ -rays. First, the nucleus of NGC 157 is a dormant supermassive black hole¹⁶⁵, which does not belong to either flat spectrum radio quasars or BL Lac objects (BL Lacs). The only blazar candidate within the 99% localization confidence area is NVSS J003456-082820 (Extended Data Fig. 8). NVSS J003456-082820 was listed as a blazar candidate in the Blazar Radio and Optical Survey (BROS¹⁶⁶) catalogue based on its spectral index between the radio bands of 0.15 GHz and 1.4 GHz and its compactness. We did not detect any optical flare from NVSS J003456-082820 in ZTF data but noted that around 20% of the orphan γ -ray flares happen without an accompanying optical flare¹⁶⁷. The true nature of NVSS J003456-082820 requires further confirmation from multifrequency observations. We studied the expectancy of one BROS catalogue object falling in the localization area of the detected γ -ray source by calculating the chance coincidence probability of observing NVSS J003456-082820. We calculated $P_{\text{ch}} = 1 - \exp[-\pi(R_0^2 + 4\sigma_\gamma^2)\rho_A]$ where R_0 is the angular distance between the γ -ray source location and NVSS J003456-082820, and σ_γ is the 68% localization uncertainties radius of the γ -ray source, and ρ_A is the surface density of BROS sources. $P_{\text{ch}} \approx 0.5$ shows that having one BROS object in the observed field of the detected γ -ray source is not surprising.

Origin of the SNe-associated γ -ray emission. Several physical processes could generate cosmic γ -rays. These processes include radioactive decay, particle–particle collisions, acceleration of charged particles (bremsstrahlung or synchrotron radiation), inverse Compton scattering and matter–antimatter annihilation. A notable category of γ -ray sources is gamma-ray bursts (GRBs), lasting from 10 ms to several hours, which is different from the gamma-ray emission that we observed in SN 2022jli with a month time scale. Gamma-ray sources with radioactive decay origin are usually associated with nucleosynthesis. For example, γ -ray emissions from ^{56}Co decay at 847 keV and 1,248 keV have been detected in some very nearby supernovae such as SN 1987A^{168,169} and SN 2014J¹⁷⁰. The GeV emission in SN 2022jli has different origins.

Efforts have been devoted to searching for other types of γ -ray emission associated with supernova explosions^{171–174}. These efforts are motivated by different mechanisms that could happen in the supernova environment producing γ -ray emissions, for example, proton–proton collisions in supernova ejecta and CSM interaction¹⁷¹ and inverse Compton scattering in the young neutron–star wind nebula^{171,172}. However, the detected γ -ray sources associated with supernovae are limited. The only tentative detections of these objects are reported for the type II supernova iPTF14hls¹⁷³ and type IIP SN 2004dj¹⁷⁵. To our knowledge, this is the first time notable GeV γ -ray emission has been detected from a SESN. We have shown that ECI or a magnetar cannot explain the observed optical light curves of SN 2022jli, which disfavours γ -ray generation from these processes. The accretion of hydrogen-rich mass from the companion star is expected to happen in the centre of the supernova ejecta. Potential γ -ray emission in accretion-powered supernovae has barely been discussed in the literature, but γ -ray emission generated in accretion-related processes in microquasars has been commonly observed, for example, in Cygnus X-3^{176,177}. The ultrahigh accretion rate required to power SN 2022jli is susceptible to launching extreme outflow winds or an accretion jet. We speculate that the observed γ -ray photons in SN 2022jli could be produced by such a wind or a jet analogous to the observed γ -ray emission in some X-ray binaries³⁰.

Data availability

Photometry and spectroscopy of SN 2022jli will be made available at the WiSeREP public database. Facilities that make all their data available in public archives promptly or after a proprietary period

include Palomar 48-inch/ZTF, VLT/X-shooter, NuSTAR, Chandra X-ray Observatory and Fermi Gamma-Ray Space Telescope. Data from the ATLAS, Gaia, ASAS-SN and KKO were obtained from public sources. The data used to perform the analysis and produce the figures for this paper are available at a public GitHub repository (<https://github.com/AtomyChan/SN2022jli>).

Code availability

The codes used to perform the analysis and produce the figures for this paper are available at a public GitHub repository (<https://github.com/AtomyChan/SN2022jli>).

35. Monard, L. *Transient Discovery Report for 2022-05-05*. Transient Name Server Discovery Report 2022-1198 (2022).
36. Tonry, J. L. et al. ATLAS: a high-cadence all-sky survey system. *Publ. Astron. Soc. Pac.* **130**, 064505 (2018).
37. Hodgkin, S. T. et al. *Gaia* Early Data Release 3. *Gaia* photometric science alerts. *Astron. Astrophys.* **652**, A76 (2021).
38. Chambers, K. C. et al. The Pan-STARRS1 Surveys. Preprint at <https://doi.org/10.48550/arXiv.1612.05560> (2016).
39. Bellm, E. C. et al. The Zwicky Transient Facility: system overview, performance, and first results. *Publ. Astron. Soc. Pac.* **131**, 018002 (2019).
40. Graham, M. J. et al. The Zwicky Transient Facility: science objectives. *Publ. Astron. Soc. Pac.* **131**, 078001 (2019).
41. Mould, J. R. et al. The *Hubble* Space Telescope Key Project on the extragalactic distance scale. XXVIII. Combining the constraints on the Hubble constant. *Astrophys. J.* **529**, 786–794 (2000).
42. Komatsu, E. et al. Seven-year *Wilkinson Microwave Anisotropy Probe* (WMAP) observations: cosmological interpretation. *Astrophys. J. Suppl. Ser.* **192**, 18 (2011).
43. Riess, A. G. et al. A comprehensive measurement of the local value of the Hubble constant with $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ uncertainty from the Hubble Space Telescope and the SHOES team. *Astrophys. J. Lett.* **934**, L7 (2022).
44. Nasonova, O. G., de Freitas Pacheco, J. A. & Karachentsev, I. D. Hubble flow around Fornax cluster of galaxies. *Astron. Astrophys.* **532**, A104 (2011).
45. Tully, R. B. et al. *Cosmicflows-2*: the data. *Astron. J.* **146**, 86 (2013).
46. Erwin, P. & Debattista, V. P. The frequency and stellar-mass dependence of boxy/peanut-shaped bulges in barred galaxies. *Mon. Not. R. Astron. Soc.* **468**, 2058–2080 (2017).
47. Poznanski, D., Prochaska, J. X. & Bloom, J. S. An empirical relation between sodium absorption and dust extinction. *Mon. Not. R. Astron. Soc.* **426**, 1465–1474 (2012).
48. Lan, T.-W., Ménard, B. & Zhu, G. Exploring the diffuse interstellar bands with the Sloan Digital Sky Survey. *Mon. Not. R. Astron. Soc.* **452**, 3629–3649 (2015).
49. Fan, H. et al. The Apache Point Observatory Catalog of Optical Diffuse Interstellar Bands. *Astrophys. J.* **878**, 151 (2019).
50. Dekany, R. et al. The Zwicky Transient Facility: observing system. *Publ. Astron. Soc. Pac.* **132**, 038001 (2020).
51. Masci, F. J. et al. The Zwicky Transient Facility: data processing, products, and archive. *Publ. Astron. Soc. Pac.* **131**, 018003 (2019).
52. Zackay, B., Ofek, E. O. & Gal-Yam, A. Proper image subtraction—optimal transient detection, photometry, and hypothesis testing. *Astrophys. J.* **830**, 27 (2016).
53. Cenko, S. B. et al. The automated Palomar 60 inch telescope. *Publ. Astron. Soc. Pac.* **118**, 1396–1406 (2006).
54. Blagorodnova, N. et al. The SED machine: a robotic spectrograph for fast transient classification. *Publ. Astron. Soc. Pac.* **130**, 035003 (2018).
55. Fremling, C. et al. PTF12os and iPTF13bvn. Two stripped-envelope supernovae from low-mass progenitors in NGC 5806. *Astron. Astrophys.* **593**, A68 (2016).
56. van der Walt, S., Crellin-Quick, A. & Bloom, J. S. SkyPortal: an astronomical data platform. *J. Open Source Softw.* **4**, 1247 (2019).
57. Coughlin, M. W. et al. A data science platform to enable time-domain astronomy. *Astrophys. J. Suppl. Ser.* **267**, 31 (2023).
58. Shappee, B. J. et al. The man behind the curtain: X-rays drive the UV through NIR variability in the 2013 active galactic nucleus outburst in NGC 2617. *Astrophys. J.* **788**, 48 (2014).
59. Kochanek, C. S. et al. The All-Sky Automated Survey for Supernovae (ASAS-SN) Light Curve Server v1.0. *Publ. Astron. Soc. Pac.* **129**, 104502 (2017).
60. Smith, K. W. et al. Design and operation of the ATLAS transient science server. *Publ. Astron. Soc. Pac.* **132**, 085002 (2020).
61. Chen, P. et al. The first data release of CNla0.02—A complete nearby (redshift < 0.02) sample of type Ia supernova light curves. *Astrophys. J. Suppl. Ser.* **259**, 53 (2022).
62. Liu, X. Multi-channel Photometric Survey Telescope—Mephisto. In *Electronic Proceedings of ‘Galactic Archaeology in the Gaia Era’ 14* (Sexten Center for Astrophysics (ScfA), 2019).
63. Yuan, X. et al. Development of the multi-channel photometric survey telescope. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 11445 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 114457M (eds Marshall, H. K. et al.) (2020).
64. Yaron, O. & Gal-Yam, A. WiSeREP—an interactive supernova data repository. *Publ. Astron. Soc. Pac.* **124**, 668 (2012).
65. Ben-Ami, S. et al. The SED machine: a dedicated transient IFU spectrograph. In *Ground-based and Airborne Instrumentation for Astronomy IV*, vol. 8446 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (eds McLean, I. S. et al.) (2012).
66. Rigault, M. et al. Fully automated integral field spectrograph pipeline for the SEDMachine: pysedm. *Astron. Astrophys.* **627**, A115 (2019).

