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Supplementary information

An infrared transient from a star engulfing a planet

In the format provided by the authors and unedited

Supplementary Information

1 Identification in ZTF The Zwicky Transient Facility is a wide-field optical time domain survey running out of the 48-inch Schmidt telescope (P48) at Palomar observatory[9,68]. With a field of view of 47 square degrees, the instrument achieves a median limiting magnitude of $r \approx 20.5\,\mathrm{mag}$ in 30 s exposures of the sky and a survey speed of ≈ 3750 square degrees per hour[69,70]. provide an overview of the various ZTF surveys undertaken in Phase-I of operations, and the survey scheduling system designed to carry out operations to maximize volumetric survey speed. The transient source ZTF 20aazusyv (hereafter ZTF SLRN-2020) was first detected in the ZTF difference imaging pipeline on UT 2020-05-16 (MJD 58985.37) at J2000 coordinates α =19:09:39.78 and δ =+05:35:04.25, and at a magnitude of $r = 20.03 \pm 0.19\,\mathrm{mag}$. The corresponding Galactic coordinates are $l = 39.979890$, $b = -1.48927$, placing this source in the direction of Galactic disk. The transient was not detected on MJD 58983.38 to a 5σ limiting magnitude of $r = 20.48$. We nominally adopt the mid-point of the last non-detection and the first detection of the transient in r-band (MJD 58984.38) as the time of start for the eruption.

We identified ZTF SLRN-2020 as a candidate classical nova as part of an ongoing systematic search for Galactic novae in optical/near-infrared (NIR) time domain surveys[60]. Nova candidates were identified in the public ZTF alert stream (g and r filters) by selecting for slow-evolving, large amplitude Galactic plane transients through a custom filter implemented on the `kowalski` time domain astronomy server[72]. The selection criteria were as follows:

1. The transient should be located within 10 degrees of the Galactic plane.

2. The transient should have no prior history of outbursts in the ZTF alert archive.

3. The transient should have brightened by > 3 mag from the nearest counterpart in the PanSTARRS1 (PS1) source catalog[73], if one exists within 2 arcsec; or the source should have no known PS1 counterpart within 2 arcsec.

4. The transient should exhibit a slow evolving light curve with $t_2 > 30$ days, where t_2 is the time taken to fade by 2 magnitudes from the peak of the outburst. This criteria distinguishes classical novae from the majority of dwarf nova outbursts that exhibit fast evolving light curves with $t_2 < 30$ days[74].

2 Photometry from ground-based time domain surveys We retrieved gri photometry of the transient from data taken with the P48 ZTF camera[9], that were processed with the ZTF data processing system[75]. Light curves were extracted using forced point spread function (PSF) photometry[75] at the location of the transient in the difference images[76], where the location was determined from the median of the positions in all published alerts of the transient. We report detections in the forced photometry for epochs where the signal-to-noise ratio (SNR) is higher than 3σ, while 5σ upper limits are reported for other epochs. While the g and r-band data were acquired as part of the ongoing ZTF public survey, the i-band data was acquired as part of an internal collaboration survey where the reference images were contaminated by the transient emission and therefore non-trivial to remove. We thus chose to use i-band photometry reported as part of the PSF-fit source catalogs[75] for each observation, where the transient is detected starting from the first i-band observation of the field on UT 2020-04-16 until the end of the observing season. As the transient was brightest in

i-band, we use the peak of the i-band light curve as the reference phase for all other observations.

Given the high cadence of the ZTF data as well as the relatively slow evolution of the transient, we performed an inverse variance weighted binning of the flux measurements in bins of 3 days to improve the SNR and report them in Table S1; however, we also show the 1-day cadence early time ZTF i-band light curve in Figure 1. We perform the same binning for reporting upper limits, where we use inverse variance weighted flux uncertainty to report the 5σ upper limit for each epoch. We also retrieved forced photometry at the source location from data taken with the Asteroid Terrestrial-impact Last Alert System (ATLAS) survey[48] using the public photometry service[77]. We performed binning using the same method on the ATLAS data and the transient emission is clearly detected in both the c and o filters. The ZTF and ATLAS photometry are presented in Table S1 and shown in Figure 1.

3 Mid-IR NEOWISE Photometry The transient location was observed during the ongoing NEOWISE all-sky mid-IR survey in the $W1$ ($3.4\,\mu$m) and $W2$ ($4.6\,\mu$m) bands[49,78]. We retrieved time-resolved coadded images of the field created as part of the unWISE project[79,80]. Due to the location of the source in a crowded field with nearby blended sources (Figure 1), we used a custom code[81] based on the ZOGY algorithm[76] to perform image subtraction on the NEOWISE images using the full-depth coadds of the WISE and NEOWISE mission (obtained during 2010-2014) as reference images. Photometric measurements were obtained by performing forced PSF photometry at the transient position on the subtracted NEOWISE images until the epoch of the last NEOWISE data release (data acquired until December 2021). Transient mid-IR emission is clearly detected in the subtracted images starting ≈ 250 days prior to the optical outburst peak. The template-subtracted

NEOWISE photometry are provided in Table S2 and shown in Figure 1.

4 Swift Observations We obtained X-ray follow-up of the transient with the Swift X-ray telescope (XRT[82]) on the Neil Gehrels Swift Observatory (Swift[11]). The Swift observatory observed the location of the transient on UT 2020-11-04 ($\approx$ 160 days after i-band peak) for a total exposure time of 1.35 ks. No source was detected at the location of the transient down to a 3σ limiting flux of 8.3×10^{-3} count s^{-1}, corresponding to a 0.3–10 keV flux of 2.8×10^{-13} ergs cm^{-2} s^{-1} for a photon index of $\Gamma = 2$. In the same observation, no source was detected with the Ultraviolet Optical telescope (UVOT[83]) in the UVW2 filter, down to a 3σ limit of 22.69 AB mag. The X-ray non-detection constrains the X-ray luminosity of the source to be $\lesssim 5.3 \times 10^{32} (d/4\,\mathrm{kpc})^2$ erg s^{-1} at this phase, and therefore is much fainter (even if placed at ≈ 20 kpc) than accretion events around neutron stars or black holes that reach at least $\gtrsim 10^{35}$ erg s^{-1} during the outburst[12,84].

5 NIR imaging follow-up We obtained NIR imaging of the transient location on UT 2021-03-31 and UT 2022-07-23 with the Wide-Field Infrared Camera (WIRC[85]) on the Palomar 200-inch telescope. We obtained dithered exposures of the field for a total exposure time of 495 s, 330 s and 330 s respectively in the J, H and Ks filters respectively on each epoch. The data were reduced using standard techniques including dark subtraction, flat-fielding, sky subtraction, astrometric and photometric calibration[60]. For the image taken in 2021 March when the transient was bright (Figure 1), we performed aperture photometry on the reduced images at the position of the transient. We provide all IR magnitudes in the Vega system. The resulting magnitudes are $J = 16.64 \pm 0.02$, $H = 15.42 \pm 0.02$ and $Ks = 14.67 \pm 0.01$ on UT 2021-03-31.

Given the crowded nature of the field as well as marginal evidence for blended sources near the transient location in the WIRC images, we obtained additional high spatial resolution Adaptive Optics (AO) assisted imaging using the Gemini South Adaptive Optics Imager (GSAOI) on the Gemini-S telescope[86,87]. The source was observed on UT 2022-04-15 as part of a Director's Discretionary Program (GS-2022A-DD-102; PI: K. De). We obtained dithered exposures of the field using Laser Guide Star (LGS) correction for a total exposure time of 300 s on source and 300 s off the source (for background subtraction) in J-band. Observations were also obtained in the H and K filters with GSAOI but were unusable due to poor atmospheric conditions. The raw images were detrended and stacked using the `DRAGONS` pipeline[88], using the source catalog from the WIRC images for astrometric and photometric calibration. The transient is clearly detected in the GSAOI images together with a likely unrelated nearby point source $\approx 0.6''$away (Figure 1).

We use the GSAOI images to measure the best position of the transient source to be at J2000 coordinates α =19:09:39.783 and δ = +05:35:04.269. The coordinates of the unrelated nearby source are α = 19:09:39.815 and δ = +05:35:04.064. The typical positional uncertainty is estimated to be $< 0.05''$by cross-matching against the Gaia DR3 catalog. We perform aperture photometry at the location of the transient to obtain a flux of $J = 19.17 \pm 0.05$ mag. We use the GSAOI positions to derive flux measurements for the transient source detected in the multi-band WIRC images from 2022 July. The source is clearly blended with the unrelated nearby source in the WIRC images, and we fit the image around the position of the transient with a `tractor` model[89] to obtain deblended flux measurements. We fix the position of the transient and nearby source as measured from the GSAOI images, and jointly fit the flux of the two sources using the measured PSF of the image to minimize the residual χ^2 using the Markov Chain Monte Carlo library `emcee`[90]. The resulting flux measurements for the transient are $J = 19.17 \pm 0.15$ mag, $H = 17.75 \pm 0.09$ mag and $Ks = 17.13 \pm 0.10$ mag.

6 Archival optical/IR observations The location of the transient was covered prior to the outburst in the Second Palomar Observatory Sky Survey (POSS-II[91]) and no source is detected at the transient position. Given the crowded field, we estimate the flux upper limit by querying the digitized Guide star catalog[92] of the POSS-II plates to estimate the approximate flux of the faintest sources in a radius of $\approx 1'$. The corresponding upper limits are provided in Extended Data Table 1. No source is reported at the transient position in the latest Gaia data release[93,94]. The position was observed in the United Kingdom Infrared Telescope (UKIRT) Galactic plane survey[20] between 2007 and 2011. A faint progenitor is detected at the position of the transient as well as reported in the UKIRT source catalog. However, the source is clearly blended with the unrelated nearby source detected in the GSAOI images, and the photometric measurements are contaminated with the nearby source as confirmed by the shifted position of the flux centroid with respect to the transient position in the GSAOI images. In order to obtain improved flux measurements for the progenitor counterpart, we fit a `tractor` model[89] to the UKIRT image as in the case of the late-time WIRC images. The source is detected in the H and K bands, but fainter than the 3σ detection threshold in J-band; we tabulate the measured fluxes from the `tractor` modeling in Extended Data Table 1. The source location was also covered in optical images acquired in the PanSTARRS1 survey[73], but the progenitor was not detected. We obtained 5σ upper limits on the progenitor optical flux by querying the PS1 source catalog in a $2'$ region around the position and estimating the median magnitude of sources at the 5σ detection threshold. The flux limits are reported in Extended Data Table 1.

