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Maia variables and other anomalies among pulsating stars

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ABSTRACT

Using data from *TESS* sectors 1–58, 479 mid-B stars with high frequencies (Maia variables) have been identified. The distribution of projected rotational velocities shows that the rotation rates of Maia variables are no different from those of SPB stars. Rapid rotation is thus ruled out as a possible cause of high frequencies. In fact, there are many Maia stars with frequencies exceeding 60 d^{-1}, which cannot be explained by rapid rotation. It is emphasized that there is a serious problem with current pulsational models. Not only are the models unable to account for the Maia stars, they fail to account for the fact that SPB and γ Dor variables form one continuous instability strip from the cool end of the δ Sct region to the hot end of the β Cep instability strip. Likewise, there is continuity between the distributions of δ Sct, Maia and β Cep variables. These observations suggest an interplay between multiple driving mechanisms rather than separate dominant mechanisms for each variablity group.

Key words: stars: early-type – stars: oscillations

1 INTRODUCTION

The Maia variables are defined as pulsating stars with high frequencies which are too hot to be classified as δ Scuti stars and too cool to be β Cephei variables. These anomalous pulsating stars have been suspected for many decades following a report by Struve (1955) of short-period variations in the star Maia, a member of the Pleiades cluster. Struve et al. (1957) later disclaimed the variability. It is now known from the *K2* space mission that Maia itself is a rotational variable with a 10-d period (White et al. 2017) and no sign of high frequencies. Recently, however, Monier (2021) has reported rapid light variations in the far ultraviolet.

In the past, ground-based observations by McNamara (1985), Lehmann et al. (1995), Percy & Wilson (2000) and Kallinger et al. (2004) have suggested that Maia variables might exist, even though pulsational models do not predict pulsational instability in these stars. From *CoRoT* observations, Degroote et al. (2009) found several low-amplitude B-type pulsators between the SPB and δ Sct instability strips, with a very broad range of frequencies and low amplitudes. More evidence for these anomalous variables emerged when Mowlavi et al. (2013) and Mowlavi et al. (2016) observed many rapidly rotating mid-B stars in the open cluster NGC 3766 which pulsate with frequencies as high as 10 d^{-1}. Several B stars which qualify as Maia variables have also been detected in the *Kepler* field (Balona et al. 2015, 2016). Using *TESS* data, Balona & Ozuyar (2020) identified 131 Maia candidates. More recently Gaia Collaboration et al. (2022) found a population of Maia stars using *Gaia* photometry, which they interpret as modified frequencies resulting from rapid rotation.

From *TESS* observations, Balona & Ozuyar (2020) found that stars pulsating at frequencies higher than about 5 d^{-1} are common among all B stars, including late-B and early A stars. Furthermore, there are no distinct regions of instability as expected from the models. The β Cep variables merge smoothly with Maia stars which merge smoothly into δ Sct stars. The same occurs for the low-frequency pulsators. SPB stars are found all along the B-type main sequence and continue into the A star region where they merge with the hot γ Dor variables. Uncertainties in effective temperature obviously contribute to the blurring of distinct instability regions, but the large numbers of early-type pulsating stars discovered by *TESS* still do not show the concentration of stars in their respective domains of instability as predicted from the models. This is evident from Fig 2 of Balona & Ozuyar (2020).

When observed equator-on, rapid rotation lowers the apparent effective temperature due to gravity darkening, shifting the star to cooler temperatures in the H–R diagram. A rapidly-rotating β Cep star could, for example, be mistaken for a Maia variable. Furthermore, gravito-inertial modes in moderate to fast rotators may have frequencies higher than normal. Thus a rapidly-rotating SPB star may also be mistaken for a Maia variable. Salmon et al. (2014) investigated these effects and concluded that their models could reproduce the observations of Mowlavi et al. (2013,

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2016). It is therefore important to investigate whether the Maia variables are truly a different class or simply rapidly-rotating β Cep or SPB stars.

One way to test this proposal is to compare the rotation rate of Maia stars with the rotation rate of SPB stars using the respective distributions of projected rotational velocities. Such a test was performed by Balona & Ozuyar (2020) using 41 Maia stars, but no significant difference could be found. However, the sample of Maia stars is rather small for a definitive conclusion.

Daszyńska-Daszkiewicz et al. (2017) considered three hypothesis for the Maia variables: rapidly rotating stars with underestimated masses, rapidly rotating stars with non-standard opacities and slowly rotating stars with non-standard opacities. While there are indications that one or more of these hypotheses might be able to explain the observations, no definite conclusions can be made at this stage.

