An 18.9 min blue large-amplitude pulsator crossing the ‘Hertzsprung gap’ of hot subdwarfs

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Blue large-amplitude pulsators (BLAPs) represent a new and rare class of hot pulsating stars with unusually large amplitudes and short periods. The evolutionary path that could give rise to such kinds of stellar configurations is unclear. Here we report a comprehensive study of the peculiar BLAP discovered by the Tsinghua University–Ma Huateng Telescopes for Survey (TMTS), namely, TMTS J035143.63+584504.2 (TMTS-BLAP-1). This new BLAP has an 18.9 min pulsation period and is similar to the BLAPs with a low surface gravity and extended helium-enriched envelope, suggesting that it is a low-gravity BLAP at the shortest-period end. In particular, the long-term monitoring data reveal that this pulsating star has an unusually large rate of period change, namely, \( \dot{P}/P = 2.2 \times 10^{-6} \text{ yr}^{-1} \). Such a significant and positive value challenges its origins from both helium-core pre-white-dwarfs and core helium-burning subdwarfs, but is consistent with that derived from shell helium-burning subdwarfs. The particular pulsation period and unusual rate of period change indicate that TMTS-BLAP-1 is at a short-lived (~10^6 yr) phase of shell helium ignition before the stable shell helium burning; in other words, TMTS-BLAP-1 is going through a ‘Hertzsprung gap’ of hot subdwarfs.

The minute-cadence observations by Tsinghua University–Ma Huateng Telescopes for Survey (TMTS) enable the search of variable stars with periods shorter than 1 h. TMTS J035143.63+584504.2 is such a newly discovered short-period variable, having an 18.9 min period and a peak-to-peak amplitude of ~0.3 mag in white light (Extended Data Fig. 1). Follow-up observations with SNOVA, a 14 inch telescope at Nan Shan station of Xinjiang Observatories (J.Z. et al., manuscript in preparation), confirmed its periodicity and revealed a clear sawtooth-shaped light curve (Extended Data Fig. 2), consistent with those of blue large-amplitude pulsators (BLAPs) discovered by the Optical Gravitational Lensing Experiment (OGLE). Moreover, the dereddened colour \((B_V - R_V)_0 = -0.47 \pm 0.19 \text{ mag}\) and absolute magnitude \(M_G = 1.43^{+0.18}_{-0.19} \text{ mag}\) derived from Gaia Early Data Release 3 (EDR3) data support the classification of TMTS J035143.63+584504.2 (hereafter TMTS-BLAP-1) as a BLAP. This object is also bright in the ultraviolet bands and has recently been identified as a BLAP candidate (that is, ZGP-BLAP-01).
through the Gaia Data Release 2 (DR2) and Zwicky Transient Facility (ZTF) Data Release 3 (DR3) data.

To date, only 24 confirmed BLAPs1,2,9–12 have been identified from more than one billion monitored stars, including a group with pulsation period longer than ~20 min (ref. 5) (classical BLAPs, hereafter) and the other group with pulsation period below ~8 min (high-gravity BLAPs6). The period–amplitude diagram of 24 confirmed BLAPs and 20 BLAP candidates7 is shown in Fig. 1. The confirmed BLAPs tend to have higher pulsation amplitudes in comparison with those candidates. There are several BLAPs located within the 8–20 min period gap7, which can roughly divide the BLAP samples into classical (low-gravity) and high-gravity groups. With the discovery of more BLAPs, the nominal period gap seems to become less distinct, whereas the scarcity in the 10–20 min period is still noticeable (Fig. 1, top histogram). Since the boundary of the period gap is arbitrary because of limited samples, TMTS-BLAP-1 probably represents a member of classical BLAPs at the shortest-period end, or a special BLAP between two groups, such as an intermediate-gravity BLAP8.

Phase-resolved spectroscopy

To further solidify the classification of TMTS-BLAP-1, we obtained a series of phase-resolved spectra using the low-resolution imaging spectrometer (LRIS)13,14 mounted on the 10 m Keck I telescope. As shown in Fig. 2, the four spectra, with 200 s exposure for each one, covered nearly a complete pulsation period. The effective temperature of TMTS-BLAP-1 varied from 25,840 to 31,780 K, with the highest temperature corresponding to maximum brightness. The change in radial velocity was found to precede the change in surface gravity by about a quarter of the pulsation period (Extended Data Fig. 3), suggesting the idea that TMTS-BLAP-1 pulsation is a radial mode15. The surface gravity and moderately high helium abundance, inferred from the best-fitting atmospheric model, are consistent with those of OGLE BLAPs6. A noteworthy spectroscopic feature in TMTS-BLAP-1 is the emergence and vanishing of the He ii 4,686 line during the 18.9 min cycle, which seems to be also present in OGLE BLAPs but has not been observed in four high-gravity BLAPs with low helium abundance16. Although the changing visibility of the He ii 4,686 line is a temperature effect, the observed difference in mean helium abundance between high-gravity and classical BLAPs may be regarded as an indicator of different evolutionary origins17,18 or status.

