

## Search for the Blazhko effect in field RR Lyrae stars using LINEAR and ZTF light curves

2 EMA DONEV<sup>1</sup> AND ŽELJKO IVEZIĆ<sup>2</sup>

3 <sup>1</sup>*XV. Gymnasium (MIOC), Jordanovac 8, 10000, Zagreb, Croatia*

4 <sup>2</sup>*Department of Astronomy and the DiRAC Institute, University of Washington, 3910 15th Avenue NE, Seattle, WA 98195, USA*

### 5 ABSTRACT

6 We analyzed the incidence and properties of RR Lyrae stars that show evidence for amplitude and  
7 phase modulation (the so-called Blazhko Effect) in a sample of  $\sim$ 3,000 stars with LINEAR and ZTF  
8 light curve data collected during the periods of 2002–2008 and 2018–2023, respectively. A preliminary  
9 subsample of about  $\sim$ 500 stars was algorithmically pre-selected using various data quality and light  
10 curve statistics, and then 228 stars were confirmed visually as displaying the Blazhko effect. This  
11 sample increases the number of field RR Lyrae stars displaying the Blazhko effect by more than 50%  
12 and places a lower limit of  $(11.4 \pm 0.8)\%$  for their incidence rate. We find that ab type RR Lyrae  
13 that show the Blazhko effect have about 5% (0.030 day) shorter periods than starting sample, a  $7.1\sigma$   
14 statistically significant difference. We find no significant differences in their light curve amplitudes and  
15 apparent magnitude (essentially, signal-to-noise ratio) distributions. No period or other differences are  
16 found for c type RR Lyrae. We find convincing examples of stars where the Blazhko effect can appear  
17 and disappear on time scales of several years. With time-resolved photometry expected from LSST, a  
18 similar analysis will be performed for even larger samples of fields RR Lyrae stars in the southern sky  
19 and we anticipate a higher fraction of discovered Blazhko stars due to better sampling and superior  
20 photometric quality.

21 **Keywords:** Variable stars — RR Lyrae variable stars — Blazhko effect

### 22 1. INTRODUCTION

23 RR Lyrae stars are pulsating variable stars with per-  
24 iodds in the range of 3–30 hours and large amplitudes that  
25 increase towards blue optical bands (e.g., in the SDSS *g*  
26 band from 0.2 mag to 1.5 mag; [Sesar et al. 2010](#)). For  
27 comprehensive reviews of RR Lyrae stars, we refer the  
28 reader to [Smith \(1995\)](#) and [Catelan \(2009\)](#).

29 RR Lyrae stars often exhibit amplitude and phase  
30 modulation, or the so-called Blazhko effect<sup>1</sup> (hereafter,  
31 “Blazhko stars”). For examples of well-sampled observed  
32 light curves showing the Blazhko effect, see, e.g., Ke-  
33 pler data shown in Figures 1 and 2 from [Benkő et al.](#)  
34 ([2010](#)). The Blazhko effect has been known for a long  
35 time ([Blažko 1907](#)), but its detailed observational prop-  
36 erties and theoretical explanation of its causes remain  
37 elusive ([Kolenberg 2008](#); [Kovács 2009](#); [Szabó 2014](#)). Var-  
38 ious proposed models for the Blazhko effect, and prin-

39 cipal reasons why they fail to explain observations, are  
40 summarized in [Kovacs \(2016\)](#).

41 A part of the reason for the incomplete observational  
42 description of the Blazhko effect is difficulties in discov-  
43 ering a large number of Blazhko stars due to tempo-  
44 ral baselines that are too short and insufficient number  
45 of observations per object ([Kovacs 2016](#); [Hernitschek &](#)  
46 [Stassun 2022](#)). With the advent of modern sky sur-  
47 veys, several studies reported large increases in the num-  
48 ber of known Blazhko stars, starting with a sample of  
49 about 700 Blazhko stars discovered by the MACHO sur-  
50 vey towards the LMC ([Alcock et al. 2003](#)) and about  
51 500 Blazhko stars discovered by the OGLE-II survey  
52 towards the Galactic bulge ([Mizerski 2003](#)). Most re-  
53 cently, about 4,000 Blazhko stars were discovered in the  
54 LMC and SMC ([Soszyński et al. 2009, 2010](#)), and an  
55 additional  $\sim$ 3,500 stars were discovered in the Galactic  
56 bulge ([Soszyński et al. 2011; Prudil & Skarka 2017](#)), both  
57 by the OGLE-III survey. Nevertheless, discovering the  
58 Blazhko effect in field RR Lyrae stars that are spread  
59 over the entire sky remains a much harder problem: only  
60 about 400 Blazhko stars in total ([Skarka 2013](#)) from all  
61 the studies of field RR Lyrae stars have been reported  
62 so far (see also Table 1 in [Kovacs 2016](#)).

Corresponding author: Željko Ivezić  
ivezic@uw.edu

<sup>1</sup> The Blazhko effect was probably discovered by Lidiya Petrovna Tseraskaya and first reported by Sergey Blazhko though exact discovery details remain unclear.

63 Here, we report the results of a search for the Blazhko  
 64 effect in a sample of  $\sim 3,000$  field RR Lyrae stars with  
 65 LINEAR and ZTF light curve data. A preliminary sub-  
 66 sample of about  $\sim 500$  stars was selected using various  
 67 light curve statistics, and then 228 stars were confirmed  
 68 visually as displaying the Blazhko effect. This new sam-  
 69 ple doubles the number of field RR Lyrae stars that  
 70 exhibit the Blazhko effect. In §2 and §3 we describe our  
 71 datasets and analysis methodology, and in §4 we present  
 72 our analysis results. Our main results are summarized  
 73 and discussed in §5.

## 74 2. DATA DESCRIPTION AND PERIOD 75 ESTIMATION

76 Analysis of field RR Lyrae stars requires a sensitive  
 77 time-domain photometric survey over a large sky area.  
 78 For our starting sample, we used  $\sim 3,000$  field RR Lyrae  
 79 stars with light curves obtained by the LINEAR aster-  
 80 oid survey. In order to study long-term changes in light  
 81 curves, we also utilized light curves obtained by the ZTF  
 82 survey which monitored the sky  $\sim 15$  years after LIN-  
 83 EAR. The combination of LINEAR and ZTF provided  
 84 a unique opportunity to systematically search for the  
 85 Blazhko effect in a large number of field RR Lyrae stars  
 86 over a large time span of two decades.

87 We first describe each dataset in more detail, and then  
 88 introduce our analysis methods. All our analysis code,  
 89 written in Python, is available on GitHub<sup>2</sup>.

### 90 2.1. LINEAR Dataset

91 The properties of the LINEAR asteroid survey and  
 92 its photometric re-calibration based on SDSS data are  
 93 discussed in Sesar et al. (2011). Briefly, the LINEAR  
 94 survey covered about 10,000 deg<sup>2</sup> of the northern sky  
 95 in white light (no filters were used, see Fig. 1 in Sesar  
 96 et al. 2011), with photometric errors ranging from  $\sim 0.03$   
 97 mag at an equivalent SDSS magnitude of  $r = 15$  to 0.20  
 98 mag at  $r \sim 18$ . Light curves used in this work include,  
 99 on average, 270 data points collected between December  
 100 2002 and September 2008.

101 A sample of 7,010 periodic variable stars with  $r < 17$   
 102 discovered in LINEAR data were robustly classified by  
 103 Palaversa et al. (2013), including about  $\sim 3,000$  field RR  
 104 Lyrae stars of both ab and c type, detected to distances  
 105 of about 30 kpc (Sesar et al. 2013). The sample used  
 106 in this work contains 2196 ab-type and 745 c-type RR  
 107 Lyrae, selected using classification labels and the *gi* color  
 108 index from Palaversa et al. (2013). The LINEAR light  
 109 curves, augmented with IDs, equatorial coordinates, and  
 110 other data, were accessed using the astroML Python  
 111 module<sup>3</sup> (VanderPlas et al. 2012).

### 112 2.2. ZTF Dataset

113 The Zwicky Transient Factory (ZTF) is an opti-  
 114 cal time-domain survey that uses the Palomar 48-inch  
 115 Schmidt telescope and a camera with 47 deg<sup>2</sup> field of  
 116 view (Bellm et al. 2019). The dataset analyzed here  
 117 was obtained with SDSS-like *g*, *r*, and *i* band filters.  
 118 Light curves for objects in common with the LINEAR  
 119 RR Lyrae sample typically have smaller random photo-  
 120 metric errors than LINEAR light curves because ZTF  
 121 data are deeper (compared to LINEAR, ZTF data have  
 122 about 2-3 magnitudes fainter 5 $\sigma$  depth). ZTF data used  
 123 in this work were collected between February 2018 and  
 124 December 2023, on average about 15 years after obtain-  
 125 ing LINEAR data. The median number of observations  
 126 per star for ZTF light curves is  $\sim 500$ .

