

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

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### 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 field 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](#)).

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<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

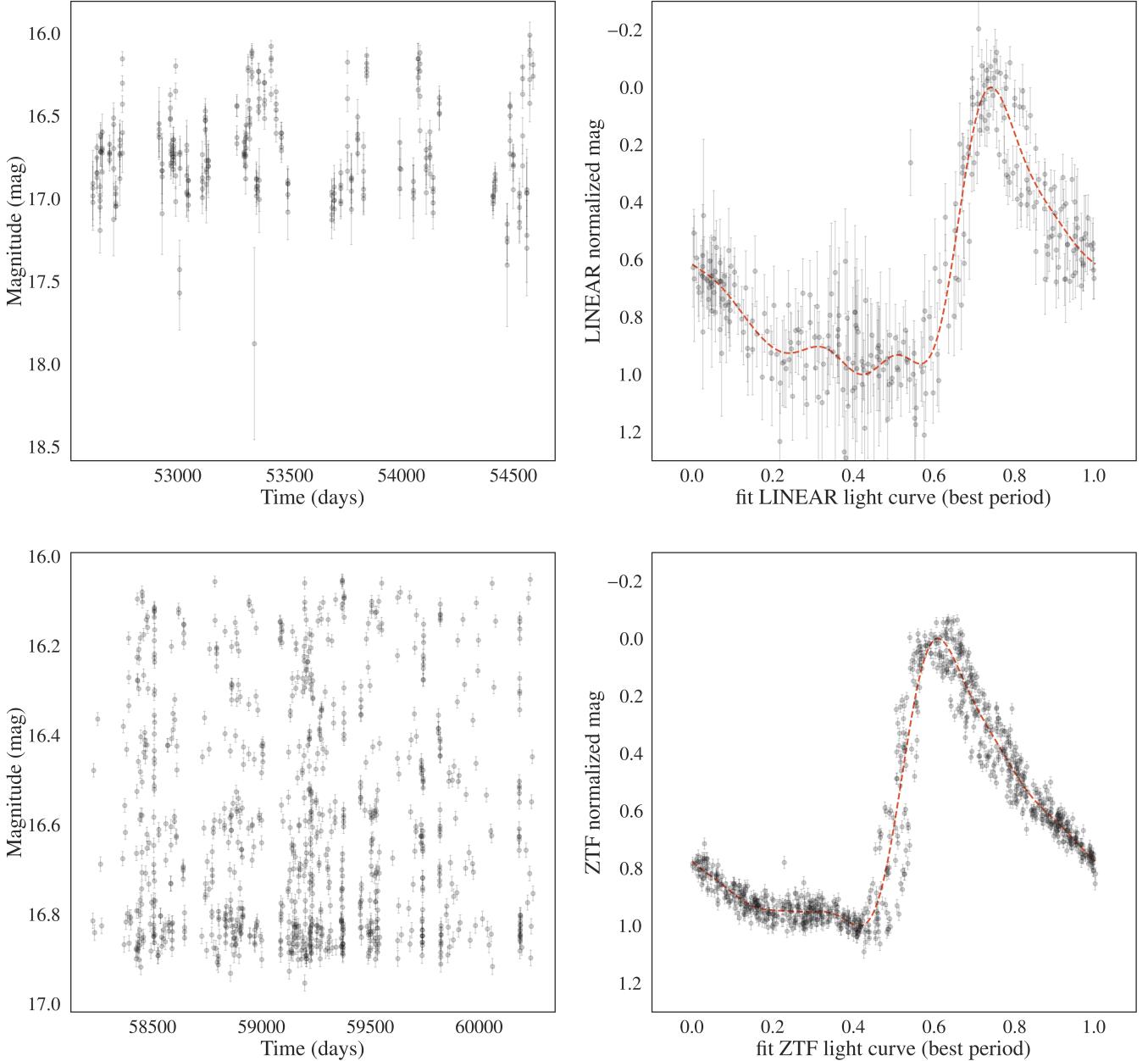
139 The first step of our analysis is estimating best-fit peri-  
 140 ods, separately for LINEAR and ZTF datasets. We used  
 141 the Lomb-Scargle method (Vanderplas 2015) as imple-  
 142 mented in *astropy* (Astropy Collaboration et al. 2018).  
 143 The period estimation used 3 Fourier components 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. RR Lyrae light curves may  
 167 experience phase changes of this magnitude (see e.g.,

<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)



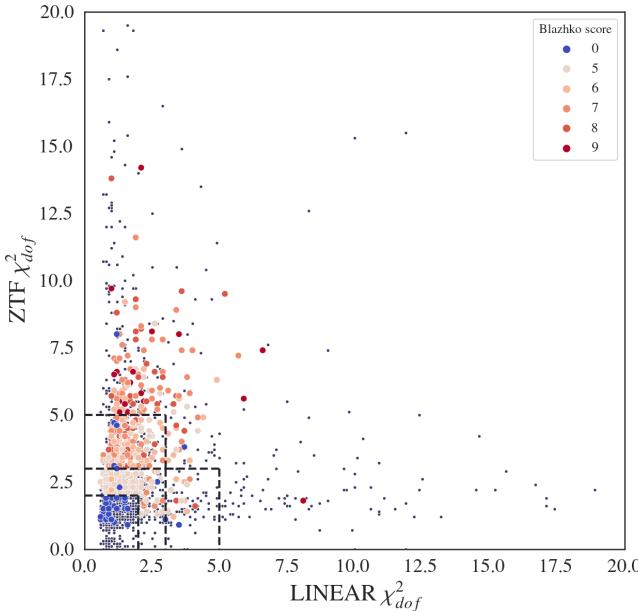
**Figure 1.** An example of a Blazhko star (LINEARid = 136668) with LINEAR (top row; period = 0.532923 day) and ZTF (bottom row; period = 0.532929 day) light curves (left panels, data points with “error bars”), phased light curves normalized to the 0–1 range (right panels, data points with “error bars”), 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.

