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A Search for Subdwarf B Binaries Using Pulsation Timing from TESS

Tomomi Otani[1], A. S. Baran[2,3], Lindsay C. Spence[1], Ted von Hippel[1], E. Lynum- Lozano[1], and Julia. M. Clark[1]
[1] Department of Physical Sciences, Embry-Riddle Aeronautical University, 1 Aerospace Blvd, Daytona Beach, FL 32114, USA; otanit@erau.edu
[2] Physics, Astronomy and Material Science Department, Missouri State University, 901 S National Ave, Springfield, MO 65897, USA
[3] ARDASTELLA Research Collaboration, USA
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Abstract

Hot subdwarf B (sdB) stars are post-main-sequence stars of high temperature and gravity. Approximately 30% of sdBs exhibit stable pressure and/or gravity-mode pulsations, which can be used via the timing method to test for companion stars and determine their orbital solutions. We used short cadence data from the Transiting Exoplanet Survey Satellite (TESS) to search for previously undiscovered companions to sdBs. In this paper, we focus on searching for companions with orbital periods shorter than 13.5 days which are detectable within one sector of TESS data (about 27 days). The timing method requires that we derive pulsation frequencies in subsets of data significantly shorter than the periods we are searching for, which we set at 0.5–1.5 day. We investigated ten sdB stars with previously detected *p*-mode pulsations for which at least one *p*-mode pulsation remains detectable with a signal-to-noise ratio > 4 within data subsets of duration 0.5–1.5 day. We find that two (TIC 202354658 and TIC 69298924) of these ten sdB stars likely have white-dwarf companions and set limits on companion masses for the other eight sdB stars.

Unified Astronomy Thesaurus concepts: B subdwarf stars (129); Pulsating variable stars (1307); Binary stars (154); Timing variation methods (1703); Pulsation frequency method (1308)

Materials only available in the online version of record: data behind figures

1. Introduction

Subdwarf B (sdB) stars are extreme-horizontal-branch stars of high temperature ($T_{\rm eff}$ = 22,000–32,000 K) and gravity (log g = 5.0–6.2). They are core helium-burning objects, found in both the Galactic disk and halo (R. A. Saffer et al. 1994). An sdB progenitor, while on the red-giant branch, loses most of its hydrogen envelope prior to the helium flash (J. G. Mengel et al. 1976; N. L. D'Cruz et al. 1996). Because of degenerate core evolution, their masses are narrowly confined to approximately 0.5 $M_\odot$ (J. Ostrowski et al. 2021). After the red-giant branch, the star burns helium in a shell for up to 10^8 yr; however, nuclear burning will not be sustained in the hydrogen envelope, and therefore the star cannot ascend the asymptotic giant branch after helium core exhaustion (U. Heber 1986) and instead will directly evolve to become a low-mass helium white dwarf (WD; P. Bergeron et al. 1997).

The most studied sdB evolution models are binary population synthesis (BPS) models constructed by Z. Han et al. (2002, 2003) that included three evolutionary channels: (1) common envelope (CE) ejection, which can produce sdB binary systems with short orbital periods; (2) Roche–lobe overflow (RLOF), which can produce sdB binary systems with long orbital periods; and (3) white-dwarf mergers, which can produce single sdB stars. For the CE ejection channel the secondary component is either a main-sequence (MS) star or a WD, with a typical orbital period between 0.1 and 20 days. Many observational studies have focused on these short orbital period systems (e.g., C. M. Copperwheat et al. 2011). To date, the orbital parameters for approximately 140 short orbital period binaries have been derived, and more than half of these have orbital periods shorter than 0.6 day (H. Ge et al. 2022). As seen in Figure 3 of H. Ge et al. (2022), radial velocity (RV) surveys to find sdB binaries with orbital periods longer than 10 days are infrequent because RV searches are inefficient in this period range. Only 11 sdB + WD binary systems with orbital periods longer than five days have been identified. Searching for binaries with orbital periods longer than typical short orbital-period binary systems provides valuable insight into the transition from detached post-CE configurations to RLOF, shedding light on angular momentum loss mechanisms and the stability of mass transfer (N. Ivanova et al. 2013).

Approximately 30% of sdB stars show detectable pulsations. The existence of sdB pulsators was theoretically predicted by S. Charpinet et al. (1997). Independently, D. Kilkenny et al. (1997) observationally discovered the very first short-period sdB variable (sdBV) star, EC 14026-2647. These stars are pressure (p) mode pulsators, with pulsations driven by internal pressure fluctuations (S. Charpinet et al. 2000). The very first long-period gravity (g) mode sdBV star, PG 1716+426, was reported by E. M. Green et al. (2003), in which buoyancy provides the restoring force. Some sdB stars have been discovered to exhibit both p- and g-mode pulsations. These objects are referred to as hybrid pulsators (A. Baran et al. 2005).

Although amplitudes were found to vary (e.g., D. Kilkenny 2010), the pulsation periods of sdBV stars are usually stable (R. Østensen et al. 2001), and therefore good chronometers. As is well known, a star's position in space may show cyclic variations due to a gravitational perturbation of a companion. From an observer's point of view, the light from a pulsating star is periodically delayed when it is on the far side of its orbit and advanced on the near side. The orbital solution of the binary system can be obtained by measuring changes in the pulsation arrival times, which is also called the light time delay. This technique has been used to search for additional

Table 1
Pulsating SdB Stars Investigated In this Work

ID	Other name	R.A. (deg)	decl. (deg)	$G_{BP} - G_{RP}$ (mag)	G (mag)	TESS Sector
TIC 47377536	PG 1047+003	162.5	–0.0	–0.4647(42)	13.4190(10)	35, 46, 72
TIC 62381958	EC 01541-1409	29.1	–13.9	–0.2618(37)	12.2460(10)	30
TIC 62483415	EC 22221-3152	336.2	–31.6	–0.4852(40)	13.6640(9)	28, 68
TIC 69298924	J08069+1527	121.7	15.5	–0.4027(49)	14.7526(12)	44–46, 71–72
TIC 136975077	KPD 2109+4401	317.9	44.2	–0.3459(23)	13.3435(7)	55–56, 75–76, 82–83
TIC 165312944	PG 1219+534	185.4	53.1	–0.4879(18)	13.1655(5)	48–49, 75–76
TIC 169285097	J2344-3427	356.1	–34.5	–0.4302(15)	10.9142(7)	29, 69
TIC 202354658	2M 1545+5955	236.3	59.9	–0.4399(31)	14.4089(11)	48–51, 58, 75–78, 82, 85
TIC 248949857	PB 8783	20.9	–5.1	0.2218(13)	12.2189(4)	30
TIC 396954061	2M 0415+0154	64.0	1.9	–0.2959(31)	14.0278(7)	32

components to pulsating stars and to derive orbital parameters of those systems.