127 The ZTF dataset for this project was created by se-  
 128 lecting ZTF IDs with matching equatorial coordinates to  
 129 a corresponding LINEAR ID of an RR Lyrae star. This  
 130 process used the *ztfquery* function, which searched the  
 131 coordinates in the ZTF database within 3 arcsec from  
 132 the LINEAR position. The resulting sample consisted of  
 133 2857 RR Lyrae stars with both LINEAR and ZTF data.  
 134 The fractions of RRab and RRc type RR Lyrae in this  
 135 sample, 71% RRab and 29% RRc type, are consistent  
 136 with results from other surveys (e.g., Sesar et al. 2010;  
 137 Clementini et al. 2023).

### 138 2.3. Period Estimation

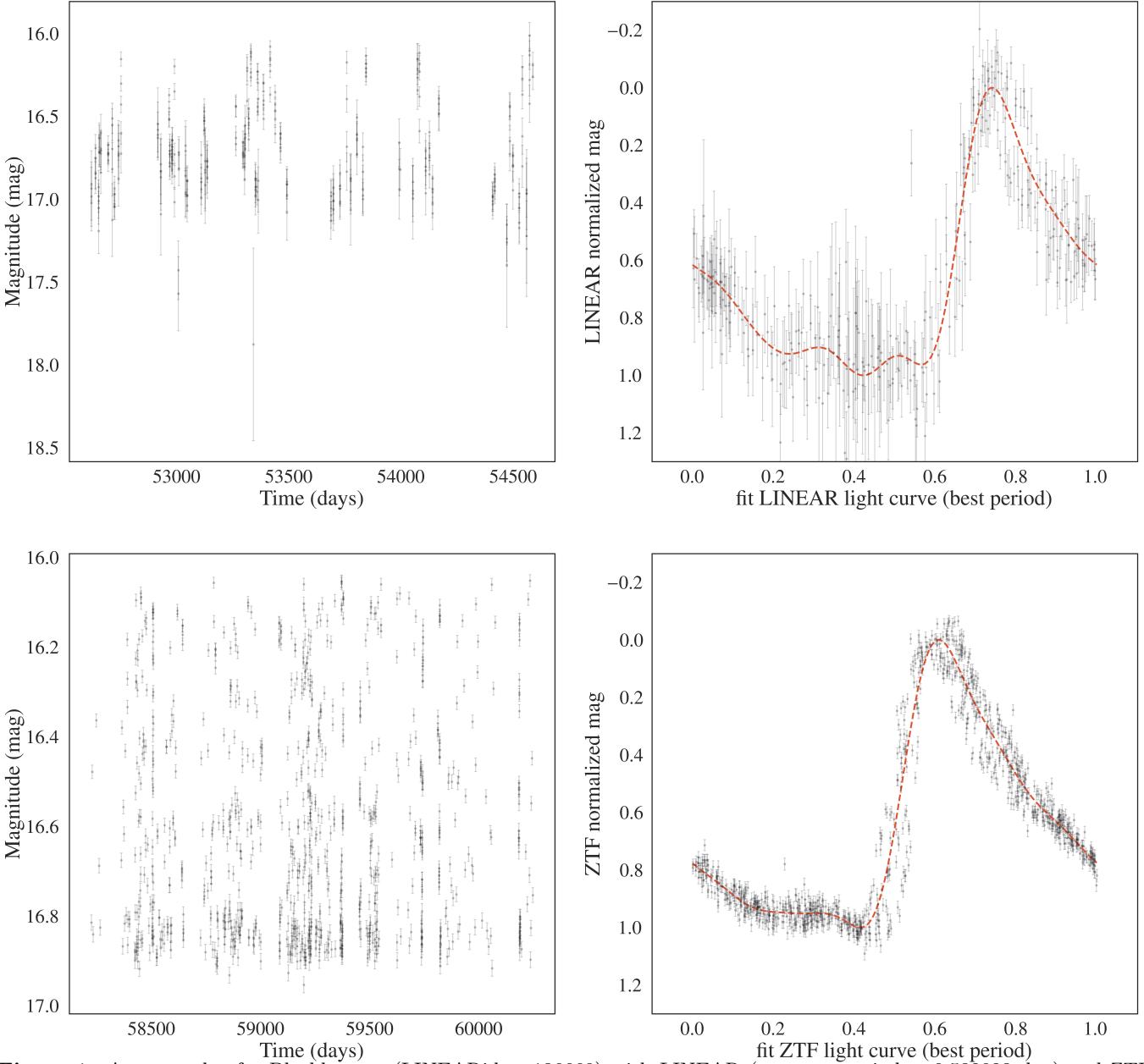
139 The first step of our analysis is estimating best-fit peri-  
 140 ods, separately for LINEAR and ZTF datasets. We used  
 141 the Lomb-Scargle method (Vanderplas 2015) as imple-  
 142 mented in *astropy* (Astropy Collaboration et al. 2018).  
 143 The period estimation used 3 Fourier components and  
 144 a two-step process: an initial best-fit frequency was de-  
 145 termined using the *autopower* frequency grid option and  
 146 then the power spectrum was recomputed around the  
 147 initial frequency using an order of magnitude smaller  
 148 frequency step. In case of ZTF, we estimated period  
 149 separately for each available passband and adopted their  
 150 median value. Once the best-fit period was determined,  
 151 a best-fit model for the phased light curve was computed  
 152 using 6 Fourier components. Fig 1 shows an example of  
 153 a star with LINEAR and ZTF light curves, phased light  
 154 curves, and their best-fit models.

155 We found excellent agreement between the best-fit  
 156 periods estimated separately from LINEAR and ZTF  
 157 light curves. The median of their ratio is unity within  
 158  $2 \times 10^{-6}$  and the robust standard deviation of their ratio  
 159 is  $2 \times 10^{-5}$ . With a median sample period of 0.56 days,  
 160 the implied scatter of period difference is about 1.0 sec.

161 Given on average about 15 years between LINEAR  
 162 and ZTF data sets, and a typical period of 0.56 days,  
 163 this time difference corresponds to about 10,000 oscilla-  
 164 tions. With a fractional period uncertainty of  $2 \times 10^{-5}$ ,  
 165 LINEAR data can predict the phase of ZTF light curve  
 166 with an uncertainty of 0.2. Therefore, for a robust de-  
 167 tection of light curve phase modulation (see e.g., Szeidl

<sup>2</sup> [https://github.com/emadonev/var\\_stars](https://github.com/emadonev/var_stars)

<sup>3</sup> For an example of light curves, see [https://www.astroml.org/book\\_figures/chapter10/fig\\_LINEAR\\_LS.html](https://www.astroml.org/book_figures/chapter10/fig_LINEAR_LS.html)



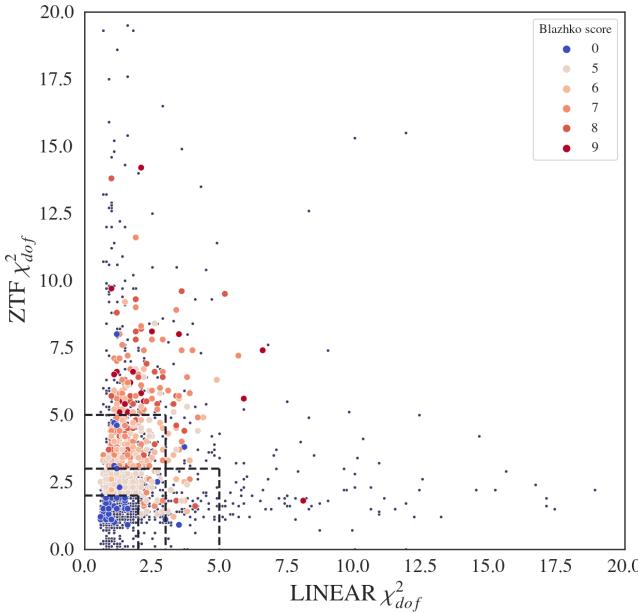
**Figure 1.** An example of a Blazhko star (LINEARid = 136668) with LINEAR (top row; period = 0.532923 day) and ZTF (bottom row; period = 0.532929 day) light curves (left panels, data points with “error bars”), phased light curves normalized to the 0–1 range (right panels, data points with “error bars”), with their best-fit models shown by dashed lines. The best-fit period is determined for each dataset separately using 3 Fourier terms. The models shown in the right panels are evaluated with 6 Fourier terms.

et al. 2011; Dagne et al. 2017), each data set must be analyzed separately. On the other hand, amplitude modulation can be detected on time scales as long as 15 years, as discussed in the following section.

We did not try to identify double-mode (RRd) stars because their expected sample fraction is below 1% (Clementini et al. 2023).