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

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

### 176 3. ANALYSIS METHODOLOGY: SEARCHING FOR 177 THE BLAZHKO EFFECT

178 Given the two sets of light curves from LINEAR and  
 179 ZTF, we searched for amplitude and phase modulation,  
 180 either during the 5–6 years of data taking by each sur-  
 181 vey, or during the average span of 15 years between  
 182 the two surveys. Starting with a sample of 2857 RR  
 183 Lyrae stars, we pre-selected a smaller sample that was  
 184 inspected visually (see below for details). We also re-  
 185 quired at least 150 LINEAR data points and 150 ZTF



**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).

186 data points (for the selected band from which we cal-  
187 culated the period) in analyzed light curves. We used  
188 two pre-selection methods that are sensitive to differ-  
189 ent types of light curve modulation: direct light curve  
190 analysis and periodogram analysis, as follows.

### 3.1. Direct Light Curve Analysis

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

$$197 \chi^2_{dof} = \frac{1}{N_{dof}} \sum \frac{(d_i - m_i)^2}{\sigma_i^2}. \quad (1)$$

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

208 uncertainties  $\sigma_i$ , or to occasional non-Gaussian measure-  
209 ment error (the so-called outliers).

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

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

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

### 3.2. Periodogram Analysis

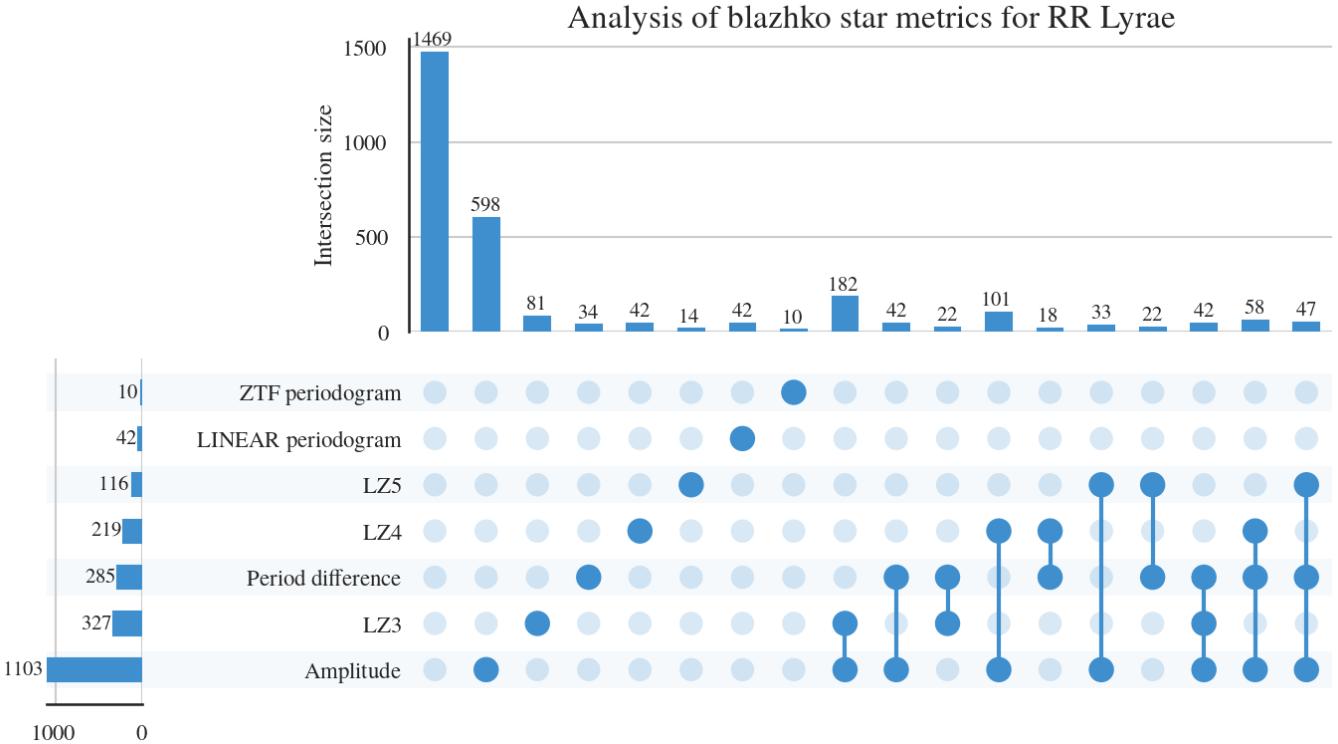
246 When light curve modulation is due to double-mode  
247 oscillation with two similar oscillation frequencies (peri-  
248 ods), it is possible to recognize its signature in the peri-  
249 odogram computed as part of the Lomb-Scargle analy-  
250 sis. Depending on various details, such as data sampling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

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

$$258 y(t) = 2 \cos(2\pi \frac{f_1 - f_2}{2} t) \sin(2\pi \frac{f_1 + f_2}{2} t). \quad (2)$$

