Rotation of ZZ Ceti stars as seen by TESS

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ABSTRACT

Context. Instead of searching for signs of stellar rotation in the broadened spectral lines of compact pulsators in the traditional way, we investigate the frequencies derived from ZZ Ceti light curves observed by the TESS space telescope. We search for signs of rotationally split frequency multiplets in order to derive the rotation rate of the stars.

Aims. We aim to derive stellar rotation periods in the TESS sample for as many white dwarf pulsators as possible.

Methods. We rely on light-curve analysis of the TESS observations, and search for closely spaced frequency multiplets that could be rotationally split pulsation modes. We work with triplet frequencies, even if one or two triplet components are only marginally detectable. We also utilise ground-based observations available from the literature to help confirming the presence of several triplets.

Results. We successfully identified rotationally split multiplets and derived rotation rates for 15 stars. Together with their stellar mass estimations, our results confirm the former findings that larger-mass WDs rotate faster than their lower-mass counterparts, as described by Hermes et al. (2017). We determined the rotation periods of seven stars for the first time.

Key words. techniques: photometric – stars: oscillations – white dwarfs

1. Introduction

ZZ Ceti or DAV stars are short-period ($P \sim 100 - 1500$ s), low-amplitude ($A \sim 0.1\%$) pulsators, with atmospheres dominated by hydrogen. Their pulsation modes are low-spherical-degree ($\ell = 1$ and 2), and low-to-mid radial-order g-modes. They are situated in the 10 500–13 000 K effective-temperature range. The $\kappa - \gamma$ mechanism (Dolez & Vauclair 1981; Winget et al. 1982) in combination with the convective driving mechanism (Brickhill 1991; Goldreich & Wu 1999) is responsible for the excitation of the observed pulsations, and they form the most populous group of pulsating white dwarf stars.

Over time, more and more interesting things about the ZZ Ceti stars have been revealed. It is long known that their pulsational behaviour depends strongly on their location within the empirical ZZ Ceti instability strip. As e.g. Hermes et al. (2017) summarises, we find fewer and lower-amplitude pulsation modes in the hot DAVs than in their cooler counterparts. However, the frequency analysis of the cooler DAVs often poses a real challenge: as Hermes et al. (2017) described based on Kepler space telescope observations, above about 800 s in period, we often found a large number of peaks under a broad envelope instead of one single peak at a given frequency, which phenomenon is reminiscent of stochastically driven oscillations. Another challenge for theory is to find explanation for the so-called outburst episodes observed also in cool DAV stars, close to the red edge of the empirical instability strip. An outburst is an average brightness increase of at least several per cent relatively quickly (in about 1 hour). The star remains in this state for several hours to one day, before the stellar brightness decreases back to the initial value. The outburst events usually recur after several days or weeks, sometimes after even longer breaks, such as in the case of HE 0532-5605 in Bognár et al. (2023). We cannot predict the duration of outbursts, neither the time of their occurrence. Further details on this phenomenon are given in the papers of Bell et al. (2015, 2016, 2017), and Hermes et al. (2015). For possible theoretical explanations – non-linear mode coupling, or phase shifts of the travelling waves reflected from the outer turning point being close to the convection zone –, see the papers of e.g. Bell et al. (2017), and Montgomery et al. (2020). For reviews of the theoretical and observational aspects of studies of white dwarf pulsators, we also recommend the papers of Winget & Kepler (2008), Fontaine & Brassard (2008), Althaus et al. (2010), Córsico et al. (2019), and Córsico (2020).