### 3. ANALYSIS METHODOLOGY: SEARCHING FOR THE BLAZHKO EFFECT

Given the two sets of light curves from LINEAR and ZTF, we searched for amplitude and phase modulation, either during the 5–6 years of data taking by each survey, or during the average span of 15 years between the two surveys. Starting with a sample of 2857 RR Lyrae stars, we pre-selected a smaller sample that was inspected visually (see below for details). We also required at least 150 LINEAR data points and 150 ZTF data points (for the selected band from which we calculated the period) in analyzed light curves. We used



**Figure 2.** A selection diagram constructed with the two sets of robust  $\chi^2_{dof}$  values, for LINEAR and ZTF data sets, where the dark blue dots represent all RR Lyrae stars and the circles represent candidate Blazhko stars (color-coded according to the legend, with B\_score representing the number of points scored from the selection algorithm). The horizontal and vertical dashed lines help visualize selection boundaries for Blazhko candidates (see text).

187 two pre-selection methods that are sensitive to differ-  
188 ent types of light curve modulation: direct light curve  
189 analysis and periodogram analysis, as follows.

### 190 3.1. Direct Light Curve Analysis

191 Given statistically correct period, amplitude and light  
192 curve shape estimates, as well as data being consistent  
193 with reported (presumably Gaussian) uncertainty esti-  
194 mates, the  $\chi^2$  per degree of freedom gives a quantitative  
195 assessment of the "goodness of fit",

$$196 \quad \chi^2_{dof} = \frac{1}{N_{dof}} \sum \frac{(d_i - m_i)^2}{\sigma_i^2}. \quad (1)$$

197 Here,  $d_i$  are measured light curve data values at times  
198  $t_i$ , and with associated uncertainties  $\sigma_i$ ,  $m_i$  are best-  
199 fit models at times  $t_i$ , and  $N_{dof}$  is the number of de-  
200 grees of freedom, essentially the number of data points.  
201 In the absence of any light curve modulation, the ex-  
202 pected value of  $\chi^2_{dof}$  is unity, with a standard devia-  
203 tion of  $\sqrt{2/N_{dof}}$ . If  $\chi^2_{dof} - 1$  is many times larger than  
204  $\sqrt{2/N_{dof}}$ , it is unlikely that data  $d_i$  were generated by  
205 the assumed (unchanging) model  $m_i$ . Of course,  $\chi^2_{dof}$   
206 can also be large due to underestimated measurement  
207 uncertainties  $\sigma_i$ , or to occasional non-Gaussian measure-  
208 ment error (the so-called outliers).

209 Therefore, to search for signatures of the Blazhko ef-  
210 feft, manifested through statistically unlikely large val-  
211 ues of  $\chi^2_{dof}$ , we computed  $\chi^2_{dof}$  separately for LINEAR  
212 and ZTF data (see Fig. 2). Using the two sets of  $\chi^2_{dof}$   
213 values, we algorithmically pre-selected a sample of can-  
214 didate Blazhko stars for further visual analysis of their  
215 light curves. The visual analysis is needed to confirm  
216 the expected Blazhko behavior in observed light curves,  
217 as well as to identify cases of data problems, such as  
218 photometric outliers.

219 We used a simple scoring algorithm, optimized  
220 through trial and error, that utilized the two values of  
221  $\chi^2_{dof}$ , augmented by period and amplitude differences, as  
222 follows. A star could score a maximum of 9 points, and  
223 a minimum of 5 points was required for further visual  
224 analysis. The  $\chi^2_{dof}$  selection boundaries are illustrated  
225 in Fig. 2. If either value of  $\chi^2_{dof}$  exceeded 5, or both ex-  
226 ceeded 3, a star was awarded 5 points and immediately  
227 selected for further analysis. If these  $\chi^2_{dof}$  criteria were  
228 not met, a star could still be selected by meeting less  
229 stringent  $\chi^2_{dof}$  selection if it also had large period or am-  
230 plitude difference between LINEAR and ZTF datasets.  
231 Stars with at least one value of  $\chi^2_{dof}$  above 2 would re-  
232 ceive 3 points and those with at least one  $\chi^2_{dof}$  above  
233 3 would receive 4 points. A period difference exceeding  
234  $2 \times 10^{-4}$  day would be awarded 1 point and two points for  
235 exceeding  $5 \times 10^{-4}$  day. Analogous limits for amplitude  
236 difference were 0.05 mag and 0.15 mag, respectively.

237 The candidate Blazhko sample pre-selected using this  
238 method includes 531 stars. For most selected stars, the  
239  $\chi^2_{dof}$  values were larger for the ZTF data because the  
240 ZTF photometric uncertainties are smaller than for the  
241 LINEAR data set. Fig. 3 summarizes the selection cri-  
242 teria and the resulting numbers of selected stars for each  
243 criterion and their combinations.

### 244 3.2. Periodogram Analysis

245 When light curve modulation is due to double-mode  
246 oscillation with two similar oscillation frequencies (peri-  
247 ods), it is possible to recognize its signature in the peri-  
248 odogram computed as part of the Lomb-Scargle analy-  
249 sis. Depending on various details, such as data sampling  
250 and the exact values of periods, amplitudes, this method  
251 may be more efficient than direct light curve analysis  
252 (Skarka et al. 2020). We also employed this method to  
253 select additional candidates, as follows.

254 A sum of two *sine* functions with same amplitudes  
255 and with frequencies  $f_1$  and  $f_2$  can be rewritten using  
256 trigonometric equalities as

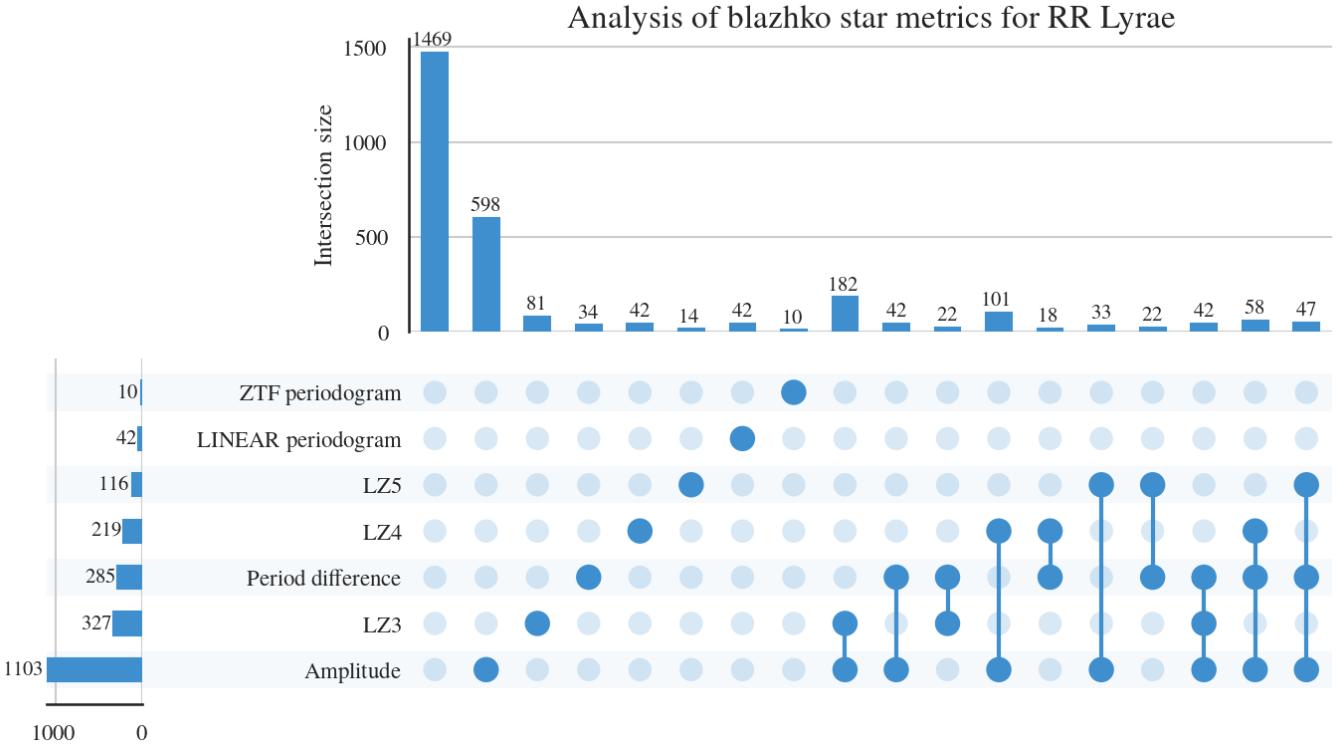
$$257 \quad y(t) = 2 \cos(2\pi \frac{f_1 - f_2}{2} t) \sin(2\pi \frac{f_1 + f_2}{2} t). \quad (2)$$