Rate of period change

BLAPs are believed to stem from either helium-core pre-white dwarfs (pre-WDs) or core helium-burning (CHeB) subdwarfs19,20,21, since stars formed from these two channels cover the BLAP region in the Hertzsprung–Russell (HR) diagram. The pre-WDs usually contract and cool, whereas the CHeB stars burn helium steadily on nuclear timescales. To explore the nature of TMTS-BLAP-1, we tried to compute the precise rate of change of its pulsation period. Since the period versus mean density relation (that is, Ritter’s relation22) is valid for BLAPs10,19,21, it is used to trace the evolution of stellar radius23.

The variation in the pulsation period of TMTS-BLAP-1 can be diagnosed using the weighted wavelet Z transform (WWZ)24, which is a practical technique for visualizing time-dependent periodicity in observation data. As shown in Fig. 3, the long-term observations from both Asteroid Terrestrial-Impact Last Alert System (ATLAS)25,26 and ZTF15,16 surveys support a consistent pulsation frequency variation in both Asteroid Terrestrial-Impact Last Alert System (ATLAS)25,26 and ZTF surveys. The pulsation frequency exhibits a large-amplitude variability of TMTS-BLAP-1 cannot be reliably determined by the simple method used elsewhere7, where the rates were directly calculated based on the difference in pulsation periods between two different epochs. The overall frequency trend in the WWZ plot suggests an average rate of period change as $P/P = 2.1 \times 10^{-6}$ yr$^{-1}$ in about 6.5 yr.

To precisely determine the rate of change of pulsation period from the pulsation frequency fluctuation, we plotted the $O – C$ diagram for TMTS-BLAP-1 using the data from ZTF, ATLAS, SNOVA and TMTS (Methods). $O – C$ is a strong diagnostic tool for evaluating the discord between times of a given event (for example, peak of pulsation) and predicted values from a stable and accurate clock27. We computed the values of $O – C = C_{\text{obs}} – C_{\text{calc}}$ following the ephemeris

$$T_{\text{max}}(E) = \text{BJD}_{\text{TDB}} = 2,457,325.0469 + 0.0131477151 \times E,$$  

(1)

where $E$ is the cycle number elapsed from the initial epoch; $T_{\text{max}}$ and $T_{\text{max}}$ represent the observed and calculated times of maximum light, respectively. A complete $O – C$ diagram is shown in Fig. 4, where the overall trend supports the fact that TMTS-BLAP-1 has a high and positive rate of period change. The $O – C$ diagram agrees with the trend and superimposed variation seen in the WWZ plot. To examine the reliability of our analysis, we also computed the $O – C$ diagram for another newly confirmed BLAP, namely, the 23.3 min ZGP-BLAP-09 (Extended Data Fig. 4), and we did not find any significant period change in its $O – C$ diagram.

Assuming that the variations in the $O – C$ diagram of TMTS-BLAP-1 is only caused by a linear pulsation period change due to stellar evolution (Methods), we obtained a rate of period change equal to $P/P = 2.19 \pm 0.19 \times 10^{-6}$ yr$^{-1}$ from the best-fitting $O – C$ model. A cyclic feature in the $O – C$ residuals is shown in Fig. 4b. Similar cyclic behaviors have been recently revealed in another BLAP, namely, HD 133729 (ref. 25). Since the stellar evolution theory favours the origin of BLAPs in a binary system28, the cyclic feature seen in the $O – C$ diagram of TMTS-BLAP-1 is most probably caused by the light-travel-time effect (LTTE) induced from orbital motion30,31. By assuming that the pulsating star orbits the barycentre of the binary system, the $O – C$ variability was
fit with the light-travel-time model of elliptical orbits\textsuperscript{30} (Methods). The best-fitting model can be used to correct the phase-folded light curves and obtain coherent light-curve shapes (Extended Data Fig. 5). The model suggests an orbital period of \(P_{\text{orb}} = 1,576 \pm 18\) days and a mass function of \(f(M) = (1.22 \pm 0.12) \times 10^{-3}\) (Table 1). The long orbital period marginally matches the orbital period distribution of hot subdwarfs derived from stable Roche lobe overflow channel\textsuperscript{15}. The derived mass function suggests that TMTS-BLAP-1 could be orbited by a low-mass star or a brown dwarf, which is below the mass limit allowed by the classical critical mass ratio (that is, \(q = 1.5\)). However, this critical mass ratio is uncertain and it could be much higher (for example, \(q_{\text{lim}} = 20.0\)) due to thermal-equilibrium mass loss\textsuperscript{32}, which allows the formation of hot subdwarfs with wide-orbit low-mass companions. Otherwise, a possibly low orbital inclination can also be responsible for the low value of the mass function\textsuperscript{31,33,34}. The L TTE model cannot explain all the details in the \(O – C\) diagram; the excess could be caused by fluctuations from a potential third star/planet. The best-fitting model also provides a more reliable estimate of the rate of period change, that is, \(P/P = 2.23 \pm 0.09 \times 10^{-3}\) yr\(^{-1}\), consistent with the estimate from the WWZ analysis. Owing to the overall trend of \(O – C\) variability, irrespective of the model selected to fit the \(O – C\) diagram, a positive and high rate of period change is inevitable. At such a large rate, the evolutionary timescale of TMTS-BLAP-1 will be only \(P/P = 4.5 \times 10^{10}\) yr. If some BLAPs rapidly evolve from 10 to 20 min, this rapid evolution within the ‘period gap’ can also help explain the observed scarcity of BLAPs with 10–20 min pulsation periods, in addition to the possible contribution from mass gap of pre-WDs\textsuperscript{35}.

