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Caught in the Act: Observations of the Double-mode RR Lyrae V338 Boo during the Disappearance of a Pulsation Mode

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Abstract

New results on the behavior of the double-mode RR Lyrae V338 Boo are presented. The Transiting Exoplanet Survey Satellite (TESS) observed this star again in 2022, and an observing campaign of the American Association of Variable Star Observers (AAVSO) was completed after the TESS observations as a follow-up. We find that the first overtone pulsation mode in this star completely disappears during the TESS observing window. This mode reappears at the end of the TESS observations, and the AAVSO observing campaign shows that in the months that followed, the first overtone mode was not only present but was the dominant mode of pulsation. This star, and potentially others like it, could hold the key to finally solving the mystery of the Blazhko effect in RR Lyrae.

Unified Astronomy Thesaurus concepts: RR Lyrae variable stars (1410); RRd variable stars (1876); Pulsating variable stars (1307); Light curves (918); Space telescopes (1547)

1. Introduction

1.1. Background

Pioneering work in the late 19th century using the new technique of photography led to the discovery of a bright (seventh magnitude) variable star in the constellation of Lyra by Williamina Fleming (E. C. Pickering 1901) that was designated RR Lyrae. This star became the archetype of a distinct class of variable star identified in old stellar populations. S. I. Bailey (1902) subclassified RR Lyrae into three types (*a*, *b*, and *c*) that were simplified into two types that are still in use today: *ab* (RRab) and *c* (RRc). These are now believed to be evolved He-core burning, low-mass stars in the instability strip of the Hertzsprung–Russell diagram with radial pulsations in the fundamental (RRab) and first overtone (RRc) modes (more detail, and additional references, can be found in H. A. Smith 1995; M. Catelan & H. A. Smith 2015). It was noted early on that some RRc types had a scatter not explainable by observational error. It was not until much later, however, that changes in the light curve due to mode mixing of the fundamental and first overtone radial pulsation modes were found in AQ Leo (A. N. Cox et al. 1980) and RR Lyrae in the globular cluster M15 (A. N. Cox et al. 1983). This subclass of double-mode pulsators, which simultaneously pulsate in both the fundamental and first overtone modes, is classified as type *d* (RRd). The comprehensive review of pulsation theory up until that point by R. F. Christy (1966) set the stage for H. E. Jørgensen & J. O. Petersen (1967) to recognize that double-mode pulsations could be important probes of the physical properties of these stars. Then J. O. Petersen (1973) introduced the diagram (later named after him) that allows a mass estimate of double-mode pulsators. RRd stars in particular were used to test differences between stellar evolution and stellar pulsation models using opacities in stellar interiors (A. N. Cox 1991) and to improve and verify nonlinear stellar pulsation models that include time-dependent turbulent convection (M. U. Feuchtinger 1998). More recently, luminosities of RRd stars from models and observations were compared (G. Kovacs & B. Karamiqucham 2021), which may help resolve the current so-called "Hubble tension" by using Population II stars (R. L. Beaton et al. 2016).

Other multiperiodic behavior has been identified among the RR Lyrae variables. The Blazhko effect, a periodic modulation of the primary light cycle, was identified in RRab stars by S. Blažko (1907) and H. Shapley (1916), and was later identified in RRc type stars. The Blazhko period is often tens of days long, and the physical mechanism causing this behavior remains uncertain, making the Blazhko effect one of the longest unanswered questions in all of astrophysics. With the unique insight available with RRd type stars, however, any of these variables exhibiting the Blazhko effect are much more interesting and important and could hold the key to solving this more than century-old puzzle.

1.2. V338 Boo

The RRd star V338 Boo has been studied for almost two decades now, and with each set of observations, there are new and interesting results.

The work of L. Oaster et al. (2006) showed that the period ratio of the first overtone to fundamental modes was normal for an RRd ($P_1/P_0 = 0.743$) but the fundamental mode amplitude was twice as large as the first overtone. Follow-up observations that were published 4 (D. A. Hurdis & T. Krajci 2010) and 6 (D. A. Hurdis & T. Krajci 2012) yr later showed that the amplitude ratio of the two pulsation modes was changing over time.

In our original paper (K. Carrell et al. 2021), hereafter C21, we presented Transiting Exoplanet Survey Satellite (TESS; G. R. Ricker et al. 2015) observations of V338 Boo from 2020 (Sectors 23 and 24). These observations showed that this star was actually undergoing changes in the amplitudes of its pulsation modes over the course of tens of days, and we were able to explain what was seen from earlier, ground-based, data. The survey strategy of TESS is such that most targets are reobserved every other year, which was the case for V338 Boo—it was observed again by TESS in Sectors 50 and 51, which correspond to 2022 March 26 to April 22 and 2022 April 22 to May 18, respectively.

Because we knew this star would be observed again by TESS in 2022, we were able to plan a campaign through the American Association of Variable Star Observers (AAVSO) to extend the baseline of observations and verify what was seen in TESS data.

In the following, we will describe the newer TESS observations (Section 2.1), the follow-up observations by AAVSO observers (Section 2.2), and the new behavior for V338 Boo (Section 3). In the end, we will describe our conclusions and discuss what they might mean (Section 4).

2. Data

2.1. TESS Observations in Sectors 50 and 51

In C21 we presented results from TESS Sectors 23 and 24, which occurred from 2020 March 18 to May 13. The results from this timeframe showed that V338 Boo started as a normal RRd star, with the first overtone mode having a higher amplitude than the fundamental mode. Over the course of those observations, however, the fundamental mode grew by a factor of 4–5, becoming the dominant mode in the later part. The first overtone mode decreased slightly, changing by less than a factor of 2. What was unknown in C21 was how this star behaved after this observational window.