The presence of an M dwarf or WD companion to the sdBV star CS 1246, suggested by this technique, was confirmed by RV measurements (B. N. Barlow et al. 2011). T. Otani et al. (2018) used this technique to obtain an orbital solution of the previously known sdB + main-sequence binary system, EC 20117-4014, while T. Otani et al. (2022) detected one of the companions to the sdB triple star system candidate, AQ Col.

Continuous long-coverage photometric data obtained from space telescopes such as Kepler and Transiting Exoplanet Survey Satellite (TESS) allow us to efficiently search for companions using this method. Recently, a short-orbital-period sdB plus WD binary system, BPM 36430, was detected using this method with TESS data and confirmed via radial velocities (B. A. Smith et al. 2022).

This work is a continuation of our search for additional components to sdB stars (T. Otani et al. 2018, 2022) with this pulsation timing method using TESS photometry. Section 2 outlines the targets and their data. Section 3 explains our analysis. Section 4 presents our results and discussion. Our conclusions and future work are summarized in Section 5.

2. Photometric Data

TESS was launched in 2018 and provides extended time-series photometry for millions of objects across the entire sky (G. R. Ricker et al. 2014). We have chosen 10 hot subdwarfs (see Table 1) with previously reported p-mode pulsations, observed by TESS during Cycle 3 and/or 4 using 20 s cadence (USC) data to properly sample minute-long p modes. These stars have either been previously identified as single stars or flagged as possible binary systems for which orbital elements (orbital period, $a \sin i$, eccentricity, and the mass function) have not been derived. We accessed the time-series data from the Mikulski Archive for Space Telescopes (MAST) and used PDCSAP_FLUX, which is simple aperture photometry (SAP_FLUX) corrected for on-board systematics, as well as the TESS Barycentric Julian date.

3. Analysis

A flux variation caused by pulsations can serve as an accurate clock. A specific phase of the flux variation can be compared with predictions. Traditionally, times of flux maxima for pulsating stars are compared from a linear ephemeris, which describes times of consecutive flux maxima. This technique is known as Observed – Calculated ($O - C$) analysis. C. Sterken (2005) discussed multiple possible solutions, with some being only corrections to either a period or reference epoch adopted in the linear ephemeris, while parabolic and sinusoidal trends mean a physical interpretation, i.e., evolutionary change and an additional companion, respectively. The $O - C$ analysis is useful for a variable star that has a single periodic variation; however, it is not suitable for stars with multiperiodic variations. S. J. Murphy et al. (2014) discussed the phase-modulation method, which is a complementary method of the traditional $O - C$ method, by which the phase modulation is extracted from the Fourier analysis of the time-shifted light curve due to the binary orbital motion. Since most of the sdB pulsators are multiperiodic, this method was used to obtain the light time delay in our analysis. In this work, we search for periodic behavior in the light time delay indicative of an additional companion to the pulsating star. In general, the orbit of the companion may be eccentric, hence the light time delay variation trend will be described with Bessel functions (see T. Otani et al. 2022) rather than a sine function. The Bessel functions include the orbital period P, $a_{\rm sdB} \sin i$, orbital eccentricity e, and the argument of periapsis ϖ. In cases with negligible orbit eccentricity, one can use a sine function, which assumes $e = 0$, while ϖ becomes undefined. From $a_{\rm sdB} \sin i$, we can also derive the mass function (details can be found in Equation (22) of T. Otani et al. 2022), and the RV amplitude, K, of the pulsating star. The RV and light time delay variation are discussed and used in, e.g., J. H. Telting et al. (2012).

To obtain the light time delay variations, we split all photometry into 0.5 day data subsets (1.5 day for TIC 69298924), and check which pulsation frequencies are still significant in those individual data subsets. Then, we derived times of flux maxima of the significant pulsation frequencies and compared these with predictions calculated from the ephemerides. A reference epoch was adopted as the timestamp of the first data point, while a period is the average value fitted across all data for that system.

Note that two closely spaced pulsation frequencies, e.g., rotationally split modes, also called multiplets, can be unresolved in data subsets and cause sinusoidal variations in the light time delay diagram, even though the variation is not because of an "actual" light time delay. This can be identified because in such a case, the pulsation amplitudes are also periodically modulated.

When there is a companion to a pulsating star, the pulsation frequency is surrounded by two additional frequencies, which altogether looks like a triplet, and can be misinterpreted as rotationally split modes. Yet these three frequencies show a different behavior. There is a sinusoidal trend in the light time delay diagram; however, the amplitude of the analyzed frequency is unmodulated. In addition, the amplitudes of the two side frequencies should obey a relation cited in Sections 2.4.2 and 2.4.3 of H. Shibahashi & D. W. Kurtz (2012). Following these approaches, our conclusion on the existence of additional companions is based on whether the amplitude shows in-phase variability with times of flux maxima, as well as the correct amplitude prediction of the side frequencies.

4. Results and Discussion

TIC 47377536 (PG 1047+003, UY Sex, Gaia DR2 3806303066866089216) was found as a variable sdB star independently by M. Billères et al. (1997) and D. O'Donoghue et al. (1998), who indicated that its optical spectrum is consistent with that of a single sdB star. According to D. Kilkenny et al. (2002) the effective temperature and the surface gravities are $T_{\rm eff} = 34\,700$ K and $\log g = 5.8 \pm 0.15$. M. D. Reed et al. (2020) analyzed photometric data obtained during Campaign 14 of the K2 mission and detected 97 frequencies. A. S. Baran et al. (2023) analyzed TESS USC data collected in Sectors 35 and 46 and detected frequencies with high amplitudes in both sectors. We obtained the light time delay diagram on these TESS USC data by splitting them into 0.5 day data subsets, using only frequencies that were detected above signal-to-noise ratio = 4 within these data subsets, which for this star were f_1, f_2, and f_3 in Sector 35 and f_2 and f_6 in Sector 64. The light time delay diagram is shown in Figure 1. We found no significant periodic variations.