In this paper, we study the rotation rates of DAV stars observed by the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015). TESS was launched on 18 April 2018, and the main goal of the mission is to find exoplanets at bright nearby stars with the transit method. However, the time sampling of the observations also allows to follow any kind of brightness variations of stars in the observed fields. The two-year primary mission provided not only 30-minute sampling of full-frame images from almost the entire sky (long cadence), but 120-second cadence observations on selected targets (short cadence). In the case of the short-period white dwarf and subdwarf pulsators, this latter mode provided suitable data sampling for analysis, see e.g. the first-light papers of the TESS Asteroseismic Science Consortium (TASC) Compact Pulsators Working Group (WG#8): Bell et al. (2019), Charpinet et al. (2019), and Bognár et al. (2020). What is more, in the case of the Extended Mission approved for 2020–2022, new, 20-second ultrashort-cadence mode observations became available, which provides an excellent opportunity to study e.g. the hot ZZ Ceti stars showing the shortest pulsation periods. Utilising these ultrashort-cadence measurements, several new candidate pulsation modes were detected in some of the southern ecliptic ZZ Ceti stars (Bognár et al. 2023).

This work focuses on the measurement of rotation rates in ZZ Ceti stars. In general, we can derive the projected equatorial velocity of a given star utilising the rotational broadening of

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spectral lines. However, we face difficulties applying this method for white dwarf stars. The strong atmospheric pressure broadens their line profiles, masking the relatively small contribution of stellar rotation to the overall broadening. Fortunately, there is a way to gather reliable information on the stellar rotation periods for pulsators: through studying the splitting effect of rotation on oscillation frequencies. The separation of these frequency components highly depends on the rotation rate in the stellar layer probed by the given pulsation mode, which offers a unique opportunity to reveal their internal rotation. The white dwarf rotation rates as a function of mass may shed light on the unknown angular momentum transport mechanism in their progenitors, coupling red-giant cores to their envelopes. For more details, we also recommend the papers of Kawaler (2003), Kawaler (2015), and Córsico et al. (2019).

As we need long time-base and precise observations to resolve the often closely spaced and low-amplitude frequency components, space-based data are our best opportunity for such measurements.

2. Analyses of the TESS data sets

Even though TESS observed hundreds of potentially pulsating DA white dwarf stars, here we do not intend to search for new DAV pulsators. We investigate the already known ZZ Ceti stars instead. For this purpose, we relied on two databases of known DAVs: Bognár & Sódor (2016, table 4) and Romero et al. (2022, table 1).

TESS observed 91 of the 180 stars listed in table 4 of Bognár & Sódor (2016), while the work of Romero et al. (2022) is based on TESS observations, therefore TESS light curves are available on all 74 new DAV stars presented in that work. Our sample altogether includes 165 DAVs with available short-cadence TESS light curves. Note that we investigated the TESS data sets up to and including sector 55 (cycle 4).

Our main goal was not to perform detailed frequency analysis of the TESS data sets of every star in our sample, but searching for possible rotationally split frequency components (preferably triplets), and using them for measuring the rotation rates of these stars.

We started with downloading all the light curves of our sample from the Mikulski Archive for Space Telescopes (MAST), and extracting the PDCSAP fluxes provided by the pre-search data-conditioning pipeline (Jenkins et al. 2016). This pipeline corrects the flux of each target to account for the contamination of nearby stars caused by the frequent crowding. Next, we corrected the light curves for long-term systematic trends, and removed outlier measurements. We divided the time strings into segments containing gaps no longer than 0.5 d. We then separately fitted and subtracted cubic splines from each segment. We used one knot point for every 200 (short cadence mode) or 1000 points (ultrashort cadence mode) to define the splines. Finally, we removed outliers with higher than 4 sigma deviation from the mean brightness. Considering that the removed trends correspond to significantly longer timescales than the DAV pulsation periods, these corrections do not affect the frequency domain of the white dwarf pulsations.

Afterwards, we analysed the corrected data sets with the command-line light-curve fitting program LCfit developed by Á. Sódor (Sodor 2012). Utilising an implementation of the Levenberg-Marquardt least-squares fitting algorithm, LCfit is capable of linear (amplitudes and phases) and non-linear (amplitudes, phases and frequencies) least-squares fittings. The program handles unequally spaced measurements, and data sets with intermittent gaps.

Finally, we inspected the obtained pulsation data. We searched for signs of regularities in the frequency spacings, preferably looking for equidistant triplets, but we also checked closely spaced frequency doublets. We accepted a frequency component as significant if its amplitude exceeded five times the local noise level in the periodogram (S/N > 5). We also checked the Lomb-Scargle periodograms produced by the LCfit program by eye in the case of stars showing probable frequency splittings. In the end, we obtained 15 stars showing frequency triplets or doublets, for further investigations.