If observations show that there is a distinct difference in rotation rate between Maia variables and the SPB stars, then the Maia variables do not deserve a separate class. On the other hand, if no difference in rotation rate is found, then the pulsational instability remains unexplained.

In this paper, we use *TESS* data from Sectors 1–58 to identify new Maia candidates as well as other pulsating A and B stars. Full details of how the search was conducted, how estimates of effective temperature were obtained and the sources of projected rotational velocities are described in Balona (2022a).

2 NEW MAIA VARIABLES

The *TESS* mission has been observing the whole sky and obtaining light curves for thousands of stars with two-minute cadence. This wide-band photometry has been corrected for long-term drifts using pre-search data conditioning (PDC, Jenkins et al. 2010). The author has been engaged in a project to classify the variability of stars hotter than about 6000 K. Results of the classification of over 120000 stars, together with their effective temperatures, $T_{\rm eff}$, luminosities, $\log L/L_\odot$, and projected rotational velocities, $v \sin i$, are reported in Balona (2022a). The values of $\log L/L_\odot$, are from Gaia DR3 parallaxes (Gaia Collaboration et al. 2016, 2018).

During this process, many stars were detected which normally would be classified as δ Sct variables, but with effective temperatures in the range 10000–18000 K. These were classified as Maia variables if frequency peaks higher than $\nu_{\rm min} = 5\,{\rm d}^{-1}$ were detected. The choices of $T_{\rm eff}$ range and $\nu_{\rm min}$ are arbitrary, but are guided by the fact that most SPB stars have frequencies not much higher than about $3\,{\rm d}^{-1}$. The full list of Maia stars (and other variables) is to be found in Balona (2022a).

The choice of $\nu_{\rm min}$ is not too important. The use of $\nu_{\rm min} = 5\,{\rm d}^{-1}$ leads to 479 Maia stars, while $\nu_{\rm min} = 10\,{\rm d}^{-1}$ still leaves 347 Maia stars. This is because most Maia variables have frequencies higher than $10\,{\rm d}^{-1}$.

The actual frequency distribution in Maia variables is shown in Fig. 1. This figure was constructed from frequency peaks with signal-to-noise ratio S/N > 5.0 irrespective of amplitude. Frequencies between 20–50 $\rm d^{-1}$ are quite common. It is clear that such high frequencies in mid-B stars are incompatible with current models. In their models of rapidly rotating SPB stars, Salmon et al. (2014) do not find any instance of pulsations with frequencies higher than $10\,{\rm d}^{-1}$. This is already an indication that rapid rotation should be discounted as an explanation for the Maia variables.

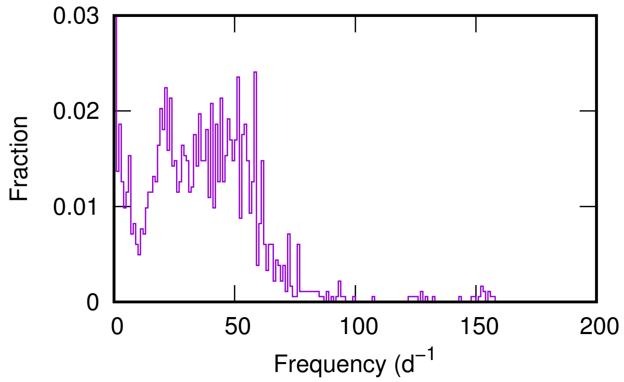

Figure 1. Frequency distribution in Maia stars.

Note that there are quite a few Maia stars which pulsate at very high frequencies. In fact, they would probably be mistaken for roAp stars, except that they are of type B and non-peculiar. The roAp stars themselves can no longer be considered a separate class (Balona 2022b).

Because stars with frequencies higher than $50\,{\rm d}^{-1}$ are of special interest, they are listed in Table 1. As described in Balona (2022a), the class MAIAH is given if the highest frequency peak lies in the range 50–60 $\rm d^{-1}$, while if it is higher than $60\,{\rm d}^{-1}$, the notation MAIAU is used. This does not indicate a separate class, but is a convenient way of identifying Maia stars with these peculiar high frequencies.

