Multi-periodic pulsations of a stripped red-giant star in an eclipsing binary system

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Low-mass white-dwarf stars are the remnants of disrupted red-giant stars in binary millisecond pulsars1 and other exotic binary star systems2–4. Some low-mass white dwarfs cool rapidly, whereas others stay bright for millions of years because of stable fusion in thick surface hydrogen layers5. This dichotomy is not well understood, so the potential use of low-mass white dwarfs as independent clocks with which to test the spin-down ages of pulsars6–9 or as probes of the extreme environments in which low-mass white dwarfs form10–12 cannot fully be exploited. Here we report precise mass and radius measurements for the precursor to a low-mass white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf. We find that only models in which this disrupted red-giant star has a thick hydrogen envelope can match the strong white dwarf.

Most white dwarfs have no internal energy sources and the mass of their hydrogen on their surfaces is small (less than $10^{-4}$ solar masses) so their ‘cooling age’ can be accurately estimated from their current luminosity. The predicted mass range for which shell flashes at the base of the hydrogen envelope occur in low-mass white dwarfs depends on the assumed composition and whether diffusion is included in the model11–13, so it is generally possible to find a scenario for a particular binary millisecond pulsar in which the white-dwarf cooling age is consistent with the pulsar’s spin-down age (inferred from the derivative of its spin period, assuming that angular momentum is lost by magnetic dipole radiation). However, recent observations have shown that the white-dwarf companion to the pulsar PSR J0751 + 1807 is much too cool to have a thick hydrogen envelope, yet the white dwarf is not massive enough to have undergone shell flashes and there is no evidence for strong irradiation by the pulsar14. The standard assumptions used to derive pulsar spin-down ages have also been called into question15,16. A better understanding of the initial hydrogen layer mass and its evolution in low-mass white dwarfs is needed so that we can make an independent test of the spin-down ages for pulsars.

Before becoming low-mass white dwarfs, stripped red-giant stars evolve at nearly constant luminosity towards higher effective temperatures. ISWASP J024743.37-251549.2 (called J0247-25 herein) was recently discovered to be a binary system in which a star in this rarely observed evolutionary phase (J0247-25B) is totally eclipsed by its companion star (J0247-25A)17. We have obtained new spectroscopic and photometric observations (Fig. 1) and used these to derive precise astrophysical parameters for both stars (Table 1).

The mass, radius and luminosity of J0247-25A are well matched by models of stars with a metal abundance in the range $Z = 0.004–0.019$, but not for models outside this range (Fig. 2). We have calculated models for the formation of J0247-25B by mass transfer onto the companion star (Fig. 2). We assumed that the mass loss rate is slower than the thermal timescale of the star, so that mass transfer ceases when the equilibrium radius of the star is smaller than the Roche lobe. This is the assumption usually made in the absence of a detailed understanding of the mass loss process10,13,19. Diffusion of elements by gravitational settling, chemical diffusion and thermal diffusion are included in our models. We also calculated models without diffusion to investigate the effects of processes such as rotation that may counteract diffusion. The mass of J0247-25B is near the lower limit for the occurrence of shell flashes—these will occur if its metal abundance is high enough ($Z \approx 0.01$) and diffusion can increase the hydrogen abundance in the regions where shell flashes can be initiated.

There is a direct relationship between orbital period, mass and composition that arises from the assumption that the mass-losing star is in equilibrium when mass transfer ceases20. We find a good match to the observed orbital period of J0247-25 for models with a similar range of metal abundance to that of J0247-25A, but not for models outside this composition range (Supplementary Table 5). This result is not strongly affected by the assumptions made about the evolution of the binary system during the mass transfer episode.