An issue not encountered with the Sector 23 and 24 data was scattered light affecting the full-frame images (FFIs). As can be seen in Figure 1, part of the Sector 50 data suffered from visible bands as a background in the image. This is a well-known problem caused by the reflective metal straps on the backs of the CCDs (see Section 6.6.1 of R. Vanderspek et al. 2018). In Sector 50 this banding structure only appeared in a subset of the images but caused us to change our background subtraction process. Our solution was to use fixed regions of the images for the aperture and background, instead of using pixels above or below a certain threshold in the entire cutout image. The aperture used for flux extraction can be found in the centers of the images in Figure 1, and the areas used for background are the rectangular areas above and below the aperture. Sector 51 did not suffer from this banding effect, but we used the same definitions for the aperture and background for consistency.

Other than this change in the definitions of the aperture and background, the same procedures were used as in C21. The `ATARRI` package (K. W. Carrell 2021) was used for an initial analysis, `search_tesscut` (C. E. Brasseur et al. 2019) from the `lightkurve` python package (Lightkurve Collaboration et al. 2018) was used to download FFI data, and a frequency analysis was done using `Period04` (P. Lenz & M. Breger 2005).

The extracted light curve from TESS Sectors 50 and 51 can be found in Figure 2. This figure is the same as Figure 1 from C21 but for the newer sectors of data. A comparison between the figures shows that the last orbit of Sector 24 looks very similar to the first orbit of Sector 50 in both the light-curve shape and the frequency analysis.

2.2. AAVSO Follow-up Observations

In anticipation of the newer TESS results for V338 Boo, and in order to see the behavior of this star after the TESS observing window, an alert was issued through the AAVSO. Alert Notice 786 (issued 2022 July 12) asked the AAVSO community to observe this star so that we could extend the observations and analysis from TESS.

In total, 9478 individual brightness measurements were submitted by 23 different observers between 2022 July 12 and 2022 August 14. Out of that total, there were 6234 quality measurements (errors <0.025 mag) in the V band by 20 different observers. These observers and their contributed number of measurements and observing nights are listed in Table 1.

3. Results

3.1. TESS

As can be seen in Figure 2, there is a definite change in both the light-curve shape and frequency analysis of different portions of the light curve as observed by TESS in Sectors 50 and 51. In particular, in Sector 51 it appears that the first overtone mode pulsation has completely disappeared from the frequency analysis.

We examined Sector 51 data in more detail to see if the first overtone mode completely disappears, or just becomes very small. To do this, we analyzed 5 day segments of data and stepped forward by 2.5 days. Figure 3 shows a timeframe around the smallest peak of the first overtone mode. In the first 5 day window (upper left panel of Figure 3), which corresponds to a TESS Julian date (TJD = JD - 2457000) window of 2695.28–2700.27, there is still evidence of the first overtone mode peak with an amplitude of about 11 mmag. Ten days later (lower left panel of Figure 3) this pulsation mode is completely gone—there is no obvious peak in the frequency analysis. Subsequent 5 day windows see the first overtone mode reappear and grow in size. This means that for a brief period of time, only a few days at most, around a TJD