3 ROTATION

As already mentioned, rotation affects the apparent location of the star in the H–R diagram due to equatorial gravity darkening and introduces new gravito-inertial modes with moderately high frequencies (Salmon et al. 2014). Gravity darkening will occur in all stars, whether pulsating or not. Therefore no bias is introduced in comparing the rotational velocities of Maia stars with main sequence stars in the same effective temperature range.

The distribution of projected rotational velocities, $v \sin i$, for 167 Maia stars and for 6547 main sequence stars in the temperature range ($10000 < T_{\rm eff} < 18000$) is shown in Fig. 2. Also shown in the same figure is a comparison with 306 SPB stars in the same temperature range. The conclusion is clear: Maia stars are not rapidly rotating SPB stars. The rotation rates of both Maia and SPB stars are the same as in normal main sequence stars.

4 DISTRIBUTION OF MAIA STARS

Fig. 3 shows the number density of δ Sct, Maia and β Cep as well as γ Dor and SPB variables as a function of effective temperature. This figure was constructed by counting the number of stars of a particular variability class within a small range of effective temperature (0.02 dex in $\log T_{\rm eff}$)

Table 1. List of Maia variables with frequencies in excess of $\nu > 50\,\mathrm{d}^{-1}$. These are classified as MAIAH if the maximum frequency $\nu_{\max} < 60\,\mathrm{d}^{-1}$ and as MAIAU if $\nu_{\max} > 60\,\mathrm{d}^{-1}$. The number of frequencies greater than $50\,\mathrm{d}^{-1}$, N, is also shown as well as the effective temperature, T_{eff} (in K) and the luminosity, $\log \frac{L}{L_\odot}$. The last column is the spectral type.

TIC	Var Type	$\nu_{\max}$	N	T_{eff}	$\log \frac{L}{L_\odot}$	Sp. Type
11218613	MAIAU	72.47	36	11300	1.20	B9
27804376	MAIAU	60.52	2	11300	1.48	B9/A1IV/V
30965889	MAIAU	60.97	1	10174	1.14	A0
51172021	MAIAU	63.37	9	12600	1.30	B8
52831545	MAIAU+ROT	66.10	17	10053	1.16	A2
52844490	MAIAH	58.35	7	10047	1.14	A2
74214081	MAIAU	93.77	1	11273	1.35	A0V
81802203	MAIAU+ROT	77.11	8	11679	1.28	A1/2V
90362296	MAIAH	58.84	1	11590	1.29	A2IV
92736909	MAIAU	62.11	2	10695	1.20	A2V
92780981	MAIAU	66.63	2	11300	1.40	B9
105262398	MAIAH	51.47	2	10466	1.29	A0
105889061	MAIAU	60.58	3	11300	1.32	B9
105896213	MAIAU	73.45	2	11300	1.37	B9
124494015	MAIAU	132.45	21	11300	1.32	B9.5V
132923245	MAIAU+FLARE	78.01	1	11300	1.44	B9
134860590	MAIAU+ROT	61.33	10	10928	1.23	A2V
134861413	MAIAU	64.78	7	11230	1.29	A3
143934120	MAIAU	60.10	3	12600	1.44	B8/A0
144710346	MAIAU	67.13	4	10460	1.16	A3
149351763	MAIAH	60.57	7	10617	1.02	A3
158735231	MAIAH	66.03	6	11300	1.22	B9
174420083	MAIAU	68.91	6	11300	1.09	B9.5V
174866532	MAIAH	51.87	1	10288	1.19	A2
182910557	MAIAU	60.43	1	10063	1.20	A3/5
183522571	MAIAU	76.18	5	10799	1.45	A1/2IV/V
193349473	MAIAH	54.70	1	11110	1.03	A2
202121249	MAIAH	55.11	4	11300	1.30	B9:V
213044863	MAIAH	50.29	1	12600	1.36	B8
220313579	MAIAU	61.50	9	10014	1.35	A2/3
238641255	MAIAU+ROT+FLARE	65.75	25	10137	1.21	A1V
246193995	MAIAH	58.86	7	14084	1.17	A0
276153207	MAIAU	68.66	9	10391	1.03	A0
282742134	MAIAH+ROT	59.99	11	11300	1.25	B9
284935176	MAIAH	72.21	3	11300	1.32	B9
286344698	MAIAU	72.73	1	10518	1.30	A2V
295643102	MAIAU	61.57	5	12600	1.40	B8
299123331	MAIAH	52.29	1	10029	1.44	A0
299486936	MAIAH	51.23	1	10740	1.12	A5
300493372	MAIAU	66.70	3	11220	1.38	A0
304570125	MAIAU	123.59	11	10523	1.16	A0
316293394	MAIAH	58.49	11	12600	1.43	B8/9IV/V
329621207	MAIAU	127.28	13	12600	1.48	B8
336435989	MAIAU	70.85	6	14129	1.02	A2
337735826	MAIAU	157.24	56	11360	1.09	A0
351193224	MAIAU	61.20	1	11300	1.03	hF0.5kA2.5mA2.5V
355775097	MAIAU	75.57	3	10744	1.33	A3/5IV:
362653719	MAIAH	52.64	1	11300	1.36	B9
363917122	MAIAH	52.91	1	10407	1.45	A2/3V
365756191	MAIAH	57.27	10	12600	1.43	B8
379937109	MAIAU	93.33	35	11300	1.39	B9
383113632	MAIAH	51.20	1	10125	0.93	
388688820	MAIAU	67.16	14	10089	1.26	A3
400022015	MAIAU	73.87	5	16022	1.02	A5
401785909	MAIAU+ROT	60.94	5	10638	1.24	A2
415545142	MAIAH	58.72	2	10184	1.29	A2
416175259	MAIAU	63.26	6	12600	1.17	B8
427399308	MAIAH	55.39	1	11300	1.23	B9
427718251	MAIAU	65.43	6	12600	1.19	B8
440638544	MAIAU	81.15	6	10561	1.18	A0
447086833	MAIAH	50.38	1	11300	1.45	B9/A1V
453542508	MAIAH	50.46	1	12600	1.42	B8
458406481	MAIAH	57.70	1	11300	1.14	B9
462199867	MAIAH	58.36	2	10610	0.97	A0
462633799	MAIAH	51.98	2	11194	1.05	A3
462781894	MAIAH	57.35	5	14437	1.18	A3
464740586	MAIAU	67.45	2	11631	1.12	A2
465777818	MAIAU	61.76	13	11007	0.98	A2