These timing residuals show no variation with an amplitude higher than 5.41 s, defined as four times the average noise level in the amplitude spectrum calculated from the light time delay diagram data points. Only the result of the light time delay for f_2 was used since f_2 provides the lowest average noise level. We used this value to estimate the upper limit of the possible companion that could still exist. Using the amplitude of the light time delay diagram (the amplitude in Equation (6) of T. Otani et al. 2022), $\tau = \frac{1}{c} a_{\rm sdB} \sin i$, the mass function can be written as:

$$f = \frac{(M_{\rm comp} \sin i)^3}{(M_{\rm sdB} + M_{\rm comp})^2} = \frac{4\pi^2 c^3 \tau^3}{G P_{\rm orb}^2}. \quad (1)$$

Solving this equation for $M_{\rm comp}$, we estimated the upper limit for the companion mass (under the assumption that $i = 90°$) to be 222.9 $M_{\rm J}$ for orbital period $P_{\rm orb} = 3$ days and 42.8 $M_{\rm J}$ for $P_{\rm orb} = 27$ days. (see Figure 2).

TIC 62381958 (EC 01541-1409, GD 1053, Gaia DR2 5149241067178231552) was found to be a pulsating hot subdwarf by D. Kilkenny et al. (2009), who reported six p-mode frequencies. Later, M. D. Reed et al. (2012) detected ∼30 pulsation frequencies including all those reported by D. Kilkenny et al. (2009). M. D. Reed et al. (2012) also reported that there are no indications that this is a binary system from the spectroscopic observations. A. S. Baran et al. (2023) used Sector 30 TESS data and detected 38 frequencies including both p and g modes. Using our analysis approach, we found f_6, f_7 and f_{30} to be significant in individual data subsets and adopted these frequencies for the pulsation timing analysis (see Figure 1). We found no variation with an light time delay variation amplitude $\geqslant$1.59 s. Only the light time delay data for f_7 were used since it provides the lowest average noise level. We estimated an upper companion mass limit for $i = 90°$ to be 55.1 $M_{\rm J}$ for $P_{\rm orb} = 3$ days and 12.1 $M_{\rm J}$ for $P_{\rm orb} = 27$ days. (see Figure 2).

TIC 62483415 (EC 22221-3152, Gaia DR2 6601695863046409600) was found as a variable sdB star by D. Kilkenny et al. (2009). B. N. Barlow et al. (2017) derived $T_{\rm eff} = 35{,}600 \pm 600$ K, $\log g = 5.86 \pm 0.15$, and $\log N({\rm He})/N({\rm H}) = -1.4 \pm 0.3$. A. S. Baran et al. (2023) detected twelve pulsation frequencies using Sector 28 TESS USC data. We analyzed the three frequencies with the highest amplitudes reported by A. S. Baran et al. (2023), f_1, f_2, and f_6, that are shown in Figure 1. Our results show no variation with amplitude higher than 3.59 s. Only light time delay data for f_1 was used since it provides the lowest average noise level. We estimated an upper companion mass limit for $i = 90°$ to be 136.1 $M_{\rm J}$ for $P_{\rm orb} = 3$ days and 27.9 $M_{\rm J}$ for $P_{\rm orb} = 27$ days (see Figure 2).

TIC 69298924 (J08069+1527DR2 654866823401111168, GALEX J080656.7+152718) was classified as an sdB star by S. Vennes et al. (2011). A. S. Baran et al. (2011) found it to be a hybrid pulsator and detected two g-mode and two p-mode frequencies. A. S. Baran et al. (2023) analyzed Sector 44-46 TESS USC data and detected only four frequencies in the p-mode region. They suggested that f_2, f_3, and f_4 may be a rotationally split triplet. Assuming this interpretation is correct the rotation period would equal 12.9 days. We applied the pulsation timing analysis only to frequency f_3 since it was the only significant frequency in individual data subsets. The result of our analysis is shown in Figure 3. The solid line in Figure 3 is our fit to the data points. A variation with a period of 12.83569 ± 0.00037 days is noticeable, while we found no significant variation of the amplitude of f_3.

Assuming the light time delay variation is caused by an unseen companion, the mass function $f = 0.161 \pm 0.022\, M_{\odot}$. The estimated amplitude of the RV variation is $K_{\rm sdB} = 49.4 \pm 2.2$ km s^{-1}. The existence of the additional companion could be verified by radial velocity observations. Following Equation 28 of H. Shibahashi & D. W. Kurtz (2012), we estimated the sum of amplitudes of side frequencies f_2 and f_4 to be 7.03(14) ppt. According to A. S. Baran et al. (2023), the sum of the observed amplitudes of these side frequencies are 7.18(42) ppt. These two values agree within their uncertainties. Given both the lack of the amplitude variation of f_3 and the consistent sum of observed/predicted amplitudes of side frequencies in this triplet, we conclude that the light time delay variation is caused by an orbiting companion to this pulsating sdB star, making the object a binary system. The light time delay variation amplitude is 29.1 ± 1.3 s, and the corresponding semimajor axis $a_{\rm sdB} \sin i = 0.0583 \pm 0.0026$ au. The orbital solution is presented in Table 2.

According to the BPS models, short orbital period sdB binaries have either MS or WD companions. Both Figure 3 of H. Ge et al. (2022) and Table 9 of A. S. Baran et al. (2019) show that sdB+MS systems have orbital periods shorter than 1.25 day. This indicates that this companion is likely a WD. According to Figure 4 the minimum mass of a companion is 0.568 $M_{\odot}$. Note that for the WD interpretation to be valid, the orbital inclination cannot have $i < 36°$ or the unseen companion would exceed the Chandrasekhar limit. Figure 5 shows the color–color diagram of known sdB binary systems. The position of the star in this diagram also supports the WD interpretation of the companion to the sdB star.