3. Doublets and triplets

Figure 1 shows the Fourier transforms calculated by Period04 (Lenz & Breger 2005) of the 15 stars with identified frequency multiplets, while Table 1 summarises the frequencies detected in these DAVs. The frequency separations of the components are also listed, as we utilised them for deriving the rotation rates.

A plausible explanation for the observed triplet structures is that these are rotationally split frequency components of $l = 1$ modes. Knowing the frequency differences of the triplet components ($\delta\nu$), we can estimate the rotation period of the pulsator.

In the case of slow rotation, the frequency differences of the $m = -1, 0, 1$ rotationally split components can be calculated (to first order) by the following relation:

$$\delta\nu_{k,\ell,m} = \delta m(1 - C_{k,\ell})\Omega, \quad (1)$$

where the coefficient $C_{k,\ell} \approx 1/\ell(\ell + 1)$ for high-overtone ($k \gg \ell$) g-modes and Ω is the (uniform) rotational frequency.

However, as described e.g. in Hermes et al. (2017), we cannot assume that all the observed doublet and triplet frequencies are high overtone modes. For the sake of comparison with the rotation rate results presented by Hermes et al. (2017), we uniformly accepted a value of $C_{k,\ell} = 0.47$ for estimating the rotation periods for each object. Table 2 summarises the results for our 15-star sample. For the calculations of rotation rates, we utilised the average value of the frequency separations ($\delta\nu_{\text{average}}$).

As one of our goals with the presented investigations is to check the mean rotation periods for the DAVs at different masses, we also had to derive the mass values of the targets. In the case of the Romero et al. (2022) database, the masses for the stars from different sources are listed in their table 1. However, for the stars selected from the database of Bognár & Sódor (2016), only the surface gravity ($\log g$) values are available, which have to be converted to masses. For this purpose, we utilised the $\log g$–M_* relations based on the evolutionary sequences published by Bédard et al. (2020) as presented on the 'synthetic colors and evolutionary sequences of hydrogen- and helium-atmosphere white dwarfs' webpage[1].

In the followings, we comment on the individual stars we identified as rotators.

TIC0007675859. We identified a wide doublet, which is possibly a triplet with a third component somewhat below the 5 S/N level. The pulsations of the star was discovered by Romero et al. (2022). Note, that this star is one of the fastest rotator found by our investigations. We see only one candidate triplet. Follow-up