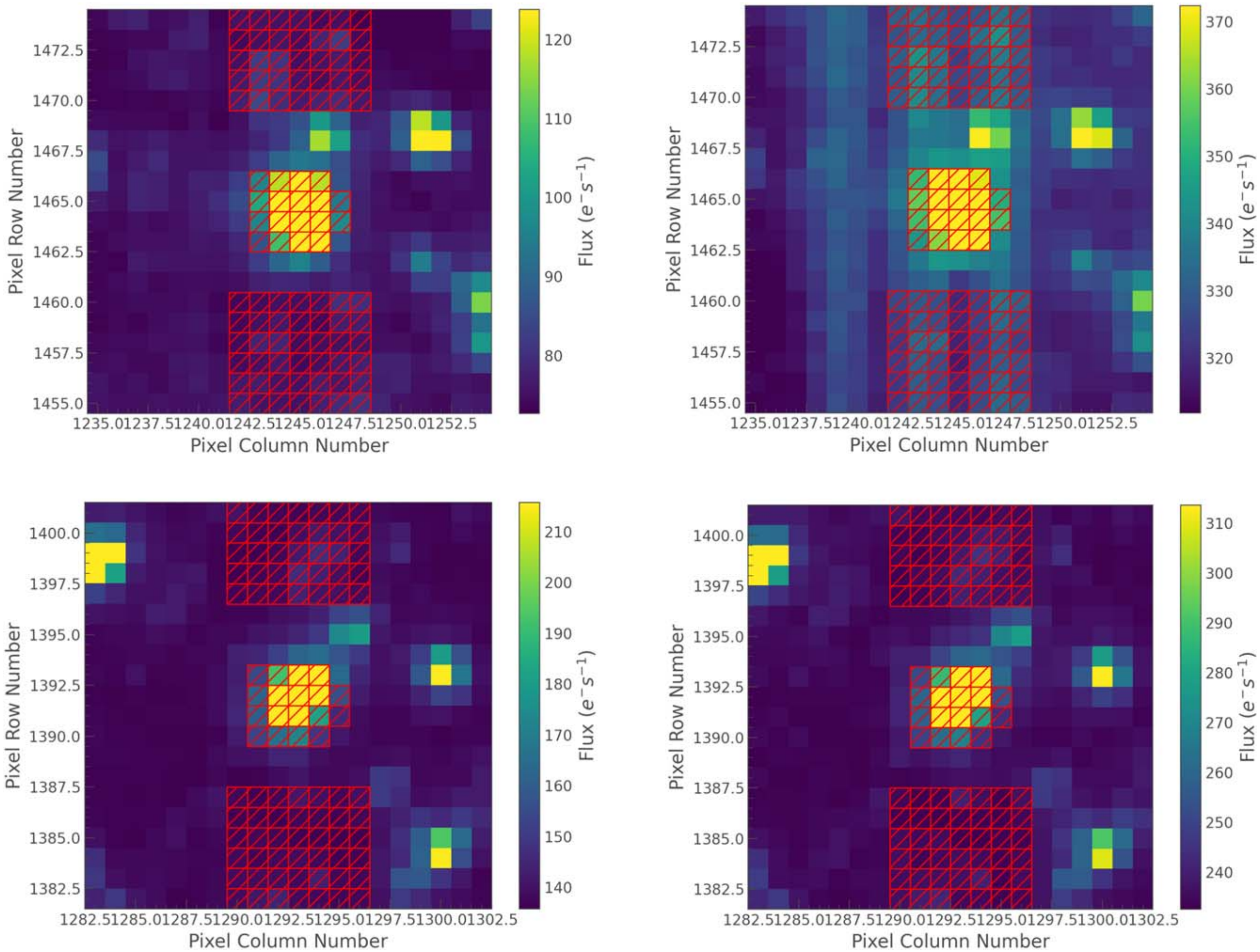

Figure 1. FFIs from Sector 50 (upper panels) and 51 (lower panels). Apertures used for flux extraction are the areas marked in red in the centers of the images. Areas used for background estimation are the rectangular regions above and below the aperture. The upper right panel is an example of an image from Sector 50 where a banded structure can be seen in the background caused by scattered light and the reflective metal straps on the backs of the CCDs.

of about 2707, V338 Boo was not pulsating in the first overtone mode.

In C21 we saw an increasing fundamental mode and a decreasing first overtone mode in this star, but the TESS observations ended before the maximum (minimum) in the change was reached. In this data, however, we cross that extreme point in the transient behavior and see that the first overtone mode does not just reach some minimum pulsation amplitude, it disappears altogether. Although there has been previous evidence of stars switching their pulsation modes from RRd to RRab or vice versa (see, e.g., J. Kaluzny et al. 1998; V. Goranskij et al. 2010; I. Soszyński et al. 2014a, 2014b; A. J. Drake et al. 2014; R. Poleski 2014), this is the first time this process has been seen in real time.

In Figure 4 we show the amplitude of the peaks in the frequency analysis as a function of time. This procedure is the same as in C21 with the new data—we analyze 5 day windows, shifting by 2.5 days through both sectors of data. While in C21 there seemed to be a monotonic increase in the fundamental mode amplitude, in Figure 4 we see that this amplitude reaches a peak at a TJD of about 2695 and then begins to decrease.

Similarly, we see that the first overtone mode in the newer data decreases, reaching a minimum value before starting to increase. However, as discussed above, this minimum is reached approximately 10 days later. In the upper left panel of Figure 4, the first overtone mode amplitude never reaches exactly zero because we find the largest amplitude in a narrow frequency range centered on the known pulsation frequencies, so at the minimum we are measuring noise in the analysis.

By comparing Figures 1 and 3 of C21 with Figures 2 and 4 here, it seems as if the behavior seen in V338 Boo is not just transient in nature, but is periodic. The light-curve shape and frequency analysis of the second orbit of Sector 24 looks very similar to the first orbit of Sector 50. The second orbit of Sector 24 started on 2020 February 29, and the first orbit of Sector 50 started on 2022 March 26, which is a difference of 697 days (inclusive). In Figure 5 we show the trends in the amplitudes of the different modes of Sectors 50 and 51, along with Sectors 23 and 24 shifted by 697 days.

There is excellent agreement between the amplitudes in Sectors 24 and 50 for the main pulsation modes, but also for their harmonics. Additionally, the two trends match up extremely well. The fact that the exact difference between the starts of Orbit 2 of Sector 24 and Orbit 1 of Sector 50 gives a shift in time that matches the periodic behavior of V338 Boo is purely coincidental.