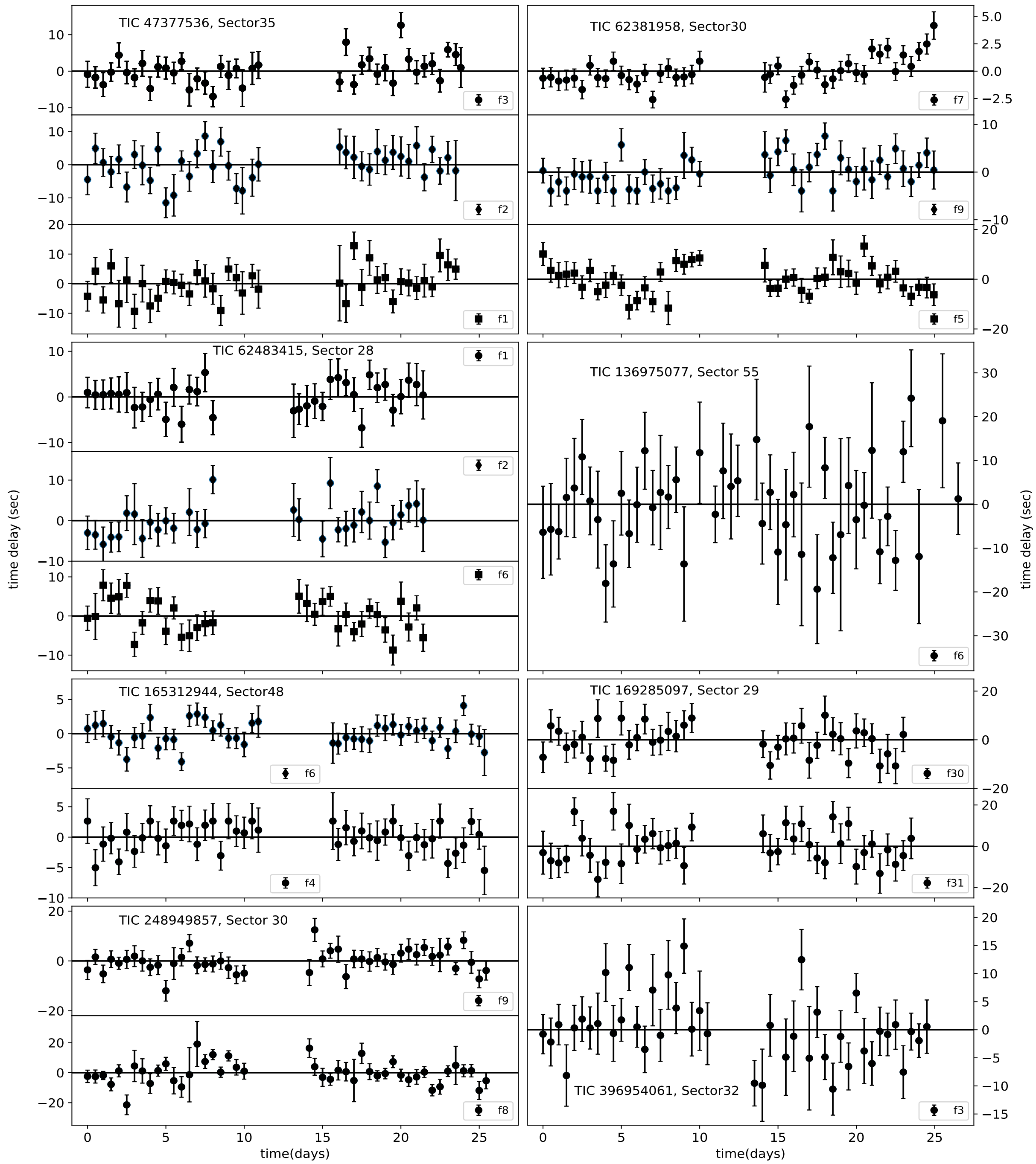

Figure 1. Pulsation timing analysis of targets with no observed periodic variations. Only the first sector in which each target was observed with a 20 s cadence is shown. When more than one pulsation frequency is used for the analysis, the pulsation with the largest amplitude is shown on top.

TIC 136975077 (V2203 Cyg, KPD 2109+4401, Gaia DR2 1970289725639077120) was classified as an sdB star by R. A. Downes (1986). C. Koen (1998) isolated seven *p*-mode frequencies. U. Heber et al. (2000) performed NLTE and LTE model atmospheres using Keck HIRES spectra and obtained $T_{\rm eff} = 31\,800 \pm 600$ K, $\log g = 5.76 \pm 0.05$, and $\log({\rm He/H}) = -2.23 \pm 0.10$. C. S. Jeffery & D. Pollacco (2000) obtained radial velocities of 2.49 and 2.68 km s^{-1} at frequencies 5.09 and 5.48 mHz and concluded that they cannot rule out the possibility that this star has a companion. A. S. Baran et al. (2024) used Sector 55 and 56 TESS USC data and reported seven frequencies. We detected only f_4 to be significant in individual data subsets. The pulsation timing analysis using f_4 is shown in Figure 1. We found no variations with amplitude higher than 4.05 s. From this value, we estimated an upper companion mass limit for $i = 90°$ to be 156.6 $M_{\rm J}$ for $P_{\rm orb} = 3$ days and 31.6 $M_{\rm J}$ for $P_{\rm orb} = 27$ days. (see Figure 2).

TIC 165312944 (PG 1219+534, KY UMa, Gaia DR2 1572188107440718848) was classified as a variable sdB star by C. Koen et al. (1999). They also indicate that its spectra and photometric colors are consistent with a single star, and there is no sign of a companion. According to the astroseismic analyses reported by S. Charpinet et al. (2005), its mass is $M_{\rm sdB} = 0.457 \pm 0.012\,M_\odot$ and $R_{\rm sdB} = 0.1397 \pm 0.0028\,R_\odot$. Analyzing combined TESS USC data collected during