**Discussion**

The significant positive rate of period change indicates that TMTS-BLAP-1 evolves towards larger stars, inconsistent with the trend predicted by the cooling process of pre-WDs \((P/P \lesssim 10^{-7}\) yr\(^{-1}\)). On the other hand, the rates derived from CHeB stars are initially very small \((P/P \lesssim 10^{-8}\) yr\(^{-1}\)), whereas their convective helium cores are growing slowly. However, at the late time of the central helium-burning phase, the stars begin to shrink owing to the deficit of the generated heating energy, resulting in an accelerated decay of their pulsation periods.

After the exhaustion of central helium in a CHeB star, its carbon-oxygen (CO) core begins to shrink and the central temperature decreases as a result of neutrino energy loss, whereas its helium envelope simultaneously expands because the energy from core
All the three models can explain the observed luminosities and effective temperatures of BLAPs, and TMTS-BLAP-1 is located exactly in the Hertzsprung gap of helium-burning stars with a hydrogen envelope mass $M_{\text{env}} = 0.01 M_\odot$. The helium-core pre-WD model predicts that the mass of TMTS-BLAP-1 is $0.30 - 0.35 M_\odot$, whereas the CHeB and SHeB models predict much larger values, that is, $\sim 0.70 M_\odot$. The different masses inferred from the above three models provide an approach of constraining the physical origin of BLAPs[20], but the stellar masses of BLAPs cannot be precisely measured from current observations because of their strong dependencies on the highly uncertain measurements of surface gravity.

Since the discovery of BLAPs[21], ‘BLAP’ has been used as a convenient term for all the pulsating stars with high effective temperature and relatively large pulsation amplitude. Obviously, it is difficult to conclude that all BLAPs share the same physical origin, given that they have different observational features including pulsation period, surface gravity, absolute magnitude, helium abundance and light-curve shape. Since BLAPs locate in a common region in the HR diagram for different candidate models, it is necessary to explore their origins using diagnostic tools other than the HR diagram.

The $P$–$P/\dot{P}$ diagram is a very efficient tool probing the physical origins of pulsars[22]. Here we adopted a similar approach, namely, the $P$–$P/\dot{P}$ diagram, to expose the differences among three candidate models. As shown in Fig. 5 (bottom), a $P$–$P/\dot{P}$ diagram was plotted for a dozen known BLAPs along with the models. It seems difficult to model the distribution of BLAPs in the diagram by a single evolutionary origin. An outstanding feature of SHeB is that the star can rapidly expand during the short-lived phase of shell helium ignition (that is, the Hertzsprung gap of hot subdwarfs), which thus leads to a prominent rate of period change for a pulsation period of $\lesssim 20$ min if their hydrogen envelope masses are similar to those of typical subdwarf B stars. The rate of period change of TMTS-BLAP-1 favours its origin of an about $0.700 M_\odot$ SHeB star with an envelope mass $M_{\text{env}} = 0.01 M_\odot$, consistent with the results derived from the HR diagram. However, neither CHeB nor helium-core pre-WD can explain such a large and positive rate of period change. The mass estimated from the hydrogen-burning models may have a large uncertainty, because the mass of the hydrogen envelope cannot be accurately determined. If some BLAPs are SHeB stars, the rapid evolution of SHeB stars crossing the Hertzsprung gap will help explain the observed scarcity of BLAPs with pulsation periods below $20$ min. Alternatively, surface-gravity/pulsation period gap between two groups of BLAPs have also been interpreted as a result of fewer helium-core pre-WDs in the intermediate-mass range[23], with the assumption that BLAPs come from helium-core pre-WDs.

It is not unexpected that some BLAPs correspond to SHeB subdwarf stars. An outstanding feature in the HR diagram is that stars evolved from the hydrogen main sequence have produced plentiful pulsator categories, but the pulsating stars corresponding to the descendants of ‘helium main-sequence stars’ (here including CHeB stars with very thin hydrogen envelopes) have hardly been revealed in the past. The evolution of hot subdwarfs could be analogous with those of well-known helium main-sequence stars, since the main difference between CHeB and core hydrogen-burning stars is the dominant element of fuel that determines the type of nuclear fusion driven in their cores. Meanwhile, some hot subdwarfs can also climb on the giant branch and finally cool down as white dwarfs.

