Of more than a thousand known cataclysmic variables (CVs), where a white dwarf is accreting from a hydrogen-rich star, only a dozen have orbital periods below 75 minutes\(^3\). One way to achieve these short periods requires the donor star to have undergone substantial nuclear evolution before interacting with the white dwarf\(^10\)–\(^14\), and it is expected that these objects will transition to helium accretion. These transitional CVs have been proposed as progenitors of helium CVs\(^13\)–\(^18\). However, no known transitional CV is expected to reach an orbital period short enough to account for most of the helium CV population, leaving the role of this evolutionary pathway unclear. Here we report observations of ZTF \(\text{J1813+4251}\), a 51-minute-orbital-period, fully eclipsing binary system consisting of a star with a temperature comparable to that of the Sun but a density 100 times greater owing to its helium-rich composition, accreting onto a white dwarf. Phase-resolved spectra, multi-band light curves and the broadband spectral energy distribution allow us to obtain precise and robust constraints on the masses, radii and temperatures of both components. Evolutionary modelling shows that ZTF \(\text{J1813+4251}\) is destined to become a helium CV binary, reaching an orbital period under 20 minutes, rendering ZTF \(\text{J1813+4251}\) a previously missing link between helium CV binaries and hydrogen-rich CVs.
Fig. 1 | Light curve of ZTF J1813+4251. a, The five-colour HIPERCAM light curve of ZTF J1813+4251, with filters us, gs, rs, is and zs arranged from top to bottom (where $\lambda_{\text{cen}}$ refers to the central wavelength of these filters). The object exhibits a strong sinusoidal component at twice the orbital frequency owing to the tidal deformation of the donor star. The system undergoes a full eclipse, in which the donor fully occults the accreting white dwarf. The timestamps of these lightcurves are given in barycentric modified Julian date, in barycentric dynamical time (BMJDDB). The depth of the eclipse varies dramatically with wavelength, with the white dwarf contributing half the luminosity in the us filter, and only about 10% in the zs filter, primarily because the white dwarf preferentially emits its radiation at shorter wavelengths than the cooler donor. b, Best-fit light-curve models of the primary and secondary eclipses of ZTF J1813+4251. These models, combined with the spectroscopically derived radial velocity semi-amplitude, allow us to robustly constrain the properties of both components in the system.

Fig. 2 | Optical spectroscopy of ZTF J1813+4251. a, A sinusoidal fit to the measured radial velocities of the donor star in ZTF J1813+4251, with a best-fit velocity semi-amplitude of $K_0 = 461.3 \pm 3.4 \text{ km s}^{-1}$ and systemic velocity of $\gamma = -36.8 \pm 2.4 \text{ km s}^{-1}$. b, The blue side of the Keck LRIS spectrum, co-added in the rest frame of the donor star, where $F_{\lambda}$ denotes the flux density as a function of wavelength. The spectrum exhibits a large number of narrow metal lines, including those from calcium, iron and magnesium, characteristic of main-sequence stars with spectral types similar to the Sun. c, The trailed blue Keck LRIS spectra, illustrating the significant wavelength shifts in the spectrum caused by the large Doppler shifts of the donor. The trailed spectra reveal that these Doppler shifts occur in the large number of narrow lines associated with the donor spectrum.
The accretion disk seen in Fig. 3d,e indicates that the donor star in ZTF J1813+4251 is transferring matter to the white dwarf, and thus is filling its Roche lobe. The Roche lobe has a scale-invariant geometry dependent only on the mass ratio of the system, and thus the geometry of the donor depends on only this mass ratio. In a binary system undergoing a total eclipse, the time between mid-ingress and mid-egress depends on only the geometry of the donor and the inclination of the system. This means that the eclipses in ZTF J1813+4251's light curve constrain the system to a unique mass ratio versus inclination relation. In addition, the depths of the primary and secondary eclipse constrain a unique radius ratio between the white dwarf and that of the donor, which, when combined with the overall geometry of the primary eclipse, yields a unique solution for the radii divided by the semi-major axis (the scaled radii), orbital inclination and thus mass ratio, because the system is Roche-lobe filling. These constraints, together with the precise donor radial velocity semi-amplitude measured from the spectra (see the co-added spectrum in Fig. 2), allow for a robust determination of the system parameters on the basis of only Roche-lobe geometry and Kepler's laws (Methods). We report these system parameters in Table 1. As the donors in transitional cataclysmic variables (CVs) are still transferring significant hydrogen and have not switched to primarily helium accretion yet, as seen in a helium CV (also known as AM CVns), these objects often exhibit a mixture of hydrogen disk lines along with unusually strong helium lines in their spectra as a result of their slowly transitioning to transferring mainly helium, and as a result, we see in Fig. 3d that the disk also exhibits significant helium emission.

Table 1 | Table of parameters

| Parameter                                      | Value                        |
|-----------------------------------------------|------------------------------|
| Right ascension                               | 18h13m11.13s                 |
| Declination                                   | +42°51′50.4″                  |
| Proper motion in right ascension               | −12.32±0.19 mas yr⁻¹         |
| Proper motion in declination                   | −2.66±0.19 mas yr⁻¹          |
| Parallax (α)                                   | 1.20±0.16mas                 |
| Distance (D)                                   | 891±15 pc                    |
| Systemic velocity (v)                         | −36.8±2.4 km s⁻¹             |
| Orbital period (Pₚ)                            | 3.06964398±0.000015 s         |
| Orbital period derivative (Pₚ)                 | −0.29±1.15×10⁻¹ s⁻¹          |
| Time of superior conjunction (Tₐ)              | 59,377,153,818±0.0000020 BMJDₜₒₑₚ |
| Radial velocity of donor (K₂)                  | 461.3±3.4 km s⁻¹             |
| Orbital inclination (i)                       | 78.80±0.18°                  |
| Semi-major axis (a)                            | 0.4000±0.0041 Rₒ              |
| White-dwarf mass (Mₚ)                         | 0.562±0.015 Mₒ                 |
| Donor mass (Mₜₒₑₚ)                            | 0.1185±0.0067 Mₒ                |
| White-dwarf radius (Rₚ)                       | 0.01374±0.00023 Rₒ               |
| Donor radius (Rₜₒₑₚ)                          | 0.1017±0.0019 Rₒ                 |
| White-dwarf temperature (Tₚ)                  | 12,600±500 K                   |
| Donor temperature (Tₜₒₑₚ)                     | 6,000±80 K                     |