67. Kim, Y. L. et al. New modules for the SEDMachine to remove contaminations from cosmic rays and non-target light: BYECR and CONTSEP. *Publ. Astron. Soc. Pac.* **134**, 024505 (2022).
68. Oke, J. B. & Gunn, J. E. An efficient low resolution and moderate resolution spectrograph for the Hale telescope. *Publ. Astron. Soc. Pac.* **94**, 586 (1982).
69. Prochaska, J. et al. Pyppelt: the Python spectroscopic data reduction pipeline. *J. Open Source Softw.* **5**, 2308 (2020).
70. Prochaska, J. X. et al. pyppelt/Pyppelt: Release 1.0.0. Zenodo (2020).
71. Fabricant, D. et al. Binospec: a wide-field imaging spectrograph for the MMT. *Publ. Astron. Soc. Pac.* **131**, 075004 (2019).
72. Kansky, J. et al. Binospec software system. *Publ. Astron. Soc. Pac.* **131**, 075005 (2019).
73. Simcoe, R. A. et al. FIRE: a facility class near-infrared Echelle spectrometer for the Magellan telescopes. *Publ. Astron. Soc. Pac.* **125**, 270 (2013).
74. Dressler, A. et al. IMACS: the Inamori-Magellan areal camera and spectrograph on Magellan-Baade. *Publ. Astron. Soc. Pac.* **123**, 288 (2011).
75. Vernet, J. et al. X-shooter, the new wide band intermediate resolution spectrograph at the ESO Very Large Telescope. *Astron. Astrophys.* **536**, A105 (2011).
76. van Dokkum, P. G. Cosmic-ray rejection by Laplacian edge detection. *Publ. Astron. Soc. Pac.* **113**, 1420–1427 (2001).
77. Goldoni, P. et al. Data reduction software of the X-shooter spectrograph. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 6269 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 62692K (eds McLean, I. S. & Iye, M.) (2006).
78. Modigliani, A. et al. The X-shooter pipeline. In *Observatory Operations: Strategies, Processes, and Systems III*, vol. 7737 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 773728 (eds Silva, D. R. et al.) (2010).
79. Freudling, W. et al. Automated data reduction workflows for astronomy. The ESO Reflex environment. *Astron. Astrophys.* **559**, A96 (2013).
80. Smette, A. et al. Molecfit: A general tool for telluric absorption correction. I. Method and application to ESO instruments. *Astron. Astrophys.* **576**, A77 (2015).
81. VanderPlas, J. T. & Ivezić, Ž. Periodograms for multiband astronomical time series. *Astrophys. J.* **812**, 18 (2015).
82. Lomb, N. R. Least-squares frequency analysis of unequally spaced data. *Astrophys. Space Sci.* **39**, 447–462 (1976).
83. Scargle, J. D. Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. *Astrophys. J.* **263**, 835–853 (1982).
84. VanderPlas, J. T. Understanding the Lomb–Scargle periodogram. *Astrophys. J. Suppl. Ser.* **236**, 16 (2018).
85. Lyman, J. D., Bersier, D. & James, P. A. Bolometric corrections for optical light curves of core-collapse supernovae. *Mon. Not. R. Astron. Soc.* **437**, 3848–3862 (2014).
86. Schlafly, E. F. & Finkbeiner, D. P. Measuring reddening with Sloan Digital Sky Survey stellar spectra and recalibrating SFD. *Astrophys. J.* **737**, 103 (2011).
87. Cardelli, J. A., Clayton, G. C. & Mathis, J. S. The relationship between infrared, optical, and ultraviolet extinction. *Astrophys. J.* **345**, 245 (1989).
88. Sharon, A. & Kushnir, D. The y-ray deposition histories of core-collapse supernovae. *Mon. Not. R. Astron. Soc.* **496**, 4517–4545 (2020).
89. Folatelli, G. et al. SN 2005bf: a possible transition event between type Ib/c supernovae and gamma-ray bursts. *Astrophys. J.* **641**, 1039–1050 (2006).
90. Taddia, F. et al. PTF11mnb: First analog of supernova 2005bf. Long-rising, double-peaked supernova Ic from a massive progenitor. *Astron. Astrophys.* **609**, A106 (2018).
91. Gutiérrez, C. P. et al. The double-peaked type Ic supernova 2019cad: another SN 2005bf-like object. *Mon. Not. R. Astron. Soc.* **504**, 4907–4922 (2021).
92. Gomez, S. et al. The luminous and double-peaked type Ic supernova 2019stc: evidence for multiple energy sources. *Astrophys. J.* **913**, 143 (2021).
93. Chugai, N. N. & Utrobin, V. P. Origin of post-maximum bump in luminous Type Ic supernova 2019stc. *Mon. Not. R. Astron. Soc.* **512**, L71–L73 (2022).
94. Gomez, S., Berger, E., Nicholl, M., Blanchard, P. K. & Hosseinzadeh, G. Luminous supernovae: unveiling a population between superluminous and normal core-collapse supernovae. *Astrophys. J.* **941**, 107 (2022).
95. Kuncarayakti, H. et al. The broad-lined Type-Ic supernova SN 2022xxf and its extraordinary two-humped light curves. *Astron. Astrophys.* **678**, A209 (2023).
96. Das, K. K. et al. Probing pre-supernova mass loss in double-peaked Type Ibc supernovae from the Zwicky Transient Facility. Preprint at <https://doi.org/10.48550/arXiv.2306.04698> (2023).
97. Piro, A. L. Using double-peaked supernova light curves to study extended material. *Astrophys. J. Lett.* **808**, L51 (2015).
98. Jin, H., Yoon, S.-C. & Blinnikov, S. The effect of circumstellar matter on the double-peaked type Ic supernovae and implications for LSQ14efd, iPTF15dtg, and SN 2020bvc. *Astrophys. J.* **910**, 68 (2021).
99. Orellana, M. & Bersten, M. C. Supernova double-peaked light curves from double-nickel distribution. *Astron. Astrophys.* **667**, A92 (2022).
100. Bersten, M. C., Tanaka, M., Tominaga, N., Benvenuto, O. G. & Nomoto, K. Early ultraviolet/optical emission of the type Ib SN 2008D. *Astrophys. J.* **767**, 143 (2013).
101. Walton, D. J., Roberts, T. P., Mateos, S. & Heard, V. 2XMM ultraluminous X-ray source candidates in nearby galaxies. *Mon. Not. R. Astron. Soc.* **416**, 1844–1861 (2011).
102. Israel, G. L. et al. An accreting pulsar with extreme properties drives an ultraluminous X-ray source in NGC 5907. *Science* **355**, 817–819 (2017).
103. Brightman, M. et al. Breaking the limit: super-Eddington accretion onto black holes and neutron stars. *Bull. AAS* **51**, 352 (2019).
104. Grzegorzek, J. *PSH Transient Classification Report for 2022-05-11*. Transient Name Server Classification Report 2022-1261, 1 (2022).
105. Cosentino, S. P. et al. *ePESTO+ Transient Classification Report for 2022-05-24*. Transient Name Server Classification Report 2022-1409, 1 (2022).
106. Drout, M. R. et al. The double-peaked SN 2013ge: a type Ib/c SN with an asymmetric mass ejection or an extended progenitor envelope. *Astrophys. J.* **821**, 57 (2016).
107. Hachinger, S. et al. How much H and He is ‘hidden’ in SNe Ib/c? - I. Low-mass objects. *Mon. Not. R. Astron. Soc.* **422**, 70–88 (2012).
108. Dessart, L., Yoon, S.-C., Aguilera-Dena, D. R. & Langer, N. Supernovae Ib and Ic from the explosion of helium stars. *Astron. Astrophys.* **642**, A106 (2020).
109. Williamson, M., Kerzendorf, W. & Modjaz, M. Modeling type Ic supernovae with TARDIS: hidden helium in SN 1994I? *Astrophys. J.* **908**, 150 (2021).
110. Tinyanont, S. et al. Keck Infrared Transient Survey I: survey description and data release 1. Preprint at <https://doi.org/10.48550/arXiv.2309.07102> (2023).
111. Dessart, L. Simulations of light curves and spectra for superluminous type Ic supernovae powered by magnetars. *Astron. Astrophys.* **621**, A141 (2019).
112. Omand, C. M. B. & Jerkstrand, A. Toward nebular spectral modeling of magnetar-powered supernovae. *Astron. Astrophys.* **673**, A107 (2023).
113. Budaj, J., Richards, M. T. & Miller, B. A study of synthetic and observed H α spectra of TT hydrae. *Astrophys. J.* **623**, 411–424 (2005).
114. Miller, B., Budaj, J., Richards, M., Koubský, P. & Peters, G. J. Revealing the nature of algol disks through optical and UV spectroscopy, synthetic spectra, and tomography of TT hydrae. *Astrophys. J.* **656**, 1075–1091 (2007).
115. Atwood-Stone, C., Miller, B. P., Richards, M. T., Budaj, J. & Peters, G. J. Modeling the accretion structure of AU Mon. *Astrophys. J.* **760**, 134 (2012).
116. Patat, F., Chugai, N. & Mazzali, P. A. Late-time H α spectrum from the hydrogen shell of SN 1993J. *Astron. Astrophys.* **299**, 715 (1995).
117. Maeda, K. et al. The Unique Type Ib Supernova 2005bf at Nebular Phases: A Possible Birth Event of a Strongly Magnetized Neutron Star. *Astron. Astrophys. J.* **666**, 1069–1082 (2007).
118. Taubenberger, S. et al. The He-rich stripped-envelope core-collapse supernova 2008ax. *Mon. Not. R. Astron. Soc.* **413**, 2140–2156 (2011).
119. Jerkstrand, A. et al. Late-time spectral line formation in Type IIb supernovae, with application to SN 1993J, SN 2008ax, and SN 2011dh. *Astron. Astrophys.* **573**, A12 (2015).
120. Fang, Q. & Maeda, K. The origin of the H α -like structure in nebular spectra of type IIb supernovae. *Astrophys. J.* **864**, 47 (2018).
121. Matheson, T. et al. Optical spectroscopy of supernova 1993J during its first 2500 days. *Astron. J.* **120**, 1487–1498 (2000).
122. Matheson, T., Filippenko, A. V., Ho, L. C., Barth, A. J. & Leonard, D. C. Detailed analysis of early to late-time spectra of supernova 1993J. *Astron. J.* **120**, 1499–1515 (2000).
123. Dessart, L., Hillier, D. J., Sukhbold, T., Woosley, S. E. & Janka, H. T. Nebular phase properties of supernova Ibc from He-star explosions. *Astron. Astrophys.* **656**, A61 (2021).
124. Marietta, E., Burrows, A. & Fryxell, B. Type Ia supernova explosions in binary systems: the impact on the secondary star and its consequences. *Astrophys. J. Suppl. Ser.* **128**, 615–650 (2000).
125. Liu, Z.-W. et al. The interaction of core-collapse supernova ejecta with a companion star. *Astron. Astrophys.* **584**, A11 (2015).
126. Dessart, L., Leonard, D. C. & Prieto, J. L. Spectral signatures of H-rich material stripped from a non-degenerate companion by a type Ia supernova. *Astron. Astrophys.* **638**, A80 (2020).
127. Kollmeier, J. A. et al. H α emission in the nebular spectrum of the type Ia supernova ASASSN-18tb. *Mon. Not. R. Astron. Soc.* **486**, 3041–3046 (2019).
128. Prieto, J. L. et al. Variable H α emission in the nebular spectra of the low-luminosity type Ia SN2018ccj/ATLAS18qtd. *Astrophys. J.* **889**, 100 (2020).
129. Elias-Rosa, N. et al. Nebular H α emission in type Ia supernova 2016jae. *Astron. Astrophys.* **652**, A115 (2021).
130. Yan, L. et al. Detection of broad H α emission lines in the late-time spectra of a hydrogen-poor superluminous supernova. *Astrophys. J.* **814**, 108 (2015).
131. Moriya, T. J., Liu, Z.-W., Mackey, J., Chen, T.-W. & Langer, N. Revealing the binary origin of Type Ic superluminous supernovae through nebular hydrogen emission. *Astron. Astrophys.* **584**, L5 (2015).
132. Murray, C. D. & Correia, A. C. M. in *Exoplanets* (ed. Seager, S.) 15–23 (Univ. Arizona Press, 2010).
133. Fruscione, A. et al. CIAO: Chandra’s data analysis system. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 6270 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 62701V (eds Silva, D. R. & Doxsey, R. E.) (SPIE, 2006).
134. Kalberla, P. M. W. et al. The Leiden/Argentine/Bonn (LAB) survey of galactic HI. Final data release of the combined LDS and IAR surveys with improved stray-radiation corrections. *Astron. Astrophys.* **440**, 775–782 (2005).
135. Güver, T. & Özel, F. The relation between optical extinction and hydrogen column density in the Galaxy. *Mon. Not. R. Astron. Soc.* **400**, 2050–2053 (2009).
136. Alp, D. et al. X-ray absorption in young core-collapse supernova remnants. *Astrophys. J.* **864**, 175 (2018).
137. Chandra, P., Chevalier, R. A., Chugai, N., Fransson, C. & Soderberg, A. M. X-ray and radio emission from type IIin supernova SN 2010jl. *Astrophys. J.* **810**, 32 (2015).
138. Immler, S. et al. *Swift* and *Chandra* detections of supernova 2006jc: evidence for interaction of the supernova shock with a circumstellar shell. *Astrophys. J. Lett.* **674**, L85 (2008).
139. Chandra, P. et al. Radio and X-ray observations of SN 2006jd: another strongly interacting type IIin supernova. *Astrophys. J.* **755**, 110 (2012).
140. Stritzinger, M. et al. Multi-wavelength observations of the enduring type IIin supernovae 2005ip and 2006jd. *Astrophys. J.* **756**, 173 (2012).
141. Harrison, F. A. et al. The *Nuclear Spectroscopic Telescope Array* (NuSTAR) High-energy X-ray mission. *Astrophys. J.* **770**, 103 (2013).
142. Wilson, W. E. et al. The Australia Telescope Compact Array Broad-band Backend: description and first results. *Mon. Not. R. Astron. Soc.* **416**, 832–856 (2011).
143. Sault, R. J., Teuben, P. J. & Wright, M. C. H. in *Astronomical Data Analysis Software and Systems IV Vol. 77* (eds Shaw, R. A. et al.) 433–436 (1995).
144. Chevalier, R. A. & Soker, N. Asymmetric envelope expansion of supernova 1987A. *Astrophys. J.* **341**, 867–882 (1989).
145. Langer, N. Presupernova evolution of massive single and binary stars. *Annu. Rev. Astron. Astrophys.* **50**, 107–164 (2012).
146. Gal-Yam, A. et al. A Wolf-Rayet-like progenitor of SN 2013cu from spectral observations of a stellar wind. *Nature* **509**, 471–474 (2014).
147. Postnov, K. A. & Yungelson, L. R. The evolution of compact binary star systems. *Living Rev. Relativ.* **17**, 3 (2014).