7 Spectroscopic follow-up Following the identification of the transient, we obtained one epoch of optical spectroscopy and one epoch of near-infrared spectroscopy of the outburst using the Low Resolution Imaging Spectrometer (LRIS[95]) on the Keck-I telescope and TripleSpec[96] on the Palomar 200-inch telescope respectively. The LRIS data were reduced using standard techniques using an automated pipeline[97], while the TripleSpec data were reduced using the `spextool` pipeline[98] followed by telluric correction and flux calibration using `xtellcor`[99]. The spectra obtained during the outburst are summarized in Extended Data Table 2. We obtained two epochs of near-infrared spectroscopic follow-up of the infrared remnant star ≈ 2 years after the outburst using the Folded-port Infrared Echellette (FIRE[100]) on the Magellan Baade telescope and one epoch using the Near-Infrared Echellette Spectrometer (NIRES[101]) on the Keck-II telescope. The observing setups are summarized in Extended Data Table 2. The FIRE data were reduced using the `pypeit` code[102] for the echelle mode data and the `firehose` pipeline[103] for the prism mode data. The NIRES data were reduced as the TripleSpec data using the `spextool` pipeline[98], followed by telluric correction using the `xtellcor` pipeline[99]. As the late-time data were acquired close in time (Extended Data Table 2), we performed an inverse variance weighted stacking of the spectra to improve the signal-to-noise ratio. The individual spectra were flux calibrated to match the contemporaneous late-time JHK photometry obtained from WIRC, and the stacked spectrum was binned to the resolution of the Keck-NIRES data ($R \approx 2700$). The final reduced and stacked spectra are shown in Figure 3.

8 VLA SiO maser search Two hours of Director's Discretionary Time was awarded on NSF's Karl G. Jansky Very Large Array (VLA) to observe the field of ZTF SLRN-2020 at 43 GHz using the most extended (A-array) configuration on 2022 April 14 under project 22A-464 (PI: De). The observations, of which about 53 minutes on ZTF SLRN-2020, were set up to be sensitive to any SiO (maser) emission between 42.25 and $43.5\,$GHz. The SiO transitions were targeted to possibly help confirm the peculiar giant merger product and to possibly measure its line-of-sight velocity to get a constraint on a (kinematic) distance to support its remarkable low luminosity.

The observations used 3C286 to calibrate the flux density scale and the instrumental bandpass response. Antenna pointing calibration in the direction of the target field was performed using J1851+0035, whereas the gain and reference calibrator J1912+0518 observed 50 cycles of 25 seconds while interspersing the 65 second observations of ZTF SLRN-2020 using a cycle time of 2 minutes (with a slew time of about 10 seconds each way). The data were inspected for bad visibilities and further processed using the general PIPEAIPS pipeline reduction procedure in AIPS. Calibration and imaging did not reveal any potential issues and the resulting synthesized beam measured about 65 by 45 mas at a position angle of -60 degrees. The calibrator J1912+0518 was measured to have a flux density of about $88 \pm 2\,$mJy/beam.

The setup was in particular targeting the (J=0-1) v=1 and v=2 transitions using a channel width of 62.5 kHz ($\approx 0.5\,$km/s) to an RMS level of $\approx 6\,$mJy/channel, although all seven possibly detectable transitions were covered using 1 MHz ($\approx 7\,$km/s) channels with an RMS of $\approx 1.2\,$mJy/channel. The $\sim$1.2 GHz line-free continuum bandwidth at 43 GHz was imaged down to an RMS of $\approx 35\mu$Jy/beam. No significant SiO line nor continuum emission was detected in the several arcseconds surrounding the infrared position of ZTF SLRN-2020, down to the 3.0σ flux uncertainty within 0.2" of the expected position. For the line emission, we searched up to $\approx 60\,\mathrm{MHz}$ ($\pm 420\,\mathrm{km/s}$) of the transition rest frequencies which is a conservative upper limit for objects bound to the Galaxy.

9 SMA search for sub-mm molecular emission ZTF SLRN-2020 was observed with the Submillimeter Array on 15 March 2022, 17 June 2022 and 21 September 2022. The SMA was in the extended configuration in the first two epochs, with 6 antennas operating in the array, and the last epoch was in the sub-compact configuration. The phase center coordinates were RA(2000) = 19:09:38.78, DEC(2000) = +05:35:04.3. Both the 230 and 240 GHz receivers were tuned to place the frequency of the CO 2-1 line, 230.538 GHz, in the spectral window 1 in the upper sideband (with each sideband providing 12 GHz of frequency coverage). With this tuning, the lower sideband covered 209.5 to 221.5 GHz and upper sideband: 229.5 to 241.5 GHz. The spectral resolution is 140 kHz, but the raw data were smoothed to an effective resolution of 1.1 MHz per channel. The primary gain calibrator was 1830+063, observed periodically for 4 min, following the integration for 15 minutes on the target source. The quasars 3C279 and BL Lac were observed for 2 hours each, to provide bandpass calibration. Absolute fluxes were calibrated using observations of MWC349a, Mars and Callisto. In the first epoch, the system temperature varied from 80 to 200K, with the atmospheric zenith optical depth (at 225 GHz) ≈ 0.1. The weather was better in the second epoch, with $\tau_{225} = 0.06 - 0.08$, and system temperatures varying from $80 - 150\,\mathrm{K}$.

The SMA data were reduced using the Millimeter Interferometer Reduction (MIR) software using the online procedure[104]. The resulting calibrated visibility data were imaged using the Common Astronomy Software Application (CASA)'s tclean task. We imaged a range of channels covering a velocity interval of $\approx \pm 60\,\mathrm{km\,s^{-1}}$ around the CO 2-1 line, producing a data cube of channel maps. The synthesized beam size in the combined observations was $1.25 \times 0.85''$, with PA of $104.2°$. No point source is detected at the position of the transient. The combined (including both datasets) continuum sensitivity is 0.17 mJy/beam while for an individual channel for the CO cube is 14.3 mJy/beam over 3 km/s.

10 Photometric analysis We compare the high cadence r and i-band light curves of ZTF SLRN-2020 to a sample of known red novae from the literature in Extended Data Figure 1. ZTF SLRN-2020 broadly exhibits a fast rise to peak starting ≈ 10 days prior to outburst peak followed by a slow decay of ≈ 2.5 mag over ≈ 200 days. While the Galactic objects V1309 Sco and OGLE-BLG-360 exhibit a long and slow rise prior to the peak of the light curve, the photometric behavior of ZTF SLRN-2020 around peak is similar to V838 Mon. The fast rise and slow decay of ZTF SLRN-2020 is also similar to many extragalactic red novae (e.g. AT 2018hso and AT 2017jfs) but the duration is longer than the fast decay of AT 2019zhd after peak. ZTF SLRN-2020 also exhibits a rapid decay around ≈ 30 days after light curve peak, similar to AT 2019zhd but with a smaller drop in magnitude. Additionally, the pre-outburst i-band variability of ZTF SLRN-2020 is similar to that of V838 Mon as well as the nearby red novae in M31 (M31-LRN-2015 and AT 2019zhd) where the progenitor variability was detected prior to the main outburst.

In Extended Data Figure 2, we also compare the color evolution of ZTF SLRN-2020 to objects in the literature. ZTF SLRN-2020 exhibits a rapid reddening around the peak of the outburst followed by a slow reddening of the $g - r$ color, while the $r - i$ color remains relatively constant. Similar reddening of the $g - r$ color is also seen in the literature red novae, although the magnitude of the progressive reddening is larger for these objects during the ≈ 100 days after peak. The slow $g - r$ color evolution of ZTF SLRN-2020 is most similar to AT 2018bwo, which also exhibits only a small change in the color over the first ≈ 40 days, while the slow $r - i$ color evolution is most similar to AT 2017jfs. Accounting for the estimated foreground Galactic extinction (see Section 12), ZTF SLRN-2020 remains relatively blue compared to the literature sample. As the progressive reddening with time is attributed to the cooling of an expanding photosphere in red novae followed by dust formation[59], the relatively slow evolution in ZTF SLRN-2020 may be related to a lower amount of photospheric expansion and dust formation relative to other objects, consistent with the modeling of the bolometric light curve and SED (see Section 12).

11 Spectroscopic features The optical outburst spectrum of ZTF SLRN-2020 (Figure 3) exhibits a relatively featureless continuum with only atomic/molecular absorption features of Na, Ba II, Hα, Mg II, TiO and VO. The TiO molecular bands are characteristic in the spectra of cold, late-type giant stars, with later type giants exhibiting deeper absorption features[106,107]. To identify the corresponding spectral type, we compared the spectrum of ZTF SLRN-2020 to a library of stellar spectra from the VLT X-shooter spectral library[108], and found a good match of the TiO/VO line depths to the M4-III type giant HV 2255. We applied a foreground extinction of $A_V = 5.5$ mag (consistent with the inferred total dust optical depth modeled in Supplementary Information, Section 12) to the spectrum of the comparison star using a standard Fitzpatrick extinction law[50] and show the comparison in Figure 3. The inferred spectral type corresponds to an effective photospheric temperature of ≈ 3600 K[109].

The optical spectrum shows a strong absorption line in the Na D doublet. We measure the total equivalent width (EW) of the line by fitting a polynomial to the absorption feature, and measure the uncertainty by creating 1000 realizations of the spectrum by adding Gaussian noise scaled to the root-mean-square noise in the adjacent part of the spectrum. We find $EW = 3.65 \pm 0.75$ Å. The strength and profile of the Na D line is known to vary with time in many types of explosive transients[110,111], and has recently been shown to be time-varying in extragalactic red novae[112]. The line becomes stronger with time in red novae, likely due to the condensation of dust in the envelope. As a result, we are unable to use the Na D feature as an indicator of the foreground extinction as for other types of Galactic transients[60,113].

The spectra of ZTF SLRN-2020 show no signatures of emission lines indicative of hot gas in the eruption, as commonly seen in other types of Galactic plane transients. In Extended Data Figure 3, we compare the optical spectrum of ZTF SLRN-2020 to other common types of Galactic stellar outbursts. While classical novae exhibit strong and broad emission lines of the Balmer series and nuclear processed material[114], accretion outbursts in binary white dwarf systems (i.e. the dwarf novae) exhibit strong Balmer absorption features together with Hα in emission, indicative of the hot gas in the accretion process.