The first five parameters are the astrometric solution reported by Gaia EDR3, at epoch 2016.0 and equinox 2000.0.
of just under 30 min. b, The future orbital period evolution of the MESA tracks. The track corresponding to ZTF J1813+4251 will reach a period minimum of about 18 min in approximately 75 million years, and will spend the next 300 million years evolving back out to a period of about half an hour as a helium CV. c, The evolution of the donor mass as a function of orbital period, reaching just a few hundredths of a solar mass as the tracks evolve out to longer orbital periods as helium CVs. d, The hydrogen remaining in the donor over the course of its future evolution. At around the period minimum, the donor star loses all remaining hydrogen. (See also ref. 13 for a comprehensive discussion of the evolution of these systems.).

A Niels Gehrels Swift observatory (Swift) X-ray telescope observation of the system revealed no detectable X-ray flux, with the X-ray luminosity of the system, $L_x$, constrained to a 3σ upper limit of $L_x < 1.22 \times 10^{30}$ erg s$^{-1}$ given an assumed distance of 891 pc inferred from Gaia EDR3, an upper limit that is consistent with the typical X-ray luminosity of a non-magnetic CV at these energies. The source was detected with the Swift Ultraviolet Optical Telescope (UVOT) in the ultraviolet, constraining the temperature of the accreting white dwarf (Methods).

As seen in Fig. 3, archival ZTF data captured an outburst of the object on 21 September 2019, brightening by over a factor of two relative to its quiescent brightness in the ZTF g and ZTF r filters. The final observation of the night during which the outburst was detected took place during the totality of the primary eclipse, and as a result the flux was significantly attenuated, indicating that this brightening must have originated from the accretor. As the white dwarf was completely eclipsed during this phase, but the flux was still partially elevated relative to quiescence, we can infer that the luminosity must be originating from the accretion disk, which was not completely occulted at this orbital phase.

We used Modules for Experiments in Stellar Astrophysics (MESA) to model the past and future evolution of systems such as ZTF J1813+4251, and Fig. 4 illustrates these evolutionary tracks. At present, ZTF J1813+4251 exhibits an elevated temperature because the white dwarf is rapidly removing matter from the donor as the orbital period shrinks, causing its radius to decrease at roughly constant luminosity. We expect to be able to detect this orbital period evolution over the next decade, as using the HiPERCAM light curve we are able to measure the mid-eclipse time, $T_{\text{m}}$, to a precision of about 0.16 s, which will allow us to test whether the angular momentum loss in the binary deviates from that expected purely owing to general relativity. Assuming that the system is evolving purely according to general relativistic orbital decay, the eclipse time will deviate from that expected if the orbital period were constant by about 7 s over the next 10 years. However, evolutionary models (Methods) indicate that magnetic braking may still be responsible for as much as two-thirds of the orbital angular momentum loss in the system, and there are other effects which may influence the orbital evolution as well such as mass transfer. As seen in Fig. 4a, d, when the system evolves to shorter orbital periods, the last remnants of hydrogen will be removed from the donor, eliminating its fuel source, and its helium-rich remnant will begin to transition to being supported by electron-degeneracy pressure. At this stage, which our models predict will occur in approximately 75 million years, ZTF J1813+4251 will have completed its transition to a helium CV system, reaching a period minimum around 18 min. Owing to it being supported by electron-degeneracy pressure, ZTF J1813+4251’s structure will undergo an important transition, in which it will begin to expand in response to mass loss, rather than shrink. This will cause further accretion to decrease the donor’s density as the system evolves to longer orbital periods, and the donor will rapidly cool as a result of adiabatic expansion in response to mass loss. We estimate that after the period minimum, the system will spend 300 million years evolving back out to an orbital period of about 30 min as a helium CV, thus spending a much larger fraction of its remaining life in this state than in its current short-lived orbital decay phase as a transitional CV.

The observation of ZTF J1813+4251 demonstrates that evolved CV donors can reach orbital periods below 20 min, and probably form helium CVs. Other known examples of candidate transitional CVs

Fig. 4 | Evolutionary tracks of ZTF J1813+4251 generated using MESA. a, The donor’s temperature evolution as a function of orbital period in transitional CVs such as ZTF J1813+4251. The wide dashed orange line, dotted red line and alternating dashed blue line indicate MESA evolutionary sequences corresponding to a transitional CV where mass loss from the donor commenced at 97%, 95% and 94% of its main-sequence lifetime, and the black star indicates the position of ZTF J1813+4252 on the red dotted track. These sequences host warmer donors than normal hydrogen CVs, whose location are indicated on the right of the plot, and evolve into the region occupied by helium CVs in the lower left corner. For comparison, we also illustrate a track for El Psc, another transitional CV candidate that will probably reach a period minimum after RLOF. b, The evolution of the donor mass as a function of orbital period, reaching just a few hundredths of a solar mass as the tracks evolve out to longer orbital periods as helium CVs. c, The hydrogen remaining in the donor over the course of its future evolution. At around the period minimum, the donor star loses all remaining hydrogen. (See also ref. 13 for a comprehensive discussion of the evolution of these systems.).
below the period minimum are either completely dominated by the flux of an accretion disk, making it difficult to characterize the properties of the donor star, or exhibit a detectable donor that is not evolved enough to reach orbital periods short enough to account for the full range of periods seen in the helium CV population. In addition, none of the known transitional CVs exhibit a clean radial velocity semi-amplitude paired with a detectable full primary and secondary eclipse like that seen in ZTF J1813+4251, making ZTF J1813+4251 the only transitional CV with robustly characterized system parameters. As seen in Fig. 4a, the most important property in predicting how evolved the donor is—and thus what period minimum it can reach—is its effective temperature. As seen in Fig. 4a, we also modelled El Psc, which is one of the few transitional CVs with enough parameter estimates to construct such models. Like ZTF J1813+4251, we expect this system to evolve into a helium CV; however, it reaches a period minimum of around 30 min rather than below 20 min. ZTF J1813+4251, which has a shorter orbital period and significantly hotter donor than any currently known transitional CV candidate below the period minimum, demonstrates that the donors of these systems can reach much more extreme states than seen in previously identified systems, and solidifies the role of this evolutionary channel in the formation of helium CVs, including those with orbital periods short enough to emit significantly in the Laser Interferometer Space Antenna (LISA) gravitational wave band. ZTF J1813+4251, with its well-characterized components, will serve as an anchor point for models of binary evolution connecting the population of hydrogen accreting CVs with evolved donors at longer orbital periods and the population of ultracompact helium CVs.