148. Hirai, R., Podsiadlowski, P. & Yamada, S. Comprehensive study of ejecta-companion interaction for core-collapse supernovae in massive binaries. *Astrophys. J.* **864**, 119 (2018).
149. Ogata, M., Hirai, R. & Hijikawa, K. Observability of inflated companion stars after supernovae in massive binaries. *Mon. Not. R. Astron. Soc.* **505**, 2485–2499 (2021).
150. Dospoglou, F. & Kalogera, V. Orbital evolution of mass-transferring eccentric binary systems. II. Secular evolution. *Astrophys. J.* **825**, 71 (2016).
151. Maund, J. R., Smartt, S. J., Kudritzki, R. P., Podsiadlowski, P. & Gilmore, G. F. The massive binary companion star to the progenitor of supernova 1993J. *Nature* **427**, 129–131 (2004).
152. Ryder, S. D. et al. Ultraviolet detection of the binary companion to the type IIb SN 2001ig. *Astrophys. J.* **856**, 83 (2018).
153. Maund, J. R., Pastorello, A., Mattila, S., Itagaki, K. & Bole, T. The possible detection of a binary companion to a type IIn supernova progenitor. *Astrophys. J.* **833**, 128 (2016).
154. Sun, N.-C., Maund, J. R., Hirai, R., Crowther, P. A. & Podsiadlowski, P. Origins of type IIn SNe 2006jc/2015G in interacting binaries and implications for pre-SN eruptions. *Mon. Not. R. Astron. Soc.* **491**, 6000–6019 (2020).
155. Fotelliti, G. et al. A blue point source at the location of supernova 2011dh. *Astrophys. J. Lett.* **793**, L22 (2014).
156. Maund, J. R. The origin of the late-time luminosity of supernova 2011dh. *Astrophys. J.* **883**, 86 (2019).
157. Tauris, M. & Takens, R. J. Runaway velocities of stellar components originating from disrupted binaries via asymmetric supernova explosions. *Astron. Astrophys.* **330**, 1047–1059 (1998).
158. Portegies Zwart, S. F. The characteristics of high-velocity O and B stars which are ejected from supernovae in binary systems. *Astrophys. J.* **544**, 437–442 (2000).
159. Kochanek, C. S., Auchettl, K. & Belczynski, K. Stellar binaries that survive supernovae. *Mon. Not. R. Astron. Soc.* **485**, 5394–5410 (2019).
160. Kochanek, C. S. Supernovae producing unbound binaries and triples. *Mon. Not. R. Astron. Soc.* **507**, 5832–5846 (2021).
161. Hameury, J. M. A review of the disc instability model for dwarf novae, soft X-ray transients and related objects. *Adv. Space Res.* **66**, 1004–1024 (2020).
162. Atwood, W. B. et al. The large area telescope on the Fermi Gamma-Ray Space Telescope mission. *Astrophys. J.* **697**, 1071–1102 (2009).
163. Abdollahi, S. et al. Incremental Fermi Large Area Telescope fourth source catalog. *Astrophys. J. Suppl. Ser.* **260**, 53 (2022).
164. Ofek, E. O. & Zuckay, B. Optimal matched filter in the low-number count Poisson noise regime and implications for X-ray source detection. *Astronomical Journal* **155**, 169 (2018).
165. Dullo, B. T., Bouquin, A. Y. K., Gil de Paz, A., Knapen, J. H. & Gorgas, J. The Black Hole mass–color relations for early- and late-type galaxies: red and blue sequences. *Astrophys. J.* **898**, 83 (2020).
166. Itoh, R. et al. Blazar Radio and Optical Survey (BROS): A catalog of blazar candidates showing flat radio spectrum and their optical identification in Pan-STARRS1 surveys. *Astrophys. J.* **901**, 3 (2020).
167. Lioudakis, I., Romani, R. W., Filippenko, A. V., Kocevski, D. & Zheng, W. Probing blazar emission processes with optical/gamma-ray flare correlations. *Astrophys. J.* **880**, 32 (2019).
168. Matz, S. M. et al. Gamma-ray line emission from SN1987A. *Nature* **331**, 416–418 (1988).
169. Teegarden, B. J. et al. Resolution of the 1,238-keV γ -ray line from supernova 1987A. *Nature* **339**, 122–123 (1989).
170. Churazov, E. et al. Gamma rays from type Ia supernova SN 2014J. *Astrophys. J.* **812**, 62 (2015).
171. Ackermann, M. et al. Search for early gamma-ray production in supernovae located in a dense circumstellar medium with the Fermi LAT. *Astrophys. J.* **807**, 169 (2015).
172. Renault-Tinacci, N., Kotera, K., Neronov, A. & Ando, S. Search for γ -ray emission from superluminous supernovae with the Fermi-LAT. *Astron. Astrophys.* **611**, A45 (2018).
173. Yuan, Q. et al. Fermi Large Area Telescope detection of gamma-ray emission from the direction of supernova iPTF14hls. *Astrophys. J. Lett.* **854**, L18 (2018).
174. Prokhorov, D. A., Moraghan, A. & Vink, J. Search for gamma rays from SNe with a variable-size sliding-time-window analysis of the Fermi-LAT data. *Mon. Not. R. Astron. Soc.* **505**, 1413–1421 (2021).
175. Xi, S.-Q. et al. A serendipitous discovery of GeV gamma-ray emission from supernova 2004d in a survey of nearby star-forming galaxies with Fermi-LAT. *Astrophys. J. Lett.* **896**, L33 (2020).
176. Fermi LAT Collaboration et al. Modulated high-energy gamma-ray emission from the microquasar Cygnus X-3. *Science* **326**, 1512 (2009).
177. Piano, G. et al. The AGILE monitoring of Cygnus X-3: transient gamma-ray emission and spectral constraints. *Astron. Astrophys.* **545**, A110 (2012).
178. Modjaz, M. et al. Optical spectra of 73 stripped-envelope core-collapse supernovae. *Astron. J.* **147**, 99 (2014).
179. Hunter, D. J. et al. Extensive optical and near-infrared observations of the nearby, narrow-lined type Ic SN 2007gr: days 5 to 415. *Astron. Astrophys.* **508**, 371–389 (2009).
180. Taubenberger, S. et al. Nebular emission-line profiles of Type Ib/c supernovae – probing the ejecta asphericity. *Mon. Not. R. Astron. Soc.* **397**, 677–694 (2009).
181. Jerkstrand, A. et al. Long-duration superluminous supernovae at late times. *Astrophys. J.* **835**, 13 (2017).