259 We can define

$$260 f_o = \frac{f_1 + f_2}{2}, \quad (3)$$



**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.

and

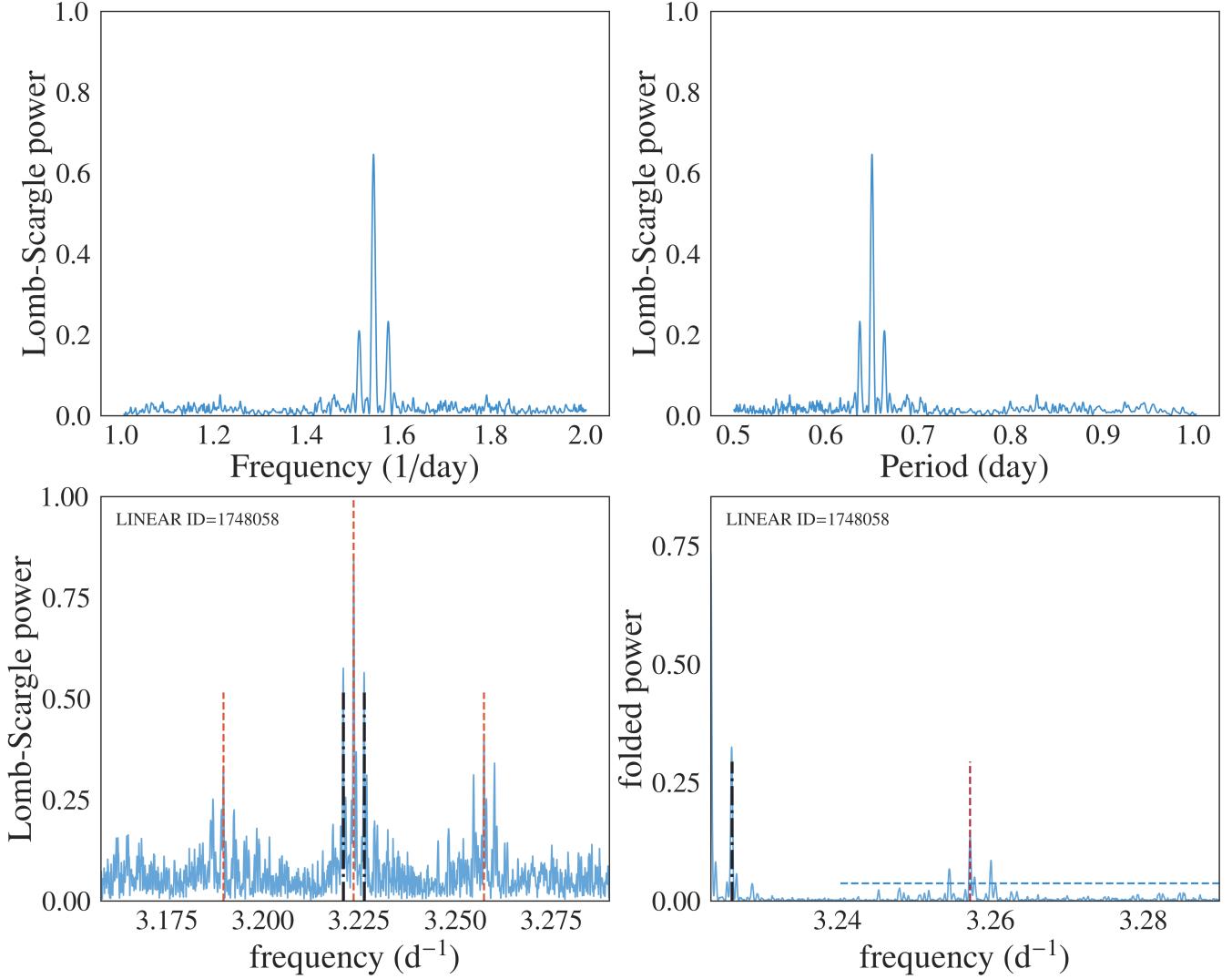
$$\Delta f = \left| \frac{f_1 - f_2}{2} \right|, \quad (4)$$

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 *sine* 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 efficient detection of moderately asymmetric peaks. However, this method is not sensitive to the subset of modulated stars where only one sidepeak is detectable (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

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



**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.

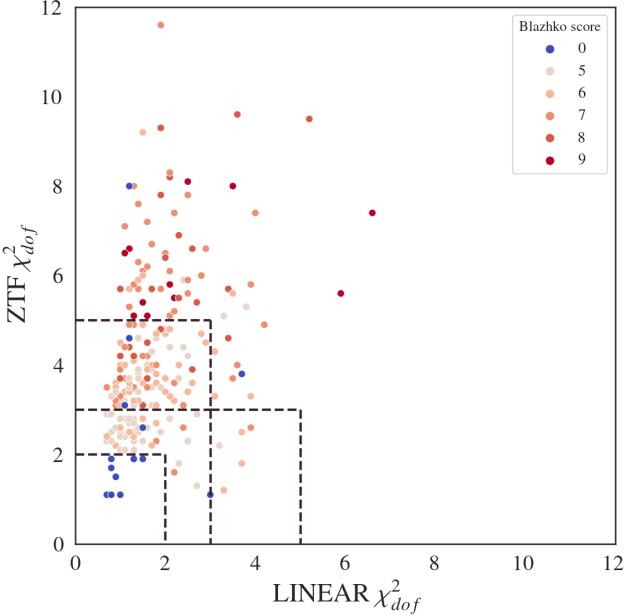
where  $f_{-,+}$  means the Blazhko sideband frequency with a higher amplitude is chosen.