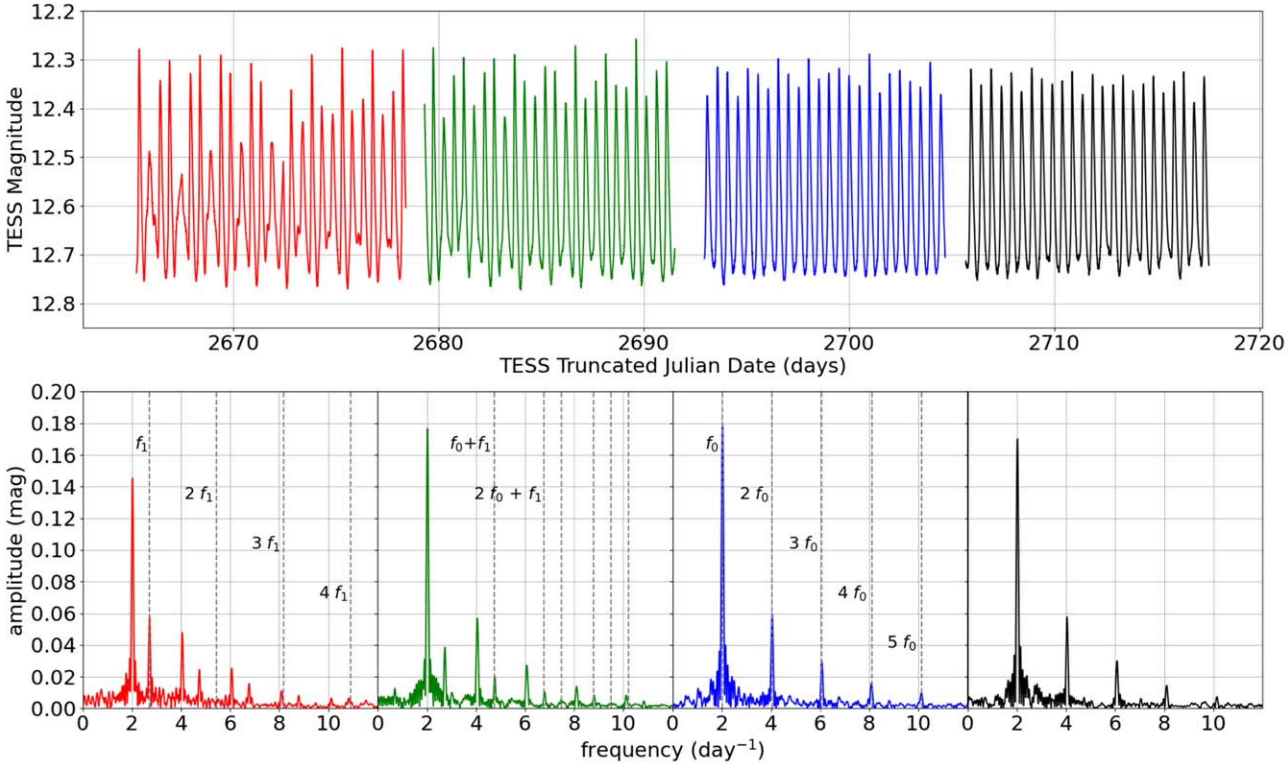

Figure 2. The upper panel shows the full light curve of V338 Boo from Sectors 50 (red and green) and 51 (blue and black) from TESS FFIs. The lower panels are a frequency analysis of the color-coded segments from the upper plot. Dashed lines and text label the locations of various peaks, with f_0 and f_1 corresponding to the fundamental and first overtone frequencies, respectively.

Table 1
A List of the Number of Individual *V* Magnitude Measurements and Number of Different Nights Observed by Each of the AAVSO Observers that Contributed in the Summer of 2022 to AAVSO Alert Notice 786

Observer Code	# of *V* Meas.	# of Nights
PDM	1105	21
HGAG	851	8
BSM	387	7
SFV	267	7
NKEA	255	6
LDRB	374	5
ATE	1017	4
VTY	234	4
MFAA	170	4
SABB	159	4
RRO	95	4
BMN	483	2
MZK	333	2
SAH	230	2
AANF	83	2
GALF	43	2
GCHB	80	1
CCHD	60	1
MMAO	7	1
BDQ	1	1

3.2. AAVSO

As mentioned in Section 2.2, Alert Notice 786 was sent out to the AAVSO community on 2022 July 12, and the first observations for this alert were taken that night. These observations were critical because the TESS observations showed that the first overtone mode completely disappeared for a brief period, but was again seen at the end of Sector 51. It was unknown, however, if the first overtone mode continued to increase in amplitude, or if it remained very small. The last day of observations of Sector 51 was 2022 May 6, so the AAVSO observing campaign began two months after this.

There were 11 AAVSO observers who took brightness measurements in the *V* band of V338 Boo for Alert Notice 786 on 4 or more nights during the campaign. Importantly, observer PDM submitted over 1100 observations on 21 different nights, which served as a comparison for several of the other data sets. We combined data from observers with 4 or more nights of observations to do a frequency analysis of V338 Boo over 34 days in the summer of 2022, which is similar in length to a single TESS sector. The observations of HGAG were shifted by +0.24 mag and the observations of ATE were shifted by +0.04 mag to match the observations of the other observers. The results of the frequency analysis are shown in Figure 6. During this timeframe, the first overtone mode pulsation is again dominant, similar to the beginning of Sector 23 (C21).

Because of the amount and duration of the AAVSO campaign observations, we were also able to split the sample up to look for trends in the amplitude ratios of the fundamental to first overtone modes. We looked at three "halves" of the data—the first half, the second half, and the middle half (half the observing window centered in the middle of the observations). While the overall AAVSO data shows that the first overtone mode is dominant (see Figure 6), we also see in Figure 7 that the amplitudes of the two pulsation modes are changing in that data set as well.