Similarly, the outbursts of young stars exhibit strong emission lines at all phases indicative of hot gas in the outflowing material. The outbursts of the FU Ori stars[115] are known to be years - decades long, while their outburst spectra show spectral types of F/G-type stars together with wind-like profiles in the H and Ca NIR triplet lines[115], inconsistent with the properties of this source. While the pre-outburst mid-IR brightening in ZTF SLRN-2020 is similar to that seen in the young star Gaia 17bpi[62], outbursts of FU-Ori stars are known to be consistently blue in color at all phases due to the accretion of hot gas, while ZTF SLRN-2020 shows a striking evolution from blue colors near the optical peak to a red SED dominated by infrared emission ≈ 1 year later (Figure 2).

When compared to young stars in terms of photometric evolution, ZTF SLRN-2020 shows some similarities to that of the EXor class of young stars that exhibit few month long outbursts[117]. However, the optical spectra of EXor outbursts are dominated by a forest of emission lines of atomic species like H and Ca II at all phases[118], indicative of magnetospheric disk emission[119], unlike that seen in the optical spectra of ZTF SLRN-2020 (Extended Data Figure 3). While red novae also exhibit emission lines at early phases[53, 59, 112, 120], the lines become progressively weaker with time as the photosphere becomes dominated by molecular absorption features from the newly formed molecules and dust[55], similar to that seen in the spectrum of ZTF SLRN-2020 around 6 months after outburst peak (Figure 3). The position of ZTF SLRN-2020 is not coincident with any known star forming regions; a search of the WISE archival images show evidence for faint diffuse emission $> 10'$ away, arguing against an association with young stars which are exclusively found in star forming regions. Together, we find the case for ZTF SLRN-2020 to be associated with a young star outburst to be unlikely.

Figure 3 shows NIR spectra of ZTF SLRN-2020 obtained during the outburst (≈ 160 days after peak) and after the fading of the infrared transient (≈ 690 days after peak). We show a zoom-in of the spectra of the individual bands in Extended Data Figure 4. We identify broad molecular absorption features of H_2O affecting the continua of the H and K-bands. In addition, we identify bandheads of TiO and VO in J-band together with weak ^{12}CO absorption bandheads in

K-band. The lack of strong emission lines of hydrogen (e.g. in the Paschen and Brackett series) as well as the CO band-heads which are ubiquitous in EXor type outbursts[117,118] further distinguishes ZTF SLRN-2020 from the population of young star outbursts.

Comparing the spectra to stars in the IRTF Spectral Library[123], the broad H_2O absorption bands and weak molecular absorption features are reasonably matched to a M7-III type star, and we show the comparisons in Figure 3 and Extended Data Figure 4. We note that although the NIR spectrum was obtained near the optical spectrum, the NIR spectrum suggests a later spectral type than the optical spectrum. Such differences have also been identified in the late-time spectra of previous Galactic red novae[18,124], where the extremely low gravity in the extended envelope of the remnant enables the formation of H_2O molecules and pushes the condensation of TiO and VO to low temperatures. The very late-time spectrum of ZTF SLRN-2020 does not show distinctive absorption features seen during the outburst, except for the broad H_2O absorption bands in H and K-band. Unlike the NIR spectrum in outburst, the late-time spectrum exhibits a clear rising continuum towards redder wavelengths in K-band, indicative of warm dust emission as inferred from the modeling of the spectral energy distribution (Supplementary Information, Section 12).

12 Spectral Energy Distribution Evolution The outburst of ZTF SLRN-2020 was detected in multiple time domain surveys with wavelength coverage extending from the optical g-band to mid-IR WISE-$W2$ band. While the optical emission likely arises from a hot photosphere, the bright mid-IR emission is indicative of a warm dust shell around the eruption. Here, we model the optical to mid-IR SED of the transient to estimate the time evolving properties of the optical photosphere and dust shell. We use the radiative dust transfer code `DUSTY`[125,126] to fit the multi-wavelength data. We assume a spherically symmetric distribution of the dust with a $\propto r^{-2}$ density profile around the star, which is assumed to be a point source. We assume the dust grains to be composed of warm silicates as indicated by the O-rich composition of the photospheric spectra[127], and with a MRN grain size distribution[128] ($\propto a^{-3.5}$) with a minimum and maximum grain size of $a_{min} = 0.005\,\mu$m and $a_{max} = 0.25\,\mu$m. We fix the thickness of the dust shell to be $Y = 5\times$ the inner radius (r_{in}) of the shell; the model SEDs are found to be relatively insensitive to this assumption since the $3 - 5\,\mu$m emission arises primarily from the hotter, inner part of the dust shell.

We fit the observed SED of ZTF SLRN-2020 at two epochs during the outburst that have NEOWISE mid-IR coverage (≈ 120 and ≈ 320 days after outburst peak; shown in Figure 1) using a Markov Chain Monte Carlo (MCMC) wrapper around the `DUSTY` code[129] using the Python `emcee` library[90]. We model the foreground wavelength-dependent interstellar extinction using a Fitzpatrick law[50] extending from the optical to the mid-IR. The resulting free parameters of the model are the dust optical depth at $0.55\,\mu$m (τ_V), the foreground visual extinction (A_V), the inner stellar temperature (T_*), the dust temperature at the inner edge of the shell (T_d) and the total flux (F). We assume flat priors on all the fit parameters and ensure convergence of the posterior sampling chains. As multi-color optical detections were available only at the ≈ 120 d epoch, we keep A_V as a free model parameter for this epoch, but fix it at the best derived value from the 120 d epoch when fitting the 320 d epoch. Nevertheless, we find that the best fit for the 320 d epoch is relatively insensitive to the assumed A_V since all the photometric data at this epoch are in the infrared bands, where the foreground extinction is less important (e.g. $A_K \approx 0.3 - 0.4$ mag).

The best-fit parameters were derived using the median of the posterior sample distribution while their confidence intervals are derived from the 16th-84th percentile (68% confidence) interval of the distributions. The derived parameters and their uncertainties are listed in Extended Data Table 3, and shown in Extended Data Figures 5 and 6. During the outburst (≈ 120 d after peak), the SED is well described by an inner photosphere with a temperature of ≈ 8900 K surrounded by a warm dust shell with $T_d \approx 1020$K. The optical depth of the dust ($\tau_V \approx 1.8$) is relatively low at this epoch. The foreground extinction is $A_V \approx 3.6$ mag, although this parameter is degenerate with the optical depth of the dust shell. While multi-epoch mid-IR data is scarce for the literature sample of red novae, similar parameters involving a relatively hot photosphere surrounded by a low optical depth dust shell were also derived at similar phases in DUSTY modeling for the nearby red nova M31-LRN-2015[53]. Towards the end of the outburst (≈ 320 d after peak), the DUSTY fitting suggests that both the internal photosphere and the surrounding dust shell have cooled substantially, while the optical depth of the dust has increased by a factor of ≈ 6.

The estimated temperature of the inner photosphere (≈ 9000 K) at the ≈ 120 d epoch is notably higher than that suggested by the spectral type of the photosphere (≈ 3500 K) obtained ≈ 60 days later. While the unavailability of contempornaeous data makes a direct comparison difficult, similar discrepanices have been observed in previous red novae with multi-wavelength datasets. Modeling for the nearby M31-LRN-2015 suggested a similar presence of a hot (> 5000 K) photosphere > 150 d after the eruption, while the optical spectral type was later than M9 (< 3000 K[59]). In the case of the well-studied V1309 Sco, the strengths of the molecular features were shown to be substantially enhanced (i.e. the spetroscopic temperature was lower than the corresponding continuum temperature) compared to a normal stellar photosphere[19], similar to that reported in V4332 Sgr[130] as well as V838 Mon[131, 132]. As argued for previous objects, we therefore suggest that these differences arise due to the presence of extended circumstellar gas surrounding the merger remnant, that produces enhanced absorption in the molecular features.

We estimate the total mass of the dust shell at an epoch[53] as,

$$\frac{M_d}{M_\odot} \approx 3.06 \times 10^{-7} \left(\frac{100\,\mathrm{cm}^2\,\mathrm{g}^{-1}}{\kappa_V}\right) \left(\frac{r_{in}}{1000\,R_\odot}\right)^2 \tau_V \tag{1}$$

where M_d is the dust mass and $\kappa_V \approx 50 - 100\,\mathrm{cm}^2\,\mathrm{g}^{-1}$ is the dust opacity for a typical dust-to-gas ratio[127]. In order to derive r_{in}, we assume a distance of 4 kpc, as indicated by the distance estimates in Supplementary Information (Section 13), and list the corresponding radius and mass values in Extended Data Table 3. The observed increase in the dust shell inner radius between the ≈ 120 and ≈ 320 days epochs suggests an expansion velocity of $v_{ej} \approx 35\,\mathrm{km\,s}^{-1}$. The low inferred velocity of the shell suggests that signatures of such an outflow would be difficult to detect in our low resolution spectra. Together with the increase in the optical depth, the increased dust mass suggests that dust formation in the ejecta shifts the SED of the transient from the optical to the IR bands. Similar abrupt dust formation has also been observed in previous red novae[8, 19, 53]. The mass estimate provides a lower limit to the total (dust + gas) ejecta mass of $\approx 10^{-6}\,\mathrm{M}_\odot$, noting that only a fraction of the ejecta has likely reached the dust condensation radius within a year after the outburst[53, 133].

13 Distance constraints and bolometric light curve We use the inferred foreground dust extinction to ZTF SLRN-2020 to place constraints on the distance to the source. In Extended Data Figure 7, we show published three dimensional Galactic dust extinction maps at the location of ZTF SLRN-2020 (created using the mwdust code[134]), the estimated A_V range inferred from the SED modeling as well as the allowed distance range for each map within the estimated A_V range. As shown, the different extinction maps are roughly consistent with each other within the estimated A_V range. Given the possible systematic differences between the different maps, we conservatively derive a distance range of $\approx 2-7$ kpc for the transient, placing this source well within the Galactic disk. As the distance ranges suggested by the different maps overlap consistently at a range of $\approx 3-4$ kpc, we nominally adopt 4 kpc as the best estimate for the source. We caution however, that as is the case for the foreground extinction, the estimated distance is degenerate with the optical depth of the circumstellar dust shell (Extended Data Figure 5).