[1] http://www.astro.umontreal.ca/~bergeron/CoolingModels

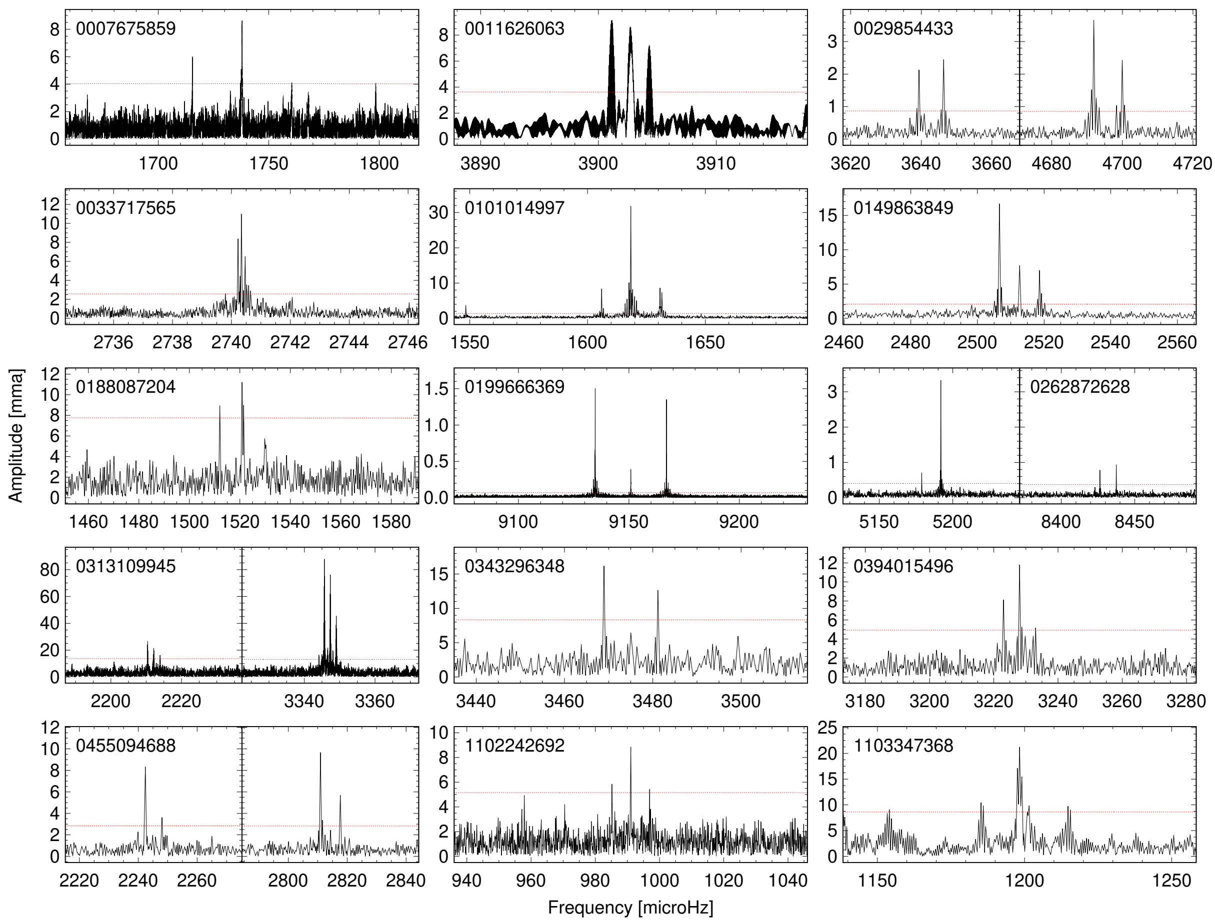

Fig. 1. Fourier transforms of the 15 stars showing doublet or triplet frequencies. Horizontal red lines denote the five signal-to-noise ratio significance levels.

observations of this star are currently ongoing from the mountain station of Konkoly Observatory, therefore, we hopefully will know more about the rotational behaviour soon.

TIC0011626063. This star is also known as GD 385. There is an unambiguous triplet in the periodogram. Kepler (1984) detected two frequencies at around $3900\,\mu$Hz, but did not find a third component. However, they have already raised the opportunity that the multiplet is the product of rotational frequency splitting.

TIC0029854433. This star is the well-known pulsator, Ross 548. We detected two doublets in the TESS data set, but considering previous literature data based on ground-based observations, we know that these are actually side components of two triplets, see e.g. Giammichele et al. (2015).

TIC0033717565. In this star we detected a triplet with frequency components close to each other. The pulsations of the star was discovered by Romero et al. (2022).

TIC0101014997. Another well-known variable, BPM 31594. It shows an unambiguous triplet. This triplet structure was discovered by ground-based observations by O'Donoghue et al. (1992), and then was confirmed by TESS observations, see Bognár et al. (2020, 2023).

TIC0149863849. Another obvious triplet emerging in the TESS periodogram. The pulsations of the star was discovered by Romero et al. (2022).

TIC0188087204. We identify a doublet in the frequency spectrum, which appears to be a part of a triplet, with a low-amplitude third frequency component. This star was also discovered by Romero et al. (2022).

TIC0199666369. It is another well-known pulsator, also known as G 226-29, the brightest known DAV star. Previous ground-based observations only showed three frequency components, see e.g. the results presented by Kepler et al. (1995). Analysis of the TESS data also confirmed this result, showing only the same triplet.