Acknowledgements We thank B. Cenko, Y. Levin, E. Pian, S. Dong, D. Lai, O. Yaron, J. Morag, Y. S. Rimalt and T. Shenar for the discussions. We thank D. J. Thompson for his comments. P.C. and A.G.-Y. thank Y. Beletsky for his assistance with Magellan telescope remote observations. This research has made use of the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Space Science Data Center (SSDC) and the California Institute of Technology (Caltech). SED Machine is based on the work supported by the National Science Foundation under grant no. 1106171. This study is based on observations obtained with the 48-inch Samuel Oschin Telescope and the 60-inch Telescope at the Palomar Observatory as part of the Zwicky Transient Facility (ZTF) project. ZTF is supported by the National Science

Foundation under grant no. AST-2034437 and a collaboration that includes Caltech, IPAC, the Weizmann Institute of Science, the Oskar Klein Center at Stockholm University, the University of Maryland, Deutsches Elektronen-Synchrotron and Humboldt University, the TANGO Consortium of Taiwan, the University of Wisconsin at Milwaukee, Trinity College Dublin, Lawrence Livermore National Laboratories, IN2P3, University of Warwick, Ruhr University Bochum and Northwestern University. Operations were conducted by COO, IPAC and the University of Wisconsin. The Gordon and Betty Moore Foundation, through both the Data-Driven Investigator Program and a dedicated grant, provided funding for SkyPortal. This work has used data from the ATLAS project. The ATLAS project is primarily funded to search for near-earth asteroids through NASA grant nos NN12AR55G, 80NSSC18K0284 and 80NSSC18K1575; by-products of the NEO search include images and catalogues from the survey area. This work was partially funded by the Kepler/K2 grant J1944/80NSSC19K0112 and HST GO-15889 and STFC grants ST/T000198/1 and ST/S006109/1. The ATLAS science products have been made possible through the contributions of the University of Hawaii Institute for Astronomy, the Queen's University Belfast, the Space Telescope Science Institute, the South African Astronomical Observatory and the Millennium Institute of Astrophysics (MAS), Chile. This study is based on the observations made with the NOT, owned in collaboration with the University of Turku and Aarhus University and operated jointly by Aarhus University, the University of Turku and the University of Oslo, representing Denmark, Finland and Norway, respectively, the University of Iceland and Stockholm University at the Observatorio del Roque de los Muchachos, La Palma, Spain, of the Instituto de Astrofísica de Canarias. One of the spectra from NOT was obtained as part of an NBI school in which M. Killi, N. Allen, K. Gould and D. Zhou participated under the leadership of J. Fynbo. This work was supported by the research project grant Understanding the Dynamic Universe funded by the Knut and Alice Wallenberg Foundation under Dnr KAW 2018.0067. The study is based on the observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme 110.25A6. The access for MMT Observatory for part of the MMT/Binospec data was supported by Northwestern University and the Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA). Mephisto is developed at and operated by the South-Western Institute for Astronomy Research of Yunnan University (SWIFAR-YNU), funded by the Yunnan University Development Plan for World-Class University and Yunnan University Development Plan for World-Class Astronomy Discipline. The Australia Telescope Compact Array is part of the ATNF, which is funded by the Australian government for the operation as a national facility managed by the CSIRO. We acknowledge the Gomeri people as the Traditional Owners of the Observatory site. The Cosmic Dawn Center (DAWN) is funded by the Danish National Research Foundation under grant no. 140. S. Schulze acknowledges support from the G.R.E.A.T. research environment, funded by Vetenskapsrådet, the Swedish Research Council, project no. 2016-06012. B.Z. is supported by a research grant from the Willner Family Leadership Institute for the Weizmann Institute of Science, a research grant from the Center for New Scientists at the Weizmann Institute of Science and a research grant from the Ruth and Herman Albert Scholarship Program for New Scientists. A.H. acknowledges the support from the I-Core Program of the Planning and Budgeting Committee and the Israel Science Foundation (ISF) and support from the ISF grant no. 647/18. This research was supported by grant no. 2018154 from the United States–Israel Binational Science Foundation (BSF). A.H. is especially grateful to the Sir Zelman Cowen Academic Initiatives for their funding and support. D.L., Xiangkun Liu, Y.F. and Xiaowei Liu acknowledge the support from special grants to the Yunnan Technology Leading Talents and Provincial Innovation Team. D.L., Xiangkun Liu, Y.F. and Xiaowei Liu also acknowledge supports from the Science and Technology Champion Project (202005AB160002) and from two team projects—the Innovation Team (202105AE160021) and the Top Team (202305AT350002)—all funded by the Yunnan Revitalization Talent Support Program. J.P.U.F. is supported by the Independent Research Fund Denmark (DFF-4090-00079) and thanks the Carlsberg Foundation for support.

Author contributions All authors reviewed the paper and contributed to the interpretation and/or data acquisition. P.C. led the studies. P.C. discovered the periodicity and the γ -ray detection, organized the follow-up observations, conducted X-ray and most optical data acquisition, conducted most of the data reduction, performed the data analysis and wrote most of the paper, including creating all the figures. A.G.-Y. contributed to the follow-up data (including observations performed with MMT/BINOSPEC, Magellan/FIRE, Magellan/FIRE, VLT/X-shooter, NuSTAR, Chandra and ATCA) and to the interpretation, wrote the paper and thoroughly reviewed it. J.S. initiated the study, obtained the spectra with SEDM and NOT, helped in developing the ideas in the paper, wrote the paper and thoroughly reviewed it. S.S. contributed to the follow-up observations with NOT and reduced the NOT spectra. R.S.P. performed the follow-up observations with the 0.8-m RC32 telescope at Post Observatory. C.L. contributed to one MMT/Binospec spectrum, reduced the Magellan/FIRE echelle spectra and contributed to the interpretation. E.O.O. contributed to the follow-up observations with NuSTAR. B.K., D.K., E.O.O., E.W. and B.Z. contributed to the interpretation and especially suggested the analysis of Fermi-LAT data. D.L. performed the Mephisto photometry. Xiangkun Liu organized the Mephisto observations. A.H. and K.R. performed the ATCA radio observation and data reduction. K.K.D., Y.Y., M.M.K. and S.R.K. contributed to the P200/DBSP spectra. C.F. contributed to the SEDM photometry. A.A.M. contributed to one MMT/BINOSPEC spectrum. S.Y. contributed to the analysis of light curves with the nickel decay model. J.P.U.F. obtained a spectrum from the NOT. S.R.K., A.J.D., J.D.N., E.C.B., S.L.G., A.W., T.J.d.L., R.L.R., G.H. and R.D. are the ZTF builders. D.L., Xiaowei Liu, Xiangkun Liu and Y.F. contributed to the observation and reduction of Mephisto data. I.L., A.S., N.L.S., P.A.M. and L.Y. contributed to the interpretation. Y.-J.Q. contributed to the observation of DBSP spectra.

Competing interests The authors declare no competing interests.

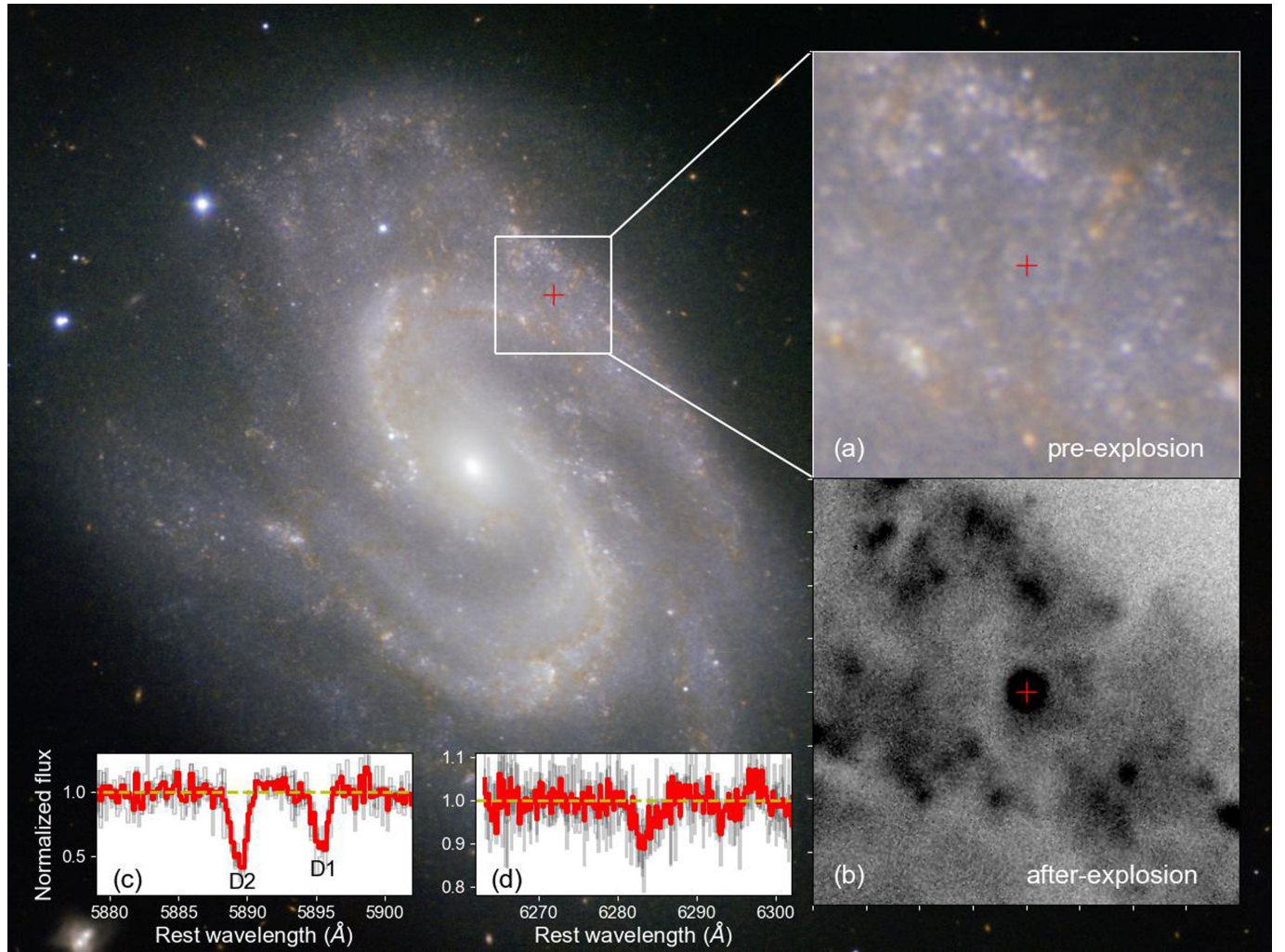
Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41586-023-06787-x>.