All the current existing pulsator categories are based on the observational facts of new pulsating variable stars, implying that we may miss potential classes from rare pulsating stars, especially those corresponding to short-lived stages of stripped-envelope stars. TMTS-BLAP-1 provides interesting observational evidence that some hot subdwarfs can leave their CHeB stage and appear as pulsating variables in a distinct region of the HR diagram. With the Legacy Survey of Space and Time and other wide-field facilities in the future, more previously unknown pulsating stars evolved from stripped-envelope stars will be discovered.

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**Fig. 4** O–C diagram for the pulsation period of TMTS-BLAP-1. a. The observed times of maximum light ($T_{\text{max}}$) were obtained from the subsets of ATLAS, ZTF, SNOVA and TMTS observations. Each subset of the ATLAS and ZTF data covers up to 20 days, whereas each subset of the TMTS and SNOVA data corresponds to an individual night. The O–C variability is modelled by assuming a linear period change (blue dashed line) and LTTE caused by orbital motion (red solid line). b, c. Residuals for linear period change (b) and LTTE caused by orbital motion (c). The error bars represent 1σ confidence throughout this paper.

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**Table**

| Instrument | Band  | Observations |
|-----------|-------|--------------|
| ATLAS     | o     |              |
| ATLAS     | c     |              |
| ZTF       |       |              |
| ZTF       | i     |              |
| ZTF       | g     |              |
| SNOVA     | C     |              |
| TMTS      |       |              |

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The evolutionary tracks from all three candidate models (helium-core pre-WD, CHeB and SHeB) are presented in Fig. 5, where one can see that the CHeB and SHeB models correspond to two distinguishable phases of helium-burning stars. All the three models can explain the observed luminosities and effective temperatures of BLAPs, and TMTS-BLAP-1 is located exactly in the Hertzsprung gap of helium-burning stars with a hydrogen envelope mass $M_{\text{env}} = 0.01 M_\odot$. The helium-core pre-WD model predicts that the mass of TMTS-BLAP-1 is $0.30 - 0.35 M_\odot$, whereas the CHeB and SHeB models predict much larger values, that is, $\sim 0.70 M_\odot$. The different masses inferred from the above three models provide an approach of constraining the physical origin of BLAPs[20], but the stellar masses of BLAPs cannot be precisely measured from current observations because of their strong dependencies on the highly uncertain measurements of surface gravity.

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and they will further improve our understanding of pulsating variable stars and hot subdwarfs.

**Methods**

**Photometric observations from TMTS and Gaia**

The minute-cadence observations from TMTS can reveal periodic variability as short as 10 min for objects brighter than 18 mag (refs. 1, 13). TMTS-BLAP-1 was captured by TMTS when they monitored two adjacent plates from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope on 24 and 25 December 2020 (ref. 1). The ultrashort pulsation period of TMTS-BLAP-1 was revealed by a Lomb–Scargle periodogram (refs. 39–41) using Python package gatspy (refs. 42, 43) and the pulsation amplitude was automatically obtained from the best-fitting Fourier model through the TMTS light-curve analysis pipeline (Extended Data Fig. 1). TMTS light-curve analysis pipeline can automatically estimate the distance, extinction, dereddened colour and absolute magnitude for targets based on the Gaia DR2 data (refs. 3–4). However, these estimates are rough. Hence, we applied more reliable methods to obtain these values. Owing to the low signal-to-noise ratio of the parallax of TMTS-BLAP-1, the theoretical SED was convolved with various filter passbands and the SED fit suggests a lower value, namely, $E(B-V) \approx 0.70$ mag. Using the distance derived from the Gaia EDR3 catalogue, $E(B-V)$ is usually difficult to be measured from low-resolution spectra. In addition, we encountered a serious degeneracy among rotation, surface gravity and spectral resolution. The best-than-average seeing (<0.7") resulted in a higher resolution, exceeding the nominal resolution of the LRS. Therefore, for consistency, we decided to keep the projected rotation velocity at 0. Likewise, we neglected microturbulence; its effects are unmeasurable in our spectra.

Supplementary Fig. 2 shows the spectral energy distribution (SED) of TMTS-BLAP-1 from the Lyman limit to 50,000 Å. The atmospheric parameters from the four LRS spectra are listed in Supplementary Table 1, and the (periodic) variations in these surface parameters are shown in Extended Data Fig. 3.

Even though XTgrid is able to fit the projected rotation velocity, it is usually difficult to be measured from low-resolution spectra. In addition, we encountered a serious degeneracy among rotation, surface gravity and spectral resolution. The better-than-average seeing (<0.7") resulted in a higher resolution, exceeding the nominal resolution of the LRS. Therefore, for consistency, we decided to keep the projected rotation velocity at 0. Likewise, we neglected microturbulence; its effects are unmeasurable in our spectra.