TIC0262872628. This pulsator is known by the name L 19-2. Ground-based observations revealed triplet structures in the light curve of the star, see Yeates et al. (2005). Considering the TESS data, we detect only adjacent components of these triplets as two doublets (Bognár et al. 2023).

TIC0313109945. We detected two triplets in the TESS light curve. The star was discovered by Romero et al. (2022).

TIC0343296348. The TESS data reveals a triplet structure in the periodogram. The star was discovered by Romero et al. (2022).

Table 1. List of ZZ Ceti stars with triplet or doublet frequencies found by the frequency analysis of the TESS light curves. The frequencies and the corresponding frequency separations of the components are also denoted.

Star	Frequencies of multiplets [μHz]	$\delta\nu$ [μHz]	Comments
0007675859	1715.42		
	1737.91	22.19	
	1760.42	22.51	doublet, with a low-amplitude third component
0011626063	3901.16		
	3902.75	1.59	
	3904.32	1.57	triplet
0029854433	3639.34		
	3646.31	6.97	
	4691.92		
	4699.94	8.02	two doublets, side components of triplets
0033717565	2740.34		
	2740.36	0.02	
	2740.39	0.03	triplet
0101014997	1605.95		
	1618.37	12.42	
	1630.78	12.41	triplet
0149863849	2506.60		
	2512.65	6.05	
	2518.64	5.99	triplet
0188087204	1512.05		
	1520.85	8.80	
	1529.86	9.01	doublet, with low-amplitude third component
0199666369	9134.73		
	9150.86	16.13	
	9167.00	16.14	triplet
0262872628	5178.86		
	5191.85	12.99	
	8426.32		
	8437.44	11.12	two doublets, adjacent components of triplets
0313109945	2210.42		
	2212.11	1.69	
	2213.92	1.81	
	3345.66		
	3347.36	1.70	
	3349.05	1.69	two triplets
0343296348	3468.97		
	3475.02	6.05	
	3481.15	6.13	triplet
0394015496	3223.02		
	3228.04	5.02	
	3233.02	4.98	triplet
0455094688	2242.39		
	2248.07	5.68	
	2810.92		
	2817.63	6.71	two doublets, side components of triplets
1102242692	985.19		
	991.06	5.87	
	996.91	5.85	doublet, with low-amplitude third component
1103347368	1185.24		
	1198.33	13.09	
	1214.77	16.44	triplet

TIC0394015496. Pronounced triplet in the TESS periodogram. The star was discovered by Romero et al. (2022).

TIC0455094688. This star is also known as HS 0507+0434B. We see two doublets in the TESS periodogram, but former ground-based observations revealed that these are actually the side components of two triplets (Fu et al. 2013).

TIC1102242692. We found a triplet stucture in the TESS periodogram, however, the side components are close to the significance limit.

Table 2. Rotation rates as calculated by Eq 1 and stellar masses of the 15 selected stars.

Star	$\delta\nu_{\text{average}}$ [μHz]	P_{rot} [hr]	M_* [$M_\odot$]
0007675859	22.35	6.6	0.91
0011626063	1.58	93.2	0.61
0029854433	3.7475	39.3	0.61
0033717565	0.025	5888.9	0.43
0101014997	12.415	11.9	0.61
0149863849	6.02	24.5	0.66
0188087204	8.905	16.5	0.41
0199666369	16.135	9.1	0.91
0262872628	12.055	12.2	0.62
0313109945	1.7225	85.5	0.38
0343296348	6.09	24.2	0.59
0394015496	5.00	29.4	0.61
0455094688	3.098	47.5	0.62
1102242692	5.86	25.1	0.58
1103347368	14.765	10.0	no data

TIC1103347368. We see at least one triplet in the TESS periodogram. The side components of the other possible triplet are under the significance level.

These objects are listed with their journal of observations in Table 3.