We use the distance and extinction estimate to derive the bolometric luminosity light curve of the optical transient around the peak of the outburst. We use the multi-color photometry from ZTF, binned in epochs of 3-days with coverage in all three (gri) filters, and fit a blackbody function to derive the effective temperature, luminosity and radius of the star for an estimated distance of 4 kpc. The ATLAS photometric filters cover very wide bandpasses over the g, r, and i bandpasses contemporaneously with the ZTF photometry, and hence we do use the c and o-band data for constructing bolometric light curves. The fitting was performed by χ^2 minimization using the Markov Chain Monte Carlo fitting Python library emcee[90]. The results are shown in Figure 2. For comparison, we also show the evolution of the corresponding parameters for well studied red novae in the literature[7] as well as the $t^{-4/5}$ luminosity decay expected for the gravitational contraction of an inflated envelope surrounding the remnant[135]. We note that a foreground extinction significantly higher than the estimated interval ($A_V \gtrsim 5$ mag) would imply unphysically high blackbody temperatures ($>> 10^5$ K), corroborating the estimated extinction and distance range.

The bolometric luminosity of ZTF SLRN-2020 shows an initial plateau at $\approx 10^{35}$ erg s^{-1} for ≈ 15 days followed by a slow decline to 2×10^{34} erg s^{-1} over the next ≈ 100 days. We estimate the duration of the plateau by fitting the bolometric light curve with an analytical model developed for light curves of Type II supernovae[136] and previously used to model light curves of red novae[53]. The fitting was performed by χ^2 minimization using the `emcee` code, and suggests a best-fit plateau duration of $t_p = 25.6^{+5.6}_{-7.1}$ days as measured from the assumed time of eruption. The resulting fit is shown in Figure 2 and provides a reasonable match to the data; however, we caution that the plateau characteristics are relatively poorly constrained due to the short duration and subsequent smooth decline. The inferred bolometric luminosity from the `DUSTY` modeling at $\approx +120$ days after outburst peak is consistent with the bolometric fitting at the latest epochs, while the `DUSTY` modeling at $\approx +320$ days shows evidence of a plateau at very late phases.

We estimate the total energy (E), luminosity (L_{90}) and duration (t_{90}) of the outburst[7] by performing trapezoidal integration on the bolometric light curve. We estimate uncertainties on these parameters by creating 1000 realizations of the bolometric luminosity light curve using the MCMC uncertainty intervals and then repeating the calculations. The corresponding estimates are $E \approx (6.5 \pm 1.7) \times 10^{41}$ erg, $L_{90} \approx (8.0 \pm 5.1) \times 10^{34}$ erg s^{-1} and $t_{90} \approx 103 \pm 20$ days for a distance of 4 kpc and foreground extinction of $A_V = 3.6$ mag. Although the t_{90} duration is found to be similar to the plateau duration (t_p) in previous objects[7], we find $t_{90} \approx 4 \times t_p$ likely due to a relatively small amount of unbound mass that contributes to the recombination luminosity on the plateau phase compared to the late-time gravitational contraction following the plateau. Considering the 68% confidence interval for the possible distance and foreground extinction, we find the total radiated energy and luminosity to be in the range $(1.0-12.1)\times10^{41}$ erg s^{-1} and $(1.1-13.6)\times10^{34}$ erg s^{-1}. In particular, even if the source was placed on the farthest side of the Galactic disk ($d\approx 20$ kpc), the estimated extinction would suggest a luminosity of $\lesssim 3.4\times10^{36}$ erg s^{-1}, suggesting that the interpretation as an very low-luminosity red nova (Figure 4) is insensitive to the assumed distance, which is not accurately constrained.

14 Progenitor photometry The progenitor of ZTF SLRN-2020 is detected only in the H and K filters of archival UKIRT images. Here, we attempt to constrain the progenitor star properties using the archival NIR photometry. In Extended Data Figure 8, we show the position of the progenitor in the M_K vs. $H-K$ color magnitude diagram as a function of distance along the Galactic disk using different three dimensional dust extinction maps. To constrain the progenitor mass, we also show stellar evolutionary tracks for stars with initial masses ranging from $0.8-3.0\,M_\odot$ from the `MIST` database[137]. Extended Data Figure 8 shows that the progenitor colors would be too blue to be consistent with any stellar tracks for distances larger than $\approx 8-10$ kpc as per the D03[65] and M06[66] models, consistent with our constraints on the distance based on the outburst SED modeling.

We find that the location of the progenitor within the estimated A_V range (shown as shaded region) is consistent with a $0.8-1.5\,M_\odot$ star on or evolving off the main sequence. Within the 90% confidence interval for the extinction, the photometric colors intersect the $1\,M_\odot$ stellar track at radii of $\approx 1-4\,R_\odot$, which we adopt as the likely initial radius of the progenitor star. However, we are unable to further constrain the progenitor properties due to the large error on the photometric color. Specifically, the allowed progenitor flux and color are also consistent with a lower mass $\approx 0.8\,M_\odot$ progenitor star; in such a case, the engulfment would have occurred while the star was on the main sequence (given the current age of the Galactic disk population) likely driven by tidal interactions[32,33,140].

The late-time WIRC photometry together with the DUSTY modeling shows that the star has both nearly returned to its original photospheric temperature ($\approx 4000 - 5000\,$K; as suggested by the DUSTY model) while also having faded marginally below the progenitor brightness likely due to the optically thick dust shell surrounding the remnant. Given the constraints on the distance, we note that if related, the projected physical separation to the source detected next to the progenitor in the GSAOI images would be $\approx 1000 - 2000\,$AU, making it an extremely wide multiple star system; however, further follow-up is necessary to confirm this scenario.

15 Constraints on pre-outburst dust ZTF SLRN-2020 exhibits a mid-IR brightening in NEOWISE data starting $\approx 7\,$months prior to the optical outburst. Here, we use the pre-outburst brightening to constrain the evolution of the mass loss rate before the red nova outburst. In Extended Data Figure 9, we show the evolution of the pre-outburst SED of the progenitor. The mid-IR source is clearly detected in both $W1$ and $W2$ bands $\approx 40\,$d prior to the optical outburst. We derive the dust temperature and mass by fitting the $W1$ and $W2$ photometry with a single-temperature modified blackbody represented by a Planck function multiplied by a grain efficiency factor (including effects of absorption and scattering). We use published values for silicate dust absorption and scattering[141].

We derive a dust temperature of ≈ 650 K and a dust mass of $M_d \approx (0.26 - 3.20) \times 10^{-6}\,M_\odot$ over the distance range of $\approx 2 - 7$ kpc at the ≈ -44 d epoch. The corresponding SED fits are shown in Extended Data Figure 9. As the transient is only detected in the $W2$-band for the ≈ -244 d epoch, we estimate the dust mass at this epoch assuming the same dust temperature (650 K; consistent with the $W1$ non-detection of the source) and use the $W2$ photometry to obtain a dust mass of $M_d \approx (0.7 - 8.8) \times 10^{-7}\,M_\odot$. Instead, if we assume a lower dust temperature of 400 K, the corresponding mass estimate is $(1.6 - 19) \times 10^{-6}\,M_\odot$ that is unlikely as it is higher than the -44 d epoch; we therefore nominally assume a temperature of 650 K. For prior epochs with no $W1$ or $W2$ detection, we only derive the maximum dust mass consistent with the NEOWISE non-detections; the SEDs fit to the NEOWISE non-detections suggest that the UKIRT NIR progenitor photometry ($\gtrsim 10$ years prior to outburst) is not affected by the mid-IR dust emission. The temporal evolution of dust mass is shown in Figure 4.

The transient also exhibits an optical brightening in i-band (compared to the archival PS1 limits), detected starting ≈ 40 d before the onset of the optical outburst. Extended Data Figure 9 shows that the progenitor had brightened by $> 20\times$ in i-band since the non-detection in PS1; however, it cannot be explained as part of the thermal emission from the dust and likely arises from the stellar photosphere. The lack of multi-color photometry precludes constraints on the temperature and radius of the star during this phase. Similar behavior, arising out of expansion and cooling of the photosphere, or tidal heating prior to red nova outbursts has been suggested in V1309 Sco[22,24], M101-2015OT[120] and M31-LRN-2015[52,53]. Although we do not have extensive pre-outburst coverage in i-band where the brightening was detected, the plateau in optical luminosity prior to the outburst is strikingly similar to V838 Mon, M31-LRN-2015 and AT 2019zhd (Extended Data Figure 1), where the constant luminosity has been attributed to ejected mass that is partially bound and forms a constant radius photosphere around the binary[16,53,135].

16 Observed rate estimates We estimate the observed rate of optical transients like ZTF SLRN-2020 by performing Monte Carlo simulations of the ZTF observing schedule together with a simulated population of ZTF SLRN-2020-like events in the Galactic plane. Our method draws from previous work on estimating rates of optical transients in ZTF [143] together with realistic methods for estimating the space distribution of Galactic plane outbursts[60]. We begin by constructing a template light curve for ZTF SLRN-2020 by fitting a Gaussian process model with a constant kernel to the peak-magnitude normalized light curve of ZTF SLRN-2020 in the r-band between phases of -20 d and 150 d from light curve peak. We do not include upper limits in the fitting process. We choose to perform this analysis only in r-band since the public survey data (where this transient was identified) includes only g and r band, while the fainter g-band light curve is poorly sampled at phases $\gtrsim 15$ days away from peak.

Using the normalized light curve template, we simulate the observing schedule of the ZTF survey between the period of 2019-06-01 and 2021-11-30 (the period over which this search was performed). We assume that the probability of ZTF SLRN-2020-like outbursts follows the stellar mass density profile of the Milky Way and therefore simulate a population of transients following the density profile in [144] (their Table 1 and 2 for a contracted halo model). For each transient, we assume the outburst light curve follows the shape of the normalized template scaled to a peak absolute magnitude of $M_r = 2.0$ (as inferred for ZTF SLRN-2020) with a nominal scatter following a Gaussian distribution with standard deviation $\sigma = 0.5$ mag. Using the Galactic spatial location of each simulated transient, we estimate the apparent magnitude evolution as a function of light curve phase using three-dimensional dust distribution maps [67].