**Spectra and SED**

To avoid a low signal-to-noise ratio (SNR) and also minimize Doppler smearing due to the fast spectral evolution of BLAPs, phase-resolved spectroscopy for these pulsating stars must be obtained from high-time-resolution observations on large-aperture telescopes. For this reason, only several BLAPs (refs. 14, 15) had phase-resolved spectroscopic observations before this work.

We obtained a series of four spectra of TMTS-BLAP-1 using the 10 m Keck I telescope and the LRIS (refs. 16–18) instrument (600/4,000 blue grism with resolving power $R = 940$; 400/8,500 red grating with resolving power $R \approx 930$). The spectra were observed at four different pulsation phases on 8 September 2021 UTC, with each spectrum having an exposure time of 200 s and a readout time of ~50 s. The spectra were reduced by the dedicated pipeline LPipe (refs. 19, 20), following standard procedures: corrections for bias and flat field, removal of cosmic rays, extraction of one-dimensional spectral, wavelength calibration through comparison lamps and flux calibration through observations of spectrophotometric standard stars. The strongest telluric absorption bands were also removed from the spectra using the standard star spectra. The spectra show strong Ca absorption lines, which are probably of interstellar origin. Our analysis confirms that the Ca K line does not move with the atmosphere.

The atmospheric parameters were determined by fitting non-local thermodynamic equilibrium (ref. 21) and the relationship between $(V, B)$ and $(V, R)$ (refs. 22, 23) to each individual spectrum. The iterative spectral analysis procedure (XTgrid (ref. 48)) applies the steepest-descent $\chi^2$ minimization to simultaneously optimize all the free parameters and search for the best-fitting model. The models included H, He, C, N, O, Mg, Si and Fe opacities in the atmospheric structure calculations as well as in the spectrum synthesis. XTgrid calculates new models on the fly and adjusts the model parameters and atomic data input to precisely link the variations in the theoretical atmospheric structure to the observable emergent spectrum. All the comparisons were done globally using the entire observed spectral range and a piecewise normalization of the model to the observation. During this iterative search, the effective temperature, surface gravity, chemical abundance and projected rotational velocity are independently adjusted for minimizing the global $\chi^2$. In parallel, the radial velocity was also determined by shifting each observation to the model. The procedure converges once the relative changes of all the model parameters and $\chi^2$ drop below 0.5% in three consecutive iterations. Next, parameter errors were measured by mapping the parameter space around the solution, including correlations between the effective temperature and surface gravity. A fit to the blue part of a single LRS observation is shown in Supplementary Fig. 1. The atmospheric parameters from the four LRS spectra are listed in Supplementary Table 1, and the (periodic) variations in these surface parameters are shown in Extended Data Fig. 3.
There are more than six-year observations from the ATLAS forced photometry server\(^2\) and the ZTF public data release 10 (refs. \(^2\)\(^7\)\(^8\)), which allows the best constraint on the rate of period change of TMTS-BLAP-1. To obtain accurate photometric measurements from the ATLAS observations, the observation epochs with SNR < 10.0 or reduced $\chi^2 > 2.0$ were excluded. For the ZTF data, all the detections with catflag = 32,768 were excluded. All the modified Julian days of the data are converted into barycentric Julian dates with barycentric dynamical time (BJDTDB).

We tried to calculate the rate of period change for TMTS-BLAP-1 using the simple method introduced elsewhere\(^2\). In their method, the rates of period change were directly estimated by the difference in pulsation periods between two different epochs. However, this results in multiple, different values of $\dot{P}/P$ (from about $1 \times 10^{-6}$ to $8 \times 10^{-6}$ yr\(^{-1}\)) for TMTS-BLAP-1, dependent on how the observational data are divided into two segments. These various $\dot{P}/P$ values have reliable SNR and are supported by both ZTF and ATLAS data and thus cannot be simply explained by statistical or systematic errors. Therefore, we realized that the observed rate of period change of TMTS-BLAP-1 may not be a constant, and the rate of period change due to stellar evolution is modulated by some extra effects. Therefore, we adopted two stronger techniques, namely, WWZ analysis and $O-C$ diagram.

**WWZ analysis and $O-C$ diagram**

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**Fig. 5 | HR diagram and period versus rate of period change diagram for three candidate BLAP models.**

- **a**, Helium-core pre-WD (dashed lines), CHeB (thin solid lines) and SHeB (thick solid lines) models are plotted on the HR diagram. The CHeB and SHeB models represent two different stages of helium-burning stars. In the regions of pulsating stars\(^2\), the BLAP region is designed based on OGLE BLAPs\(^2\). Beneath the main sequence, the cooling sequence and helium-burning stars are shaded by different patterns.
- **b**, Pre-WD (dashed lines), CHeB (thin solid lines) and SHeB (thick solid lines) are shown in the $P-\dot{P}/P$ diagram. The hydrogen envelope masses for helium-burning stars were assumed to be $0.011 \, M_\odot$.
- **c**, The rates for OGLE BLAPs were taken from another work\(^2\). They were roughly estimated by the difference in pulsation periods between two different epochs, and should be refined by $O-C$ diagrams in future research if one wants to further investigate their physical origins. The rate of HD 133729 is provided in another work\(^1\). The shaded area denotes a rough period range where the BLAPs are significantly less populated. The arrows indicate the direction of evolution.
and the O–C diagram, to diagnose and reveal the rate of period change for TMTS-BLAP-1.