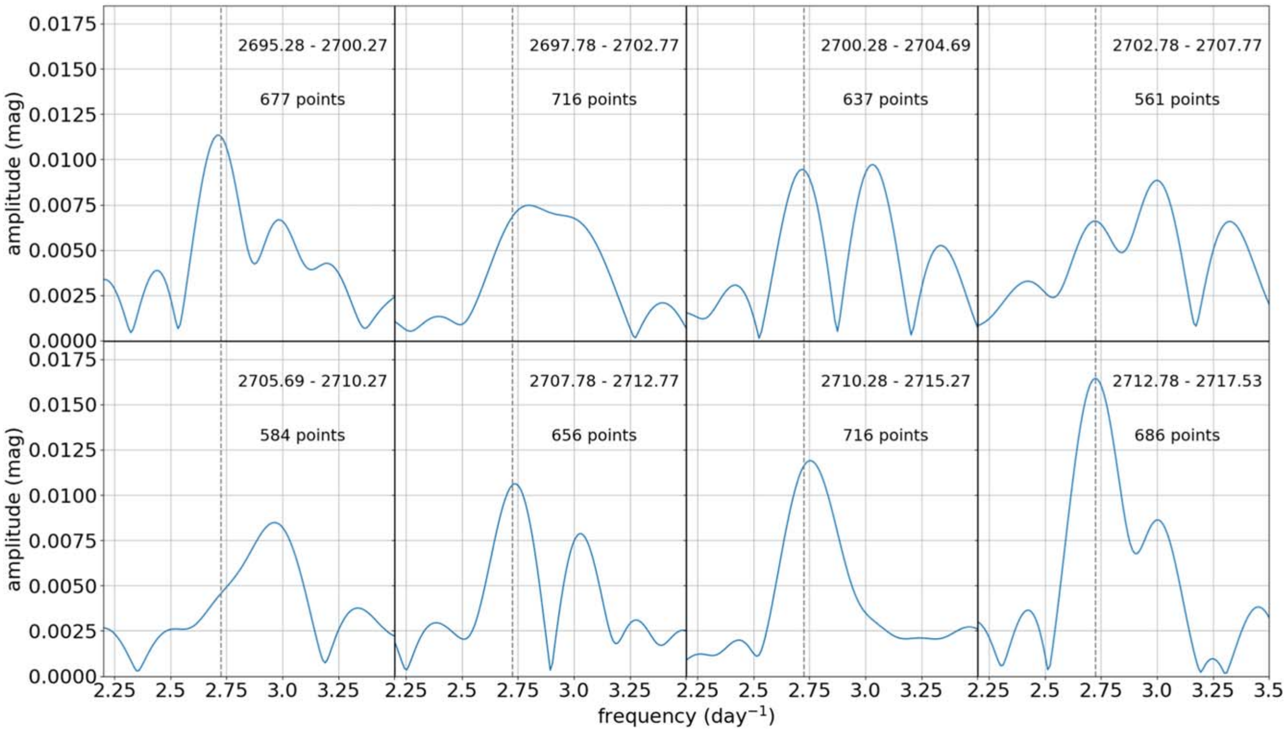

Figure 3. Frequency analysis of V338 Boo in the frequency range around its first overtone mode. Each panel is a 5 day window of data, increasing by 2.5 days at each step from left to right and 10 days from top to bottom. The TESS Julian date range is given in the upper right of each panel, and below that is the number of data points in that date range. The vertical dashed line shows the location of the first overtone mode frequency.

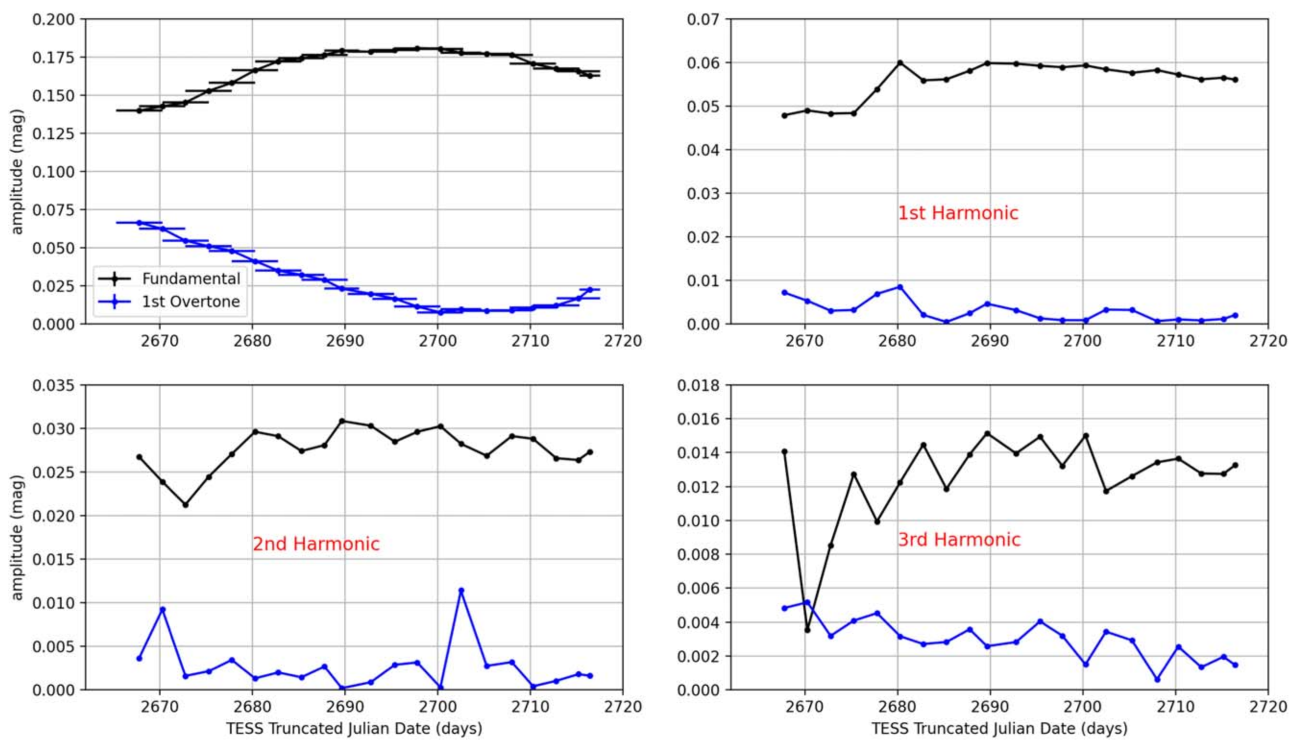

Figure 4. Amplitude of the fundamental mode (black) and first overtone mode (blue) for the primary peak (top-left panel), first harmonic (top-right), second harmonic (bottom-left), and third harmonic (bottom-right) for V338 Boo. This is the same as Figure 3 of C21 but with data from TESS Sectors 50 and 51.

4. Conclusions and Discussion

The observations from TESS and the AAVSO campaign show us that the changes initially seen in V338 Boo appear to be periodic in nature and not just transient. This is an important distinction and is helpful in determining the possible physical mechanisms causing this behavior.

Additionally, the first overtone mode completely disappears for a brief period of time and then reappears shortly after.