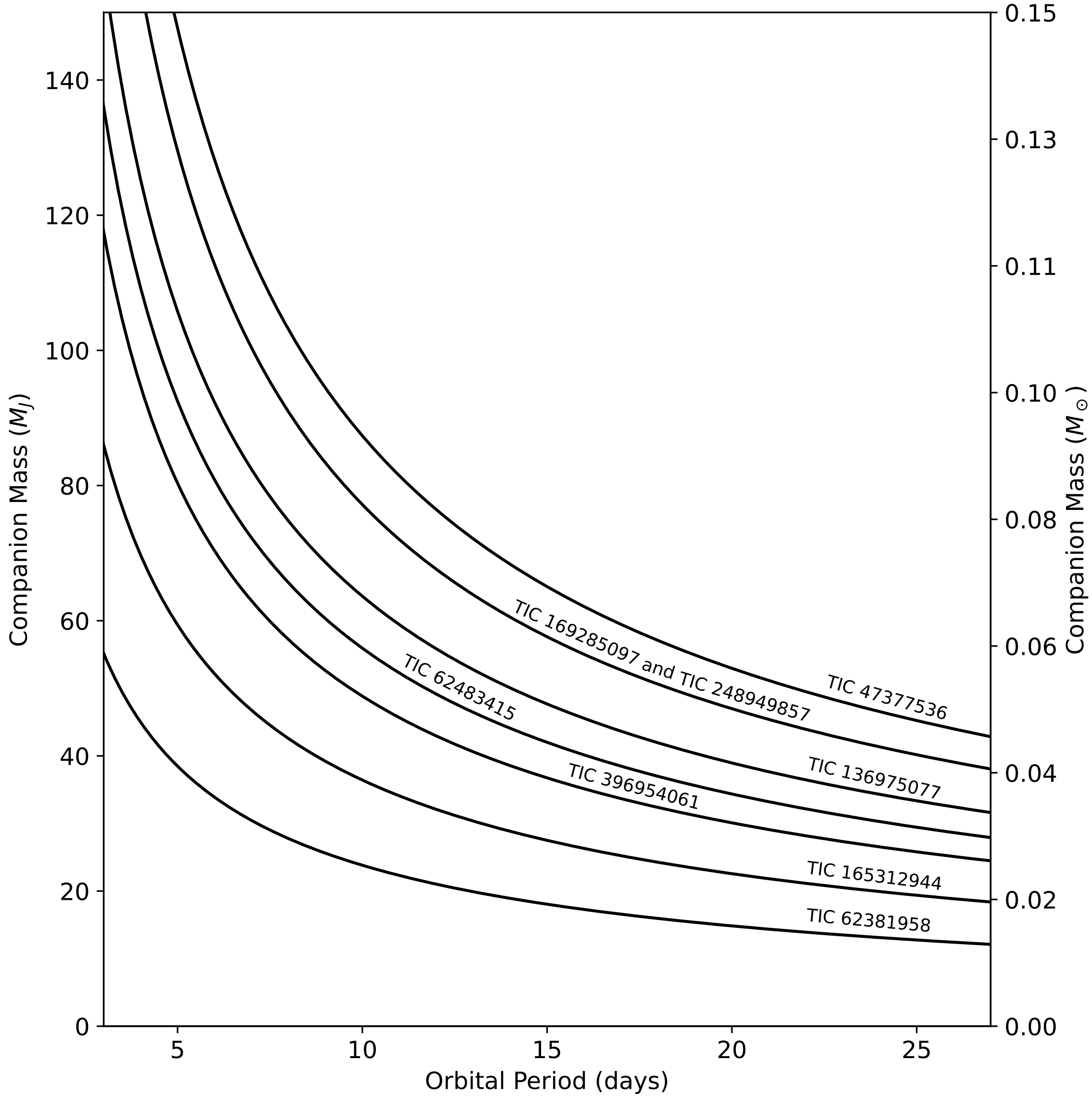

Figure 2. Upper companion mass limits for $i = 90°$ for each target using all available TESS sectors in the analysis.

Sectors 48 and 49 A. S. Baran et al. (2024) detected nine pulsation frequencies. We used only the two frequencies with the highest amplitudes reported by A. S. Baran et al. (2024), f_6 and f_4, for the pulsation timing analysis (see Figure 1). We found no variations with amplitude higher than 2.39 s, from which we estimated an upper companion mass limit for $i = 90°$ to be 86.0 M_J for $P_{orb} = 3$ days and 18.4 M_J for $P_{orb} = 27$ days (see Figure 2).

TIC 169285097 (HE 2341-3443, SB 815, Gaia DR2 2312392250224668288) was identified as an sdB star by J. A. Graham & A. Slettebak (1973), while R. H. Østensen et al. (2010) found it to be a pulsator. A. Kawka et al. (2015) searched for binary systems using spectroscopy and radial velocity methods; however, they did not find any evidence of a companion. S. K. Sahoo et al. (2020) analyzed 120 s cadence photometry data of TESS Sector 2 and obtained 43 pulsation frequencies, including six p-mode pulsations. A. S. Baran et al. (2023) used TESS USC data collected in Sector 29 and reported 34 frequencies. In addition to Sector 29 we also analyzed Sector 69 USC data. Only two frequencies reported by A. S. Baran et al. (2023), f_{30} and f_{31}, were significant in individual data subsets, so those frequencies were used for the pulsation timing analysis (see Figure 1). We found no variations with amplitude higher than 4.86 s, corresponding to an upper companion mass limit for $i = 90°$ of 195.3 M_J for $P_{orb} = 3$ days and 38.3 M_J for $P_{orb} = 27$ days (see Figure 2).

TIC 202354658 (PG 1544+601, Gaia DR2 1627040062 490757120) was classified as an sdB star by R. F. Green et al. (1986). A. S. Baran et al. (2024) analyzed consecutive TESS Sector 48-51 USC data and detected eight pulsation frequencies identified as p-modes. Three frequencies, f_5, f_6 and f_7, indicate the possibility of being rotationally split modes. Assuming the interpretation of a triplet is correct, the rotation period would be 17.3 days. A. S. Baran et al. (2024) found two other equally spaced frequency patterns among f_1, f_2, and f_3, and f_4, f_5, and f_8, with both spacing equal to 2.09 μHz. The authors pointed out that this could be due to a companion with a period of 5.5 days. To test this possibility we split TESS USC data into 0.75 day data subsets and performed our pulsating timing analysis.