Online content

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Methods

Period search
We performed a period search using a GPU implementation of the generalized Lomb–Scargle algorithm, an analogue of the Fourier transform optimized for data with non-equispaced sampling. This search was based on newly generated forced point-spread-function photometry performed at the coordinates of all Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1) sources in ZTF images over a period range of 250 d to just 2 min. By systematically searching all 1,220,038,476 unique sources in the Pan-STARRS1 source catalogue with more than 50 ZTF epochs, we eliminated biases of previous searches relying on colour- or astrometric-based selections, which represents a major advancement in probing for short-period astrophysical variables across the northern sky. We searched a total of 1,461,592 trial frequencies per source, corresponding to an oversampling factor of 2. In total, given that we searched 1,220,038,476 sources, this means a total of 1.78 × 10^13 trial frequencies were searched, and each source had on average approximately 10^2 epochs. This search was completed in six weeks on a single desktop containing four Nvidia 2080 Ti GPUs, and this same desktop was used to perform the forced point-spread-function photometry of all Pan-STARRS sources in ZTF images.

Keck LRIS observation
We obtained the Keck LRIS observations using the 600/4,000 grism as the dispersive element on the blue arm and the 600/7,500 grating on the red arm. We used 2 × 2 binning on both channels to reduce both readout noise and readout time, and used an exposure time of 120 s to mitigate the impact of orbital Doppler smearing on individual exposures. We reduced the Keck LRIS observations using a publicly available LPipe automated data-reduction pipeline.

Keck Echelle Spectrograph and Imager observation
We obtained sixteen 120-s-medium-resolution spectra using the Echelle Spectrograph and Imager (ESI) on the 10-m W. M. Keck II Telescope on Mauna Kea. These exposures were obtained in the cross-dispersed echelle mode and were binned 2 × 2 to reduce readout overheads and readout noise. The data were reduced using the Mauna Kea Echelle Extraction (MAKEE) pipeline.

HiPERCAM observation
We reduced the HiPERCAM data using the publicly available pipeline, and selected several comparison stars in each filter to ensure accurate absolute flux calibrations. The pipeline performed aperture photometry with a dynamic full-width at half-maximum. We used 9 s, 3 s, 3 s, 3 s and 3 s exposures in the u, g, r, i, and z filters, respectively. The charge-coupled devices were operated with conventional amplifiers using frame readout to effectively eliminate readout overheads. The total observation lasted 150 min, or about 3 orbital cycles.

Swift X-ray telescope observation
We obtained a 2,777-s Swift observation of ZTF J1813+4251 (observation ID 00014355002) to constrain the X-ray flux associated with the mass transfer in the system. We do not detect the source with significance, and thus we used an annulus background aperture centred on the source, with an inner radius of 7.5 arcsecond and an outer radius of 15 arcsecond. We find an apparent magnitude of 21.20 ± 0.1 (statistical) ± 0.03 (systematic) m_{AB}.

Spectral-energy-distribution analysis
We estimated the spectroscopic properties of the donor in ZTF J1813+4251 by fitting atmospheric models to the in-eclipse spectral energy distribution (SED), as our spectra are composed of contributions from both the white dwarf and the accretion disk with exposures too long to have obtained a completely in-eclipse spectrum. We use the in-eclipse apparent magnitudes of the system to obtain an uncontaminated SED of the donor star, and fit the BT-NextGen (GNS93) atmospheric models for low-mass stars to the SED, allowing the metallicity, flux scale and temperature to vary, and fixing the surface gravity to log(g)_{donor} = 5.43 (centimetres–grams–seconds) on the basis of an estimate derived from an initial light-curve model that used the Gaia EDR3 estimated temperature of 6,088 K for the donor. Using the UltraNest kernel density estimator, we sampled over these parameters and obtained a donor temperature estimate of T_{donor} = 6,000 ± 80 K. The metallicity preferred the lowest possible value covered by the atmospheric model grids, Z_{donor} = −1.5[Fe/H]. Owing to the evolved nature of the donor, we consider this metallicity estimate based on main-sequence models to be dubious, and thus do not report it in the table; we suspect the uncertainties in the T_{donor} are also probably underestimated, although we are unable to appropriately quantify the model error associated with using model atmospheres for main-sequence stars on such an extreme evolved star. We overplot the best-fit atmospheric models with the donor and accretor SEDs in Extended Data Fig. 1.

We are also able to precisely measure the contribution of the white dwarf to the SED because of the eclipses in the light curve, and thus we performed an SED fit to it as well to estimate T_{WD}. A fit to the optical SED using a white-dwarf model with a fixed log(g)_{WD} = 7.90 (cgs) based on an initial light-curve model yields an estimated effective temperature of T_{WD} = 12,600 ± 500 K.