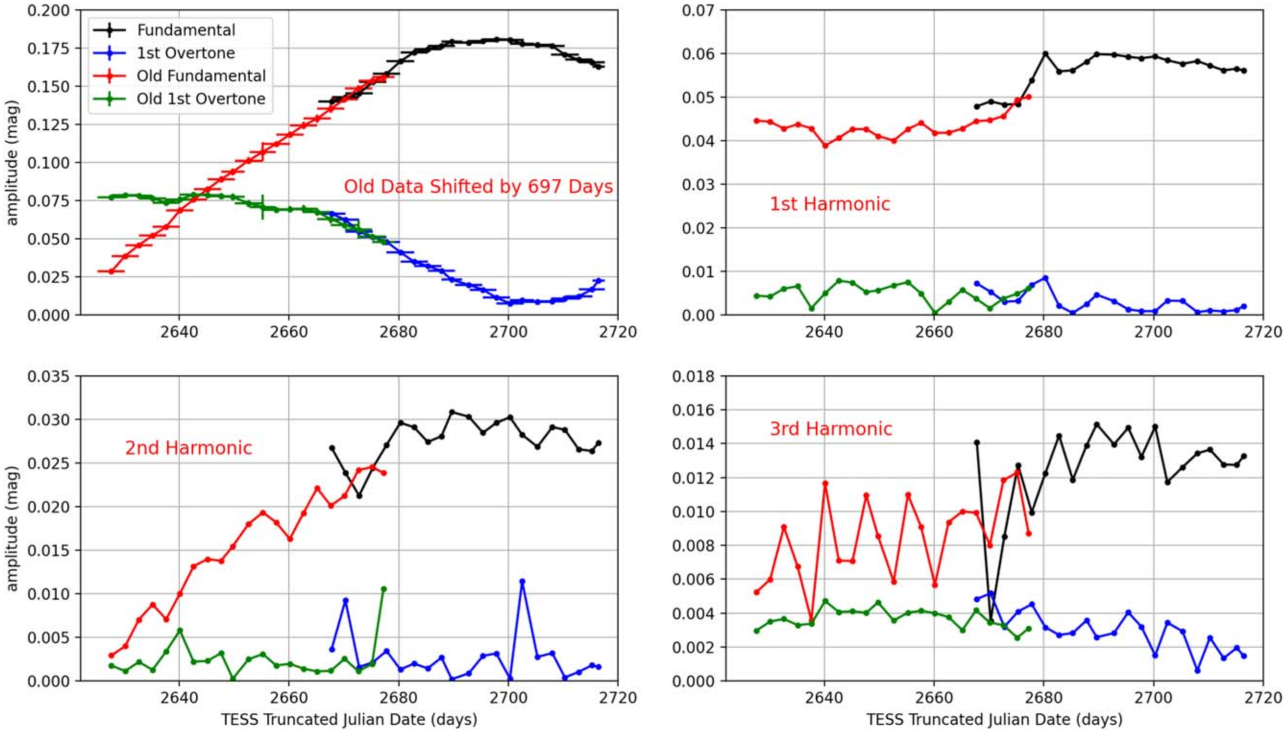

Figure 5. The same as Figure 4 with the data from Sectors 23 and 24 (C21) shifted in time by 697 days and overlaid.

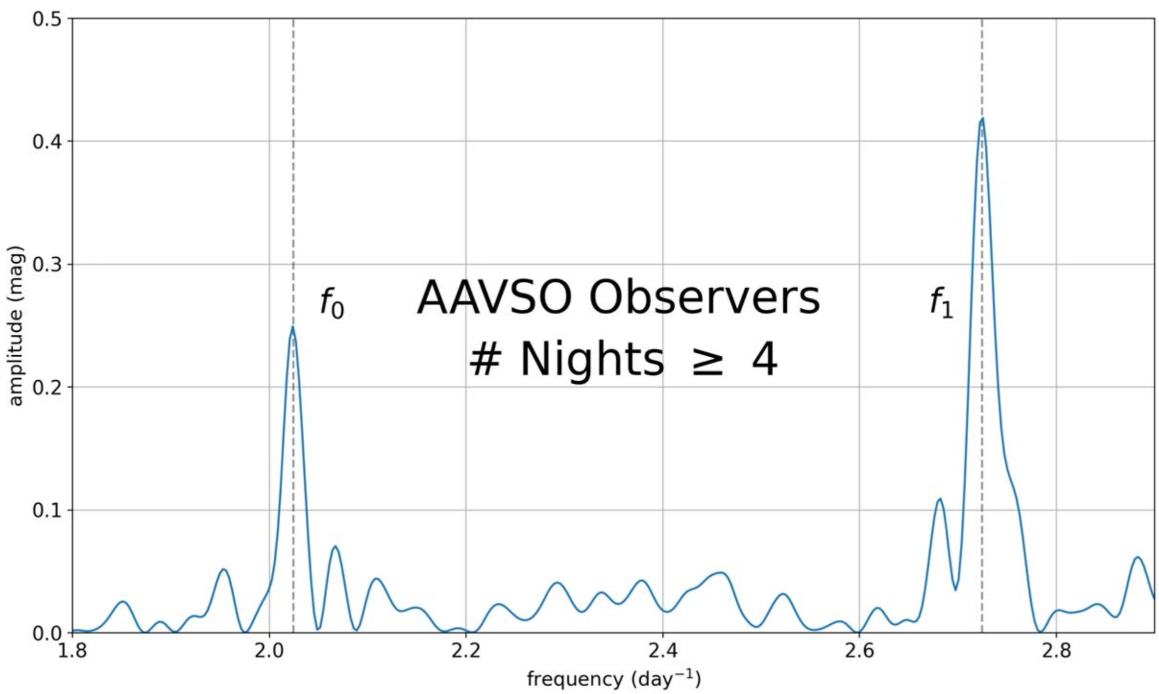

Figure 6. Frequency analysis of observations taken for Alert Notice 786 of the AAVSO by observers with 4 or more nights of observations. The fundamental mode frequency (f_0) and first overtone mode frequency (f_1) are shown with dashed vertical lines.

Therefore, either something in the stellar interior is regenerating this pulsation mode, or there is a "memory" in the star that restarts this mode (e.g., R. B. Stothers 2006).

4.1. Mode-switching Behavior

There are still unanswered questions related to this object. First, is this "mode-switching" behavior? Previous results (see, e.g., J. Kaluzny et al. 1998; V. Goranskij et al. 2010; A. J. Drake et al. 2014; I. Soszyński et al. 2014a, 2014b; R. Poleski 2014) have shown that other RR Lyrae have been observed as one type (e.g., RRd) and in subsequent observations they are a different type (e.g., RRab).