For the pulsation timing analysis we used only two frequencies that were significant in individual data subsets of data, i.e., f_2 and f_5. The result of our analysis is shown in Figure 6. The solid line in Figure 6 is our fit to the light time

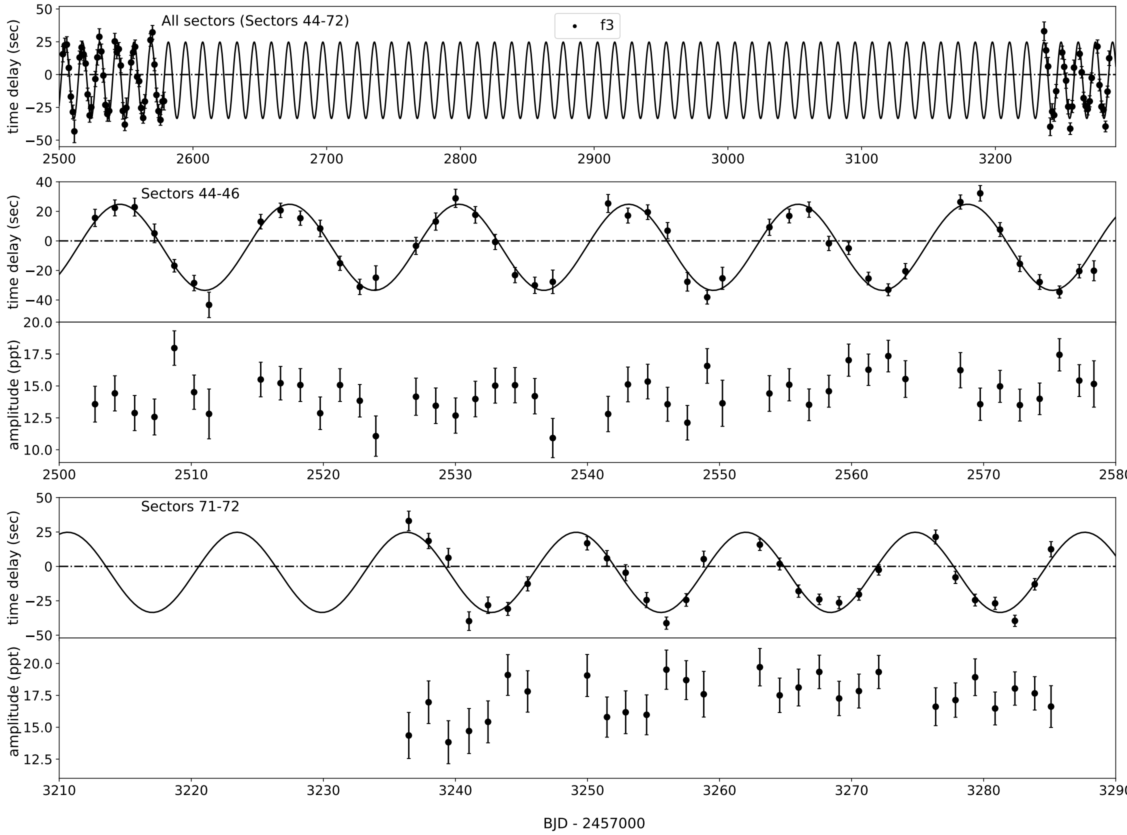

Figure 3. Pulsation timing analysis of TIC 69298924 using f_3 (the largest amplitude pulsation). (Row1) Pulsation timing analysis of all available sectors, Sectors 44–46, and 71–72. (Row 2 and 3: top) The pulsation timing analysis of Sectors 44–46 and Sectors 71–72. The solid curve shows the best-fit sinusoid. (Row 2 and 3: Bottom) The pulsation amplitude variations of each sector.

(The data used to create this figure are available in the online article.)

Table 2
Orbital Parameters for TIC 202354698 and TIC 69298924 Binary Systems

Parameters	TIC 202354698	TIC 69298924
Period, P (day)	5.54078 ± 0.00061	12.83569 ± 0.00037
Amplitude, $a_{\rm sdB} \sin i$ (s)	13.49 ± 0.65	29.1 ± 1.3
Mass function, f ($M_\odot$)	0.086 ± 0.012	0.161 ± 0.022
Radial velocity of sdB star, $K_{\rm sdB}$ (km s^{-1})	53.1 ± 2.6	49.4 ± 2.2

delay data points. It represents a sinusoidal variation with a period of 5.54078 ± 0.00061 days and and amplitude of 13.49 ± 0.65 s. Based on the orbital period, similarly to TIC 69298924, the companion of TIC 202354658 is likely a WD. The amplitudes of both f_2 and f_5 show no significant variation. The minimum mass of a companion is $0.416\,M_\odot$ (see Figure 4). Note that if the inclination is below $i = 29°$, the total mass of the system would exceed the Chandrasekhar limit. Figure 5 shows the color–color diagram of known sdB binary systems. The position of the star in this diagram is also consistent with the WD interpretation. Since the rotation period of the sdB star is 17.3 days, which is longer than the orbital period of 5.54 days, this binary system is subsynchronous.

The derived sums of amplitudes of side frequencies f_1 and f_3, as well as f_4 and f_8, are 2.96(25) ppt and 2.98(25) ppt, respectively. According to A. S. Baran et al. (2024), the sum of the observed amplitudes of these two pairs of side frequencies are 2.76(32) ppt and 2.56(33) ppt, respectively. The corresponding values agree within their uncertainties. The lack of amplitude variations of f_2 and f_5, as well as consistent sums of amplitudes of side frequencies indicates the presence of an unseen companion, supporting the interpretation of this object as a binary system. The orbital solution is included in Table 2. The mass function as computed from the pulsation timing variation is $f = 0.086 \pm 0.012\ M_\odot$. The estimated amplitude of the RV variations is $K_{\rm sdB} = 53.1 \pm 2.6$ km s^{-1}.

TIC 248949857 (PB 8783, EO Cet, Gaia DR2 2482171 590176492928) is a known subdwarf O (sdO) and main-sequence F-spectroscopic binary system (C. S. Jeffery & D. Pollacco 2000). The primary component was originally classified as an sdB pulsator by C. Koen et al. (1997). R. H. Østensen (2012) analyzed the spectra and reclassified this as an sdO star. A. S. Baran et al. (2023) used Sector 30 TESS USC data and confirmed 11 frequencies that were previously reported by D. O'Donoghue et al. (1998) and V. Van Grootel et al. (2014). We found frequencies f_8 and f_9 to be significant in individual data subsets, so those frequencies were used for the pulsation timing analysis (see Figure 1). We detected no variation with amplitude higher than 4.84 s. Using this, we estimated an upper limit of companion mass for $i = 90°$ to be 193.8 $M_{\rm J}$ for $P_{\rm orb} = 3$ days and 38.1 $M_{\rm J}$ for $P_{\rm orb} = 27$ days (see Figure 2). We expect that the progenitor of this binary went through the RLOF and the orbital period is at least hundreds of days, therefore one sector of TESS data