As in previous works[60], for each value of the Galactic event rate, we simulate a population of outbursts such that the number of events follows a Poisson distribution with a mean equal to the assumed rate. We perform 100 simulations for each value of the assumed rate, repeating the actual ZTF observation schedule to estimate the number of recovered events. Using the same selection criteria for long-lived Galactic plane outbursts as used to identify ZTF SLRN-2020, we calculate the median number of events that pass our selection criteria within this simulated sample, as well as its 68% confidence interval. In order to derive the best-fit rate and its uncertainty given the one confirmed event in our search, we construct a distribution of the fraction of simulations that produce the one observed event as a function of the global rate. We fit a skewed normal function to this distribution to estimate a Galactic rate (with 68% confidence intervals)

$$r_0 = 4.3^{+7.5}_{-3.1}\,\mathrm{yr}^{-1} \tag{2}$$

where r_0 is the Galactic event rate. However, we caution that i) the one observed event represents a lower limit to the actual number of events since it was not possible to obtain follow-up spectroscopy for all transients, ii) rate estimates from a single observed event are subject to large uncertainties and iii) the observed rates are subject to the recovery efficiency of the ZTF subtraction pipeline for faint transients in dense Galactic plane fields which have not been quantified for this simulation. Nevertheless, the observed rate estimate provides an order-of-magnitude estimate of the Galactic rate for comparison with theoretical estimates. If we assume that the rates of SLRNe scale similarly as novae in the Milky Way and the Magellanic clouds, our derived rate suggests that similar events may be occurring in the Large Magellanic cloud at a rate of ≈ 1 per $5 - 10$ years, such that prior surveys like Optical Gravitational Microlensing Experiment (OGLE[146]) may have detected similar outbursts.

17 Light Curve Modeling and Interpretation ZTF SLRN-2020 has a uniquely low energy among the population of red novae transients. Here we discuss the interpretation of this light curve, with a focus on estimating the mass of the unseen companion object whose engulfment caused the red nova outburst. It is useful to compare ZTF SLRN-2020 to the properties of the particularly-well studied source V1309 Sco. Because of the extended period of pre-outburst eclipsing behavior in V1309 Sco, the system properties pre-merger are well known. The primary star of V1309 Sco was an $\approx 1.4 M_{\odot}$, $3.5 R_{\odot}$ sub giant[21], and the mass ratio was 0.094[23], implying a companion mass of $\approx 0.13 M_{\odot}$. The radiated energy was $\approx 3 \times 10^{44}$ erg. The outburst itself ejected an inferred $\approx 3 \times 10^{-2} M_{\odot}$ of material with an observed velocity of 150 km s^{-1}, about $1/3$ the surface escape velocity of the donor star [7].

By comparison, ZTF SLRN-2020 has very similar inferred primary star properties of $\approx 1\,\mathrm{M}_{\odot}$ and a likely radius of $1 - 4\,\mathrm{R}_{\odot}$. This association implies a similar primary star at a similar evolutionary state. The radiated energy of $\approx 6.5 \times 10^{41} (d/4\,\mathrm{kpc})^2$ erg represents a significantly less energetic coalescence than V1309 Sco. Similarly, the inferred ejecta mass is much lower than that of V1309 Sco at $\approx 3 \times 10^{-5}\,\mathrm{M}_{\odot}$ at $\approx 100\,\mathrm{km\,s^{-1}}$ during the plateau phase of the recombination-powered transient (Figure 4). In merger-powered transients, the loss of orbital energy powers the outburst. Thus, a characteristic energy scale for the ejecta, which originate as the companion plunges into the donor, is the orbital energy of the pair separated by the donor star radius, $\Delta E_{\rm orb} \sim GM_1M_2/2R_1$. Though the companion object may fall deeper, depositing energy into its surroundings[147], unless that energy deposition becomes comparable to the binding energy of the entire overlying layers it does not drive freely-expanding ejecta in the same manner as the surface interaction. Thus we apply R_1 in what follows as the characteristic radius of interaction.

Given that M_1 and R_1 are similar for V1309 Sco and ZTF SLRN-2020, we can use the observed energetics to trace the companion mass M_2. The radiated energy of ZTF SLRN-2020 is approximately $10^3\times$ lower than V1309 Sco. Similarly the ejecta mass (which is directly proportional to the events' kinetic energies given the similar system escape velocities) is $\sim 10^3\times$ lower in ZTF SLRN-2020 than that of V1309 Sco. Scaling linearly down from the companion mass of $\approx 0.13M_\odot$, these properties point to a planetary mass companion for ZTF SLRN-2020 with mass of on the order of 0.1 Jupiter-masses, where these properties scale with the uncertain distance squared, $(d/4{\rm kpc})^2$. Following the same line of reasoning, but assuming a slightly more compact, sun-like primary star for ZTF SLRN-2020, this scaling indicates a companion mass that is a factor of ~ 2 smaller, $0.05M_J$, or approximately Neptune's mass.

Theoretically, we can put limits on the lowest plausible mass for the companion of ZTF SLRN-2020 by requiring that the characteristic change in orbital energy is larger than the radiated energy. We note that this is a stringent lower limit; in V1309 Sco, the radiative efficiency, estimated as $\epsilon_{\rm rad} \approx E_{\rm rad}/(GM_1M_2/2R_1) \approx 3\times10^{-3}$. Estimating M_2 this way for a higher radiative efficiency, we find an object as small as $M_2 \gtrsim 6\times10^{27}{\rm g}(\epsilon_{\rm rad}/0.1)^{-1} = m_\oplus(\epsilon_{\rm rad}/0.1)^{-1}$, satisfies $M_2 \gtrsim E_{\rm rad}/(\epsilon_{\rm rad}GM_1/2R_1)$ for a sun-like host star. Indeed, it is worth considering the possibility of higher radiative efficiencies because one might expect less adiabatic degradation of the radiated energy in ZTF SLRN-2020 relative to V1309 Sco because the transient photosphere is closer to the ejection radius of the original star.

Comparably, we can place a constraint on the plausible minimum radius for the captured object based on its rate of orbital decay and the luminosity that it injects into the surrounding envelope[4],

$$L_{\rm decay} \sim 10^{36} \left(\frac{\eta}{10^{-3}}\right) \left(\frac{M_1}{M_\odot}\right)^{5/2} \left(\frac{R_1}{R_\odot}\right)^{-9/2} \left(\frac{R_2}{R_\oplus}\right)^{2} \quad (3)$$

where R_2 is the radius of the captured companion and $\eta = \rho/\bar{\rho}$, the ratio of the local to enclosed density. This ratio is a step function of radius at the stellar surface, for context, however, in a sun-like star at 90% of the radius of the star, $\eta \sim 3 \times 10^{-3}$. This formula scales with R_2^2, because in the low-mass regime of planetary captures, the geometric (rather than gravitational) cross section of the objects determines their decay rates[4]. Thus, an object as small as Earth radius would provide energy rapidly enough to power the transient peak of ZTF SLRN-2020.

Considered together, the energetics of the light curve require a minimum engulfed object of at least terrestrial, rocky planet size. Scaling linearly from the properties of the stellar merger with the most comparable pre-outburst host, V1309 Sco, implies a larger, likely gaseous, planet, on the order of Neptune mass or greater. Given the uncertain distance to the source, we note that if the source were conservatively even as close as $\approx 1\,$kpc away, the resulting lower energetics would scale the corresponding planet mass to about an Earth mass object in the context of the comparison to V1309 Sco.

18 Constraints from Pre-Outburst Detections We can also draw information about the engulfment that occurred from the IR detections and limits in the years prior to the coalescence. The presence of dusty shells prior to the outburst indicates an ongoing encounter, which escalates to produce the transient itself. Qualitatively similar precursor brightening has been observed in red novae transients such as V1309 Sco[8] and M31-LRN-2015[52,53]. At a minimum, this suggests that the star–planet encounter is not a single-passage collision in a highly eccentric orbit, but is a prolonged encounter that increases in strength to leading to the point of the outburst[28].

Given the estimated dust masses at the two pre-outburst epochs of detection, we can try to understand the origin of this material. In what follows, we consider two categories of models. One is based on the angular momentum required to shrink the planetary orbit to the point of engulfment. The other model considers the energy injected into the stellar surface layers by the decaying planetary orbit. At the order of magnitude level, the expelled mass is on the order of the planet mass in the energy or angular momentum cases. To order of magnitude in the angular momentum model, the characteristic angular momentum of the orbit is $L_{\rm orb} = M_1 M_2 / M \sqrt{GMa}$, where $M = M_1 + M_2$. For $M_1 \gg M_2$, we can approximate this as $L_{\rm orb} \approx M_2 \sqrt{GM_1 a}$. If material is pulled from the star and expelled with specific angular momentum similar to that of the planet, $l_2 \approx \sqrt{GM_1 a}$, a mass similar to the planet mass needs to be expelled to tighten the planetary orbit, $\Delta m \approx \Delta L_{\rm orb}/l_2 \approx M_2$. In the energy model, we assume that $\Delta E_{\rm orb} \approx GM_1 M_2 / 2R_1 = f_{\rm mech} \Delta m v_{\rm esc}^2 / 2$, where $f_{\rm mech}$ is an efficiency factor less than unity to account for radiative losses. Solving for Δm, we find $\Delta m \approx f_{\rm mech} M_2$. Thus, the pre-outburst detections of $\approx 10^{-4} M_\odot$ of gas and dust point to a planet of at least similar mass, or approximately $0.1 M_J$.

We derive more detailed models that consider the temporal evolution in the angular momentum model from the separation of stellar Roche lobe overflow to the point of contact. We use the the `RLOF` software[148], which integrates the cumulative mass loss given coefficients of specific angular momentum loss motivated by hydrodynamic simulations of this process[25,29]. These models have successfully explained the dynamics of orbital decay and the observations of increasing obscuration in V1309 Sco[22,24,25,149], but we caution that we must extrapolate them to several orders of magnitude lower companion mass than they have been systematically tested for. We must assume several parameters of the binary system. We adopt a $1M_\odot$ and $2R_\odot$ fiducial model, and compare to $1M_\odot$, $1R_\odot$ and $1M_\odot$, $4R_\odot$ examples to demonstrate the degree to which varying this within the uncertainty affects the result. We further assume that the structure of the star is approximated by a $\Gamma_{\rm s} = 4/3$ polytrope, that the gas adiabatic index is $\gamma = 5/3$ and that the star is not initially corotating with the companion orbit. These parameters each moderately affect the specific angular momentum loss that accompanies mass loss and orbital decay ($\sim 50\%$ differences in the predicted mass loss with varying parameters[25]). We then convert the estimated total mass lost to a dust mass assuming that the dust-to-gas mass ratio[127] is 5×10^{-3}.