Correspondence and requests for materials should be addressed to Ping Chen.

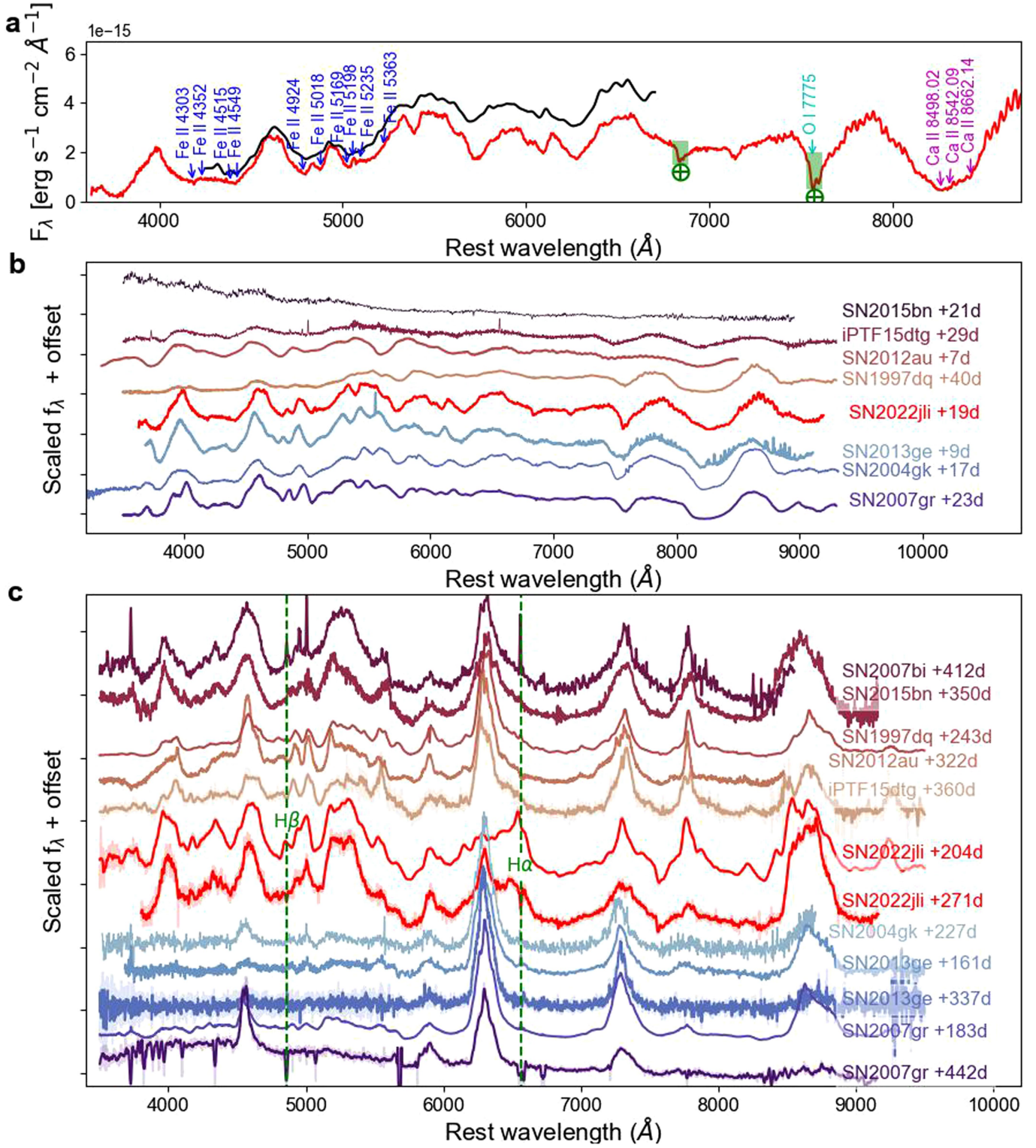
Peer review information Nature thanks Fernando Patat and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.

Reprints and permissions information is available at <http://www.nature.com/reprints>.



Extended Data Fig. 1 | SN 2022jli and the host galaxy NGC 157. The background image shows the three-color (Y, H, K bands) image of NGC 157 taken before the supernova explosion with the HAWK-I instrument on ESO's Very Large Telescope (VLT) at the Paranal Observatory in Chile (Credit: ESO). The red plus symbol in the figure indicates the position of SN 2022jli. Inset panels: **a**, zoom-in view around SN 2022jli showing the nearby environment in NIR; **b**, zoom-in

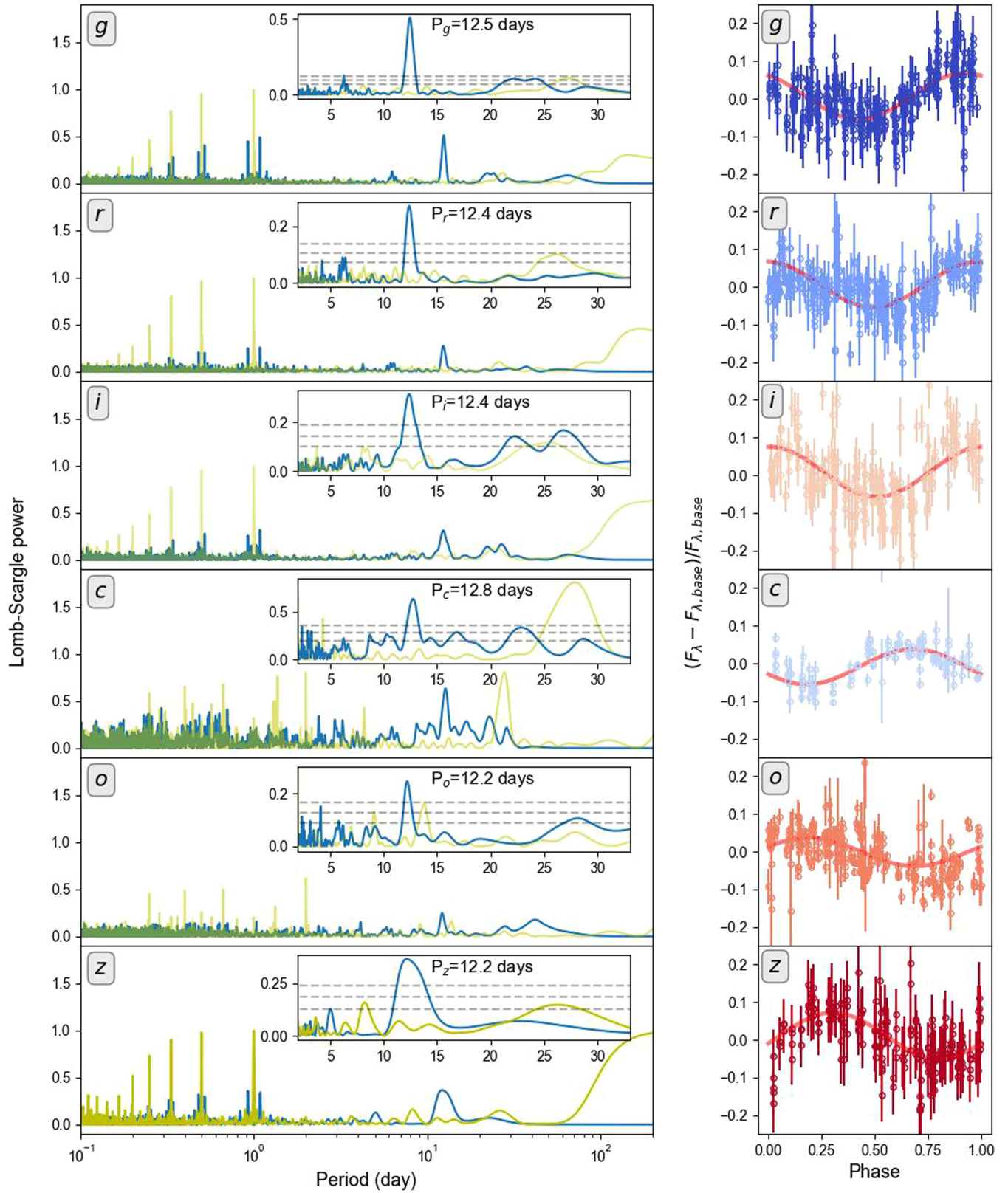
view around SN 2022jli on an r -band image taken with Magellan/IMACS on 2022 December 15; **c**, Na I absorption lines from the host galaxy; **d**, the narrow diffuse interstellar band absorption (DIB6283) from the host galaxy. **a, b**, Share the same field of view size. **c, d**, The red spectrum shows the averaged spectrum of three X-Shooter spectra and one IMACS spectrum, whereas the individual spectra are shown in grey in the background.



Extended Data Fig. 2 | Spectral evolution and comparison of SN 2022jli.