In C. M. Clement & V. P. Goranskij (1999), they examine the behavior of the RR Lyrae variable V79 in the M3 globular cluster over ∼50 yr of observations. Many of the years had very few observations, and therefore the authors restricted

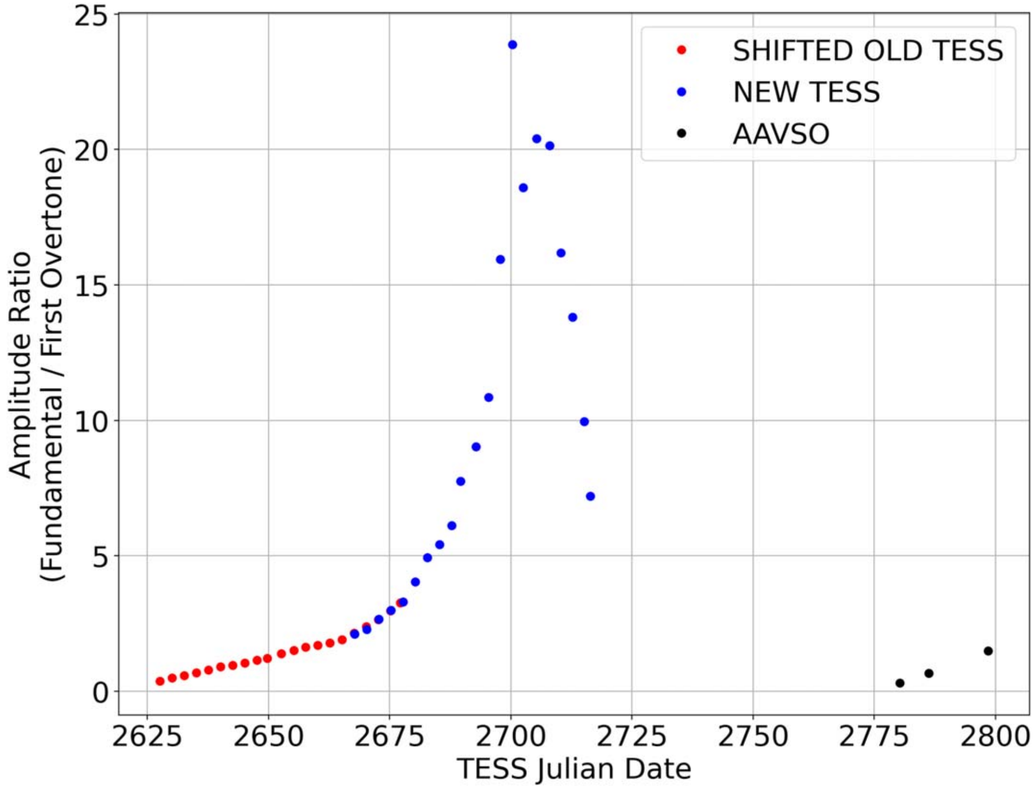

Figure 7. The amplitude ratios of the fundamental mode pulsations to the first overtone mode pulsations for TESS data from 2020 (red points) and 2022 (blue points), and the AAVSO observing campaign (black points).

some of the analysis to only those years with more than 40 observations. This resulted in 11 yr from the historical data in which they determined the primary period of pulsation for this star. They saw there was a large variation in the primary period—both in the value of the period itself and in the primary mode in which the star appeared to be pulsating. In the year 1976, there were 108 observations, by far the most of any year in the historical data, and this allowed the authors to look for changes on smaller timescales. In their Figure 2, there are changes apparent on the timescale of approximately 1 month.

This analysis and the results are very similar to what we saw in C21 with previous data of this star (L. Oaster et al. 2006; D. A. Hurdis & T. Krajci 2010, 2012); the sparse sampling of the periodic changes showed that V338 Boo was behaving strangely, but it was unclear why. So, it is possible, if not likely, that RR Lyrae dubbed as "mode-switching" from sparsely sampled data are in fact exhibiting periodic changes just like those seen in V338 Boo.

4.2. Blazhko Effect

A second question: is this related to the Blazhko effect seen most commonly in RRab stars, but also seen in RRc stars? As shown here, the changes of V338 Boo seem to be periodic, and if this star were an RRab or RRc, it would certainly be considered a Blazhko variable.

A useful comparison can be found in J. Jurcsik et al. (2014). They identified four RRd stars in the globular cluster M3 that exhibited modulations of both the fundamental and first overtone mode pulsation amplitudes, which they attributed to the Blazhko effect. There are some important differences between those stars and V338 Boo, however.

First, for both the M3 stars and V338 Boo there are periodic amplitude modulations of both pulsation modes. But as shown here, there is a short period where the first overtone mode completely disappears from V338 Boo (we note that this could not be seen in J. Jurcsik et al. 2014 even if it were present because of the sparse sampling of the light curves).

Second, all four stars in J. Jurcsik et al. (2014) had period ratios of the radial pulsation modes that were anomalous. However, the period ratio of the pulsation modes of V338 Boo is well within what is considered normal for RRd variables.

And finally, only one of the four RRd stars in J. Jurcsik et al. (2014) had amplitude changes of the modes that were synchronized in any way (anticorrelated in this case). The periodic changes we see in amplitudes of the two pulsation modes of V338 Boo are anticorrelated, which matches the one example in J. Jurcsik et al. (2014).

An anticorrelation is an important fact when trying to determine the cause of these changes. This likely means that the changes seen in V338 Boo are coupled, or drawing from and storing to the same energy source. These changes could be due, for example, to competition in the κ mechanism itself (P. Moskalik et al. 2015), or changes in turbulent motions that generate transient magnetic fields (R. B. Stothers 2006).

We also note that three of the M3 RRd stars from J. Jurcsik et al. (2014) had amplitude changes that were not synchronized, and even the periods of the amplitude changes within the same star were different. This could mean that stars labeled as "mode-switching" are actually changing periodically in the same manner—when they are observed as RRab stars, the first overtone mode is in a long period of very low amplitude. Mode-switching, therefore, may be part of a periodic change in the pulsations and not an abrupt, transient phenomenon. In fact, as shown in R. Wilhelm et al. (2023), transient behavior can be mimicked by the constructive and destructive interference of periodic signals within RR Lyrae stars.