258 We can define

$$259 \quad f_o = \frac{f_1 + f_2}{2}, \quad (3)$$

260 and

$$261 \quad \Delta f = \left| \frac{f_1 - f_2}{2} \right|, \quad (4)$$



**Figure 3.** The figure shows selection criteria and the resulting numbers of pre-selected Blazhko star candidates for each criterion and their combinations ( $x$  in  $LZx$  corresponds to the number of scored points in the  $\chi^2_{dof}$  vs.  $\chi^2_{dof}$  diagram (see Fig. 2). The dots represent each case a star can occupy, where every solid dot is a specific criterion that is satisfied. Connections between solid dots represent stars which satisfy multiple criteria. Each dot combination has its own count, represented by the horizontal countplot. The vertical countplot shows the total number of stars that satisfy one criteria (union of all cases). For example, a total of 116 stars passed the LZ5 criterion, with 14 of them satisfying only  $\chi^2$  criterion, 33 also had a significant amplitude change, 22 had a significant period difference, and 47 had both a significant period and amplitude difference along with the satisfied  $\chi^2$  criterion. The sum of all specific cases is 116.

with  $\Delta f \ll f_o$  when  $f_1$  and  $f_2$  are similar. The fact that  $\Delta f$  is much smaller than  $f_o$  means that the period of the  $\cos$  term is much larger than the period of the basic oscillation ( $f_o$ ). In other words, the  $\cos$  term acts as a slow amplitude modulation of the basic oscillation. When the amplitudes of two  $\sin$  functions are not equal, the results are more complicated but the basic conclusion about amplitude modulation remains. When the power spectrum of  $y(t)$  is constructed, it will show 3 peaks: the main peak at  $f_o$  and two more peaks at frequencies  $f_o \pm \Delta f$ . We used this fact to construct an algorithm for automated searching for the evidence of amplitude modulation. Fig 4 compares the theoretical periodogram produced by interference beats with our algorithm's periodogram, signifying that local Blazhko peaks are present in real data.

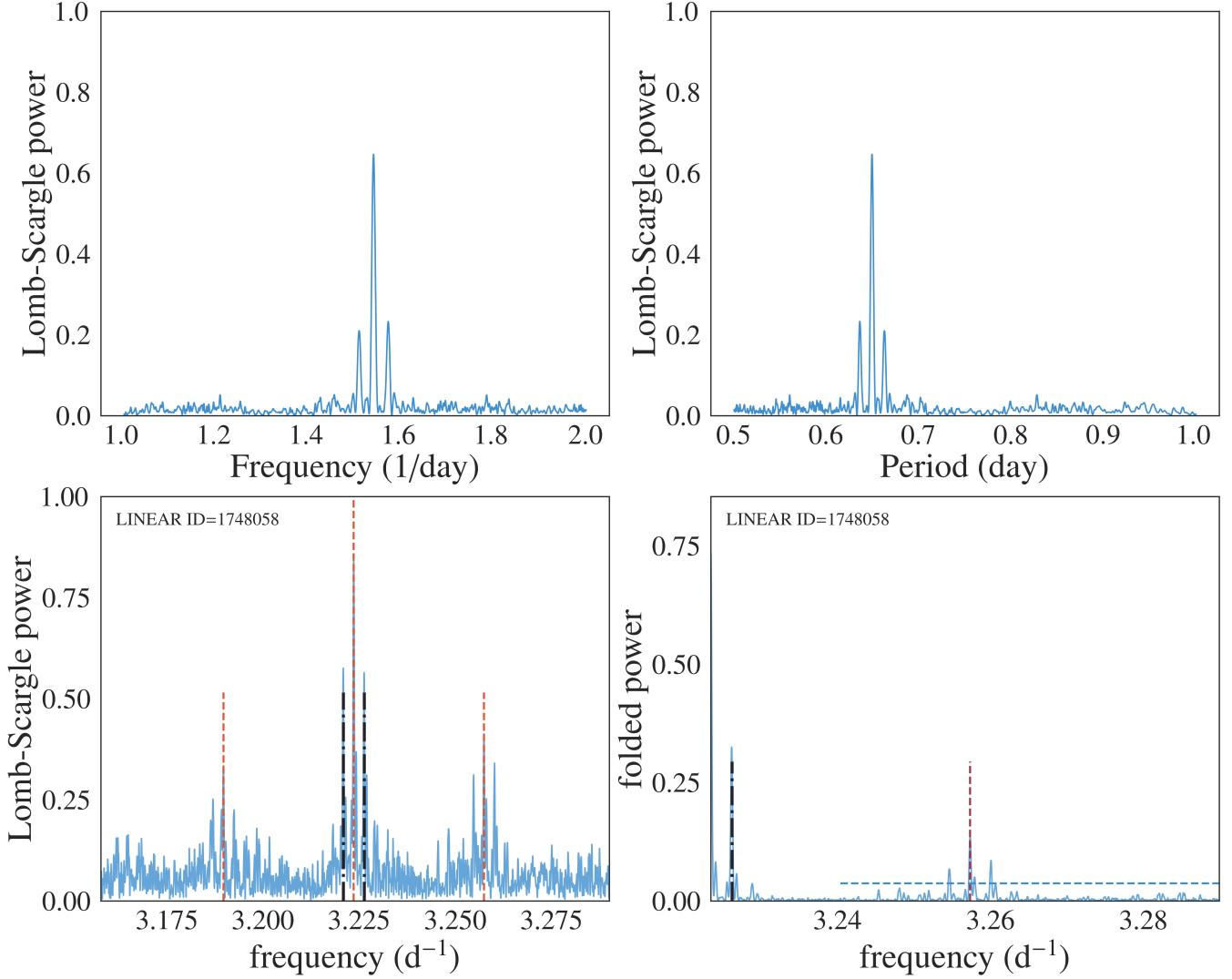
After the strongest peak in the Lomb-Scargle periodogram is found at frequency  $f_o$ , we search for two equally distant local peaks at frequencies  $f_-$  and  $f_+$ , with  $f_- < f_o < f_+$ . The sideband peaks can be highly asymmetric (Alcock et al. 2003) and observed periodograms can sometimes be much more complex

(Szczygieł & Fabrycky 2007). We fold the periodogram through the main peak at  $f_o$ , multiply the two branches and then search for the strongest peaks in the resulting folded periodogram that is statistically more significant than the background noise. The multiplication of the two branches allows for detection of moderately asymmetric peaks (Netzel et al. 2018; Molnár et al. 2023). The background noise is computed as the scatter of the folded periodogram estimated from the interquartile range. We require a “signal-to-noise” ratio of at least 5, as well as the peak strength of at least 0.05 for ZTF, while 0.10 for LINEAR data. If such a peak is found, and it doesn’t correspond to yearly alias, we select the star as a candidate Blazhko star and compute its Blazhko period as

$$P_{BL} = |f_{-,+} - f_o|^{-1},$$

where  $f_{-,+}$  means the Blazhko sideband frequency with a higher amplitude is chosen.

The observed Blazhko periods range from 3 to 3,000 days, and Blazhko amplitudes range from 0.01 mag to about 0.3 mag (Szczygieł & Fabrycky 2007). In this work, we selected a smaller Blazhko range due to the



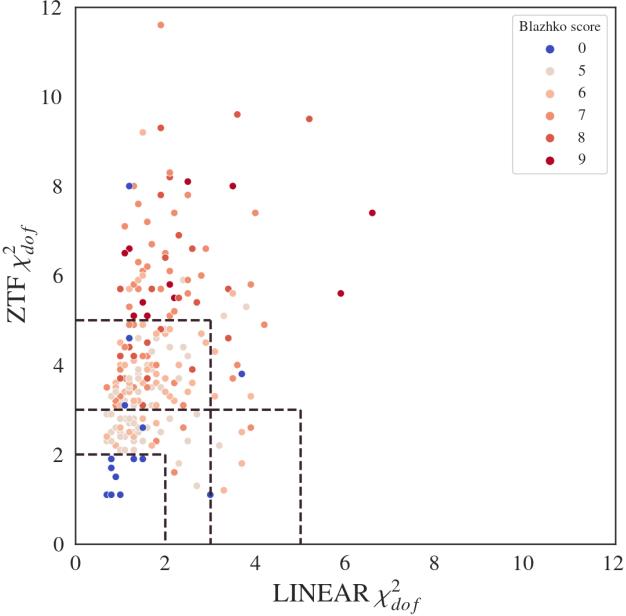
**Figure 4.** The top two panels show a simulated periodogram for a sum of two *sine* functions with similar frequencies  $f_1$  and  $f_2$  – the central peak corresponds to their mean (see eqs. 3 and 4). The bottom left panel shows a periodogram for an observed LINEAR light curve for  $ID = 1748058$ , and the bottom right panel shows its folded version (around the main frequency  $f_o = 3.223 \text{ d}^{-1}$ ). In the bottom left panel, the three vertical dashed lines show the three frequencies identified by the algorithm described in text, and the two dot-dashed lines mark yearly aliases around the main frequency  $f_o$ , at frequencies  $f_o \pm 0.0274 \text{ d}^{-1}$ . The two vertical lines in the bottom right panel have the same meaning, and the horizontal dashed line shows the noise level multiplied by 5.

limitations of our data: 30–325 days. With this additional constraint, we selected 52 candidate Blazhko stars. Fig. 4 shows an example where two very prominent peaks were identified in the LINEAR periodogram.