Atmospheric analysis
We summed the phase-resolved LRIS spectra in the rest frame of the donor and performed fits with atmospheric models to estimate a temperature independently of the SED based analysis. We broaden the spectra by the predicted rotational velocity in the donor and convolve the synthetic spectra with the instrument resolution. We fix the relative contributions of the white dwarf and donor by fixing the radius of each object in our spectroscopic models, as well as the overall distance to the system. Using hydrogen-rich, DA white-dwarf models in combination with the BT-NextGen (GNS93) low-mass main-sequence models, we construct a grid of composite spectra to carry out the fitting procedure. Extended Data Fig. 2 shows our best fit, as well as a fit based on the temperatures derived from the SED. We consider both fits acceptable, although the estimated temperatures differ by about 1,200 K. We consider the temperature derived from the SED to be more reliable, as it uses the Swift UVOT measurement, which strongly constrains the white-dwarf temperature (the estimated spectroscopic temperature of 13,780 ± 380 K significantly overestimates the Swift UVOT luminosity).
Radial velocity analysis

We measured radial velocities from the Keck LRIS spectra by fitting nine narrow absorption lines with Voigt profiles. We fit the Fe I lines at 4,271.7602 Å, 4,325.7616 Å, 4,383.5447 Å, 4,404.7501 Å, 4,599.6921 Å, 4,920.5028 Å and 4,957.5965 Å, the Mg I lines at 4,702.9909 Å and the Ca I line at 4,226.73 Å. We forced all lines to share the same Doppler shift and full-width at half-maximum for both the Gaussian and Lorentzian components of the Voigt profile as common free parameters, but allowed the amplitude of each line to vary individually. We used a least-squares minimizer to fit each individual spectrum for a Doppler shift relative to the rest frame, and then fit a sinusoidal function to these velocities to derive a semi-amplitude and systemic velocity, as seen in Fig. 2a, with uncertainties derived from the covariance matrix of the fit.

We validate the semi-amplitude and systemic velocity with an independent cross-correlation analysis. We try two cross-correlation spectral templates: a template matched to the spectral type, and a template created from summing the ZTF J1813+4251 spectra shifted to the rest frame of the donor. We cross-correlate the individual spectra from 4,900 Å to 5,600 Å, a wavelength range filled with narrow absorption lines and dominated by the F-type star. We find statistically identical results, \( K = 463.2 \) km s\(^{-1}\), consistent within the 1σ uncertainty of the published value (Table 1).

Rotational broadening analysis

We co-added the phase-resolved ESI spectra in the rest frame of the donor using the radial velocity semi-amplitude derived from the LRIS spectroscopy. Owing to the highly nonlinear dispersion in the instrument, only the red end of each echelle order exhibited signal above the read-noise floor, and the SNR of the co-added spectra was too low to obtain a useful constraint on the rotational broadening of the donor. As illustrated in Extended Data Fig. 3, we fit four lines, the Fe I lines at 4,920.5028 Å and 4,957.5965 Å and the Ca I lines at 6,122.22 Å and 6,162.17 Å. These fits yielded measured rotationally broadened velocities of 159 km s\(^{-1}\), 178 km s\(^{-1}\), 129 km s\(^{-1}\) and 184 km s\(^{-1}\), with a large scatter owing to the low SNR of the spectra, but with values roughly in agreement of the predicted value of 145 km s\(^{-1}\) (they are on average slightly higher, but were not corrected for Doppler smearing, which should inflate values by several tens of kilometres per second. Future higher-SNR moderate-to-high-resolution spectroscopy could yield a more precise measurement, which would serve as a test of the parameters reported in Table 1.

Light-curve analysis

The core of our analysis was based on the modelling of ZTF J1813+4251’s HIPERCAM light curves using the LCURVE light-curve modelling code\(^{42}\). LCURVE simulates two stars in a Roche potential, determining the flux at each surface element of the star, taking into account effects such as limb darkening and gravity darkening, and computes the flux as seen from the perspective of an observer at a given inclination and orbital phase. Although this code is numerical, below we outline a simplified analytic argument demonstrating why the modelling code is able to robustly constrain the parameters in the system. Extended Data Fig. 4 illustrates this idealized example and provides all relevant analytic expressions.

Because ZTF J1813+4251 undergoes a total eclipse, in which the white dwarf passes completely behind the donor, we are able to measure three parameters from it: the fractional flux depth in-eclipse with respect to the out-of-eclipse flux, \( F_i \), the third contact phase corresponding to the start of egress relative to the mid-eclipse time, \( \phi_i \), which measures the duration of the flat-bottomed portion of the eclipse when the white dwarf is completely obscured, and the fourth contact phase, \( \phi_f \), which measures the end of egress with respect to the mid-eclipse time, and in combination with the third contact phase, describes the duration of egress (one could alternatively use the first and second contact phases, which measure the start and end of ingress, but these are degenerate with the third and fourth contact phases). In an idealized circular orbit involving two spherical objects, the sum and differences of the scaled radii of the two components are constrained by the following two expressions:

\[
\sin^2(i)\sin^2(2\pi\phi_i) + \cos^2(2\pi\phi_i) = \left( \frac{R_{\text{Donor}}}{a} - \frac{R_{\text{WD}}}{a} \right)^2
\]

\[
\sin^2(i)\sin^2(2\pi\phi_f) + \cos^2(2\pi\phi_f) = \left( \frac{R_{\text{Donor}}}{a} + \frac{R_{\text{WD}}}{a} \right)^2
\]

where \( R_{\text{WD}} \) and \( R_{\text{Donor}} \) are the radii of the components, scaled to the semi-major axis. Although the primary eclipse gives three parameters to measure, its geometry depends on four physical parameters: the orbital inclination, \( i \), the scaled radii of the two components, and the surface brightness ratio of the two components, \( J \). This means that to constrain the parameters of the system from the primary eclipse alone, it is necessary to invoke an additional constraint such as a white-dwarf mass–radius relation, or by constraining the surface brightness ratio using temperature estimates of the components, which depend on model atmospheres. However, we detect the secondary eclipse in the system, when the white dwarf transits the donor. This provides one additional geometric constraint, as we can measure the flux depth during the secondary eclipse as a fraction of the out-of-eclipse flux, \( F_s \) (the duration of ingress/egress and the base of the secondary eclipse should be identical to that of the primary, so the only additional parameter is the depth). Using the flux level in the two eclipses, we can constrain the ratio of the radii of the two components, using the following relation:

\[
\frac{R_{\text{WD}}}{R_{\text{Donor}}} = \sqrt{\frac{1 - F_s}{F_s}}
\]

In addition, the surface brightness ratio is also constrained by the relative depths of the eclipses, and is given by:

\[
J = \frac{1 - F_s}{1 - F_s}
\]

The above expressions are only applicable for a highly idealized case of two spherical objects transiting each other, and thus only approximate in the case of ZTF J1813+4251, which hosts a highly distorted donor. The LCURVE modelling simulates the fully distorted donor, and thus accounts for the complexities accompanied by this.