All the models that provide a good match to the observed properties of J0247-25B have thick hydrogen envelopes (about 0.005 solar masses). We did produce models for J0247-25B with thin hydrogen envelopes but found that for any reasonable estimate of the composition these models never have properties like J0247-25B. Given the strong observational constraints on the mass, radius, luminosity, age, orbital period and composition for J0247-25 and the pulsation

Table 1 | Properties of J0247-25

| Parameter | J0247-25A | J0247-25B |
|-----------|-----------|-----------|
| Mass (solar masses) | 1.356 ± 0.007 | 0.186 ± 0.002 |
| Radius (solar radii) | 1.697 ± 0.011 | 0.368 ± 0.005 |
| Effective temperature (K) | 7.730 ± 0.200 | 11.380 ± 0.400 |
| log[Luminosity (solar luminosities)] | 0.97 ± 0.05 | 0.31 ± 0.06 |
| log[Surface gravity (cm s$^{-2}$)] | 4.111 ± 0.006 | 4.576 ± 0.011 |
| Inclination (degrees) | 95 ± 5 | 30 ± 3 |
| Orbital period (days) | 0.6678295 ± 0.0000004 | |
| Time of mid-eclipse (TDB) | 2,454,454.1066 ± 0.0002 | |
| Distance (pc) | 1.035 ± 0.55 | |

The masses and radii were derived from an analysis of our Ultracam photometry and UVES spectroscopy (Fig. 1, Supplementary Notes and Supplementary Table 2). The time of mid-eclipse is Barycentric Dynamical Time (TDB) given as a Julian date. We measured the effective temperatures of the stars by fitting models to the observed flux distribution of the binary from ultraviolet to infrared wavelengths, simultaneously with the constraints on the surface brightness ratio and luminosity ratio at the $i$ band from the analysis of the eclipses (Supplementary Table 4 and Supplementary Fig. 4). The projected equatorial rotation velocity $v_\text{rot}$ is measured from the Doppler broadening of the spectral lines (Supplementary Figs 3 and 5).

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Figure 1 | Observations of J0247-25. a, Flux as a function of orbital phase for one primary eclipse of J0247-25 observed with Ultracam on the 3.6-m New Technology Telescope at the European Southern Observatory (ESO). From bottom to top: u' band (356 nm), g' band (483 nm, offset by 0.04 units) and r' band (626 nm, offset 0.08 units). Each point corresponds to an integration time of 5 s. The primary eclipse is caused by the occultation of J0247-25B by the larger, cooler star J0247-25A. A secondary eclipse due to the transit of J0247-25B and a second primary eclipse were also observed (Supplementary Table 1). b, Radial velocity as a function of orbital phase for J0247-25A (circles) and J0247-25B (squares) measured from high-resolution spectra obtained with the Ultraviolet and Visual Echelle Spectrograph (UVES) on the ESO 8.2-m Very Large Telescope. Solid lines show the predicted radial velocities for a circular orbit and our adopted values of the radial velocity semi-amplitudes, \( K_A = 33.9 \text{ km s}^{-1} \) and \( K_B = 247.2 \text{ km s}^{-1} \). c, Power spectra of the data shown in panel a (arrow) before eclipse (phase range, 0.85–0.92). The peaks near 240 cycles per day have the highest amplitude at u' band and the lowest amplitude at r' band. d, Power spectra of the data shown in panel a (arrow) obtained during total eclipse (phase range 0.95–1.05). The peaks near 220 cycles per day with amplitudes of 0.15% to 0.4% do not appear in the power spectrum during the eclipse and so must originate from J0247-25B. The pulsations near 40 cycles per day originate in J0247-25A, so this must be an SX Phe-type star (a metal-poor \( \delta \) Scuti star).