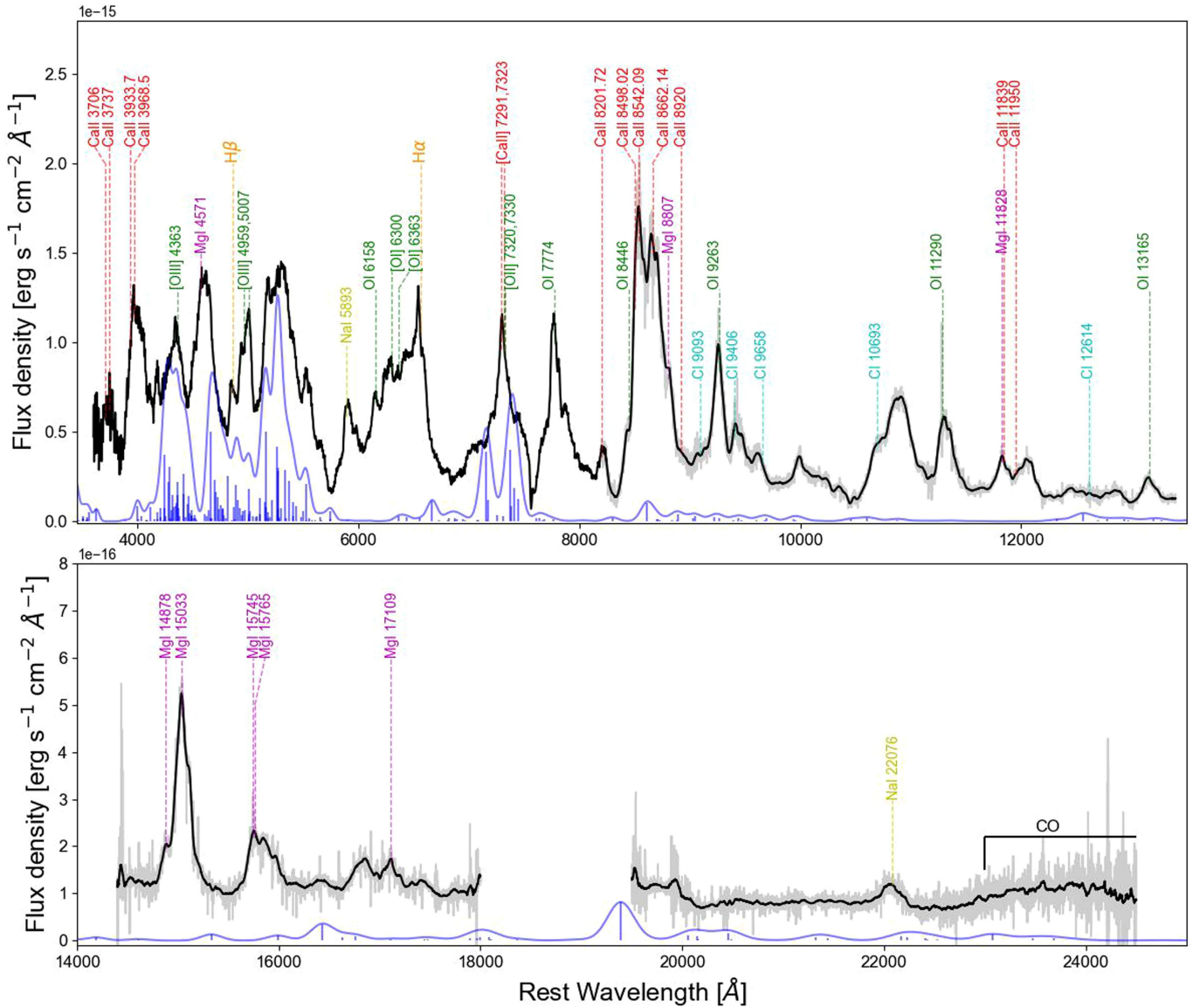
a, Photospheric spectra of SN 2022jli. The +6d spectrum and the +19d spectrum are shown in black and red, respectively. The identified absorption lines of Fe II, O I, and Ca II are indicated with the arrows. A blue-shifted velocity of 8,200 km s^{-1} has been applied to all the lines. **b**, The +19d spectrum of SN 2022jli compared with photospheric spectra of other SNe. The comparison objects include:

normal SNe Ic (SN 2004gk¹⁷⁸, SN 2007gr¹⁷⁹), SN Ib/c (SN 2013ge¹⁰⁶), “Hypernovae” (SN 1997dq^{12,13,180}), Hydrogen-poor SLSNe (SN 2015bn^{5,181}), and other long-lasting peculiar SESNe (SN 2012au¹⁴, iPTF15dtg¹⁵). **c**, Late-time spectra of SN 2022jli and other comparison SNe. The comparison objects are the same as in **b** except that we have added another Hydrogen-poor SLSN SN 2007bi¹¹. The vertical dashed lines mark the wavelength of H α and H β .



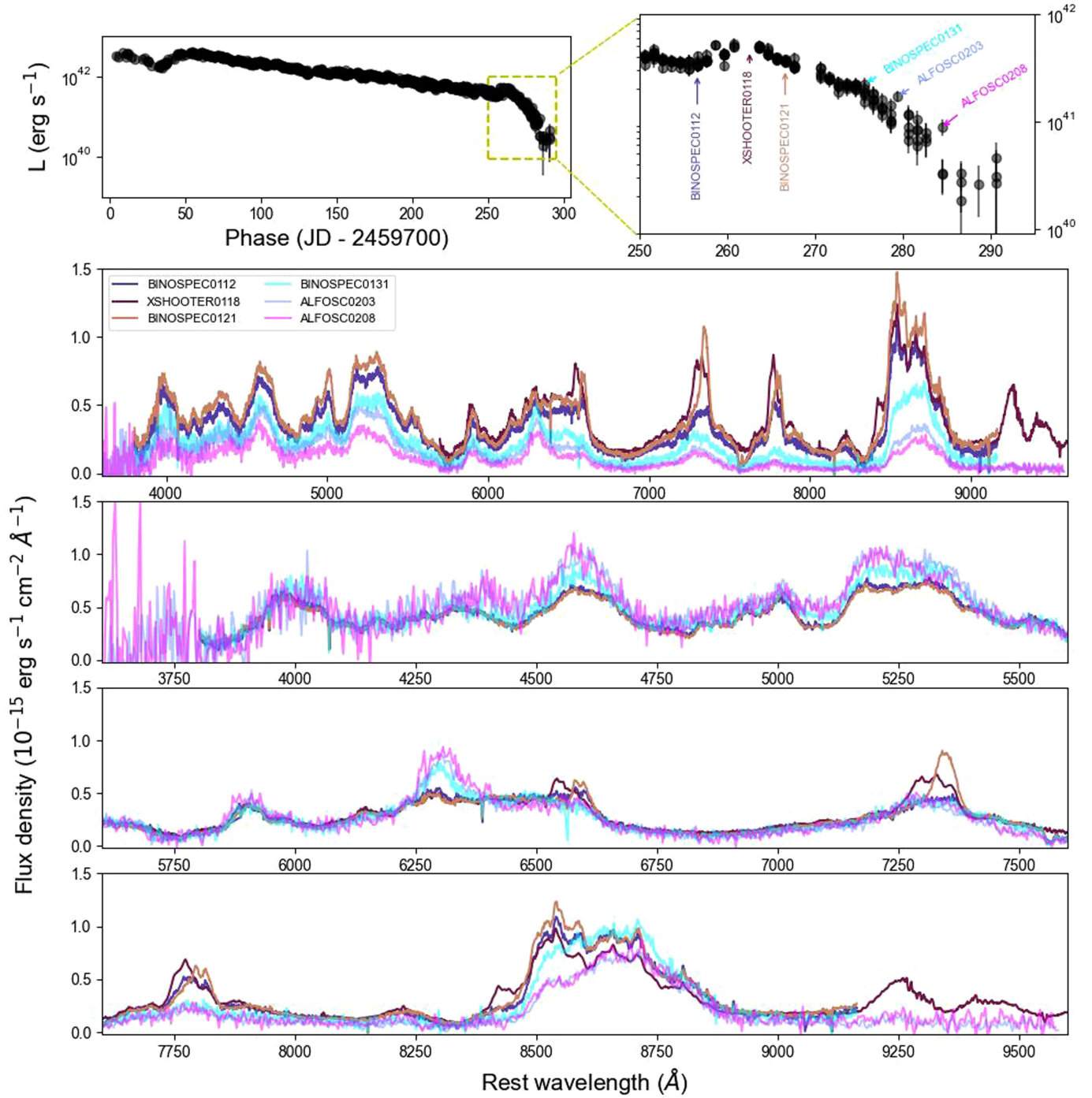
Extended Data Fig. 3 | Periodicity analysis of light curves in the individual bands. Left: the Lomb-Scargle power spectrum of the light curve (blue) and the observation window function (yellow). The zoom-in panel shows the region of interest around the true periodic signal. The horizontal lines indicate the false

alarm probability (FAP) levels of 10^{-3} , 10^{-6} , and 10^{-9} from bottom to top. Right: the phase-folded subtracted and normalized light curve. The period adopted for the folding corresponds to the peak power in the zoom-in panel on the left.



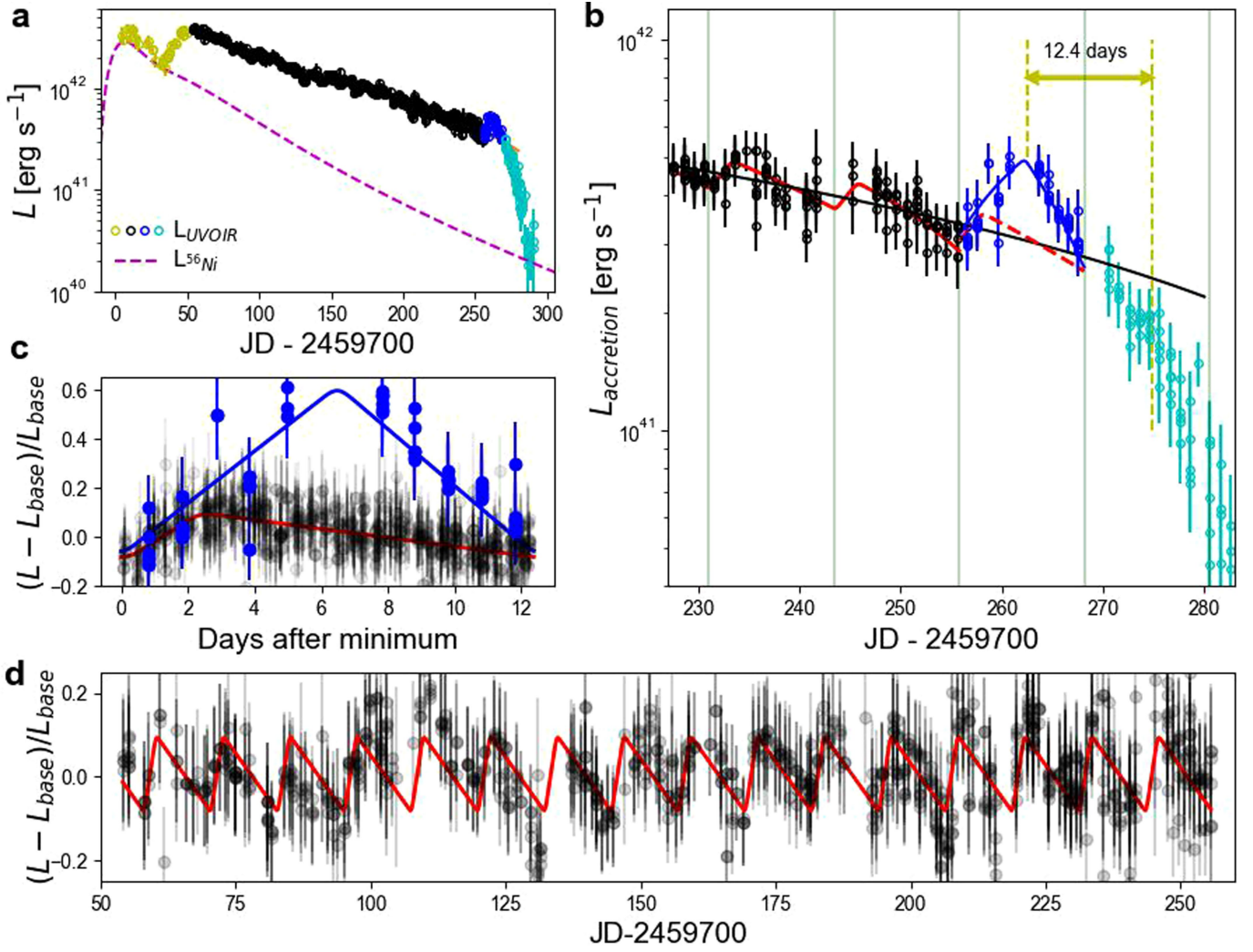
Extended Data Fig. 4 | Optical and NIR spectra of SN 2022jli around +210 days after discovery (optical spectrum taken with NOT/ALFOSC on 2022 November 25 and NIR spectrum taken with Magellan/FIRE on 2022 December 15). The NIR spectrum has been scaled to match the flux of the optical spectrum in the overlapping region. The prominent features and the corresponding ions (or molecules) that likely contributed to the emission lines