The fact that the donor is filling its Roche lobe (which we know because the system is mass transferring) allows us to place an additional constraint, as a Roche-lobe-filling donor in a binary that undergoes a full eclipse must obey a pair of nonlinear parametric equations that map any given eclipse geometry to a unique mass ratio, \( q \), versus inclination relation\(^{12}\). As we have already solved for a unique inclination given the primary and secondary eclipse geometry using the above expressions, this means we also obtain a unique mass ratio as a result of the Roche-lobe-filling assumption. We have also measured a velocity semi-amplitude of the donor, \( K_s \), which is given by the binary mass function:

\[
M_{\text{WD}}\sin^2(i) = \frac{P_b K_s^3}{2\pi G}
\]

where \( G \) is the gravitational constant. As we have already solved for a unique mass ratio and inclination, and have determined the orbital period, this expression yields a solution for \( M_{\text{WD}} \) which, in combination with the mass ratio, also yields a solution for \( M_{\text{Donor}} \). Finally, as we
have determined both component masses in the system, and know the orbital period, we can use Kepler's law to solve for the semi-major axis of the system:

\[
\frac{a^3}{P_b^2} = \frac{GM_{\text{Donor}} + M_{\text{WD}}}{4\pi^2},
\]

(6)

and thus, we use the semi-major axis in combination with the previously determined scaled radii \(R_{\text{WD}}\) and \(R_{\text{Donor}}\) to compute the physical radii of the components, \(R_{\text{Donor}}\) and \(R_{\text{WD}}\). Thus, using the orbital period, four parameters measured from the eclipse geometry, the Roche-lobe-filling nature of the donor and its radial velocity semi-amplitude, we are able to determine a unique solution for both component masses, radii, the semi-major axis of the system, the surface brightness ratio of the components and the orbital inclination.

When modelling the light curve, we used Gaussian priors constraining the radial velocity semi-amplitude based on the spectroscopic analysis. We sampled over the orbital inclination, \(i\), the time of superior conjunction of the white dwarf, \(T_o\), the mass of the white dwarf, \(M_{\text{WD}}\), the mass of the donor star, \(M_{\text{Donor}}\), the white-dwarf-to-donor surface brightness ratio in each filter, \(j\), and the radius of the white dwarf, \(R_{\text{WD}}\). We did not sample over the radius of the donor star, as we instead fixed it to fill the Roche lobe. We fixed the limb-darkening and gravity-darkening coefficients based on the temperature estimate of the white dwarf and donor star derived from atmospheric fits.43–46

The strong O'Connell effect and contribution of the disk to the light curve makes it challenging to model the ellipsoidal variations in the system. We subtracted a term at the orbital frequency out of the light curve to account for this effect. However, we discovered there was a slight residual phase offset between the time of superior conjunction of the white dwarf inferred from these corrected ellipsoidal variations, and that indicated by the primary eclipse.

Given that the system undergoes a full eclipse of the white dwarf and has a Roche-lobe-filling donor, rather than attempt to model the full light curve and account for the complexities in the ellipsoidal variations, we elected to model only points around the primary and secondary eclipses (within ±160 s of the mid-eclipse times), as the geometry of these contain all the information needed to fully constrain the system, and provide a more robust set of constraints than relying on ellipsoidal variations, which depend on quantities such as the gravity-darkening coefficients of the exotic donor star in each passband. The results of this modelling yielded the values reported in Table 1, and Extended Data Fig. 5 illustrates the best-fit model overplotted with the primary and secondary eclipses, as well as the full light curve, whereas Fig. 1 illustrates the model fit to all the binned primary and secondary eclipses. All of our models included a first-order linear polynomial with both a slope degree of freedom and arbitrary flux offset to minimize impacts of modulation owing to the O'Connell effect near the eclipses on our models. We emphasize that we did include ellipsoidal variations in our model, but also ran a test model with a second-order polynomial fit around each eclipse to remove the sensitivity of our model to the ellipsoidal variations (which can influence the inferred mass ratio), and other effects such as contributions from the accretion disk, effectively making the models sensitive to only the geometry of the eclipses of the donor and white dwarf themselves (as those contain all the information needed to constrain the system in a highly model-independent manner). We found that the parameter estimates derived from the models with the second-order polynomial included were consistent with those derived by simply using a first-order polynomial, indicating that effects such as the ELVs were not influencing the parameter estimates, and that the eclipses indeed are the dominant features influencing the constraints in the system.

We used the Ultrastar package to perform the final parameter estimation by combining the light-curve modelling of the eclipses and the donor's radial velocity semi-amplitude constraint. The derived parameters are reported in Table 1, and Extended Data Fig. 5 illustrates the posterior distributions of these parameters.

As a sanity check regarding our assumptions, we conducted an independent modelling exercise, in which we did not assume a Roche-filling donor, but instead invoked a white-dwarf-mass–radius relation47 for the accreting white dwarf, and we found that the models converged to values consistent with those derived from the models that assumed a Roche-filling donor. We expected this model to converge to similar values, because the values of the white-dwarf mass and radius we found with our Roche-filling model agree remarkably well with a white-dwarf-mass–radius relation.