We performed the WWZ analysis for the ATLAS o-band and ZTF r-band light curves using the Python package libwwz. The timescale for determining the decay constant is set to 600 days in the procedure. The number of time bins for each WWZ plot is set to 100 and the frequency bin width is 2 × 10^−4 cycle day^−1. The WWZ powers across all the frequencies in each time bin were divided by the maximum power in the bin.

The O–C diagram is difficult to compute when the observation cadence is much longer than the photometric period of the target. To bring out the details of period changes for TMTS-BLAP-1, we developed a method to estimate the times of maximum light (Tmax) from the ATLAS and ZTF survey observations. First, we fitted the entire light curve in each band using the three-harmonic Fourier model as

\[
\text{Mag}(A_k, \phi_k, T) = A_0 + \sum_{k=1}^{3} A_k \sin(2\pi k f T + \phi_k),
\]

where \(T\) represents the time of observation and \(f\) is the pulsation frequency inferred from the Lomb–Scargle periodogram; \(A_k\) and \(\phi_k\) represent the Fourier amplitudes and phases, respectively. These Fourier parameters uniquely determine the light-curve shapes in each band. Then, the ATLAS and ZTF data were split into 20 day subsets, and the subsets with fewer than five data points were excluded. This results in 132 subsets. However, owing to the deficit of data points in individual subsets, the light curve from each subset is difficult to be fitted with a model that includes seven free parameters.

By assuming that the light-curve shapes have not significantly changed over the survey observations, the light curves of the subsets can be modelled using fixed Fourier parameters \((A_k, \phi_k)\) with a free parameter \(\Phi\) for phase offset, namely,

\[
\text{Mag}(\Phi, T) = \sum_{k=1}^{N} A_k \sin(2\pi k f T + \phi_k). \tag{2}
\]

For the O–C diagram, we obtained a preliminary O–C diagram using the \(T_{max}\) values. The Fourier parameters and light-curve shapes were determined assuming a constant pulsation period. Owing to the period changes over the survey observations, the amplitudes of light curves were actually underestimated (Extended Data Fig. 5). To obtain more accurate light-curve shapes in each band, we modelled the O–C diagram and obtained new ephemerides to correct the pulsation phase of each epoch. This results in much more coherent pulsation profiles for phase-folded light curves (Extended Data Fig. 5b,d). Hence, the peak-to-peak pulsation amplitudes for the ZTF r band and ATLAS o band are 245 ± 3 and 245 ± 4 mmag, respectively. The Fourier parameters derived from the corrected phase-folded light curves were used to compute the times of maximum light (\(T_{max}\)) again. Finally, we obtained the O–C diagram (Fig. 4).

In the case of a linear period change, the O–C diagram can be given as a function of cycle number \(E\) (ref. 27):

\[
(O - C)_{\text{linear}} = \Delta T_0 + \Delta \nu E + \frac{1}{2} \nu^2 E^2, \tag{3}
\]

where \(\Delta T_0\) and \(\Delta \nu\) are the offsets for initial epoch and pulsation period in the ephemeris (equation (1)), respectively. Also, \(\nu\) is the average pulsation period over the whole time interval, which is directly inferred from the Lomb–Scargle periodogram. In the case of LTT induced by orbital motion, \(O – C\) can be expressed as

\[
(O - C)_{\text{LTT}} = (O - C)_{\text{linear}} + a_1 \sin \left( \frac{1 - e^2}{1 + e \cos \omega} \sin(v + \omega) \right), \tag{4}
\]

where \((O - C)_{\text{linear}}\) represents the contribution from pulsation period change due to stellar evolution (equation (3)); \(a_1\) is the projected semimajor axis of absolute orbit; \(e\) and \(\omega\) are the eccentricity and longitude of periastron, respectively; and \(v\) is the true anomaly (which is a function of eccentricity \(e\), orbital period \(P_{\text{orb}}\), time of periastron passage \(T_0\), and time of observation \(t\) (ref. 30)). To fit the O–C diagram using the models in equations (3) and (4), we introduced a free parameter \(\sigma\) for offsetting the systematic uncertainties and adopted the likelihood function \(\mathcal{L}\) introduced elsewhere15, namely,

\[
\log \mathcal{L} = -\frac{1}{2} \sum_i \left( \frac{(O - C)^2 - \sigma_i^2}{\sigma_i^2 + \sigma_f^2} \right) - \frac{N}{2} \log \left( \sigma_f^2 + \sigma_i^2 \right) - \frac{N}{2} \log 2\pi.
\]