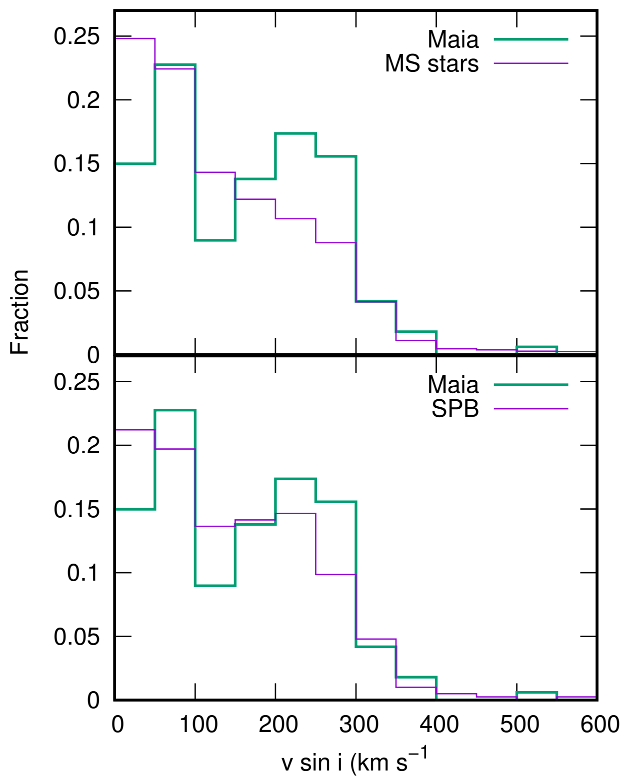

Figure 2. Top panel: the distribution of projected rotational velocity, $v \sin i$, for Maia variables (heavy green histogram) and for main sequence stars in the same temperature range. The bottom panel shows the distributions for Maia and SPB stars in the same temperature range.