Timing analysis

Owing to the substantial contribution of magnetic braking to the predicted orbital decay rate of the system, we undertook an effort to constrain the orbital decay rate, \(\dot{P}_o\). as we predict that this value should be a factor of a few larger than what it would be owing to purely general relativistic orbital decay, \(\dot{P}_o^{\text{GR}} = (-4.27 \pm 0.24) \times 10^{-13}\) s^-1. We use the HIPERCAM light curve in combination with archival data from ZTF, the Palomar Transient Factory and the Catalina Real Time Transient Survey to constrain \(\dot{P}_o\). We find a value consistent with zero, with an uncertainty of 10^{-12} s^-1, larger than the predicted value owing to pure general relativity, indicating that we need to continue monitoring the system for the next several years to reach a degree of precision to test whether the orbital evolution is consistent with pure general relativity.

Accretion-disk analysis

To estimate the white-dwarf radial velocity semi-amplitude, we tried to obtain radial velocities from the centroid of the Hα emission component of the accretion disk by fitting a pair of Lorentzians with positive amplitude and a symmetric splitting around a central radial velocity value. Owing to the low SNR of the individual spectra and significant contamination from the Hα absorption line of the donor star (and possibly from the white dwarf itself), we were unable to extract a radial velocity for the accretor in this manner. However, we used the masses estimated from our model to construct a co-added spectrum in the rest frame of the accretor, as seen in Fig. 3, and then fit the accretion-disk profile to determine the splitting between the red and blue components in the disk. We find a splitting of 17.33 ± 0.49 Å, which corresponds to a velocity of 810 ± 23 km s^-1. Assuming a Keplerian disk, this corresponds to a radius of 0.163 ± 0.009 \(R_{\text{WD}}\) around the white dwarf. This is approximately 79% the radius of the white dwarf's Roche lobe, a regime in which material should not be able to maintain a stable orbit.48 We verify that we find a similar result with the He I line at 6.678 Å. It is possible that the splitting in the disk lines is underestimated owing to underlying contamination from the donor and white-dwarf absorption lines, but our results suggest that the matter producing the emission in this system exists near the limit of where a stable accretion disk can form in the white dwarf's Roche lobe.

We also investigated the object's ZTF power spectrum to look for signatures of a peak associated with a superhump excess, which could allow for an independent measurement of the mass ratio in the system. However, the only peaks we were able to identify in the power spectrum were those associated with the orbital period and beat frequencies of the orbital period and the sidereal day.

Curiously, the accretion disk does not manifest itself in a deep eclipse of the donor, which is something we would expect for an optically thick accretion disk. This may suggest that the instantaneous mass transfer rate of the system is lower than the longer-term average mass transfer rate predicted by our MESA models, as some models would predict an optically thick accretion disk given the estimated average mass transfer rate. This is in contrast to some other subperiod minimum systems such as GALEX J194419.33+491257.0, which exhibits signatures of a higher mass transfer rate, although we emphasize that the donor in ZTF J1813+4251 is significantly more evolved than any other known
To investigate the formation history and future evolution of ZTF J1813+4251, we calculated a grid of binary evolution models using MESA (version r12778)\textsuperscript{10,11}. These models build on those calculated by ref.\textsuperscript{12}, which used them to interpret observations of evolved CVs with longer periods (2–6 h). See also the extensive grid of CV models, including ultrashort period systems with helium donors, generated with MESA in ref.\textsuperscript{13}.

We initialized the models with a detached, circular-orbit binary containing a $1.1M_\odot$ zero-age main-sequence star (the donor) and a $0.55M_\odot$ point mass representing the white dwarf. Following ref.\textsuperscript{14}, we use the Skye plus Chabrier, Mazevet, Soubiran equation of state. Orbital angular momentum is removed through gravitational wave radiation and magnetic braking. Roche-lobe radii are computed using the fit from ref.\textsuperscript{15}, and mass transfer rates during Roche-lobe overflow are determined following the prescription from ref.\textsuperscript{16}. We model mass transfer as being fully non-conservative, with the mass that is transferred from the donor to the white dwarf eventually being lost from the vicinity of the latter. The orbital separation evolves under the assumption that the mass that is lost has the same specific angular momentum as the accretor. Although mass transfer in real CVs is not instantaneously non-conservative, the mass accreted by the white dwarf is expected to be ejected from the system by classical nova explosions, which recur on a timescale that is short compared with the timescale on which the orbit evolves.

Magnetic braking follows the prescription from ref.\textsuperscript{17}, with $\gamma_{mb} = 3$. Following ref.\textsuperscript{18}, we assume that the magnetic braking torque is exponentially suppressed when the donor’s convective envelope contains less than 2% of the star’s mass. This is the default implementation of magnetic braking in MESA as of version r15140; it effectively makes magnetic braking inefficient when the donor’s effective temperature is $T_\text{eff} \geq 6,000$ K. We turn magnetic braking off at the period minimum. We explored models with initial periods ranging from 0.5 d to 3 d. At fixed donor mass, longer initial periods lead to donors that are older, and hence more evolved, at the onset of mass transfer. In Extended Data Table 1 and Extended Data Fig. 8, we highlight models that have similar properties to ZTF J1813+4251 at a period of 51 min. These models begin mass transfer just as the donor is completing its main-sequence evolution. Models with shorter initial periods begin mass transfer before the donor has undergone significant nuclear evolution; these evolve into normal CVs. Models with significantly longer initial periods begin mass transfer as the donor is evolving up the giant branch and terminate their evolution as extremely low-mass white dwarfs with long periods (in the case of stable Roche-lobe overfilling) or short periods (in the case of common envelope evolution).

In all the models shown in Extended Data Fig. 8, there is an initial period of thermal-timescale mass transfer in which the mass transfer rate reaches about $10^{-7}M_\odot$ yr$^{-1}$ and most of the donor’s outer envelope is lost. By the time the models reach a period of 6 h, all that remains of the donor is a helium core and a puffy hydrogen envelope containing a few $\times 10^{-2}M_\odot$ of hydrogen. This envelope is steadily removed as the orbit shrinks, still driven primarily by magnetic braking. At periods of a few hours, the donors in these models are very similar to the evolved CVs in the ref.\textsuperscript{19} sample. They heat up as their envelope is removed, with the more evolved models (those in which mass transfer begins later) being hotter at fixed orbital period.