The dust masses expected from modeled systems are shown in Figure 4. We see that the modeled dust masses and non-detections in the pre-outburst data are broadly consistent with a model that exhibits an exponentially increasing circumbinary distribution of gas and dust as it progresses toward merger. In overall normalization, our curves are most consistent with a mass ratio of $q \approx 10^{-3}$ to 10^{-1}, implying a companion mass of $\sim 10^{-2}M_\odot$, or $10M_J$. This mass is considerably larger than the energy or angular momentum order of magnitude scalings alone indicate. This is because of the characteristic timescale of the exponential decay of the orbit in the `RLOF` model, which implies that most of the mass loss is concentrated in the final orbits prior to coalescence. We emphasize here that to make more robust inferences will require calibrating these energy and angular momentum based models of orbital decay to the planetary, rather than stellar, mass range in question. This mass estimate is also larger than the mass inferred from the recombination powered transient's mass and energy budget, as discussed in the section above. However, both mass estimates are strongly suggestive of a planetary (rather than stellar or brown dwarf) mass companion object producing the ZTF SLRN-2020 transient.

19 Understanding a Planetary Engulfment The planetary mass range inferred from various lines of evidence points to the fact that ZTF SLRN-2020 probes new parameter space among the red novae. Hydrodynamic simulations of stellar coalescence have suggested that as the mass ratio decreases, a smaller fraction of the shock-heated material is truly unbound from the system and ejected [28,29]. The remaining, bound material settles into a shock-heated, rotating envelope in which spiral shocks play an important role in redistributing energy and angular momentum[29]. An extension of this is the limit that the smallest companions should be too insignificant to eject any mass from the host star when they are engulfed. Thus, we suggest that the combination of pre-cursor and lightcurve data shown in Figure 4 are indicative of a system in which the majority of the shock-heated stellar atmosphere remains bound. Indeed, this is strongly suggested by inferred velocities in Figure 4, which are much less than the local escape velocity at 3×10^{11} cm of $\approx 300\,\mathrm{km\,s^{-1}}$.

If most of the stellar atmosphere mass remains bound following the engulfment, this would attribute the plateau luminosity to the recombination of a comparatively small unbound mass fraction ($\approx\ 3 \times 10^{-5} M_\odot$). It also informs our understanding of the brightness and colors of ZTF SLRN-2020 over the hundred-day observing window. ZTF SLRN-2020's temperature remains higher than other red novae and its photosphere radius, following its initial expansion to $\approx 3 \times 10^{11}$ cm $\approx\ 4.3\,\mathrm{R}_\odot$, gradually decreases rather than growing. These trends both indicate that following an initial period of mass ejection, we may be witnessing the hydrodynamic and thermal relaxation of still-bound stellar material that has been disturbed by the engulfment of the substellar companion. Indeed, the late-time light curve follows a roughly $t^{-4/5}$ power-law, which is consistent with observations of other merger remnants[135].

We note that the small ejected mass is consistent with the non-detection of molecular line emission in the SMA and VLA observations. While a detailed molecular excitation analysis is beyond the scope of the work given the non-detection, we can interpret these data with comparisons to the molecular line observations of V1309 Sco[150]. Observations with the Atacama Large Millimeter Array detected the 230 GHz CO transition in V1309 Sco ≈ 8 years after merger at a flux level of $\approx\ 3.3\,\mathrm{Jy\,km\,s^{-1}}$ (peak line flux of $\approx\ 13$ mJy for the measured line width of $\sigma\ \approx\ 100\,\mathrm{km\,s^{-1}}$). As the distance to V1309 Sco[8] is similar to that estimated for ZTF SLRN-2020, and assuming similar molecular excitation conditions as in V1309 Sco, we estimate that the relevant line flux in ZTF SLRN-2020 would be $\approx 10^{-3}\times$ V1309 Sco (peak line flux of $\lesssim\ 0.02$ mJy) if the molecular line fluxes scale approximately linearly with the inferred mass of the unbound material (Figure 4). Noting that ZTF SLRN-2020 was observed at a much earlier phase and therefore may have different excitation conditions, the non-detection of molecular emission is consistent with the small inferred ejecta mass in the eruption. While SiO maser emission at 43 GHz was only detected for V838 Mon[151,152], we use similar scaling arguments and accounting for the larger distance to V838 Mon, we estimate the maser line flux in ZTF SLRN-2020 to be $\sim 10^{-4}\times$ fainter ($\lesssim 0.5$ mJy at peak for a resolution of $\approx 0.5\,\mathrm{km\,s^{-1}}$) and hence consistent with the non-detection ($\lesssim 6$ mJy).

A particularly relevant consideration is the relative density of planets and their host stars. Planets are tidally disrupted outside of their host stars when their density is lower than that of the star they orbit[3]. When the planetary density is higher than that of the host star, the planet can plunge into the stellar envelope, shock-heating its surroundings as it is engulfed. Given the similarity of ZTF SLRN-2020 to other, engulfment-powered red novae transients, we strongly suspect that the planetary companion was engulfed by its host star (though see Bear et al[153] for a discussion of the possible signatures of tidally disrupted planets). This implies that the planet be denser than the host.

The upper end of the range of mass possibilities for the companion of ZTF SLRN-2020 nears the mass range of brown dwarfs, which extends from roughly $13M_J$ to $80M_J$. Could ZTF SLRN-2020's companion object be a brown dwarf rather than a planet? We suggest that this is substantially less likely because brown dwarf companions at similar separations to hot Jupiters are nearly an order of magnitude more rare[1]. The close-companion portion of this "brown dwarf desert" may be caused by the more-rapid tidal decay of these objects orbits into their host stars: even if these objects were formed at similar rates to hot Jupiters, many would coalesce with their host stars during the pre-main sequence. Since ZTF SLRN-2020 shows no evidence of being a young star there seems to be substantially more support for a planetary companion.

20 Theoretical Planetary Engulfment Event Rates Planets and substellar objects decay toward merger with their host stars through a combination of tidal orbital decay (due to asynchronous rotation of the host star with the companion orbit) and stellar evolution (which increases the radius of the host star while lowering its spin rate)[33]. For example, the currently observed population of hot Jupiter exoplanets all have inferred tidal decay times of less than 10^{10} yr. Tidal decay has been directly detected for WASP 12b[34,35,154,155]. Even without tidal decay, each of these planets will surely merge with its host star as these stars increase in radius on the sub giant and giant branches. Additionally, planets can be scattered or torqued into eccentric orbits that cause them to interact with their host stars at periapse[156–159].

There are uncertainties in the propagation of this observed distribution to an engulfment event rate. As Metzger et al[3] have noted, the distribution of known planets at the closest separations implies a much higher coalescence rate than the apparent number at larger separations (see their Figure 1). This points to a need to resupply planets to these close-in orbits to maintain the currently-observed distribution. The occurrence of very close, Jupiter-like planets implies a coalescence rate of ~ 0.1 yr^{-1} in the galaxy[3], while the number of hot Jupiters at slightly larger separations (with tidal decay timescales of 10^9 to 10^{10}) appears to be fewer. Whether this relates to observational selection effects or is an intrinsic property of the population is currently under discussion[155].

With these caveats in mind, we can produce an order of magnitude estimate of the planetary engulfment rate as follows. The total mass of stars in the Milky Way is $\sim 6.4 \times 10^{10} M_{\odot}$[160]. In a Salpeter IMF, approximately 1/3 of this mass comes from stars greater than a solar mass (which is roughly the fraction that evolve off of the main sequence in less than 10^{10} yr). This implies that roughly 10^{10} stars have evolved off of the main sequence in the history of the galaxy. If 1% of these stars hosted hot Jupiters[1,161], then the time-averaged hot Jupiter engulfment rate would be $(10^8/10^{10}\mathrm{yr}) \sim 10^{-2}$ yr^{-1}. Considering planets more broadly, the known exoplanet population is consistent with a fraction on the order of unity of all stars hosting some kind of planet. Thus, the overall planetary engulfment rate from this broader population would be ~ 1 yr^{-1}.

In practice, these time-averaged estimates represents a lower limit because they do not account for the apparent resupply of planets to close in orbits or stellar impacts[156], perhaps through dynamical scatterings (for example, Stephan et al[162] estimate an engulfment rate of 0.1 yr^{-1} from A-type stars alone). The normalization of these theoretical rates suggests that the detection of a planet engulfment by ZTF is perhaps fortunate, but not extremely unlikely. On the other hand, observational constraints on this rate through transient discoveries may soon provide important insights into the architecture and evolution of extrasolar planetary systems.

21 A Missing Link in Star–Planet Coevolution As the existence of exoplanetary systems have become increasingly clear[1], the discovery of a planetary engulfment event has been long-awaited[163]. There have been numerous theoretical predictions of the multi-wavelength signatures of these events as they occur[3,4,27,153,164–169]. In particular, predictions have focused on their possible appearance as optical transients, but many have over-estimated the luminosity and underestimated the event duration relative to ZTF SLRN-2020, because they have imagined fast ejecta moving at similar to the stellar escape velocity. A notable exception comes from Yamazaki et al[166], whose predictions for emission from a shock-heated plasma bubble show characteristic temperatures, photosphere radii, and peak luminosities very similar to those observed in ZTF SLRN-2020, strengthening the interpretation of a small quantity of shock-heated mass powering the early emission. Recently, Lau et al[170] have presented hydrodynamic models of a hot Jupiter engulfment, which suggest that on the order of $10^{-5}M_\odot$ of stellar atmosphere is expelled, which is intriguingly consistent with the light curve estimates of Figure 4. More detailed comparison of this range of models to ZTF SLRN-2020's emerging properties will be crucial to guide future search efforts.