Stellar evolution models

To explore the unusual observational properties of BLAPs, we have performed calculations for all the three candidate physical models using state-of-art stellar evolutionary code Modules for Experiments in Stellar Astrophysics (MESA; v. 12115)65–68. According to the HR diagram and \(T_{\text{eff}}\)-logg diagram from BLAPs69, these pulsators between main-sequence and subdwarf B stars may stem from the core-contraction phase of helium WDs with massive cores (for example, \(M_{\text{He}} > 0.25M_\odot\)) or from low-mass helium-burning stars (\(M < 1.00 M_\odot\)). In our calculations, we adopted the opacity tables from the Opacity Project53. However, atomic diffusion and turbulent mixing can change the abundance for subdwarf B stars66,69, whereas rotational mixing and gravitational settling compete with each other to affect the atmospheric composition of pre-ELM WDs70. Both atomic diffusion and radiative levitation can lead to opacity-driven pulsations in post-common envelope objects with effective temperatures similar to BLAPs69,70. Nevertheless, we do not attempt to include atomic diffusion, radiative levitation and additional mixing mechanism in our current models; detailed calculations are very complicated and time-consuming.

To construct the helium-core pre-WD models, we evolved 1.800 M_\odot solar-metallicity (Z = 0.02) main-sequence stars up to the red giant branch until their helium cores reached the mass thresholds (for example, 0.25M_\odot and 0.35M_\odot) in a mass step of \(\Delta M = 0.01 M_\odot\). The hydrogen envelope is artificially removed by an extremely rapid mass-loss rate (2.0 × 10^{−4} M_\odot yr^{−1})3,8 until the envelope masses are less than 0.01M_\odot. Afterwards, we replace the rapid mass-loss rate with a classical Reimers’ wind30 during the core-contraction phase until their luminosities decrease below \(L_{\odot}\).
To obtain the helium-burning models, including CHeB and (unstable and stable) SHeB phases, as well as avoid uncertainties in binary evolution, we constructed solar-metallicity ($Z = 0.02$) zero-age CHeB stars with mass in the range of $0.5$–2.0$M_\odot$. The hydrogen envelope with mass of $0.001$–0.01$M_\odot$ is added onto the surface of the naked helium core by accretion\(^{32}\). All the nuclear reactions inside the stars are shut off during the accretion phase and restored afterwards. The stellar evolution terminates at log $g = 3.8$ owing to the extreme time consumption during the helium giant phase or terminates on the WD cooling track. The CHeB phase corresponds to the stage when the star has a central helium-burning convective core, where SHeB stars have a contracting CO core (unstable helium-shell burning) or a degenerate CO core (stable helium-shell burning). As introduced above, whether the central helium is exhausted is the criterion for differentiating CHeB and SHeB phases, whereas unstable and stable SHeB phases are distinguished by whether the helium-burning zone moves outwards. The boundaries between successive phases are clearly shown in Fig. 4 (blue dash–dot lines). The green area between the lines corresponds to the Hertzsprung gap for helium-burning stars.

**Pulsation period**

BLAPs are thought to be excited by the $\kappa$-mechanism due to the Z bump (also named iron-group elements)\(^{2,33}\)\(^{4,33}\), which is enhanced through the action of radiative levitation\(^{3,20,46,67}\). We suggest that some BLAPs—whether from CHeB or SHeB channels—have similar excitation mechanisms.

The variations seen in log $g$ and radial velocity of TMTS-BLAP-1 (Extended Fig. 3) support the previous assumption that pulsations of BLAPs are in the radial fundamental mode\(^{10,21}\),\(^{2,33}\). Therefore, we adopt the Ritter’s relation\(^{10}\) to estimate the pulsation period. This relation yielded for pulsating stars connects the pulsation period with stellar mean density. Hence, the pulsation period $P$ of BLAPs can be computed through the available stellar parameters from evolutionary tracks\(^{5,49}\), namely,

$$P = \frac{2\pi}{f_{\text{dyn}}} = \frac{2\pi}{f} \left( \frac{GM}{R^3} \right)^{-1},$$

where $\omega_{\text{dyn}}$, $M$, and $R$ are the stellar dynamical frequency, mass and radius, respectively. Since the oscillations in BLAPs are the fundamental mode, we adopted the dimensionless frequency $f = 3.725$ (that is, the median of $f = 3.65$–3.80 (ref. \(^{10}\))). The rates of period change were calculated using $\dot{P} = \Delta P/\Delta t$, where $\Delta P$ and $\Delta t$ represent the period and age difference between successive nodes on evolutionary tracks, respectively. To test the validity of Ritter’s relation and that the pulsation of radial fundamental mode can be efficiently excited, we further perform the asteroseismic analysis for the helium-burning model with $M_{\text{core}} = 0.70M_\odot$ and $M_{\text{env}} = 0.01M_\odot$ by adopting the oscillation code GYRE\(^{68–70}\). For radial fundamental modes of both adiabatic and non-adiabatic pulsations, we find that the Ritter’s relation is effectively consistent with the model calculations within an accuracy of 8%. The asteroseismic analysis indicates that the radial fundamental modes can be excited for both CHeB and SHeB phases even if the atomic diffusion and radiative levitation processes are not included.