Note that in the meantime Uzundag et al. (2023) published their frequency analysis and modelling result on another ZZ Ceti star, G 29-38. TESS observed this star in sectors 42 and 56, respectively. Comparing the results of the frequency analyses of both light curves, they identified rotational frequency triplets, and also a quintuplet, from which the estimated rotation period of G 29-38 is about 1.35 ± 0.1 d. The mass of the star considering the outcome of the asteroseismic period fits is $M_* = 0.632 \pm 0.03\,M_\odot$, which is close to the spectroscopic measurements.

4. Summary and conclusions

We cannot talk about white dwarf rotation rates in the space age without mentioning the work of J.J. Hermes and his coworkers published in 2017 (Hermes et al. 2017). They collected the previous results on ground-based observations and completed it with their sample based on Kepler and K2 measurements. One of their findings was that WDs in the 0.51–0.73 solar mass range have a mean rotation period of 35 hrs with a standard deviation of 28 hrs. They also presented the rotation rates as a function of mass in their paper. Another interesting finding is that apparently the more massive WDs rotate faster, however, more observations are needed to confirm this finding.

Hermes et al. (2017) calculated all rotation periods via rotationally split pulsation frequencies, detected by ground- and space-based observations. Note that all white dwarfs presented in their paper appear to be isolated stars, so these rotation periods should be representative of the endpoints of single-star evolution.

These results inspired our work to perform a similar investigation in the TESS data. Utilising doublets we have to be careful with the interpretation of the rotation rates, as from a doublet frequency we cannot decide if these are side components or adjacent members of a triplet, or even components of a possible quintuplet or higher-order multiplet. Thus, we decided to work with triplet frequencies only. However, as a pulsation component being a member of a triplet means strict frequency constraint, we somewhat relaxed the amplitude S/N requirement for accepting the detection of some triplet members. Ground-based observations also helped to confirm whether there is a triplet in a given frequency domain or not.

Another consideration of our work was that if there was an ultrashort-cadence time series of a star, we preferred that data set, since it is expected that frequencies of ZZ Ceti stars emerge above the Nyquist limit of the 120-second sampling data sets.

Tables 4 and 5 present the comparisons of our rotation periods with the previous results and the new detections, respectively. As Table 5 shows, in the case of seven stars, it was possible to determine their rotation periods for the first time.

Our results are in agreement with the former findings that larger-mass WDs rotate faster than their lower-mass counterparts. Notably, our two fastest rotators TIC0007675859 and G 226-29 has the largest stellar masses, as shown in Fig. 2.

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Table 3. Journal of observations of the 15 DAV pulsators showing doublet or triplet structures in their TESS periodograms. *TIC* refers to the TESS Input Catalog identifier for the object, N is the number of data points after cleaning the light curve, δT is the total length of the data sets including gaps, and *Sect.* is the serial number of the sector(s) in which the star was observed. *US* and *S* denotes that we utilised the ultrashort or the short cadence mode observations, respectively. The start time in BJD is the time of the first data point in the data set. The *CROWDSAP* keyword represents the ratio of the target flux to the total flux in the TESS aperture.

Object	TIC	Start time (BJD-2 457 000)	N	δT (d)	G mag	Sect. (Cadence)	CROWDSAP
–	0007675859	2390.655	388881	405.5	16.3	40,52–54 (US)	0.29
GD 385	0011626063	2419.993	194107	376.1	15.1	41,54 (US)	0.07
Ross 548	0029854433	2115.890	91784	25.7	14.2	30 (US)	0.98
–	0033717565	2036.280	107277	353.4	16.5	27–29, 32, 35, 36, 39 (S)	0.70
BPM 31594	0101014997	2115.887	191458	54.1	15.1	30–31 (US)	0.90
–	0149863849	2361.776	106133	27.9	13.6	39 (US)	0.15
–	0188087204	2282.141	14913	23.9	16.8	36 (S)	0.38
G 226-29	0199666369	2390.654	1023148	433.6	12.3	40,41,48–55 (US)	0.98
L 19-2	0262872628	2333.857	218835	55.9	13.4	38,39 (US)	0.78
–	0313109945	2390.651	506832	378.3	18.6	40,41,47,48,53 (US)	0.08
–	0343296348	1629.139	50104	760.6	15.9	39 (US)	0.26
–	0394015496	1325.300	46191	759.4	15.8	28 (US)	0.39
HS 0507+0434B	0455094688	1437.990	16629	25.7	15.4	5 (S)	0.44
WD 1526+558	1102242692	2640.430	213467	77.1	17.1	49–51 (US)	0.93
WD 1521-003	1103347368	2698.355	39187	19.2	15.8	51 (US)	0.12