An even larger body of effort has been devoted to understanding the long-lasting effects of substellar engulfment[5,43,44,167,171–175], with the motivation that if a large fraction of stars engulf one or more planets as they evolve, perhaps these events leave long-lasting impacts on the observable stellar characteristics. One possible property that has been invoked is secular declines in luminosity, which might trace the cooling of a star following the mechanical addition of heat from an engulfment[4,41]. Another is enrichment of the stellar atmosphere by lithium and other elements carried by the planet bulk composition in higher abundance than the star[44]. Lithium is thought to be a particularly useful tracer because its fragile structure is dissociated in stars, but persists in substellar objects[5,43,174,176,177]. Observations of the remnant of ZTF SLRN-2020 at relatively high spectral resolution could search for signs of lithium enrichment and serve as a useful benchmark for these theories, as well as compare to recent studies of other red novae remnants[178]. A final possible signature that has been extensively considered is stellar rotation, with enhancements in otherwise-slow rotation rates thought to be be possible due to the deposition of angular momentum as the planet is engulfed[46,179,180]. Since the total angular momentum budget of a substellar engulfment is well-known, the impact on the observable spin rate (as well as the evolution of that spin rate) becomes deeply revealing about the transport of angular momentum in the stellar interior. As future work traces each of these properties in ZTF SLRN-2020 and similar future transients, we anticipate that these events will serve as a crucial missing link in connecting the properties of observed planetary systems to the transients they produce and their effects on their host stars.

Table S1: Optical/NIR photometry of ZTF SLRN-2020 in the AB magnitude system.

MJD	Phase (d)	Filter	Mag	Instrument
58955.44	-38.95	r	> 19.70	P48+ZTF
58972.44	-21.95	r	> 20.41	P48+ZTF
58975.46	-18.93	r	> 20.14	P48+ZTF
58978.49	-15.90	r	> 20.25	P48+ZTF
58983.38	-11.01	r	20.56 ± 0.18	P48+ZTF
58986.46	-7.93	r	19.37 ± 0.05	P48+ZTF
58991.48	-2.91	r	18.07 ± 0.03	P48+ZTF
58995.46	1.07	r	17.95 ± 0.01	P48+ZTF
58998.46	4.07	r	18.01 ± 0.02	P48+ZTF
59005.31	10.92	r	17.90 ± 0.14	P48+ZTF
59009.40	15.01	r	18.41 ± 0.03	P48+ZTF
59013.35	18.96	r	18.45 ± 0.02	P48+ZTF
59017.39	23.00	r	18.64 ± 0.03	P48+ZTF
59022.27	27.88	r	18.96 ± 0.04	P48+ZTF
59025.37	30.98	r	18.74 ± 0.04	P48+ZTF
59033.34	38.95	r	18.89 ± 0.07	P48+ZTF
59037.37	42.98	r	19.02 ± 0.04	P48+ZTF
59041.29	46.90	r	19.10 ± 0.04	P48+ZTF
59045.34	50.95	r	19.10 ± 0.04	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and NIR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59049.34	54.95	r	19.07 ± 0.04	P48+ZTF
59052.36	57.97	r	19.15 ± 0.03	P48+ZTF
59057.33	62.94	r	19.15 ± 0.05	P48+ZTF
59061.25	66.86	r	19.06 ± 0.10	P48+ZTF
59064.32	69.93	r	19.26 ± 0.06	P48+ZTF
59070.30	75.91	r	19.41 ± 0.05	P48+ZTF
59075.25	80.86	r	19.37 ± 0.08	P48+ZTF
59079.21	84.82	r	19.51 ± 0.05	P48+ZTF
59082.25	87.86	r	19.55 ± 0.10	P48+ZTF
59087.25	92.86	r	19.42 ± 0.12	P48+ZTF
59091.19	96.80	r	19.58 ± 0.10	P48+ZTF
59094.30	99.91	r	19.31 ± 0.08	P48+ZTF
59098.17	103.78	r	19.41 ± 0.07	P48+ZTF
59107.26	112.87	r	19.57 ± 0.15	P48+ZTF
59111.21	116.82	r	19.68 ± 0.05	P48+ZTF
59114.28	119.89	r	19.64 ± 0.10	P48+ZTF
59118.23	123.84	r	19.70 ± 0.13	P48+ZTF
59122.20	127.81	r	19.55 ± 0.11	P48+ZTF
59129.11	134.72	r	19.91 ± 0.16	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and NIR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59135.14	140.75	r	20.04 ± 0.11	P48+ZTF
59139.13	144.74	r	20.19 ± 0.14	P48+ZTF
59146.11	151.72	r	20.26 ± 0.26	P48+ZTF
59151.10	156.71	r	20.17 ± 0.21	P48+ZTF
59155.08	160.69	r	> 18.01	P48+ZTF
59164.12	169.73	r	19.86 ± 0.26	P48+ZTF
59169.14	174.75	r	20.08 ± 0.19	P48+ZTF
59182.07	187.68	r	20.14 ± 0.15	P48+ZTF
59185.08	190.69	r	20.08 ± 0.12	P48+ZTF
59188.08	193.69	r	20.27 ± 0.15	P48+ZTF
59194.07	199.68	r	> 19.84	P48+ZTF
59248.56	254.17	r	20.88 ± 0.28	P48+ZTF
59251.57	257.18	r	20.62 ± 0.22	P48+ZTF
59254.57	260.18	r	20.53 ± 0.22	P48+ZTF
59264.54	270.15	r	20.76 ± 0.14	P48+ZTF
59267.54	273.15	r	21.12 ± 0.14	P48+ZTF
59320.48	326.09	r	21.02 ± 0.29	P48+ZTF
59373.39	379.00	r	21.25 ± 0.32	P48+ZTF
58944.48	-49.91	g	> 19.96	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and NIR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
58955.48	-38.91	g	> 20.38	P48+ZTF
58963.40	-30.99	g	> 21.60	P48+ZTF
58966.46	-27.93	g	> 21.38	P48+ZTF
58974.48	-19.91	g	> 20.87	P48+ZTF
58978.42	-15.97	g	> 20.66	P48+ZTF
58986.41	-7.98	g	21.41 ± 0.16	P48+ZTF
58991.40	-2.99	g	19.87 ± 0.05	P48+ZTF
58994.43	0.04	g	19.78 ± 0.04	P48+ZTF
58998.42	4.03	g	19.83 ± 0.05	P48+ZTF
59002.46	8.07	g	19.89 ± 0.09	P48+ZTF
59012.33	17.94	g	20.34 ± 0.07	P48+ZTF
59016.36	21.97	g	20.72 ± 0.08	P48+ZTF
59020.39	26.00	g	20.74 ± 0.09	P48+ZTF
59024.36	29.97	g	20.65 ± 0.11	P48+ZTF
59028.36	33.97	g	20.85 ± 0.18	P48+ZTF
59034.25	39.86	g	> 19.92	P48+ZTF
59037.25	42.86	g	> 20.22	P48+ZTF
59040.27	45.88	g	21.03 ± 0.13	P48+ZTF
59043.35	48.96	g	20.97 ± 0.09	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and NIR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59048.36	53.97	g	21.11 ± 0.15	P48+ZTF
59052.29	57.90	g	21.00 ± 0.10	P48+ZTF
59055.29	60.90	g	21.29 ± 0.18	P48+ZTF
59060.38	65.99	g	20.92 ± 0.19	P48+ZTF
59064.22	69.83	g	> 20.34	P48+ZTF
59067.32	72.93	g	21.52 ± 0.25	P48+ZTF
59072.23	77.84	g	21.49 ± 0.21	P48+ZTF
59076.27	81.88	g	21.37 ± 0.19	P48+ZTF
59080.21	85.82	g	21.11 ± 0.21	P48+ZTF
59084.19	89.80	g	21.47 ± 0.22	P48+ZTF
59091.23	96.84	g	> 20.68	P48+ZTF
59095.21	100.82	g	> 20.74	P48+ZTF
59098.21	103.82	g	21.36 ± 0.21	P48+ZTF
59107.17	112.78	g	> 20.52	P48+ZTF
59111.13	116.74	g	21.61 ± 0.20	P48+ZTF
59114.21	119.82	g	> 21.00	P48+ZTF
59117.23	122.84	g	> 20.32	P48+ZTF
59121.17	126.78	g	> 20.40	P48+ZTF
59125.17	130.78	g	> 20.02	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and NIR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59131.17	136.78	g	> 20.26	P48+ZTF
59135.12	140.73	g	> 21.24	P48+ZTF
59139.11	144.72	g	> 21.07	P48+ZTF
59146.13	151.74	g	> 18.03	P48+ZTF
59149.18	154.79	g	> 20.02	P48+ZTF
59153.13	158.74	g	> 20.12	P48+ZTF
59157.15	162.76	g	> 19.88	P48+ZTF
59167.14	172.75	g	> 20.53	P48+ZTF
59171.13	176.74	g	> 20.38	P48+ZTF
58962.43	-31.96	i	20.65 ± 0.26	P48+ZTF
58964.49	-29.90	i	20.41 ± 0.09	P48+ZTF
58968.49	-25.90	i	20.48 ± 0.16	P48+ZTF
58971.47	-22.92	i	20.53 ± 0.17	P48+ZTF
58972.49	-21.90	i	20.57 ± 0.17	P48+ZTF
58976.43	-17.96	i	20.13 ± 0.16	P48+ZTF
58983.40	-10.99	i	19.56 ± 0.18	P48+ZTF
58985.37	-9.02	i	18.38 ± 0.03	P48+ZTF
58991.38	-3.01	i	17.08 ± 0.02	P48+ZTF
58994.39	0.00	i	17.06 ± 0.02	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
58996.41	2.02	i	17.06 ± 0.04	P48+ZTF
58997.37	2.98	i	17.13 ± 0.04	P48+ZTF
59001.35	6.96	i	17.18 ± 0.05	P48+ZTF
59004.37	9.98	i	17.30 ± 0.05	P48+ZTF
59005.39	11.00	i	17.57 ± 0.11	P48+ZTF
59008.46	14.07	i	17.54 ± 0.05	P48+ZTF
59009.34	14.95	i	17.54 ± 0.03	P48+ZTF
59012.47	18.08	i	17.53 ± 0.02	P48+ZTF
59017.35	22.96	i	17.61 ± 0.05	P48+ZTF
59018.33	23.94	i	17.77 ± 0.03	P48+ZTF
59022.33	27.94	i	17.87 ± 0.02	P48+ZTF
59026.33	31.94	i	17.78 ± 0.02	P48+ZTF
59031.31	36.92	i	18.01 ± 0.05	P48+ZTF
59032.29	37.90	i	18.02 ± 0.03	P48+ZTF
59035.29	40.90	i	18.00 ± 0.08	P48+ZTF
59036.35	41.96	i	18.00 ± 0.02	P48+ZTF
59040.35	45.96	i	18.08 ± 0.04	P48+ZTF
59042.27	47.88	i	18.11 ± 0.03	P48+ZTF
59045.32	50.93	i	18.11 ± 0.04	P48+ZTF