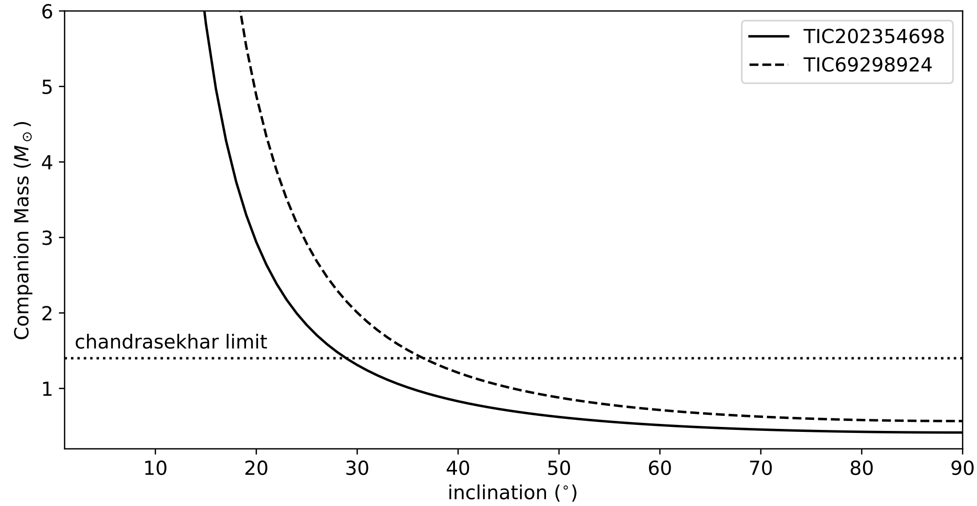

Figure 4. Possible companion masses for TIC 202354698 and TIC 69298924 as a function of orbital inclination.

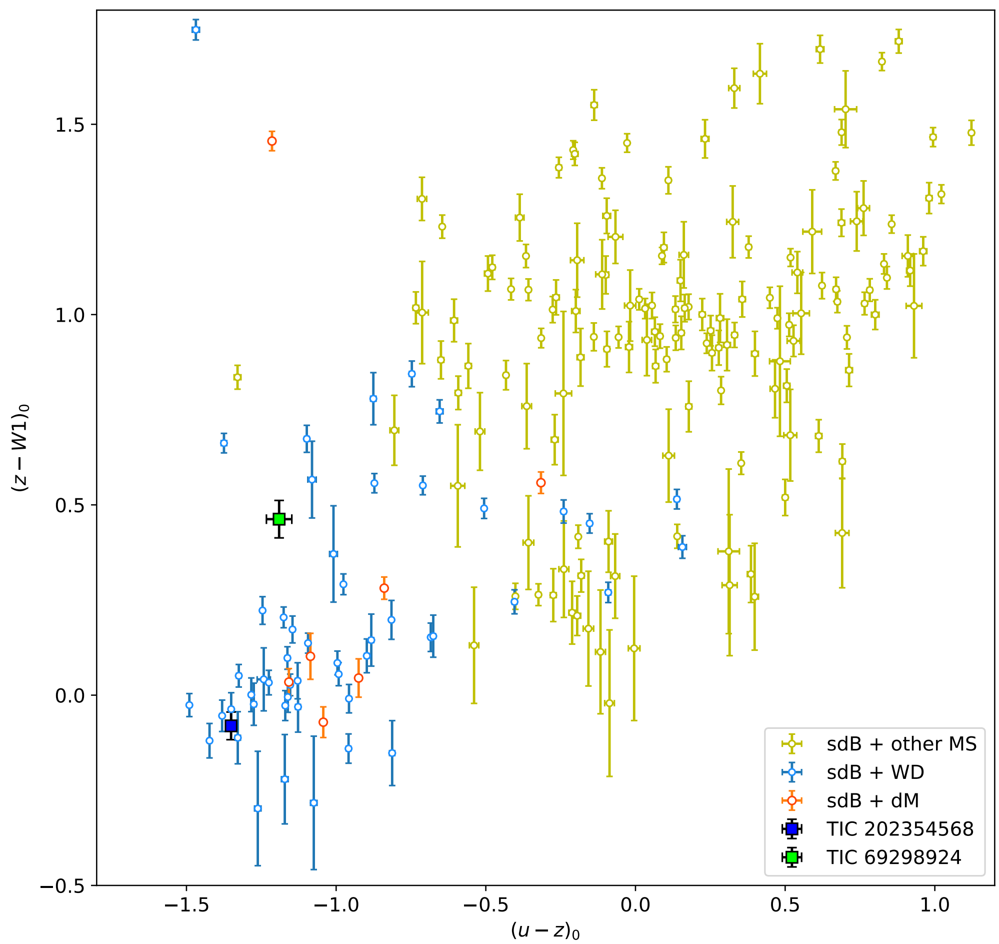

Figure 5. Color–color diagram for all available sdB binaries in the (S. Geier 2020) database. TIC 202354698 and TIC 69298924 are indicated by filled squares.

(about 27 days) is insufficient to detect light time delay variations.

TIC 396954061 (2M 0415+0154, Gaia DR2 3259060049366022400) is a known sdB pulsator. R. Oreiro et al. (2009) detected three *p*-mode frequencies and derived $T_{\rm eff} = 34{,}000 \pm 500$ K and $\log g = 5.80 \pm 0.05$. Their spectra and radial velocity search concluded that this is either a single or an sdB+WD system with a period longer than a few days. A. S. Baran et al. (2023) used Sector 32 TESS USC data and found three pulsation frequencies, one of which is the same frequency reported by R. Oreiro et al. (2009). We found that only f_3 is significant in individual data subsets, so we only used f_3 for the pulsation timing analysis (see Figure 1). We detected no variation with amplitude higher than 3.16 s. Using this, we