are marked. The spectrum in blue shows the mock spectrum of Fe II, Fe III and Ni II emission, and the vertical lines indicate emission from individual transitions which give relatively strong emission. The absolute strength of the mock spectrum is arbitrary, and the relative strength between different transitions for the same ion was calculated for a temperature of 10^4 K, and an electron density of 10^7 cm^{-3} .



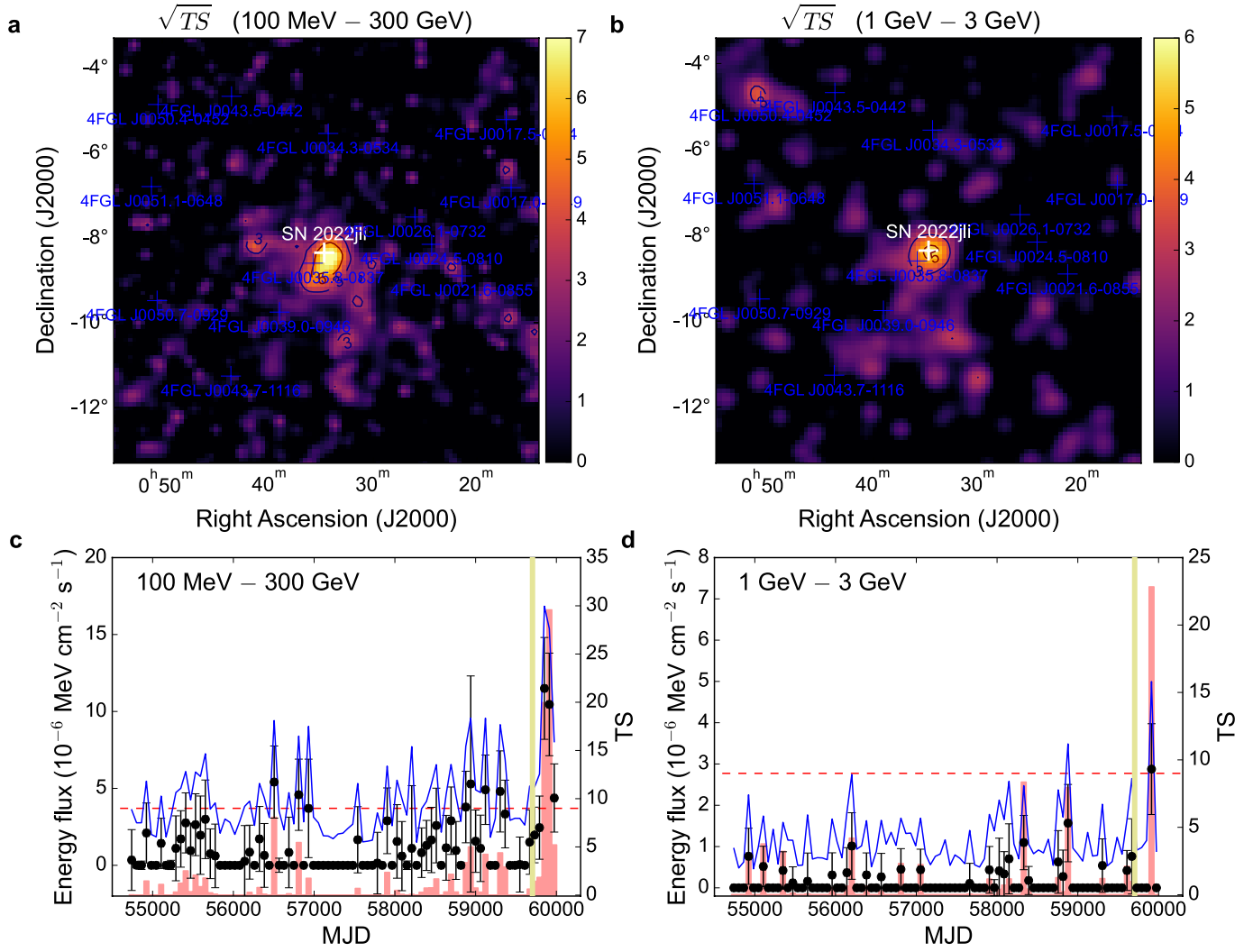
Extended Data Fig. 5 | Spectral evolution of SN 2022jli before and during the fast decline phase of the light curve. The top left panel shows the bolometric light curve, and the top right panel shows the zoom-in view of the fast decline phase of the light curve. The second panel shows the six epochs of spectra as indicated in the top right panel. The bottom three panels show the

zoom-in view of the spectra within different wavelength ranges. All spectra in the bottom three panels have been scaled to have the same integrated luminosity between 3800 to 9000 Å as the BINOSPEC spectrum taken on 12 January 2022.



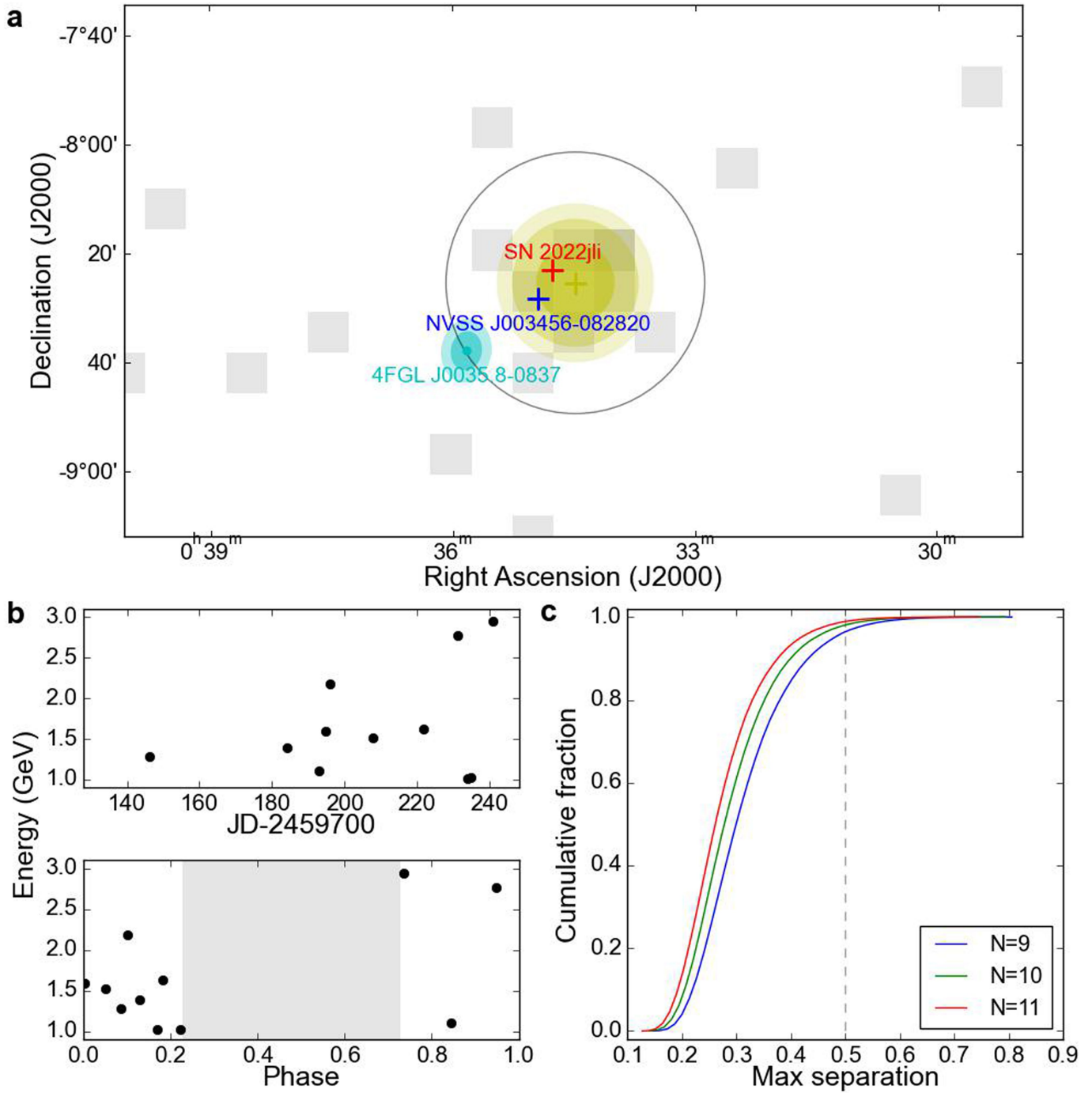
Extended Data Fig. 6 | Pseudo-bolometric light curve of SN2022jli. **a**, The points show the pseudo-bolometric light curve from 3750 Å to 25000 Å. These data points share the same colours with the other panels to indicate different phases. The black shows the gradual decline phase during which the constant relative undulation is detected. The last bump before the fast-declining phase is shown in blue, and the fast-declining phase is shown in cyan. The magenta line shows the radioactive decay model with $0.15 M_{\odot} {}^{56}\text{Ni}$. **b**, Zoom-in view of the accretion-powered pseudo-bolometric light curve, $L_{\text{accretion}} = L_{\text{UVOIR}} - L_{56\text{Ni}}$, before and during the fast-declining phase. The black solid line shows the linear

fit to data between 200 and 260 days after JD = 2,459,700. The red solid line shows the best-fit undulation model to the data, while the red dashed line shows the extrapolation of the undulation model if the SN follows the previous undulations. The vertical green lines mark the 12.4-day periods with the left three lines at the minima of the undulation profiles. **c**, The undulation profiles of the gradual-declining phase and the last bump. **d**, The relative undulation of the accretion-powered pseudo-bolometric light curve. The red line shows the empirical undulation model adopting the same empirical undulation profile as in **c**.