### 3.2.1. Visual Confirmation

The sample pre-selected for visual analysis includes 531 RR Lyrae stars ( $479 + 52$ ), or 18.1% of the starting LINEAR-ZTF sample. Visual analysis included the following standard steps (e.g., Jurcsik et al. 2009; Prudil & Skarka 2017):

- 284 1. The shape of the phased light curves and scatter of  
285 data points around the best-fit model were examined  
286 for signatures of anomalous behavior indicative  
287 of the Blazhko effect. Fig. 6 shows an example  
288 of such behavior where the ZTF data and fit show  
289 multiple coherent data point sequences offset from  
290 the best-fit mean model.
- 301 2. Full light curves were inspected for their repeatability  
302 between observing seasons (Fig. 7). This  
303 step was sensitive to amplitude modulations with  
304 periods of the order a year or longer.



**Figure 5.** Analogous to figure 2, except that here only 228 visually verified Blazhko stars are shown.

3. The phased light curves normalized to unit amplitude were inspected for their repeatability between observing seasons. This step was sensitive to phase modulations of a few percent or larger on time scales of the order a year or longer. Fig. 8 shows an example of a Blazhko star where season-to-season phase and amplitude modulations are seen in both the LINEAR data and (especially) the ZTF data. Another example is shown in Fig. 9 where only phase modulation is visible, without any discernible amplitude modulation<sup>4</sup>.

After visually analyzing the starting sample of 531 Blazhko candidates, we visually confirmed expected Blazhko behavior for 228 stars (214 out of 479 and 14 out of 52). LINEAR IDs and other characteristics for confirmed Blazhko stars are listed in Table 1 (Appendix A). Statistical properties of the selected sample of Blazhko stars are discussed in detail in the next section.

#### 4. RESULTS

Starting with a sample of 2857 field RR Lyrae stars with both LINEAR and ZTF data, we constructed a subsample of 1996 with light curves of sufficient quality and selected and verified 228 stars that exhibit convincing Blazhko effect. In this section we compare various statistical properties of selected Blazhko stars to those of the starting sample.

<sup>4</sup> The physical reason for this behavior remains unclear, see Derekas et al. (2004); Sóder et al. (2017); Le Borgne & Klotz (2019).

#### 4.1. The Blazhko Incidence Rate

The implied incidence rate for the Blazhko effect is  $11.4 \pm 0.8\%$ . Due to selection effects and unknown completeness, this rate should be considered as a lower limit. When ab and c types are considered separately, the rate is slightly higher for the former than for the latter:  $12.1 \pm 0.9\%$  vs.  $9.2 \pm 1.3\%$ . The difference of  $2.9\%$  has low statistical significance ( $< 2\sigma$ ).

#### 4.2. Period, Amplitude and Magnitude Distributions

Marginal distributions of period, amplitude and apparent magnitude for the starting sample and Blazhko stars are compared in Fig. 10. Encouragingly, their magnitude distributions are statistically indistinguishable which indicates that the completeness is not a strong function of the photometric signal-to-noise ratio. This result is probably due to the fact that the sample is defined by the depth of LINEAR survey, while ZTF survey is deeper than this limit and its photometric quality is approximately constant across the probed magnitude range.

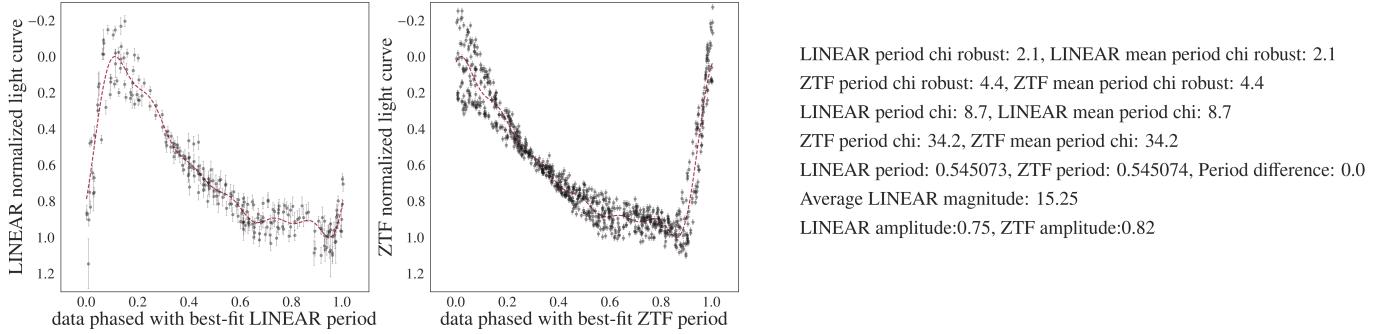
The suspected differences in amplitude and period distributions are further explored in Fig. 11. It is already discernible by eye that the period distribution for Blazhko stars of ab type is shifted to smaller values than for the starting sample. We have found that the median period for ab type Blazhko stars is about 5% shorter than for the starting RR Lyrae sample. This difference is significant at the  $7.1\sigma$  level. At the same time, the difference in median amplitudes for ab type stars corresponds to only  $0.6\sigma$  deviation. No statistically significant differences are found in period and amplitude distributions for c type stars.

If modulation amplitudes are correlated with periods such that larger modulation amplitudes occur in shorter period RRab stars, and if our selection efficiency is lower for smaller modulation amplitudes, then the detected period shift for ab type Blazhko stars might be at least partially due to combination of these two effects. This possibility does not appear likely. First, as we discussed in preceeding section, our sample is defined by the depth of LINEAR survey, while ZTF survey is significantly deeper than this limit and its photometric quality is approximately constant across the probed magnitude range. Since it is sufficient for a star to display the Blazhko effect only in ZTF to be included in the sample, we do not expect strong selection effects (except for the LINEAR magnitude cutoff of course). Furthermore, Skarka et al. (2020) searched for period - modulation amplitude correlation using a large sample of stars with OGLE measurements and did not find any.

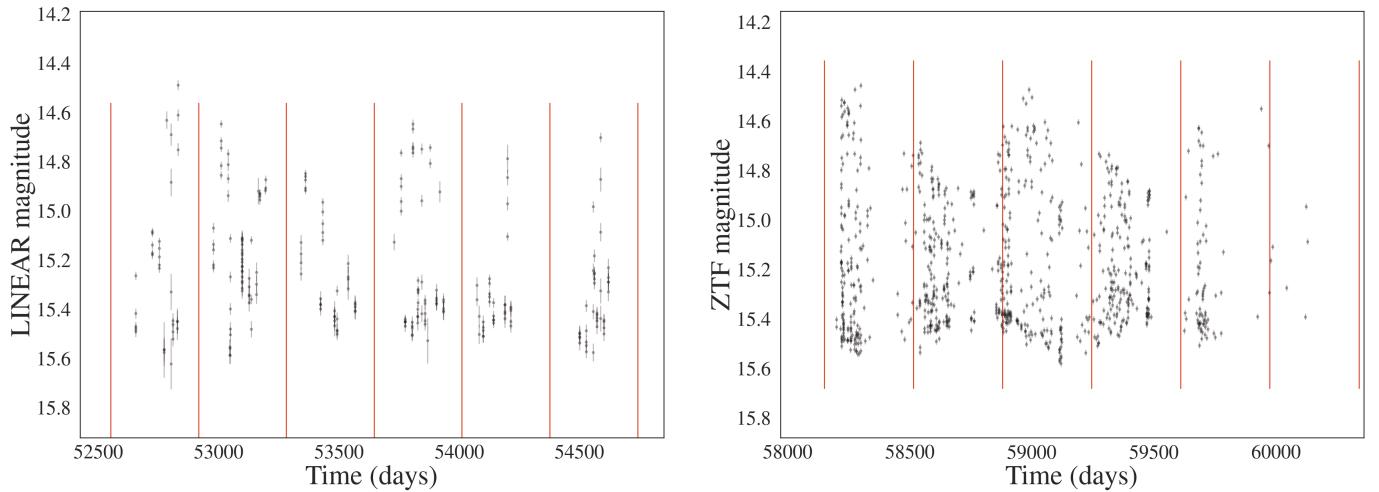
#### 4.3. Long-term behavior of Blazhko Stars

During visual analysis, we noticed that some Blazhko stars exhibit convincing Blazhko effect either in LINEAR or in ZTF data, but not in both surveys. Fig. 12 shows an example where amplitude modulation is clearly

## STAR 1140 from 2857



**Figure 6.** An illustration of visual analysis of phased light curves for the selected Blazhko candidates. The left panel shows LINEAR data and the right panel shows ZTF data (symbols with “error bars”) for star with LINEARid = 10030349. The dashed lines are best-fit models. The numbers listed on the right side were added to aid visual analysis. Note multiple coherent data point sequences offset from the best-fit mean model in the right panel.



**Figure 7.** An illustration of visual analysis of full light curves for the selected Blazhko candidates with emphasis on their repeatability between observing seasons, marked with vertical lines (left: LINEAR data; right: ZTF data). Data shown are for star with LINEARid = 10030349. Note strong amplitude modulation between observing seasons.