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 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):

1. The shape of the phased light curves and scatter of data points around the best-fit model were examined for signatures of anomalous behavior indicative of the Blazhko effect. Fig. 6 shows an example of such behavior where the ZTF data and fit show multiple coherent data point sequences offset from the best-fit mean model.



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

- 302 2. Full light curves were inspected for their repeatability between observing seasons (Fig. 7). This step was sensitive to amplitude modulations with periods of the order a year or longer.
- 303 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>.

317 After visually analyzing the starting sample of 531 Blazhko candidates, we visually confirmed expected 318 Blazhko behavior for 228 stars (214 out of 479 and 14 out 319 of 52). LINEAR IDs and other characteristics for 320 confirmed Blazhko stars are listed in Table 1 (Appendix A). 321 Statistical properties of the selected sample of Blazhko 322 stars are discussed in detail in the next section.

#### 324 4. RESULTS

325 Starting with a sample of 2857 field RR Lyrae stars 326 with both LINEAR and ZTF data, we constructed a

<sup>4</sup> The physical reason for large phase modulations remains unclear: stellar companions may cause small variations through the light-time effect (Hajdu et al. 2021), but some RRc stars show phase variations well exceeding that (e.g., Derekas et al. 2004; Sóder et al. 2017; Le Borgne & Klotz 2019).

327 subsample of 1996 with light curves of sufficient quality 328 and selected and verified 228 stars that exhibit convincing 329 Blazhko effect. In this section we compare various 330 statistical properties of selected Blazhko stars to those 331 of the starting sample.

#### 332 4.1. The Blazhko Incidence Rate

333 The implied incidence rate for the Blazhko effect is 334  $11.4 \pm 0.8\%$ . Due to selection effects and unknown com- 335 pleteness, this rate should be considered as a lower limit. 336 When ab and c types are considered separately, the 337 rate is slightly higher for the former than for the lat- 338 ter:  $12.1 \pm 0.9\%$  vs.  $9.2 \pm 1.3\%$ . The difference of 2.9% 339 has low statistical significance ( $< 2\sigma$ ).

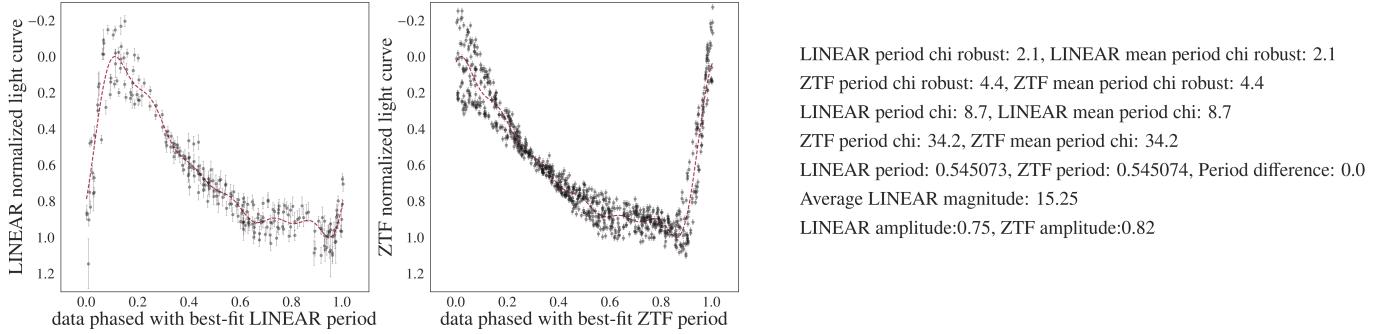
#### 340 4.2. Period, Amplitude and Magnitude Distributions

341 Marginal distributions of period, amplitude and ap- 342 parent magnitude for the starting sample and Blazhko 343 stars are compared in Fig. 10. Encouragingly, their mag- 344 nitude distributions are statistically indistinguishable 345 which indicates that the completeness is not a strong 346 function of the photometric signal-to-noise ratio. This 347 result is probably due to the fact that the sample is 348 defined by the depth of LINEAR survey, while ZTF sur- 349 vey is deeper than this limit and its photometric quality 350 is approximately constant across the probed magnitude 351 range.