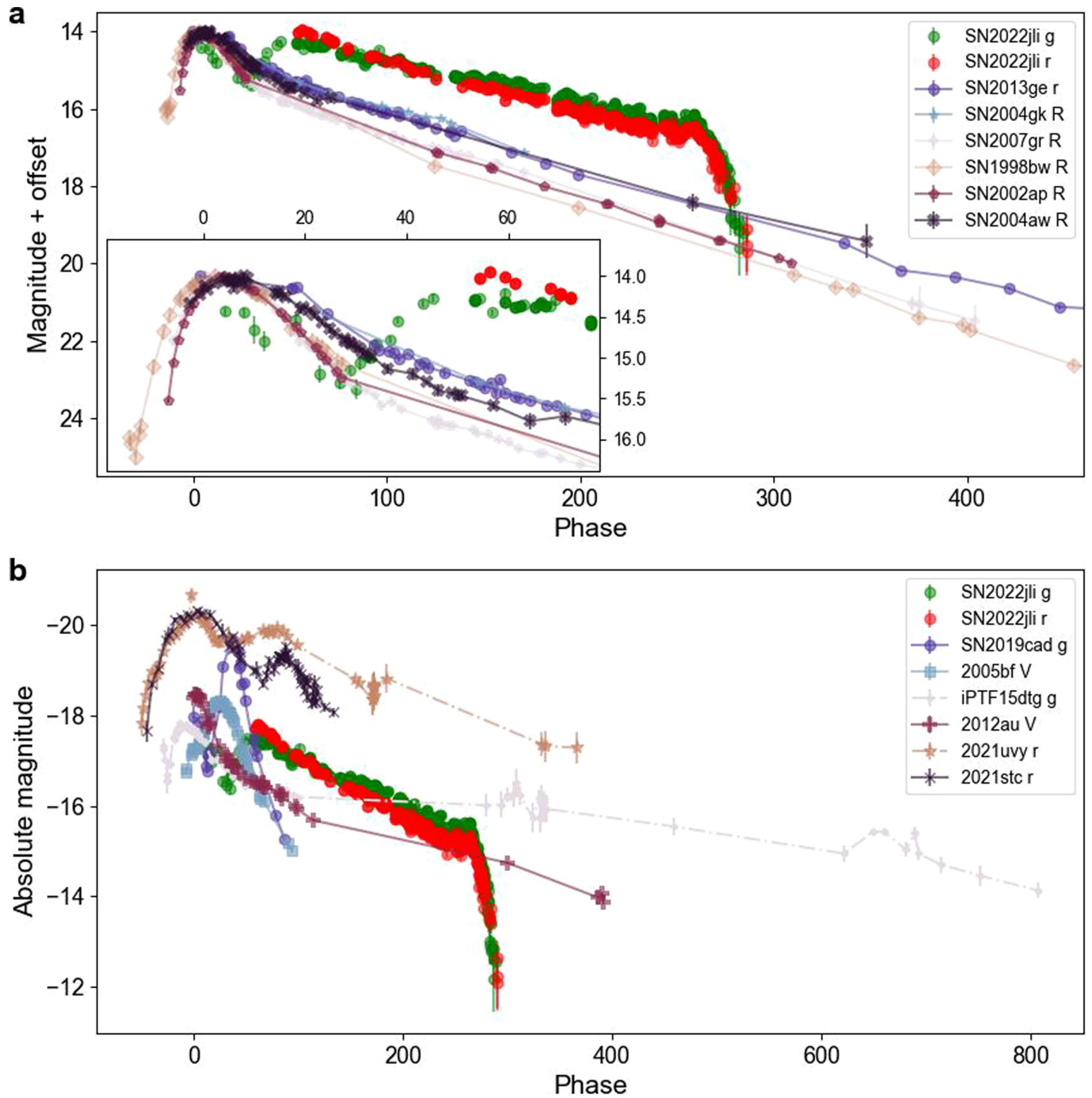
Extended Data Fig. 7 | Detection and light curve of the new γ -ray source. The top panels show the Test Statistic (TS) map of the region of interest in the direction of SN 2022jli. **a**, The result of data observed from 1 May 2022 to 1 March 2023 in the broad energy band (100 MeV – 300 GeV). **b**, The result of data observed from 1 November 2022 to 1 January 2023 in the narrow energy band (1 – 3 GeV). The sources from the 4FGL-DR3 catalogue shown with blue plus symbols have been modelled and subtracted from the map. The bottom panels show the γ -ray light curves of the detected source at the position of SN

2022jli with a bin size of 2 months. **c**, The energy range of 100 MeV to 300 GeV. **d**, The energy range of 1 GeV to 3 GeV. The black points show the measured energy flux from the likelihood modelling with the Fermi-LAT analysis tool. The blue lines give the upper limit of energy flux within a 95% confidence interval. The red histograms show the Test Statistics values on the right axis. The horizontal dashed red line marks $TS=9$. The vertical yellow lines mark the discovery time of SN 2022jli.



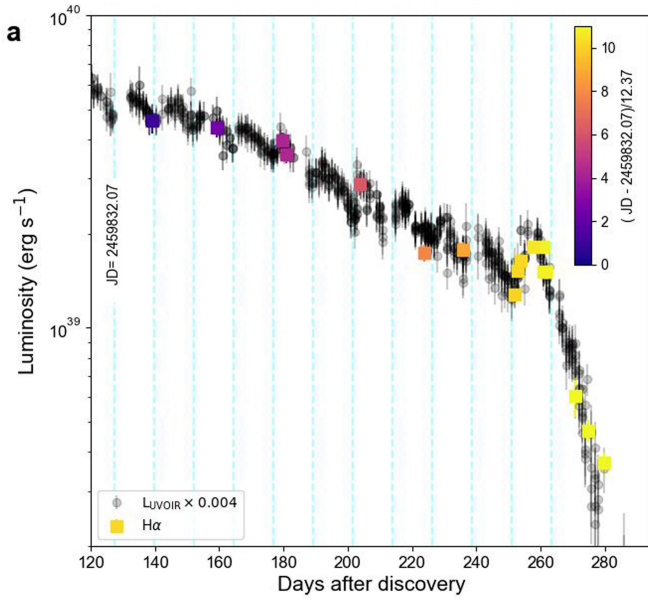
Extended Data Fig. 8 | Localization and potential periodicity of the new γ -ray source. **a**, The background mosaic grey pixels show the count map of 1–3 GeV photons detected between 1 November 2022 and 1 January 2023. The pixel size is $0.125^\circ \times 0.125^\circ$. The yellow plus symbol shows the best-localized position of the new γ -ray source, and the surrounding yellow contours show the corresponding 68%, 95%, and 99% confidence area. SN 2022jli, the red plus symbol, is within the 68% uncertainty region of the detected γ -ray source. The blazar candidate NVSS J003456-082820 is shown with the blue plus symbol and is within the 95% uncertainty region of the new γ -ray source. In the central $1.625^\circ \times 1.625^\circ$ field, there is one detected γ -ray source from the LAT 12-year Source Catalog (4FGL-DR3), 4FGL J0035.8-0837. The black circle has a radius of

0.4° corresponding roughly to the 50% containment radius of the averaged PSF over the energy range between 1 GeV and 3 GeV. **b**, The distribution of 1–3 GeV photons of the new γ -ray source. The top panel shows the photon energy and detection time. The bottom panel shows the distribution after folding the light curve with a period of 12.4 days. The reference time (phase=0) corresponds to the minimum of the optical undulation profile. Most of the γ -ray photons come from the rising phase of the optical bump. The 11 photons are within the half-containment radius shown in **a**. **c**, The cumulative distribution of the maximum separation between any two photons that would be achieved by drawing N photons randomly distributed in a time range of 120 days.

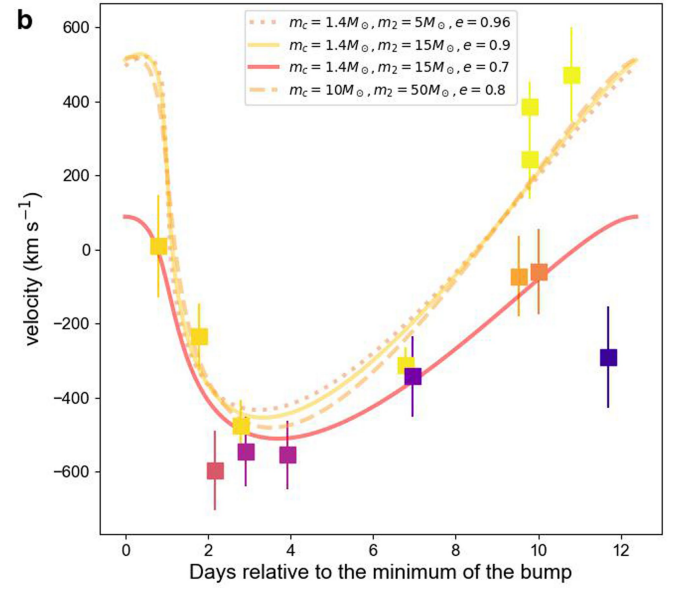


Extended Data Fig. 9 | Light curve of SN 2022jli compared with those of other supernovae. a, Comparison with Type Ic supernovae dominantly powered by radioactive decay showing clear exponential decay tails. All the comparison supernovae have been shifted to have a peak at 14th magnitude.

The inset panel shows a zoom-in view around the peak light. **b,** Comparison with the long-lasting SN 2012au (SN Ib), and other supernovae with double-peaked light curves.



Extended Data Fig. 10 | Evolution of the accretion-powered H α emission.
a, The line luminosity of the H α emission compared with the pseudo-bolometric luminosity. **b**, The velocity of the H α emission. The data points share the same colour as in **a**, indicating the phase of the corresponding spectrum. The lines



show the orbital velocity model with specific orbital parameters in the legend. An edge-on view (inclination angle $i = 90$ degrees) is adopted for all models. The orbital parameters include compact remnant mass m_c , companion star mass m_2 , and orbital eccentricity e . The errorbars are 1σ confidence intervals.