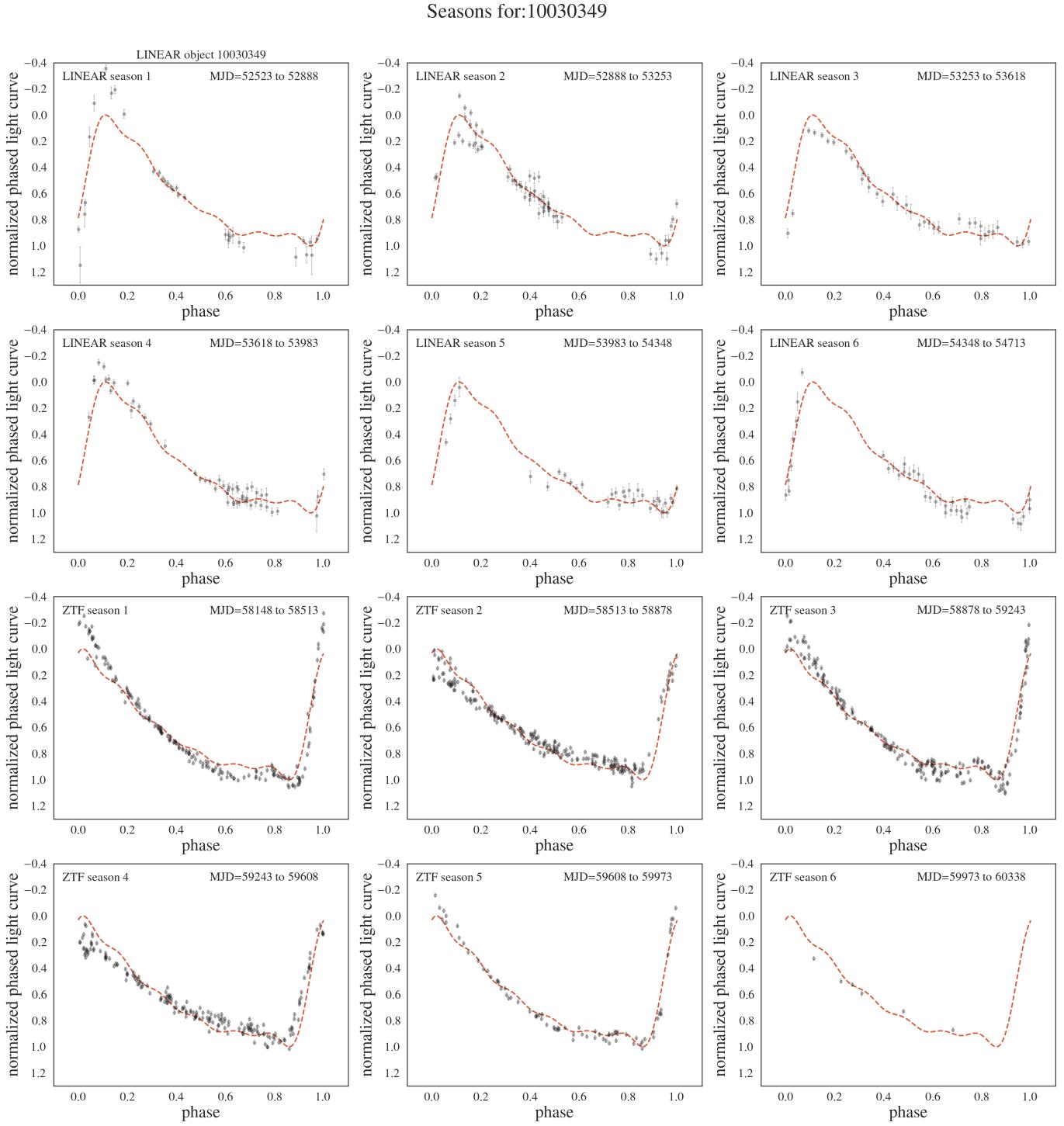
seen in LINEAR light curves, while not discernible in ZTF light curves. There are also examples of stars where Blazhko effect is evident in ZTF but not in LINEAR data (e.g., LINEARid = 19466437, 14155360). This finding strongly suggests that Blazhko effect can appear and disappear on time scales shorter than about a decade.

## 5. DISCUSSION AND CONCLUSIONS

We found excellent agreement between the best-fit periods for RR Lyrae stars estimated separately from LINEAR and ZTF light curves. Only one star in our sample (CT CrB, LINEARid=17919686), was previously reported as a Blazhko star (Skarka 2013). The sample of 228 stars presented here increases the number of field RR Lyrae stars displaying the Blazhko effect by more than 50% and places a lower limit of  $(11.4 \pm 0.8)\%$  for their incidence rate. The reported incidence rates for

the Blazhko effect range from 5% (Szczygieł & Fabrycky 2007) to 60% (Szabó et al. 2014). Differences in reported incidence rates can occur due to varying data precision, the temporal baseline length, and differences in visual or algorithmic analysis. For a relatively small sample of 151 stars with Kepler data, a claim has been made that essentially every RR Lyrae star exhibits modulated light curve (Kovacs 2018). The difference in Blazhko incidence rates for the two most extensive samples, obtained by the OGLE-III survey for the Large Magellanic Cloud (LMC, 20% out of 17,693 stars; Soszyński et al. 2009) and the Galactic bulge (30% out of 11,756 stars; Soszyński et al. 2011) indicates a possible variation of the Blazhko incidence rate with underlying stellar population properties.

We find that ab type RR Lyrae which show the Blazhko effect have about 5% (0.030 day) shorter periods than starting sample. While not large, the statis-



**Figure 8.** The phased light curves normalized to unit amplitude of the overall best-fit model are shown for single observing seasons and compared to the mean best-fit models (top six panels: LINEAR data; bottom six panels: ZTF data). Data shown are for star with LINEARid = 10030349 (period = 0.54073 day). Season-to-season phase and amplitude modulations are seen in both the LINEAR and the ZTF data.

tical significance of this difference is  $7.1\sigma$ . At a similar uncertainty level ( $\sim 1\%$ ), we don't detect period difference for c type stars, and don't detect any difference in amplitude distributions. We also find that for some stars the Blazhko effect is discernible in only one dataset. This finding strongly suggests that Blazhko effect can appear and disappear on time scales shorter than about a decade, in agreement with literature (Jurcsik et al. 2009; Poretti et al. 2010; Benkő et al. 2014).

The LINEAR and ZTF datasets analyzed in this work were sufficiently large that we had to rely on algorithmic pruning of the initial sample. The sample size problem will be even larger for surveys such as the Legacy Survey of Space and Time (LSST; Ivezić et al. 2019). LSST will be an excellent survey for studying Blazhko effect (Hernitschek & Stassun 2022) because it will have both a long temporal baseline (10 years) and a large number of observations per object (nominally 825; LSST Science Requirements Document<sup>5</sup>). We anticipate a higher fraction of discovered Blazhko stars with LSST than reported here due to better sampling and superior photometric quality, since the incidence rate of the Blazhko effect increases with sensitivity to small-amplitude modulation, and thus with photometric data quality (Jurcsik et al. 2009).

The size and quality of LSST sample will motivate further developments of the selection algorithms. One obvious improvement will be inspection of neighboring objects to confirm photometric quality, as well as inspection of images to test implication of an isolated point source (e.g., blended object photometry can be affected by variable seeing beyond aperture correction valid for isolated point sources). Another improvement is forward modeling of the Blazhko modulation, rather than searching for  $\chi^2$  outliers (Benkő et al. 2011; Guggenberger et al. 2012). For example, Skarka et al. (2020) classified Blazhko stars in 6 classes using the morphology of their amplitude modulation (the most dominant class includes 90% of the sample). They also found bimodal distribution of Blazhko periods, with two compo-

nents centered on 48 d and 186 d. These results give hope that forward modeling of the Blazhko effect will improve the selection of such stars.