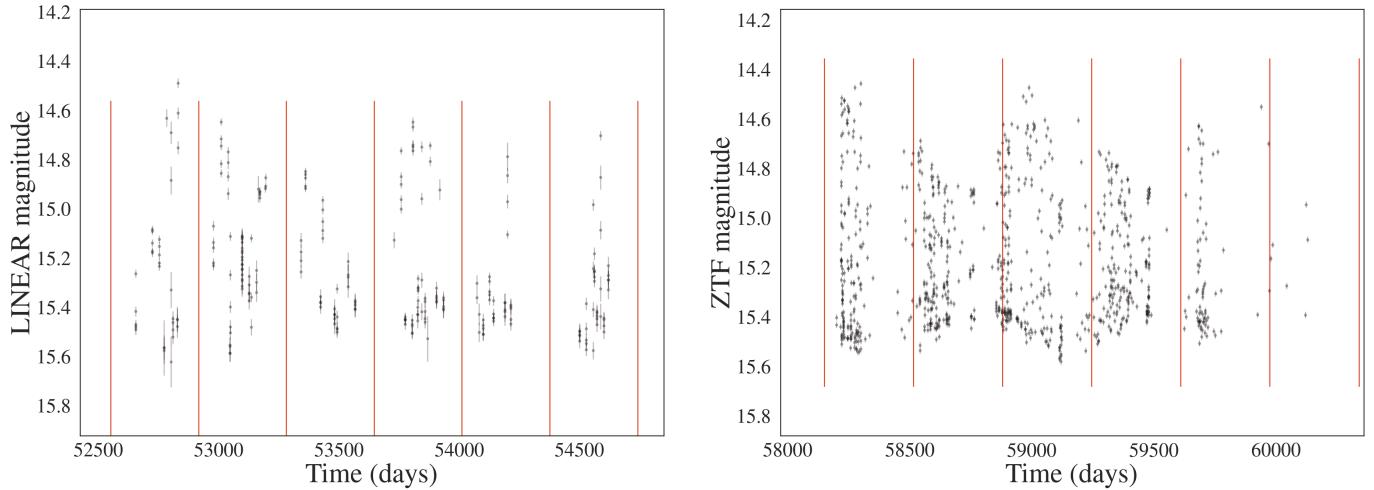
352 The suspected differences in amplitude and period 353 distributions are further explored in Fig. 11. It is al- 354 ready discernible by eye that the period distribution for 355 Blazhko stars of ab type is shifted to smaller values than 356 for the starting sample. We have found that the median 357 period for ab type Blazhko stars is about 5% shorter 358 than for the starting RR Lyrae sample. This difference 359 is significant at the  $7.1\sigma$  level. At the same time, the 360 difference in median amplitudes for ab type stars cor- 361 responds to only  $0.6\sigma$  deviation. No statistically sig- 362 nificant differences are found in period and amplitude 363 distributions for c type stars.

364 If modulation amplitudes are correlated with periods 365 such that larger modulation amplitudes occur in shorter 366 period RRab stars, and if our selection efficiency is lower 367 for smaller modulation amplitudes, then the detected 368 period shift for ab type Blazhko stars might be at least 369 partially due to combination of these two effects. This 370 possibility does not appear likely. First, as we discussed 371 in preceeding section, our sample is defined by the depth 372 of LINEAR survey, while ZTF survey is significantly 373 deeper than this limit and its photometric quality is 374 approximately constant across the probed magnitude 375 range. Since it is sufficient for a star to display the 376 Blazhko effect only in ZTF to be included in the sam- 377 ple, we do not expect strong selection effects (except for 378 the LINEAR magnitude cutoff of course). Furthermore, 379 Skarka et al. (2020) searched for period - modulation 380 amplitude correlation using a large sample of stars with 381 OGLE measurements and did not find any.

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.

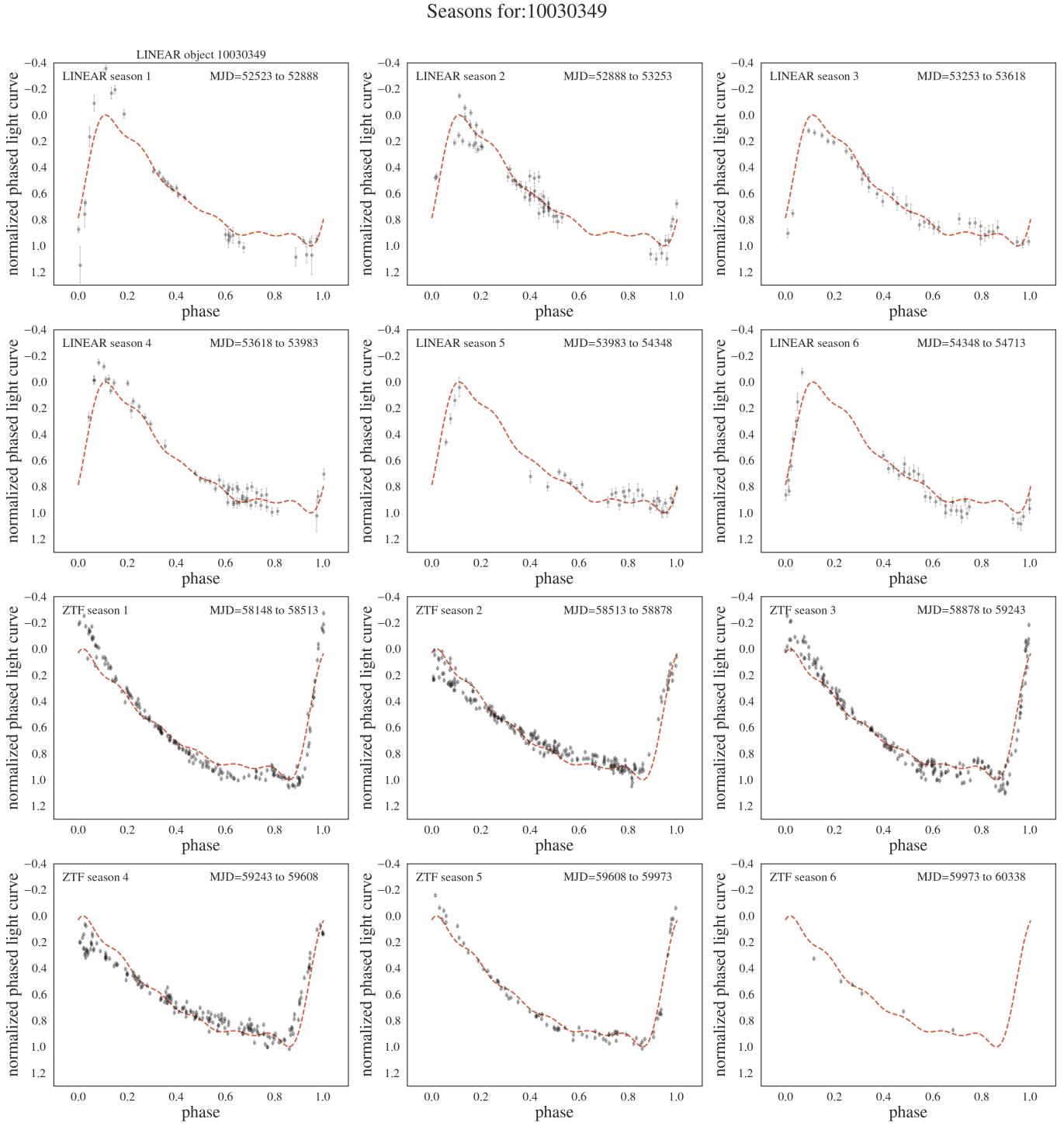
#### 4.3. Long-term behavior of Blazhko Stars