By the time the models reach $P_\text{b} = 51$ min, their surface is predicted to be about 75% helium by mass. The surface nitrogen-to-carbon ratio is predicted to be about 2,000 times the solar value, because the present-day surface of the donor was previously inside the carbon–nitrogen–oxygen-burning core whereas the donor was on the main sequence. The predicted mass transfer rates and accretor temperatures at 51 min differ significantly between the three models we show: the more evolved models with higher $T_\text{eff}$ have less efficient magnetic braking and thus lower mass transfer rates.

We calculate the effective temperature of the accretor assuming that it is set by compressional heating, as described by equation (2) of ref.\textsuperscript{20}. This makes the accretor temperature a sensitive probe of the time-averaged accretion rate. Both the donor and accretor temperatures of ZTF J1813+4251 are best-matched by the model with $t_{\text{RLOF}}/t_{\text{GB}} = 0.95$. Here $t_{\text{RLOF}}$ is the main-sequence lifetime the donor would have if it were an isolated star, and $t_{\text{GB}}$ is the age of the system at the onset of Roche-lobe overflow. In this model, magnetic braking is still the dominant mode of angular momentum loss, leading to a predicted orbital inspiral that is a factor of about three larger than expected from gravitational radiation alone.

The models reach a minimum period between 13 min and 22 min. After this, their orbits begin to widen and they transition to primarily helium mass transfer with fully degenerate donors. The predicted inspiral time is about 70 Myr for the model with $t_{\text{RLOF}}/t_{\text{GB}} = 0.95$. Observational constraints on the period derivative will test these models, allowing us to directly measure the relative importance of magnetic braking and gravitational waves in removing angular momentum from the system.

### Data availability

Reduced HiPERCAM photometric data, LIRIS spectroscopic data and MESA tracks resulting from the models are available at https://github.com/kburface/ZTFJ1813+4251.git. The ZTF data used are all in the public domain. The proprietary period for the spectroscopic data will expire at the start of 2022, at which point the raw spectroscopic images will also be accessible via the Keck observatory archive.

### Code availability

Upon request, the corresponding author will provide the code (primarily in Python) used to analyse the observations, create the MESA models and any data used to generate the figures (MATLAB was used to generate most of the figures). The LCURVE modelling code can be found at https://github.com/trmrsh/cpp-lcurve.

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**Author contributions** K.B.B. discovered the object, conducted the LCURVE light-curve analysis, spectroscopic data reduction and analysis of Keck LRIS and ESI data, the reduction and analysis of the Swift UVOT and X-ray telescope data, and was the primary author of the manuscript. K.E.-B., T.R.M. and S.R. contributed to the interpretation of the object and the implications of its evolutionary history, and helped in responding to the referees reports. K.E.-B. performed the MESA modelling used to construct Fig. 4, and supplied the section and figure on this in the extended data. T.R.M. conducted the HIPERCAM data reduction. S.R. constructed independent models of the system as a sanity check of those used in this paper. W.R.B. performed the cross-correlation radial velocity measurement as a sanity check of that obtained by fitting Voigt profiles to the absorption lines. K.B.B., K.E.-B., T.R.M., S.R., W.R.B., I.C., D.C., V.S.D., J.F., B.T.G., M.J.G., E.K., S.R.K., S.P.L., P.M., P.R.-G., J.V.R. and R.A.S. contributed comments and edits to the paper. V.S.D. is the principal investigator of HIPERCAM. P.R.-G. was the principal investigator of the HIPERCAM proposal that observed the object. A.J.D., R.G.D., S.L.G., R.R.L., F.J.M., R.R. and R.M.S. are ZTF authors. S.R.K., T.A.P., M.J.G. and E.C.B. are the principal investigator, the co-investigator, the project scientist and the survey scientist of ZTF, respectively.

**Competing interests** The authors declare no competing interests.

**Additional information**

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Extended Data Fig. 1 | Fit of ZTF J1813+4251's SED. **a)** A fit to the donor star's SED. The blue vertical lines represent the measured donor star SED as inferred from the apparent magnitude during the primary eclipse. Because of the high SNR of the HiPERCAM data, these uncertainties are very small, and we have added a systematic five percent uncertainty associated with contribution from the accretion disk. The red diamonds represent the filtered averaged apparent magnitudes of the best-fit synthetic spectrum, and this synthetic spectrum is plotted in black.