The term "Blazhko effect" is loosely defined to encompass many different types of changes in the light curves of RR Lyrae. As such, we argue that V338 Boo should be considered a variable of this type. But is the same physical mechanism causing the changes seen in V338 Boo and those seen by J. Jurcsik et al. (2014)? And more broadly in the RRab and RRc variables? Could behavior that seems to be abrupt and/or transient (e.g., J. F. Le Borgne et al. 2014) actually be due to the interference of periodic signals (e.g., R. Wilhelm et al. 2023)? The Blazhko effect seems to occur much more frequently in RRab types than RRc types (see, e.g., Z. Prudil & M. Skarka 2017 and H. Netzel et al. 2018 for incidence rates from the Optical Gravitational Lensing Experiment, and K. Kolenberg et al. 2010 and H. Netzel et al. 2023 for incidence rates from Kepler), but why is this the case? In other words, what physical conditions within RRab stars make them more likely to exhibit this phenomenon?

The mystery of the Blazhko effect may be best approached by studying double-mode RR Lyrae. V338 Boo exhibits periodic changes in both pulsation modes, and those changes are anticorrelated. However, this is not the case with all Blazhko RRd stars (J. Jurcsik et al. 2014; R. Smolec et al. 2015). Identifying commonalities and differences between these RRd stars will help point us to physical properties that could be driving the changes. It may also mean that different physical mechanisms are found to be responsible for behavior currently labeled as the Blazhko effect.

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References

Bailey, S. I. 1902, AnHar, 38, 1
Beaton, R. L., Freedman, W. L., Madore, B. F., et al. 2016, ApJ, 832, 210
Blažko, S. 1907, AN, 175, 325
Brasseur, C. E., Phillip, C., Fleming, S. W., Mullally, S. E., & White, R. L. 2019, Astrocut: Tools for creating cutouts of TESS images, Astrophysics Source Code Library, ascl:1905.007
Carrell, K., Wilhelm, R., Olsen, F., et al. 2021, ApJL, 916, L12
Carrell, K. W. 2021, ATARRI: A TESS Archive RR Lyrae Classifier, Astrophysics Source Code Library, ascl:2105.003
Catelan, M., & Smith, H. A. 2015, Pulsating Stars (New York: Wiley)
Christy, R. F. 1966, ARA&A, 4, 353
Clement, C. M., & Goranskij, V. P. 1999, ApJ, 513, 767
Cox, A. N. 1991, ApJL, 381, L71
Cox, A. N., Hodson, S. W., & Clancy, S. P. 1983, ApJ, 266, 94
Cox, A. N., King, D. S., & Hodson, S. W. 1980, ApJ, 236, 219
Drake, A. J., Graham, M. J., Djorgovski, S. G., et al. 2014, ApJS, 213, 9
Feuchtinger, M. U. 1998, A&A, 337, L29
Goranskij, V., Clement, C. M., & Thompson, M. 2010, in Variable Stars, the Galactic halo and Galaxy Formation, ed. C. Sterken, N. Samus, & L. Szabados (Moscow: Sternberg Astronomical Institute of Moscow University), 115
Hurdis, D. A., & Krajci, T. 2010, JAVSO, 38, 1
Hurdis, D. A., & Krajci, T. 2012, JAVSO, 40, 268
Jørgensen, H. E., & Petersen, J. O. 1967, ZAp, 67, 377
Jurcsik, J., Smitola, P., Hajdu, G., & Nuspl, J. 2014, ApJL, 797, L3
Kaluzny, J., Hilditch, R. W., Clement, C., & Rucinski, S. M. 1998, MNRAS, 296, 347
Kolenberg, K., Szabó, R., Kurtz, D. W., et al. 2010, ApJL, 713, L198
Kovacs, G., & Karamiqucham, B. 2021, A&A, 653, A61
Le Borgne, J. F., Poretti, E., Klotz, A., et al. 2014, MNRAS, 441, 1435
Lenz, P., & Breger, M. 2005, CoAst, 146, 53
Lightkurve Collaboration, Cardoso, J. V. d. M., Hedges, C., et al. 2018, Lightkurve: Kepler and TESS time series analysis in Python, Astrophysics Source Code Library, ascl:1812.013
Moskalik, P., Smolec, R., Kolenberg, K., et al. 2015, MNRAS, 447, 2348
Netzel, H., Molnár, L., Plachy, E., & Benkő, J. M. 2023, A&A, 677, A177
Netzel, H., Smolec, R., Soszyński, I., & Udalski, A. 2018, MNRAS, 480, 1229
Oaster, L., Smith, H. A., & Kinemuchi, K. 2006, PASP, 118, 405
Petersen, J. O. 1973, A&A, 27, 89
Pickering, E. C. 1901, AN, 154, 423
Poleski, R. 2014, PASP, 126, 509
Prudil, Z., & Skarka, M. 2017, MNRAS, 466, 2602
Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, JATIS, 1, 014003
Shapley, H. 1916, ApJ, 43, 217
Smith, H. A. 1995, RR Lyrae Stars (Cambridge Astrophysics Series), 27 (Cambridge: Cambridge University Press)
Smolec, R., Soszyński, I., Udalski, A., et al. 2015, MNRAS, 447, 3756
Soszyński, I., Dziembowski, W. A., Udalski, A., et al. 2014a, AcA, 64, 1
Soszyński, I., Udalski, A., Szymański, M. K., et al. 2014b, AcA, 64, 177
Stothers, R. B. 2006, ApJ, 652, 643
Vanderspek, R., Doty, J. P., Fausnaugh, M., et al. 2018, TESS Instrument Handbook, https://archive.stsci.edu/missions-and-data/tess
Wilhelm, R., Carrell, K., Means, H. H., et al. 2023, AJ, 165, 194