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 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 re-

ported 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



**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.

417 the Blazhko incidence rate with underlying stellar pop-  
 418 ulation properties.

419 We find that ab type RR Lyrae which show the  
 420 Blazhko effect have about 5% (0.030 day) shorter pe-  
 421 riods than starting sample. While not large, the statis-  
 422 tical significance of this difference is  $7.1\sigma$ . At a similar  
 423 uncertainty level ( $\sim 1\%$ ), we don't detect period differ-  
 424 ence for c type stars, and don't detect any difference  
 425 in amplitude distributions. We also find that for some  
 426 stars the Blazhko effect is discernible in only one dataset.  
 427 This finding strongly suggests that Blazhko effect can  
 428 appear and disappear on time scales shorter than about  
 429 a decade, in agreement with literature (Jurcsik et al.  
 430 2009; Poretti et al. 2010; Benkő et al. 2014).

431 The LINEAR and ZTF datasets analyzed in this work  
 432 were sufficiently large that we had to rely on algorithmic  
 433 pruning of the initial sample. The sample size problem  
 434 will be even larger for surveys such as the Legacy Sur-  
 435 vey of Space and Time (LSST; Ivezić et al. 2019). LSST  
 436 will be an excellent survey for studying Blazhko effect  
 437 (Hernitschek & Stassun 2022) because it will have both  
 438 a long temporal baseline (10 years) and a large number  
 439 of observations per object (nominally 825; LSST Sci-  
 440 ence Requirements Document<sup>5</sup>). We anticipate a higher  
 441 fraction of discovered Blazhko stars with LSST than re-  
 442 ported here due to better sampling and superior photo-  
 443 metric quality, since the incidence rate of the Blazhko  
 444 effect increases with sensitivity to small-amplitude mod-  
 445 ulation, and thus with photometric data quality (Jurcsik  
 446 et al. 2009).

447 The size and quality of LSST sample will motivate  
 448 further developments of the selection algorithms. One  
 449 obvious improvement will be inspection of neighboring  
 450 objects to confirm photometric quality, as well as inspec-  
 451 tion of images to test implication of an isolated point  
 452 source (e.g., blended object photometry can be affected  
 453 by variable seeing beyond aperture correction valid for  
 454 isolated point sources). Another improvement is for-  
 455 ward modeling of the Blazhko modulation, rather than  
 456 searching for  $\chi^2$  outliers (Benkő et al. 2011; Guggen-  
 457 berger et al. 2012). For example, Skarka et al. (2020)  
 458 classified Blazhko stars in 6 classes using the morphol-  
 459 ogy of their amplitude modulation (the most dominant  
 460 class includes 90% of the sample). They also found bi-  
 461 modal distribution of Blazhko periods, with two compo-  
 462 nents centered on 48 d and 186 d. These results give  
 463 hope that forward modeling of the Blazhko effect will  
 464 improve the selection of such stars.

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 483 Oschin Telescope 48-inch and the 60-inch Telescope at  
 484 the Palomar Observatory as part of the Zwicky Tran-  
 485 sient Facility project. ZTF is supported by the Na-  
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 489 stitute of Science, the Oskar Klein Center at Stock-  
 490 holm University, the University of Maryland, Deutsches  
 491 Elektronen-Synchrotron and Humboldt University, the  
 492 TANGO Consortium of Taiwan, the University of Wis-  
 493 consin at Milwaukee, Trinity College Dublin, Lawrence  
 494 Livermore National Laboratories, IN2P3, University of  
 495 Warwick, Ruhr University Bochum, Northwestern Uni-  
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 505 endorsed by the United States Government.