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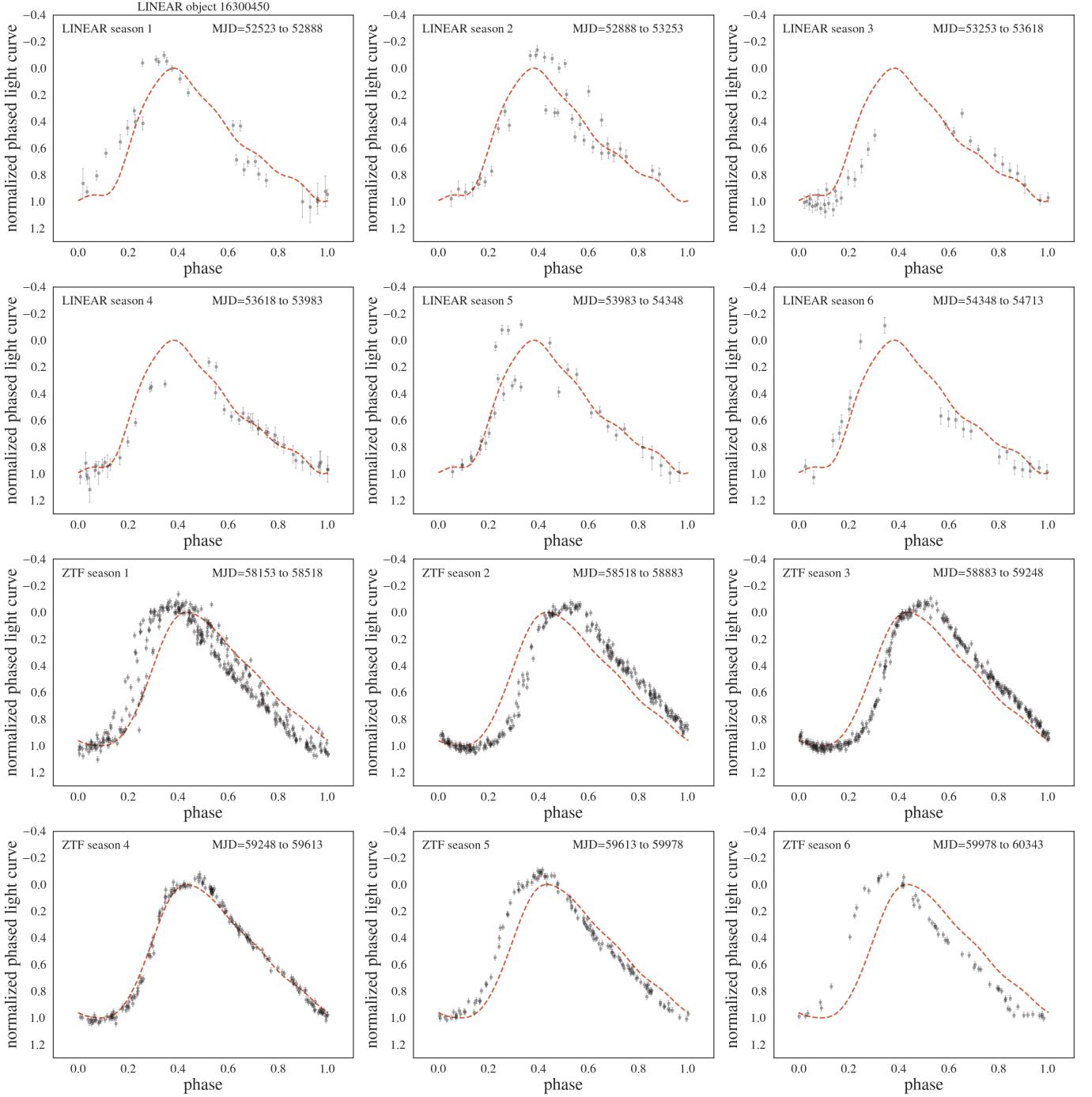
*Software:* Astropy (Astropy Collaboration et al. 2018, 2022), Matplotlib (Hunter 2007), SciPy (Virtanen et al. 2020), astroML (VanderPlas et al. 2012)

## APPENDIX

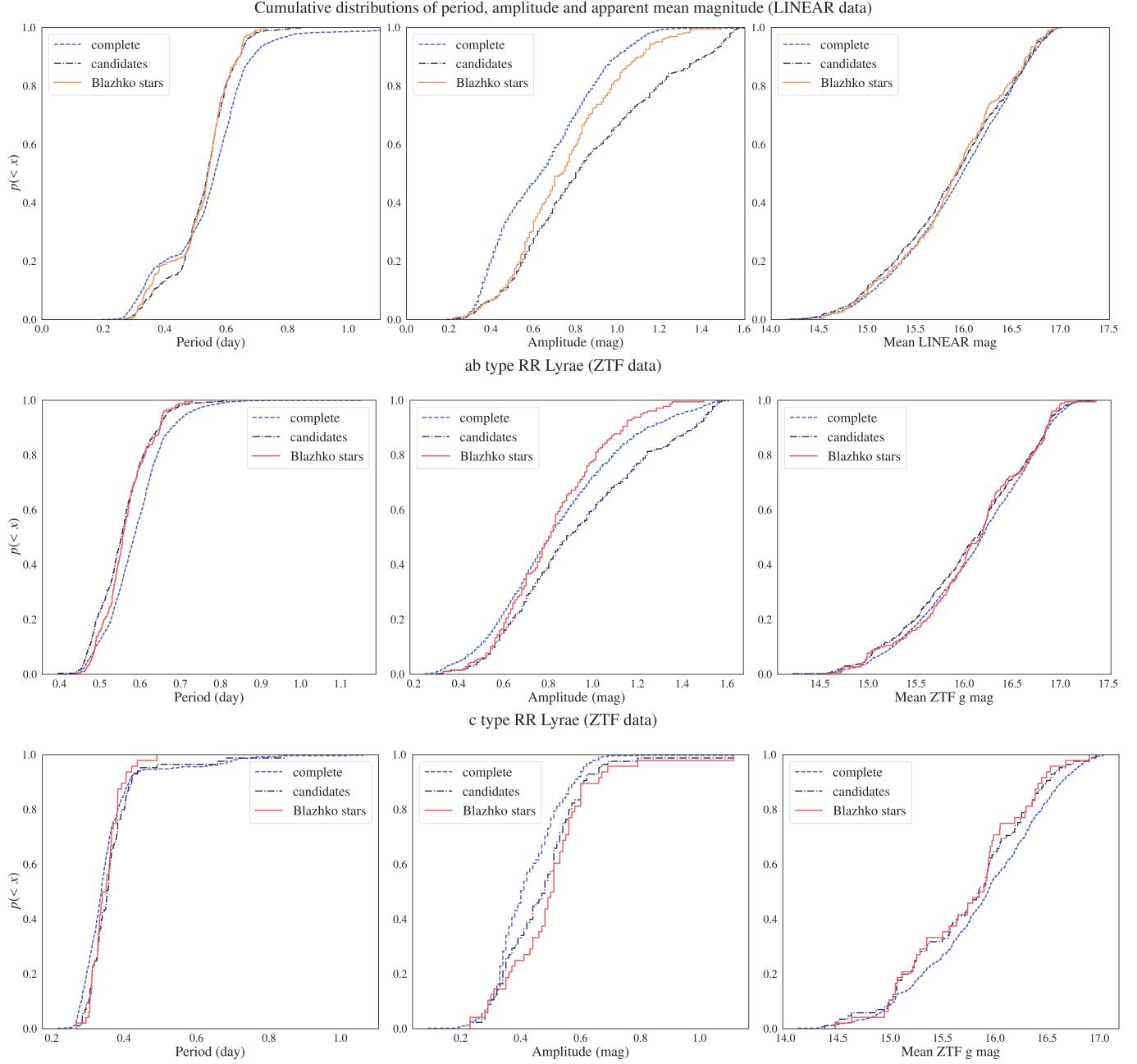
Table 1: The first 10 confirmed Blazhko stars with their LINEAR IDs in the first column and then, for both LINEAR and ZTF, their computed light curve periods (day), the number of data points per light curve, robust and ordinary  $\chi^2$  values, and light curve amplitudes, followed by amplitude difference between LINEAR and ZTF, the strength and period of Blazhko peaks in their periodograms, light curve type (1: ab, 2: c), detection significance flag for the periodograms (Z, L or “-” for no detection; the strength and period of Blazhko peaks are not reliable when “-”) and the selection score (see Sections 3.1 and 3.2 for details). The full table is available in online edition.