Figure 2 | Positions of J0247-25A and J0247-25B in the Hertzsprung–Russell diagram. J0247-25A is plotted as a filled circle, and J0247-25B as a filled diamond. The error on the luminosity is correlated with the effective temperature \( T_{\text{eff}} \) so the error range (1 s.d.) is plotted as a diagonal line. Two of our models for the formation of J0247-25B are shown, one including the effects of diffusion \((Z = 0.004, \text{ solid line, final mass is } 0.187 \text{ solar masses})\) and one without \((Z = 0.002, \text{ dotted line, final mass is } 0.185 \text{ solar masses})\). These models are plotted from the initiation of mass transfer at log \( [T_{\text{eff}} (K)] = 3.8 \), log \( [Luminosity \text{ (solar luminosities)}] = 0.5 \). The cross on each track marks the end of the mass transfer phase. A model for a star with a mass of 1.35 solar masses and a composition typical for thick-disk stars \(([\text{Fe/H}] = -1.0, [\text{Z}/\text{Fe}] = +0.6, Z = 0.005)\) is plotted with a dashed line. A similar model for stars with \([\text{Fe/H}] = 0.0\) and a very high helium abundance \((Y = 0.4, Z = 0.019)\) is plotted with a dot-dashed line. No match is found for any models with metal abundance outside the range \(Z = 0.004–0.019\). The instability strip for \( \delta \) Scuti-type pulsations with radial order \( k = 4 \) is indicated by light-grey shading.

Large, cooler star J0247-25A. A secondary eclipse due to the transit of J0247-25B and a second primary eclipse were also observed (Supplementary Table 1).

- The primary eclipse is caused by the occultation of \( \text{J0247-25B} \) by the larger, cooler star \( \text{J0247-25A} \).
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- The non-radial modes in J0247-25B behave like gravity modes near the core and like pressure modes in the outer layers of the star. These mixed modes can be used to study the entire structure of the star: for example, to measure its internal rotation profile. Information on the interior structure of J0247-25B is also contained in the radial modes (Fig. 3). The pulsation periods are comparable to the thermal relaxation timescale in the second partial ionization zone of helium, so the change in opacity in this region (acting like a heat engine) may be driving these oscillations (the \( \kappa \)-mechanism). This suggests that other
Figure 3 | Adiabatic pulsation frequencies for models of J0247–25B.

a. Pulsation frequencies for radial oscillation modes (ℓ = 0) and non-radial modes with angular degree ℓ = 1 and ℓ = 2 calculated using the adiabatic approximation for a model of a star similar to J0247–25B. Short lines at the top of the plot indicate the observed pulsation frequencies of J0247–25B. The spacing of the three frequencies shown cannot be explained using radial modes only. The order of the radial modes shown is k = 10. b. The frequency spacing between two adjacent radial modes, Δν, as a function of the mean stellar density Λ for models with and without diffusion are shown using filled and open symbols, respectively. The value of Δν shown here is the mean value in the region of the theoretical power spectrum near the observed frequencies for J0247–25B. The difference in Δν between models with and without diffusion is a result of the sharp change in the speed of sound in the second partial ionization zone for helium, due to the high helium abundance in this zone (Y = 0.6) for models without diffusion. The measured density of J0247–25B indicated using vertical dotted lines (± 1 s.d.), can be measured to high precision in this bright eclipsing binary star. As a result, models with and without diffusion can be distinguished if two of the observed pulsation frequencies are found to be radial modes.

low-mass white-dwarf precursors23 with effective temperatures similar to J0247–25B may also show pulsations. Thus, the discovery of pulsations in J0247–25B opens up the possibility for a much-improved understanding of the structure and formation of low-mass white dwarfs and their environments through the application of asteroseismology to this new class of pulsating variable stars.

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Author Contributions P.F.L.M. analysed the light curves and spectroscopy and wrote the paper. A.M.S. calculated the models of the formation and evolution of J0247–25B. A.M. conducted the investigation into the pulsation properties of J0247–25B. T.R.M. and P.F.L.M. produced the light curves from the Ultracam images. U.H. calculated the theoretical stellar spectra used to check our effective temperature estimates for J0247–25B. T.R.M., V.S.D., S.L. and C.C. are responsible for the operation and maintenance of Ultracam and contributed to the planning and execution of the observations. B.S. calculated the synthetic stellar spectra and performed the comparison with the observed spectra for J0247–25A. V.S. and E.B. contributed to the execution of the observations.

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