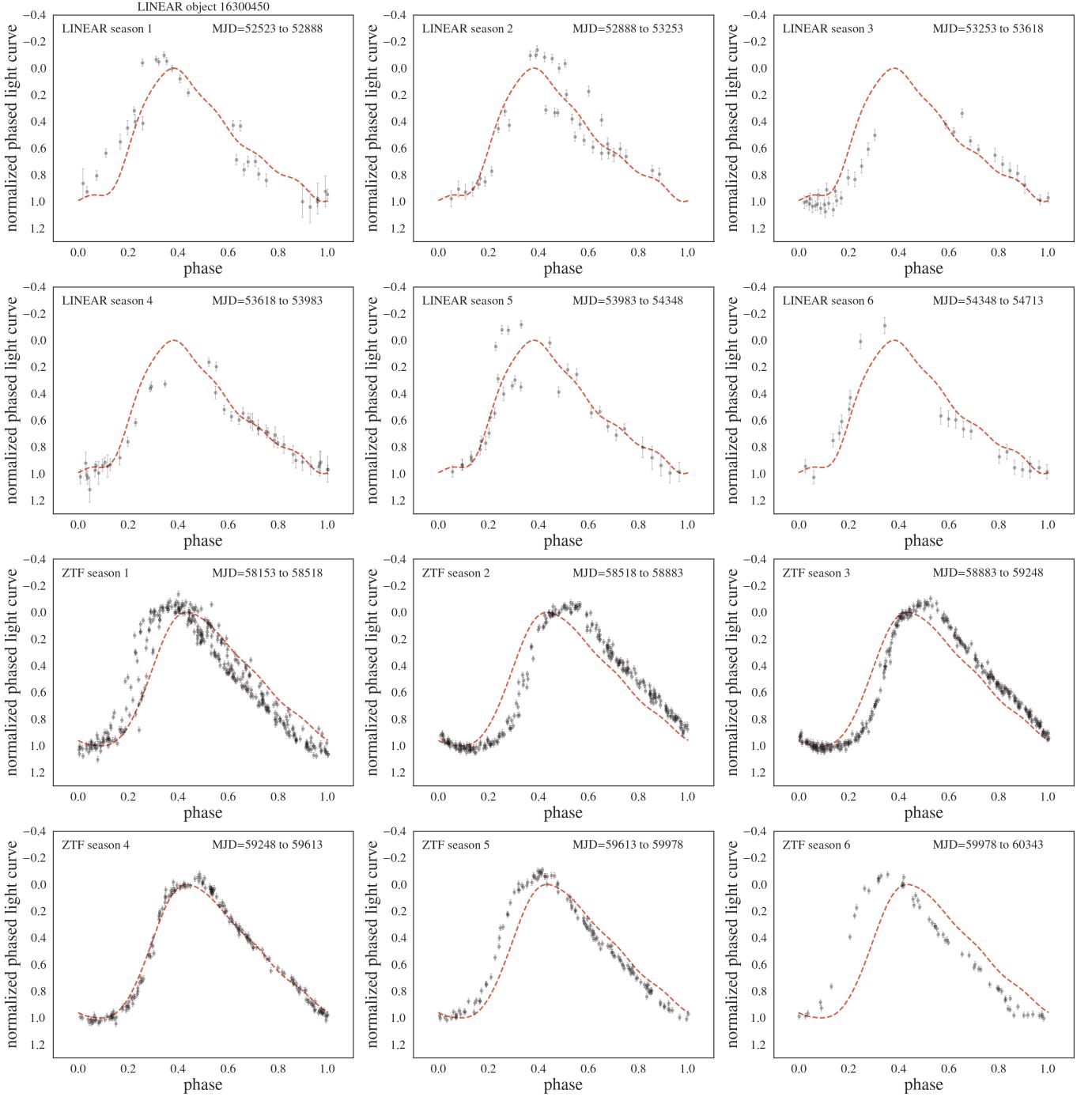
506 *Software:* Astropy (Astropy Collaboration et al.  
 507 2018, 2022), Matplotlib (Hunter 2007), SciPy (Virtanen  
 508 et al. 2020), astroML (VanderPlas et al. 2012)

## APPENDIX

510 Table 1: The first 10 confirmed Blazhko stars with their LINEAR IDs in the first column and then, for both LINEAR  
 511 and ZTF, their computed light curve periods (day), the number of data points per light curve, robust and ordinary