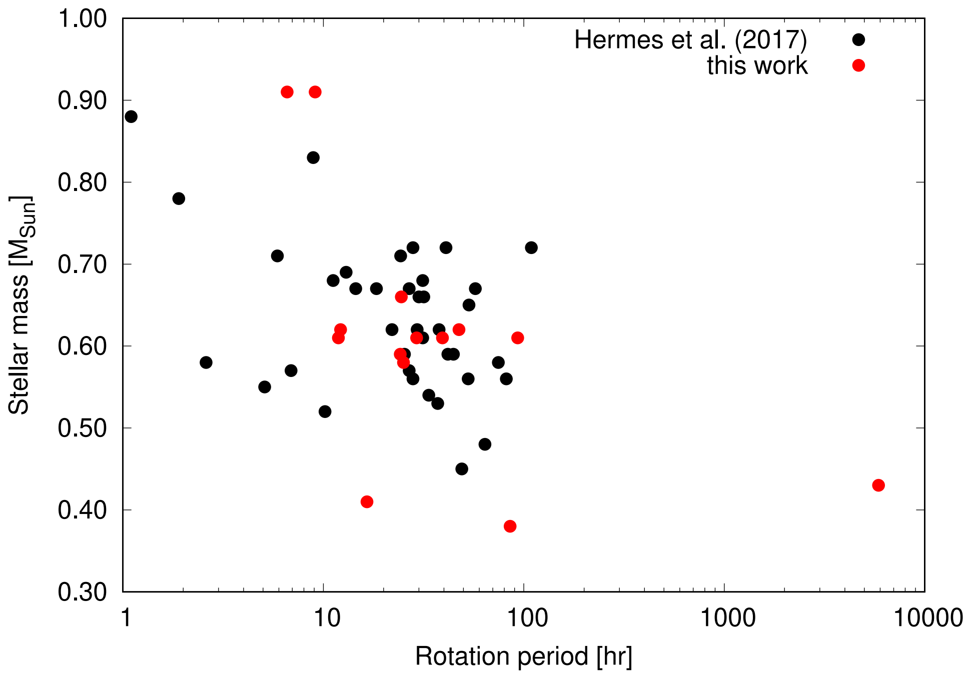

Fig. 2. Rotation periods, determined by this work, versus stellar mass from literature data, together with similar results of Hermes et al. (2017). Red dots denote our results, while black dots mark the sample of Hermes et al. (2017).

Table 4. Comparison of the rotation periods obtained by us with the results published by Hermes et al. (2017) (table 4), Romero et al. (2022) (table 8), and O'Donoghue et al. (1992).

Star	P_{rot} [hr]	Reference	This work [hr]
0007675859	5.2	Romero et al. (2022)	6.6
0029854433 (Ross 548)	37.8	Hermes et al. (2017)	39.3
0101014997 (BPM 31594)	11.6	O'Donoghue et al. (1992)	11.9
0199666369 (G 226-29)	8.9	Hermes et al. (2017)	9.1
0262872628 (L 19-2)	13.0	Hermes et al. (2017)	12.2
0343296348	24.5	Romero et al. (2022)	24.2
0394015496	29.8	Romero et al. (2022)	29.2
0455094688 (HS 0507+0434B)	40.9	Hermes et al. (2017)	47.5

Table 5. Stars not listed neither in Hermes et al. (2017) (table 4) nor Romero et al. (2022) (table 8).

Star	P_{rot} [hr]
0011626063	93.2
0033717565	5888.9
0149863849	24.5
0188087204	16.5
0313109945	85.5
1102242692	25.1
1103347368	10.0