**Data availability**

The ZTF $r$- and $g$-band photometry can be obtained from the NASA/IPAC Infrared Science Archive (https://irsa.ipac.caltech.edu). The ATLAS $o$- and $c$-band magnitudes can be obtained from the ATLAS forced photometry server (https://fallingstar-data.com/forcedphot). All the reduced light curves and spectra used for this work, as well as some evolutionary tracks, are available via Zenodo at https://doi.org/10.5281/zenodo.6425425. Source data are provided with this paper.

**Code availability**

The codes of Thusty (v. 207) and Synspec (v. 53) that are used for generating (non-local thermodynamic equilibrium) model atmospheres and producing synthetic spectra are available at https://www.as.arizona.edu/hubeny, and the services of online spectral analyses (XTgrid) are provided from Astroserver (www.astroserver.org). The Python package libwwz (v. 1.2.0) for WWZ analysis can be obtained from https://pypi.org/project/libwwz. The general tools for timing analysis are provided from Python package gatspy (v. 0.3) (http://www.astrolm.org/gatspy or https://zenodo.org/record/47887). The software MESA (v. 12115) used for stellar evolutionary calculations is available at http://mesastar.org.

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Author contributions

J.L., C.W., X.W. and P.N. drafted the manuscript. A.V.F., T.W. and Y.C. also helped with the manuscript, and A.V.F. edited it in detail. X.W. is the PI of TMTS and SNOVA. J.L. discovered this source by analysing the large-volume data from TMTS observations and performed the timing analysis to determine its rate of period change. C.W. computed the stellar evolution models for helium-burning stars and helium-core pre-WDs, and H.X. provided some key ideas for these models. T.W. contributed to the asteroseismic theory and analysis. P.N. determined the atmospheric parameters from Keck I LRIS spectra. Y.C., S.Y., Y.L. and D.X. assisted in the spectral analysis. The Keck I LRIS spectra were provided by A.V.F.’s group (including A.V.F., T.G.B., W.-K.Z. and Y.Y.). A.I., A.E. and Juja Zhang contributed to the observations with SNOVA and the Lijiang 2.4 m telescope, and X. Zeng reduced these data. X.W., J.M., G.X., J.Z. and J.L. contributed to the building, pipeline and database of TMTS. G.X., J.M., X.J., H.S., Z.W., L.C., F.G., Z.C., W. Li, W. Lin, H.L. and X. Zhang contributed to the operations of TMTS.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | TMTS L-band (close to white-light) light curves of TMTS-BLAP-1 taken on December 24 and 25, 2020 (UT). The red solid lines represent the best-fitting models of Fourier series truncated at fourth harmonic.
Extended Data Fig. 2 | Phase-folded light curves for every subset of ATLAS, ZTF, TMTS, and SNOVA data. Every subset of ATLAS and ZTF data covers up to 20 days, while each subset of TMTS and SNOVA data covers only one night. The observed time of maximum light ($T_{\text{max}}$) for every subset is shown above the plots. Since the phases here were all calculated using the ephemeris of Eq. (1), the pulsation phases $\phi = 0$ (the vertical dot-dashed lines) here correspond to the calculated times of maximum light, namely $T_{\text{max}}$. 
Extended Data Fig. 3 | Folded light curve and surface parameters against pulsation phase. a, corrected ZTF $r$-band folded light curve with a best-fitting 3-harmonic Fourier model overplotted (red solid line); b,c,d, radial velocity (RV), effective temperature ($T_{\text{eff}}$) and surface gravity ($\log g$) against pulsation phase. The solid curves are the best-fitting sinusoidal curves, and the purple dashed line in panel d represents the prediction from the time-derivative of the best-fitting model of radial velocity\(^3\).
**Extended Data Fig. 4** | O-C diagram for the pulsation period of ZGP-BLAP-09.

The observed time of maximum light ($T_{\text{max}}^0$) was obtained from the 20-day subsets of ATLAS and ZTF. The O-C values were calculated following the ephemeris $T_{\text{max}} = \text{BJD}_{\text{TDB}} 2,458,218.5012 + 0.016158353 \times E$. Because ZGP-BLAP-09 lacks similar cyclic behavior in the diagram, the O-C variability is modeled only by assuming the linear period change.
Extended Data Fig. 5 | Phase-folded light curves of TMTS-BLAP-1. The folded light curves are derived from ZTF r-band (panels a,b) and ATLAS o-band (panels c,d) observations. a,c, The light curves are folded using a constant period inferred from the Lomb–Scargle periodogram. b,d, The light curves are folded using the new ephemeris derived from the O–C diagram. The red solid lines represent the best-fitting 3-harmonic Fourier models.