<sup>5</sup> Available as ls.st/srd

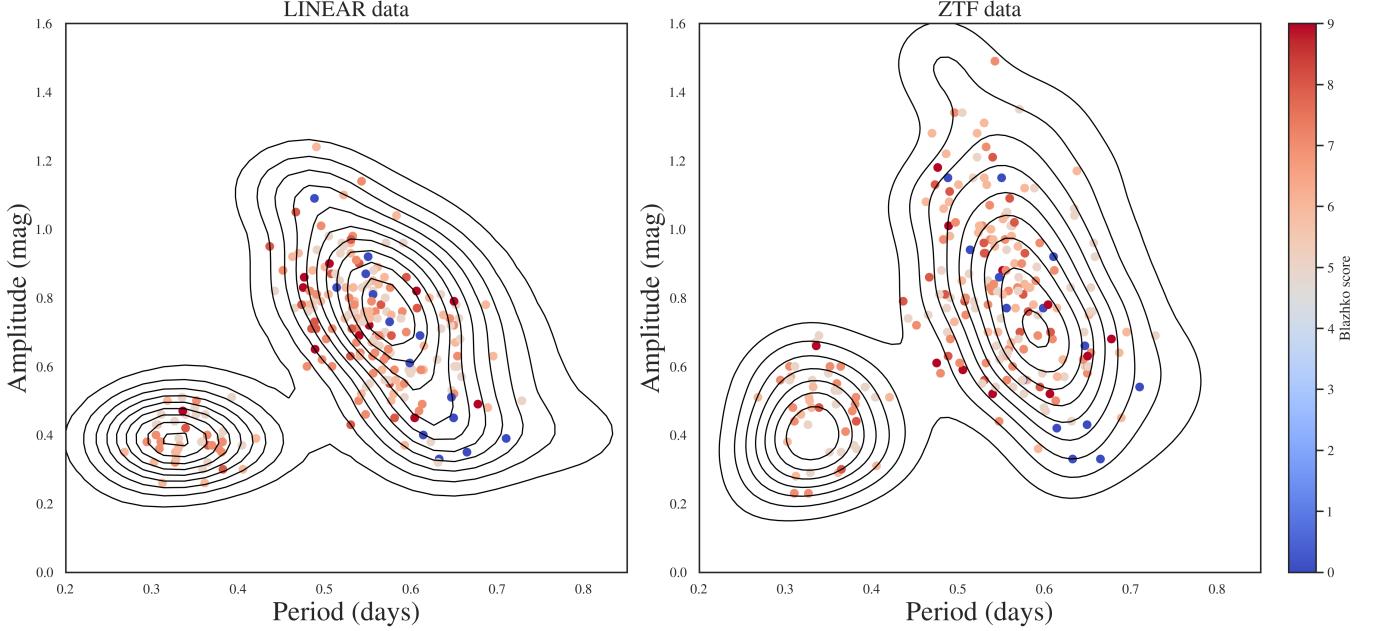
## Seasons for:16300450



**Figure 9.** Analogous to Fig. 8, except that star with LINEARid = 16300450 is shown (period = 0.33562 day). Unlike example shown in Fig. 8, only phase modulation is visible here, without any amplitude modulation, in both LINEAR and ZTF light curves.



**Figure 10.** A comparison of cumulative distributions of period (left), amplitude (middle) and apparent magnitude for starting sample, selected Blazhko candidates and visually verified Blazhko stars. The top row is based on LINEAR data and both ab type and c type stars. The middle and bottom rows are based on ZTF data, and show separately data for ab type and c type stars, respectively. The differences in period and amplitude distributions are further examined in figure 11.



**Figure 11.** Comparison of amplitude–period distributions (the Bailey diagram) for the starting sample of 1,996 RR Lyrae stars (contours) and 228 selected candidate Blazhko stars (symbols). The clump in the lower left corresponds to c type RR Lyrae and the other one to ab type. Note that the period distribution for ab type Blazhko stars is shifted left (by about 0.03 day, or 5%).

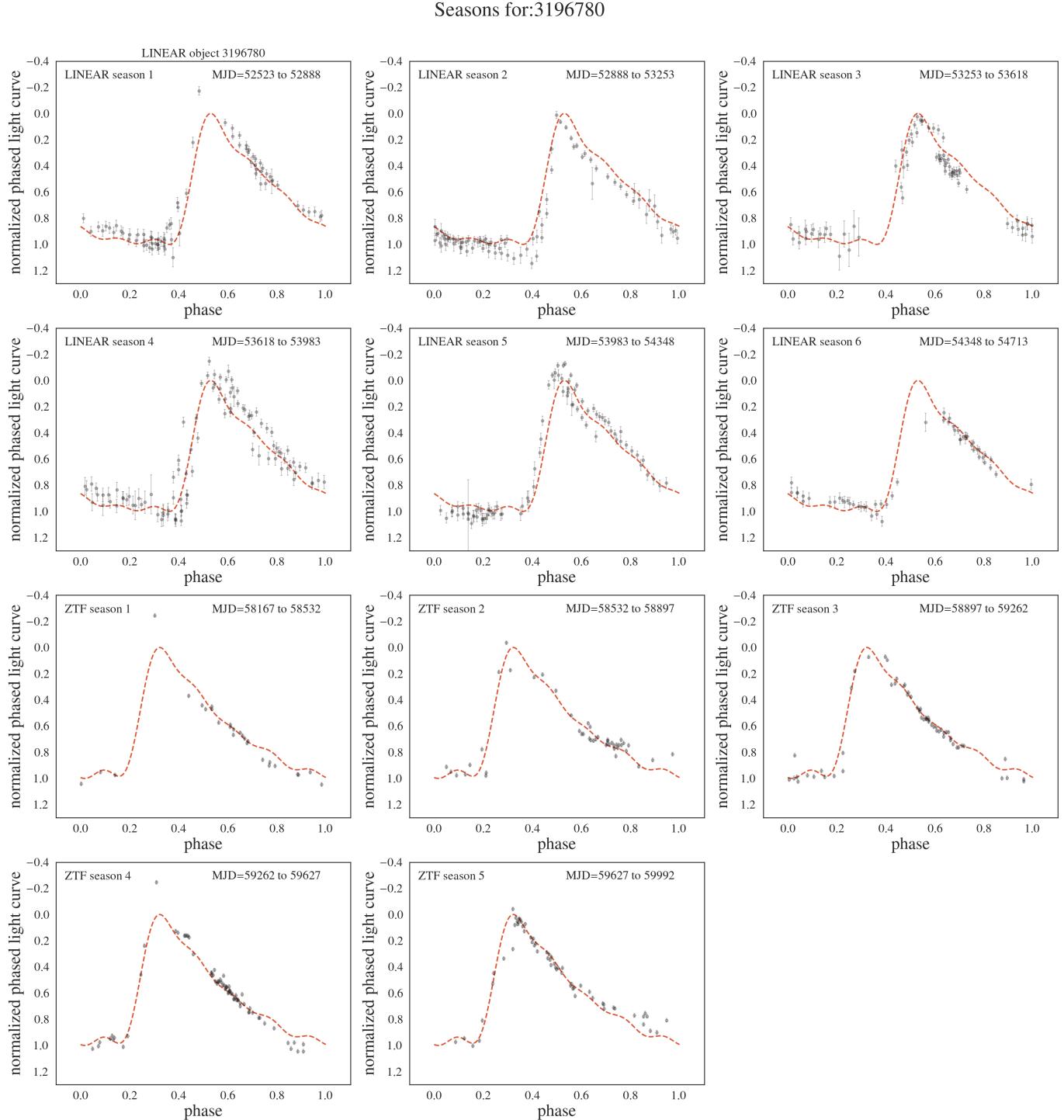
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LID	P <sub>L</sub>	P <sub>Z</sub>	N <sub>L</sub>	N <sub>Z</sub>	χ <sub>L,r</sub> <sup>2</sup>	χ <sub>Z,r</sub> <sup>2</sup>	χ <sub>L</sub> <sup>2</sup>	χ <sub>Z</sub> <sup>2</sup>	A <sub>L</sub>	A <sub>Z</sub>	δA	Bp <sub>L</sub>	Bp <sub>Z</sub>	Bp <sub>L</sub>	Bp <sub>Z</sub>	t	f	B <sub>s</sub>	B <sub>f</sub>
158779	0.609207	0.609189	293	616	1.6	3.9	3.7	34.2	0.47	0.68	0.21	1.6443	1.6444	352.7337	350.2	1	-	7	1
263541	0.558218	0.558221	270	503	2.9	6.6	15.8	110.4	0.64	0.82	0.18	1.8621	1.8025	14.1513	89.9	1	-	7	1
393084	0.530027	0.530033	493	372	1.1	3.2	1.6	19.2	0.96	1.31	0.35	1.9447	1.8896	17.2369	347.2	1	-	6	1
810169	0.465185	0.465212	289	743	2.1	2.8	6.0	15.1	0.77	0.75	0.02	2.2232	2.2230	13.6017	13.6	1	-	5	1
924301	0.507503	0.507440	418	189	1.9	9.3	13.8	162.9	0.87	0.79	0.08	2.0043	1.9763	29.5072	178.4	1	-	8	1
970326	0.592233	0.592231	275	552	1.1	2.1	1.9	7.7	0.51	0.75	0.24	1.7563	1.6992	14.7656	93.2	1	-	5	1
999528	0.658401	0.658407	564	213	1.2	2.7	1.8	21.7	0.57	0.92	0.35	1.5527	1.5510	29.5247	31.0	1	-	5	1
1005497	0.653607	0.653605	607	192	1.1	2.1	2.1	12.4	0.60	0.83	0.23	1.5639	1.5481	29.4638	55.1	1	-	5	1
1092244	0.649496	0.649558	590	326	1.2	3.6	2.3	32.1	0.72	0.58	0.14	1.5735	1.5640	29.5421	40.8	1	-	7	1
1240665	0.632528	0.632522	468	311	3.0	1.1	25.2	1.6	0.33	0.33	0.00	1.6149	1.5865	29.4942	182.3	1	Z	0	2

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**Figure 12.** Analogous to Fig. 8, except that star with LINEARid = 3196780 is shown. Amplitude modulation is clearly seen in LINEAR light curves (top two rows), while not discernible in ZTF light curves (bottom two rows). Additional stars with similar behavior include LINEARid = 2889542, 7723614, 8342007. This behavior strongly suggests that Blazhko effect can appear and disappear on time scales shorter than about a decade.

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