**b)** A fit to the accreting white dwarf SED. The vertical blue lines represent the SED of the white dwarf, as measured by modelling the amount of flux lost during the primary eclipse, when it is occulted by the donor. We added a five percent model error to this SED in the optical to account for contribution from accretion features which might cause the white dwarf to deviate from a standard hydrogen-rich DA model spectrum. The surface gravity of the white dwarf in the model spectrum was fixed using the values derived from the light-curve analysis. The red diamonds illustrate the filter averaged apparent magnitudes from the synthetic spectrum, which is plotted in black. In both panels, we have omitted the HiPERCAM\(_z\)-band measurement, which exhibits an excess likely associated with the accretion disk. The model deviates from the observed spectrum around the hydrogen absorption lines due to emission lines from the accretion disk around the white dwarf.
Extended Data Fig. 2 | Fit of ZTF J1813+4251’s optical spectrum. a, A best-fit spectral model consisting of a low-mass main-sequence model and a hydrogen-rich white dwarf model to the observed spectrum of ZTF J1813+4251. The model, shown in red, has been convolved with the resolution of the spectrograph and rotationally broadened, and fit to the spectrum co-added in the rest frame of the donor, shown in black. b, A model spectrum fixed to the parameters derived from the SED analysis. We consider this model more reliable because it takes into account the Swift ultraviolet flux measurement, which strongly constrains the temperature of the white dwarf. The model, shown in blue, slightly underfits the blue part of the spectrum, plotted in black, which may be due to the presence of an accretion disk, or simply a systematic error introduced in the data reduction.
Extended Data Fig. 3 | Fit of rotational broadening in ZTF J1813+4251’s ESI spectrum. Rotationally broadened atmospheric model fits to the moderate resolution ESI spectra of ZTF J1813+4251. Owing to the low SNR of the spectra, we were unable to constrain the rotational broadening of the lines with a precision better than approximately 50 km s⁻¹, but the measured values are consistent with the predicted value of 145 km s⁻¹.
Extended Data Fig. 4 | Idealized constraints of light-curve modelling in ZTF J1813+5251. A panel illustrating an idealized version of the basic constraints we obtain by modelling the primary and secondary eclipses of ZTF J1813+5251, which depend only on Roche geometry and Kepler’s laws. Using the light curve, we are able to measure the orbital period, \( P_b \), the in-eclipse flux levels as a fraction of the out-of-eclipse flux, \( F_1 \) and \( F_2 \), and the third and fourth contact phases of the eclipse, \( \phi_3 \) and \( \phi_4 \). By combining these five quantities we can determine from the light curve, with the donor radial velocity semi-amplitude measured from the spectra, \( K_2 \), and our knowledge that the donor is Roche-lobe-filling, we are able to obtain a robust solution for the two component masses, \( M_1 \) and \( M_2 \), the radii of the two components, \( R_1 \) and \( R_2 \), the surface brightness ratio, \( J \), the semi-major axis of the binary, \( a \), and the orbital inclination, \( \iota \). The idealized expressions tying these constraints to the observable quantities are listed in the right half of the figure. We would like to emphasize that these are idealized expressions, and caution readers that there are further important subtleties not discussed here (for example, in a Roche-filling system, the relevant radii in the above equations \( R_1 \) and \( R_2 \) are complicated to define because of the ellipsoidal deformation of the components, however, light-curve modelling codes such as LCURVE take these effects into account–this means for example that the \( R_2 \) in expressions 3 and 4 is not exactly the same as the \( R_2^* \) in expression 5, as in the former case, \( R_2 \) is measured perpendicular to the line between the two stars, whereas in the latter case, \( R_2^* \) is a volume-averaged radius).
Extended Data Fig. 5 | Corner plots of posterior distribution from LCURVE model. A corner plot of some of the quantities derived from our final model, illustrating clean convergence in the distributions for all quantities. We would like to note that the radii are volume-averaged radii, and that $R_2$ was not directly sampled (instead, the two masses + inclination are sampled, and because the system is fully eclipsing $R_2$ is determined uniquely by the mass ratio and inclination). We also sampled over the surface brightness ratio $J$, but did not include it in these corner plots because we have five different $J$s (one for each filter - we avoided using a common $J$ because doing this correctly requires atmospheric corrections in each passband, and the solutions for the other free params are largely independent of $J$). To ensure that using a different $J$ for each filter was not influencing the other free params, we modelled all 5 filters independently, and found that they all converged to parameters in agreement with the combined fit.
Extended Data Fig. 6 | Detailed fits and residuals of eclipses and overall HiPERCAM light curve. **a**, Our best-fit model of the primary eclipse, with the model shown as a solid black line, the binned data as red points, and the model without an eclipse as the dashed black line. In this figure, a linear polynomial component (of the functional form \( y = a \times t \), where \( t \) is the time from mid-eclipse (we applied separate corrections for the primary and secondary), has been subtracted out of both the model and the data for better visualization. We constructed the model by simultaneously fitting data around the primarily eclipse as well as data from the secondary eclipse (panel **c**). **b**, A best-fit of the eclipse-derived model constructed from the eclipse data shown in panels **a** and **c** to the full HiPERCAM light curve. While the model roughly reproduces the correct amplitude of ellipsoidal variations, it does not fully capture the structure seen in the full light curve. **c**, Our best-fit model to the secondary eclipse, with a linear correction subtracted out of both the data and models. **d**, The residuals of the best fit of the eclipse-derived model to the full dataset shown in panel **b**. As is readily apparent, the strongest residuals occur out-of-eclipse, and are likely to arise because of a combination of effects from the accretion disk, and an O’Connell effect associated with the donor.
Extended Data Fig. 7 | Kinematic orbit of ZTF J1813+4251 in the Milky Way. A set of panels illustrating the orbit of ZTF J1813+4251 around the Milky Way. The system is consistent with residing in the Galactic thick disk, orbiting between 5 and 8 kpc from the Galactic Centre, within half a kpc of the Galactic disk in height.
Extended Data Fig. 8 | MESA evolutionary models of ZTF J1813+4251. MESA binary evolution models (Extended Data Table 1). Red, black and blue lines show models that overflow their Roche lobes after 94, 95 and 97 percent of the donor’s main-sequence lifetime. The dashed vertical line shows 51 minutes.
Extended Data Table 1 | Model parameters of MESA models

| $P_p^{\text{init}}$ [day] | $t_{\text{RLOF}}/t_{\text{MS}}$ | $P_p^{\text{RLOF}}$ [day] | $T_{\text{eff, Donor}}$ [K] | $M_{\text{Donor}}$ [M$_\odot$] | $P_p^{\text{min}}$ [min] | $\log(\dot{M}/M_\odot \text{ yr}^{-1})$ | Time since RLOF [Gyr] |
|--------------------------|-------------------------------|--------------------------|-----------------------------|-----------------------------|----------------|----------------------------------|------------------|
| 2.63                     | 0.94                          | 0.60                     | 5068                        | 0.100                       | 22             | $-9.31$                          | 0.55             |
| 2.69                     | 0.95                          | 0.63                     | 6009                        | 0.107                       | 18             | $-9.75$                          | 0.63             |
| 2.75                     | 0.97                          | 0.66                     | 7156                        | 0.115                       | 13             | $-10.46$                         | 1.26             |

All models have an initial donor mass of 1.1 M$_\odot$ and a white dwarf mass of 0.55 M$_\odot$. The three models correspond to the red, black and blue lines in Extended Data Fig. 8.