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Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59047.30	52.91	i	18.17 ± 0.06	P48+ZTF
59060.28	65.89	i	18.22 ± 0.04	P48+ZTF
59068.31	73.92	i	18.36 ± 0.04	P48+ZTF
59070.27	75.88	i	18.45 ± 0.03	P48+ZTF
59073.27	78.88	i	18.48 ± 0.07	P48+ZTF
59075.29	80.90	i	18.43 ± 0.06	P48+ZTF
59076.26	81.87	i	18.49 ± 0.08	P48+ZTF
59079.25	84.86	i	18.53 ± 0.04	P48+ZTF
59085.29	90.90	i	18.54 ± 0.05	P48+ZTF
59087.23	92.84	i	18.45 ± 0.03	P48+ZTF
59091.18	96.79	i	18.41 ± 0.03	P48+ZTF
59094.25	99.86	i	18.38 ± 0.10	P48+ZTF
59095.23	100.84	i	18.41 ± 0.03	P48+ZTF
59098.23	103.84	i	18.44 ± 0.05	P48+ZTF
59106.17	111.78	i	18.57 ± 0.05	P48+ZTF
59110.19	115.80	i	18.59 ± 0.04	P48+ZTF
59112.21	117.82	i	18.67 ± 0.06	P48+ZTF
59112.27	117.88	i	18.64 ± 0.07	P48+ZTF
59114.17	119.78	i	18.65 ± 0.07	P48+ZTF

Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59116.18	121.79	i	18.65 ± 0.06	P48+ZTF
59118.17	123.78	i	18.68 ± 0.03	P48+ZTF
59121.12	126.73	i	18.70 ± 0.08	P48+ZTF
59121.13	126.74	i	18.70 ± 0.03	P48+ZTF
59125.13	130.74	i	18.79 ± 0.07	P48+ZTF
59125.14	130.75	i	18.77 ± 0.03	P48+ZTF
59128.19	133.80	i	18.89 ± 0.08	P48+ZTF
59128.22	133.83	i	18.84 ± 0.05	P48+ZTF
59137.00	142.61	i	19.16 ± 0.02	P48+ZTF
58958.58	-35.81	c	> 20.53	ATLAS
58966.52	-27.87	c	> 20.29	ATLAS
58970.57	-23.82	c	> 20.01	ATLAS
58990.48	-3.91	c	19.12 ± 0.05	ATLAS
58994.47	0.08	c	18.81 ± 0.05	ATLAS
58998.47	4.08	c	18.88 ± 0.05	ATLAS
59022.45	28.06	c	20.23 ± 0.20	ATLAS
59026.48	32.09	c	19.75 ± 0.10	ATLAS
59050.41	56.02	c	20.45 ± 0.20	ATLAS
59054.48	60.09	c	> 19.88	ATLAS

Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59071.35	76.96	c	20.55 ± 0.28	ATLAS
59074.41	80.02	c	20.35 ± 0.17	ATLAS
59078.34	83.95	c	20.19 ± 0.19	ATLAS
59082.33	87.94	c	20.52 ± 0.25	ATLAS
59102.30	107.91	c	20.48 ± 0.16	ATLAS
59106.32	111.93	c	20.66 ± 0.24	ATLAS
59110.27	115.88	c	20.38 ± 0.24	ATLAS
59130.31	135.92	c	20.95 ± 0.25	ATLAS
59138.28	143.89	c	> 20.32	ATLAS
59142.22	147.83	c	> 20.23	ATLAS
58944.60	-49.79	o	> 19.10	ATLAS
58949.48	-44.91	o	> 19.42	ATLAS
58956.59	-37.80	o	> 19.86	ATLAS
58960.62	-33.77	o	> 19.93	ATLAS
58964.54	-29.85	o	> 19.43	ATLAS
58968.53	-25.86	o	> 19.96	ATLAS
58972.51	-21.88	o	> 20.15	ATLAS
58976.54	-17.85	o	> 19.58	ATLAS
58980.49	-13.90	o	> 19.68	ATLAS

Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
58984.58	−9.81	o	19.45 ± 0.06	ATLAS
58988.47	−5.92	o	18.41 ± 0.04	ATLAS
58992.50	−1.89	o	17.63 ± 0.02	ATLAS
58996.55	2.16	o	17.67 ± 0.10	ATLAS
59000.46	6.07	o	17.79 ± 0.02	ATLAS
59004.41	10.02	o	18.01 ± 0.03	ATLAS
59008.59	14.20	o	18.18 ± 0.05	ATLAS
59016.44	22.05	o	18.22 ± 0.07	ATLAS
59020.39	26.00	o	18.45 ± 0.05	ATLAS
59024.34	29.95	o	18.45 ± 0.04	ATLAS
59028.44	34.05	o	18.54 ± 0.04	ATLAS
59031.47	37.08	o	18.72 ± 0.05	ATLAS
59036.49	42.10	o	18.67 ± 0.05	ATLAS
59040.53	46.14	o	18.91 ± 0.06	ATLAS
59044.43	50.04	o	18.79 ± 0.08	ATLAS
59048.41	54.02	o	18.82 ± 0.06	ATLAS
59052.45	58.06	o	18.77 ± 0.06	ATLAS
59058.33	63.94	o	18.75 ± 0.04	ATLAS
59061.34	66.95	o	18.94 ± 0.12	ATLAS

Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59064.42	70.03	o	18.86 ± 0.13	ATLAS
59068.42	74.03	o	18.96 ± 0.06	ATLAS
59072.44	78.05	o	18.96 ± 0.08	ATLAS
59076.40	82.01	o	18.99 ± 0.07	ATLAS
59080.36	85.97	o	19.25 ± 0.07	ATLAS
59084.33	89.94	o	19.19 ± 0.06	ATLAS
59088.34	93.95	o	19.30 ± 0.12	ATLAS
59092.33	97.94	o	19.27 ± 0.13	ATLAS
59096.36	101.97	o	19.02 ± 0.06	ATLAS
59100.30	105.91	o	19.22 ± 0.08	ATLAS
59104.33	109.94	o	19.23 ± 0.09	ATLAS
59108.29	113.90	o	19.36 ± 0.10	ATLAS
59112.28	117.89	o	19.36 ± 0.10	ATLAS
59115.34	120.95	o	19.42 ± 0.11	ATLAS
59120.32	125.93	o	19.19 ± 0.14	ATLAS
59126.25	131.86	o	19.74 ± 0.14	ATLAS
59129.27	134.88	o	19.39 ± 0.12	ATLAS
59136.28	141.89	o	19.71 ± 0.18	ATLAS
59140.23	145.84	o	19.58 ± 0.14	ATLAS

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Table S1: Photometry of ZTF SLRN-2020 in the optical and IR bands (continued).

MJD	Phase (d)	Filter	Mag	Instrument
59144.21	149.82	o	19.57 ± 0.17	ATLAS
59148.22	153.83	o	> 18.39	ATLAS
59154.24	159.85	o	19.49 ± 0.10	ATLAS
59158.19	163.80	o	19.53 ± 0.17	ATLAS
59164.23	169.84	o	19.44 ± 0.12	ATLAS
59184.19	189.80	o	19.49 ± 0.16	ATLAS

Table S2: Template-subtracted NEOWISE mid-IR photometry of ZTF SLRN-2020.

MJD	Phase days	Filter	Flux mJy
55296.47	-3697.92	$W1$	0.16 ± 0.11
55479.51	-3514.88	$W1$	0.00 ± 0.08
56940.99	-2053.40	$W1$	-0.12 ± 0.13
57122.03	-1872.36	$W1$	0.11 ± 0.21
57300.01	-1694.38	$W1$	-0.02 ± 0.14
57487.55	-1506.84	$W1$	0.02 ± 0.21
57658.98	-1335.41	$W1$	-0.08 ± 0.14
57851.76	-1142.63	$W1$	-0.09 ± 0.19
58021.99	-972.40	$W1$	-0.07 ± 0.12
58217.44	-776.95	$W1$	0.02 ± 0.22
58381.60	-612.79	$W1$	-0.13 ± 0.13
58583.15	-411.24	$W1$	0.02 ± 0.22
58747.25	-247.14	$W1$	0.07 ± 0.14
58949.95	-44.44	$W1$	0.26 ± 0.22
59113.93	119.54	$W1$	2.21 ± 0.13
59314.32	319.93	$W1$	1.03 ± 0.23
59478.41	484.02	$W1$	0.42 ± 0.12
55296.47	-3697.92	$W2$	0.03 ± 0.09

Table S2: Template-subtracted NEOWISE mid-IR photometry of ZTF SLRN-2020 (continued).

MJD	Phase days	Filter	Flux mJy
55479.51	-3514.88	$W2$	0.03 ± 0.08
56940.99	-2053.40	$W2$	-0.12 ± 0.09
57122.03	-1872.36	$W2$	0.00 ± 0.10
57300.01	-1694.38	$W2$	-0.16 ± 0.10
57487.55	-1506.84	$W2$	-0.12 ± 0.11
57658.98	-1335.41	$W2$	-0.12 ± 0.09
57851.69	-1142.70	$W2$	-0.09 ± 0.11
58021.99	-972.40	$W2$	-0.01 ± 0.10
58217.44	-776.95	$W2$	0.00 ± 0.10
58381.60	-612.79	$W2$	-0.15 ± 0.11
58583.15	-411.24	$W2$	0.01 ± 0.13
58747.25	-247.14	$W2$	0.13 ± 0.10
58949.88	-44.51	$W2$	0.47 ± 0.12
59113.93	119.54	$W2$	2.60 ± 0.11
59314.32	319.93	$W2$	1.12 ± 0.13
59478.41	484.02	$W2$	0.40 ± 0.12