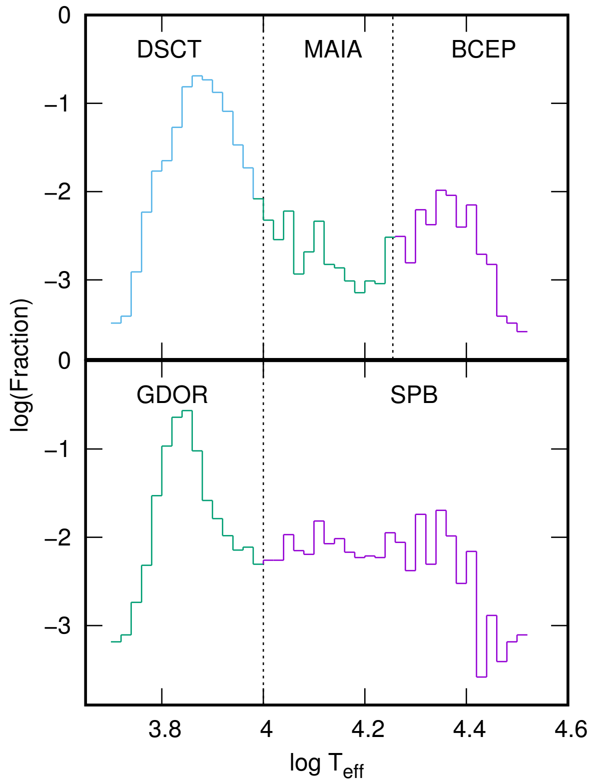

Figure 3. The distribution of δ Sct, Maia and β Cep variables (top panel) and the γ Dor and SPB stars (bottom panel).

within the main sequence band. The main sequence band is defined by $-0.5 < \Delta \log L/L_\odot < 1.5$, where $\Delta \log L/L_\odot$ is the luminosity above the zero-age main sequence.

The figure illustrates the problem pointed out by Balona & Ozuyar (2020): there are no distinct instability regions among hot stars. There is no doubt that uncertainty in the effective temperature is responsible for much of the blurring. The typical uncertainty in $\log T_{\rm eff}$ is about 0.02 dex (which is the bin size in the figure), so it seems unlikely to be the sole reason. The figure also appears to suggest that Maia stars are not a separate class, but an extension of the δ Sct variables to mid-B spectral types. It also shows that the γ Dor and SPB variables form a continuous group, quite unlike predictions from stellar models.

Pulsations in δ Sct stars are driven by the opacity κ mechanism operating in the He II zone of partial ionization. This mechanism does not work for effective temperatures as high as $T_{\rm eff} \approx 16000$ K, which, judging from Fig. 3, is the highest temperature for pulsation in Maia stars. According to the latest models, pulsational driving of low degree modes in δ Sct stars does not occur for $T_{\rm eff} > 9000$ K (Xiong et al. 2016). On the other hand, the mechanism responsible for the SPB variables is not capable of driving the high frequencies, even taking rapid rotation into account. It is clear that an unknown source of pulsational driving is at work.

5 CONCLUSIONS

From *TESS* light curves, 479 stars have been identified as Maia variables. These are defined as main sequence stars with $10000 < T_{\rm eff} < 18000$ K and frequencies greater than 5 d^{-1}. By comparing the projected rotational velocities of the stars with those of main sequence stars or SPB stars in the same temperature range, it is shown that Maia stars are not rapidly rotating. Therefore the idea that the high frequencies in Maia stars are due to rapid rotation (Salmon et al. 2014) is refuted. Moreover, such an idea cannot explain frequencies of over 50 d^{-1} seen in some Maia stars.

It is also demonstrated that there is no clear separation in effective temperature between δ Sct and Maia variables or between β Cep and Maia variables. Indeed, as Fig. 3 shows, there is no clear separation between any variability group among early-type stars, as already pointed out in Balona & Ozuyar (2020). While uncertainties in $T_{\rm eff}$ may be partly responsible for the blurring of instability regions, it seems unlikely that this is the sole cause. There is clearly something wrong with current pulsation models. Since the models cannot explain visible pulsations on the stellar surface, it is difficult to place much value on results derived from unseen internal pulsations.

It is possible that there is an interplay of different mechanisms which vary in driving ability with effective temperature. The discovery that starspots are pervasive along the main sequence (Balona 2022c) is relevant. This indicates that A and B stars have a complex structure in the upper layers which has not been taken into account in the models. The resulting changes in physical parameters will most likely to lead to changes in pulsational properties of the models.

To resolve these issues requires revised pulsational modeling of A and B stars. In order to understand the roAp-like frequencies in some mid-B stars (Table 1), modes of high degree should receive particular attention. However, this cannot be done until we have a better understanding of the upper stellar layers. Therefore, an in-depth study of tye causes of rotational light modulation in A and B stars is required.

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DATA AVAILABILITY

All data are incorporated into the article is available though the author and described in Balona (2022a).

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