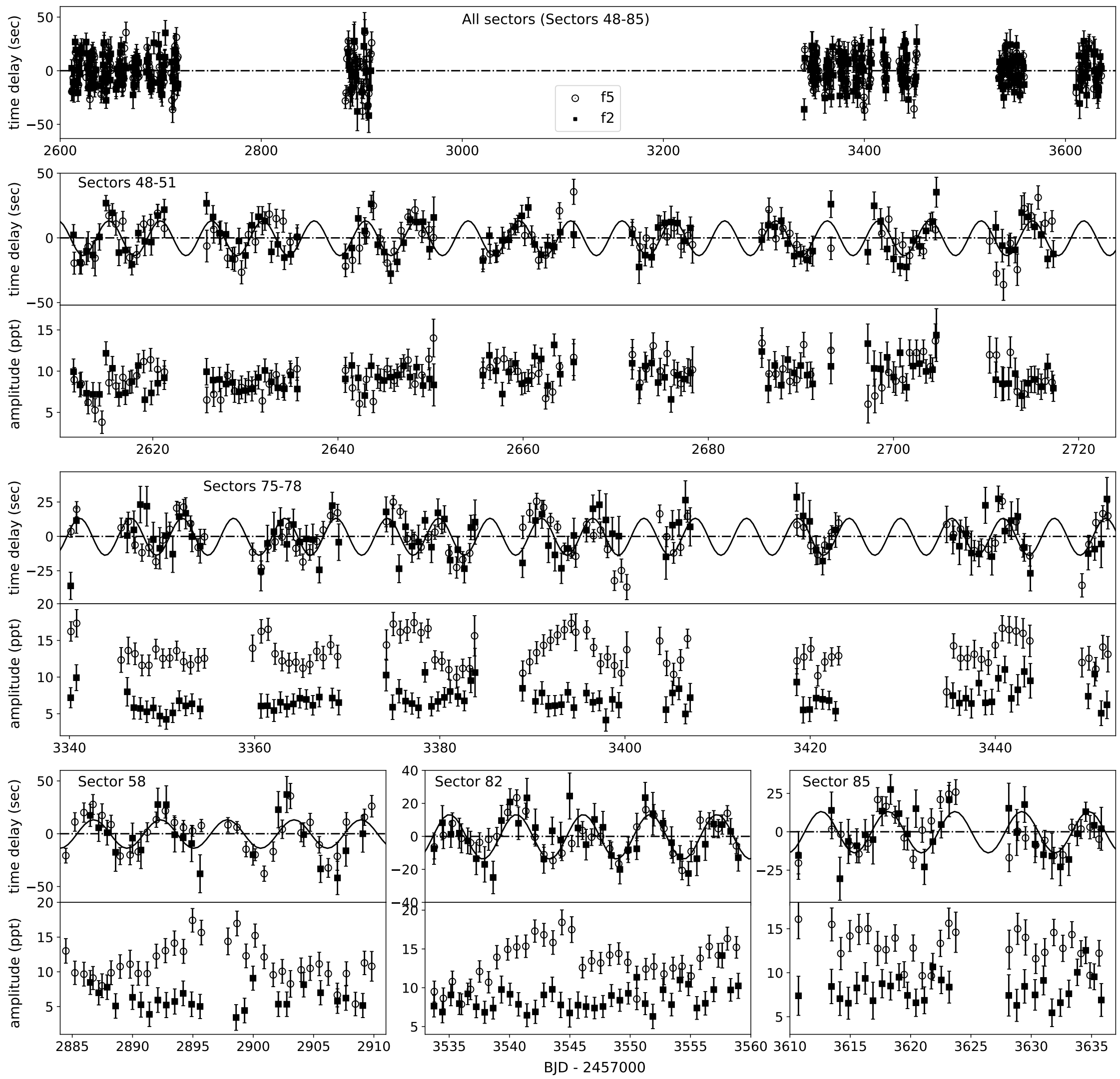

Figure 6. Pulsation timing analysis of TIC 202354658 using f_5 (the largest amplitude pulsation—shown in "•") and f_2 (the second largest amplitude pulsation—shown in "■"). (Row1) Pulsation timing analysis of all available sectors, Sectors 48–51, 58, 75–78, 82, and 85. (Row2–4: top) The pulsation timing analysis of each sector. The solid curve shows the best-fit sinusoid. (Row2–4: bottom) The pulsation amplitude variations of each sector.
(The data used to create this figure are available in the online article.)

estimated an upper companion mass limit for $i = 90°$ to be 117.5 M_J for $P_{orb} = 3$ days and 24.5 M_J for $P_{orb} = 27$ days (see Figure 2).

5. Conclusions

We used Transiting Exoplanet Survey Satellite ultrashort cadence data to search for companions to pulsating sdB stars with the light time delay. We focused on orbital periods shorter than 13.5 days which are detectable with one sector of TESS data (about 27 days). We investigated ten pulsating sdB stars reported by A. S. Baran et al. (2023, 2024) and detected clear indications of pulsation modulation characteristic of binary systems in TIC 202354658 and TIC 69298924. For the TIC 202354658 system, we find that the orbital period is 5.54078 ± 0.00061 days and $a_{sdB} \sin i$ is 13.49 ± 0.65 s. If the orbital inclination is below $i = 29°$, the mass of this unseen companion exceeds the Chandrasekhar limit. Since the stellar rotation period of TIC 202354658 is 17.3 days, this binary system is an example of subsynchronous system. For the TIC 69298924 system, the orbital period is 12.83569 ± 0.0003 days and $a_{sdB} \sin i$ is 29.1 ± 1.3 s. If the inclination is below $i = 36°$, the mass of this unseen companion exceeds the Chandrasekhar limit. Based on the orbital period length and a color–color diagram, we concluded that in both cases the companions are likely to be white dwarfs. We also estimated orbital radial velocity amplitudes as an aid in planning future spectroscopic observations that can be used to test our analysis and conclusions.

Although many observational studies have been done on the short orbital period sdB systems formed by the common envelope channel, more than half of them have orbital periods shorter than 0.6 days and the study of sdB binaries with orbital periods longer than 5 days is limited. Searching for binaries with orbital periods longer than typical CE binary systems, i.e., longer than a few days, provides valuable insights into sdB binary formation theories.

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All the TESS data used in this paper can be found in MAST: D. A. Caldwell et al. (2020).

Facility: TESS.

ORCID iDs

Tomomi Otani https://orcid.org/0000-0002-1691-8479
A. S. Baran https://orcid.org/0000-0001-6446-6617
Ted von Hippel https://orcid.org/0000-0002-5775-2866

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