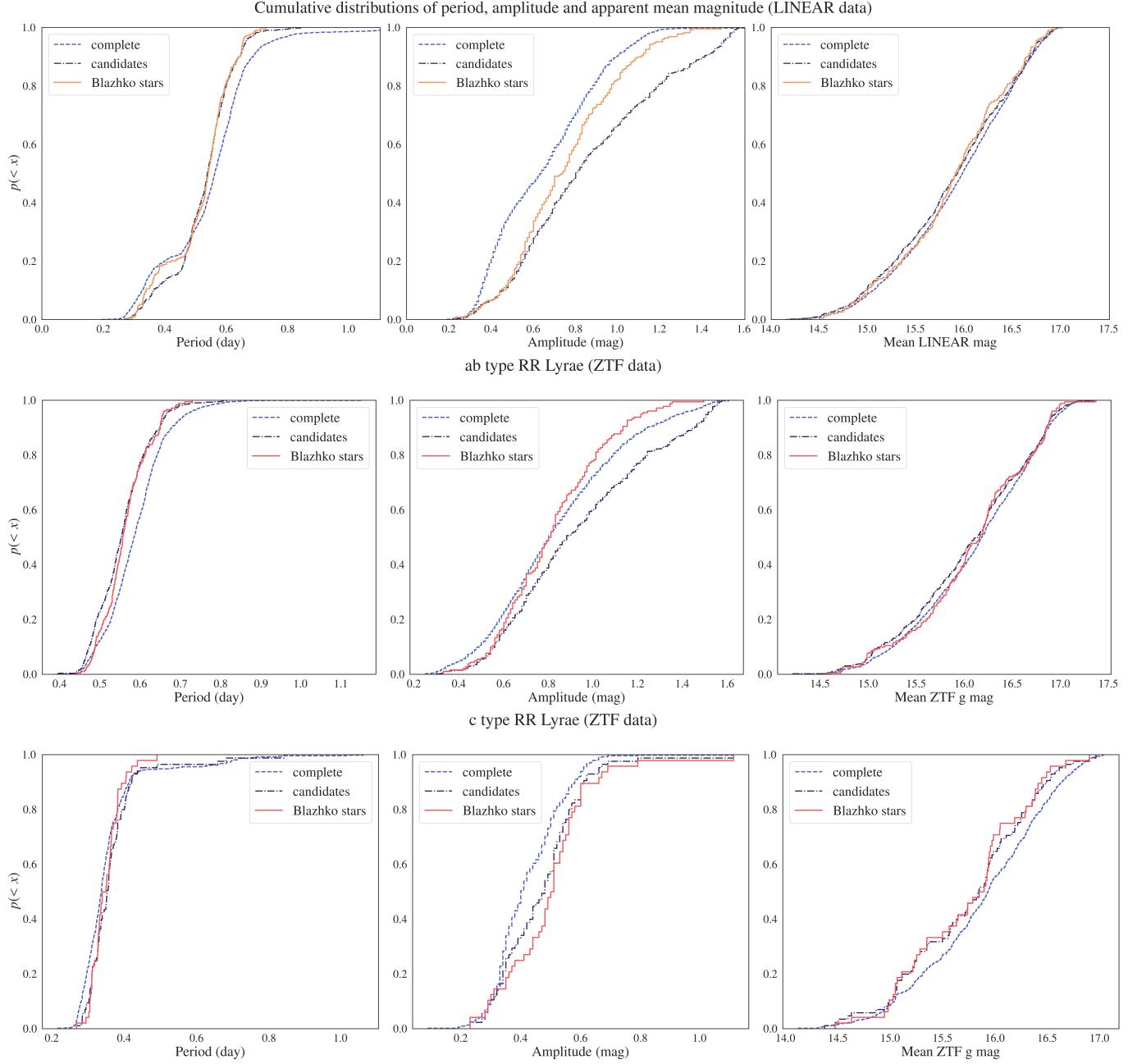
<sup>5</sup> Available as ls.st/srd

## Seasons for:16300450

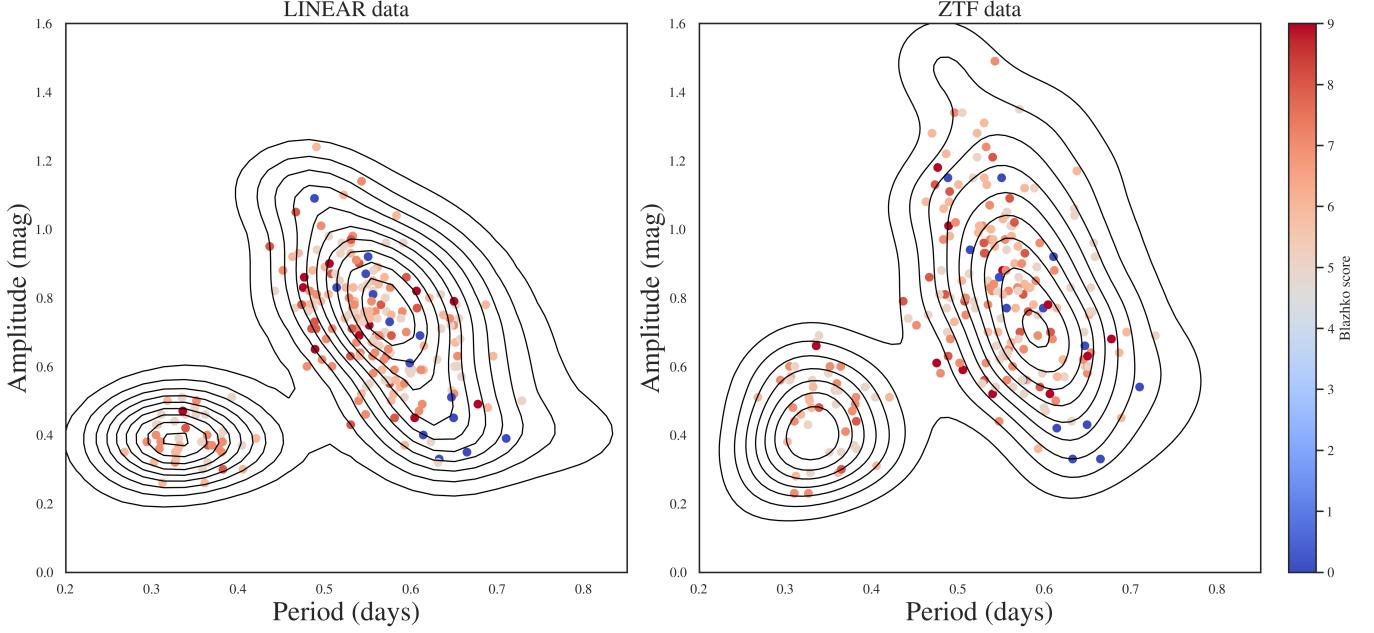


**Figure 9.** Analogous to Fig. 8, except that star with LINEARid = 16300450 is shown (period = 0.33562 day). Unlike example shown in Fig. 8, only phase modulation is visible here, without any amplitude modulation, in both LINEAR and ZTF light curves.

<sup>512</sup>  $\chi^2$  values, and light curve amplitudes, followed by amplitude difference between LINEAR and ZTF, the strength  
<sup>513</sup> and period of Blazhko peaks in their periodograms, light curve type (1: ab, 2: c), detection significance flag for the  
<sup>514</sup> periodograms (Z, L or “-” for no detection; the strength and period of Blazhko peaks are not reliable when “-” ) and  
<sup>515</sup> the selection score (see Sections 3.1 and 3.2 for details). The full table is available in online edition.



**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%).

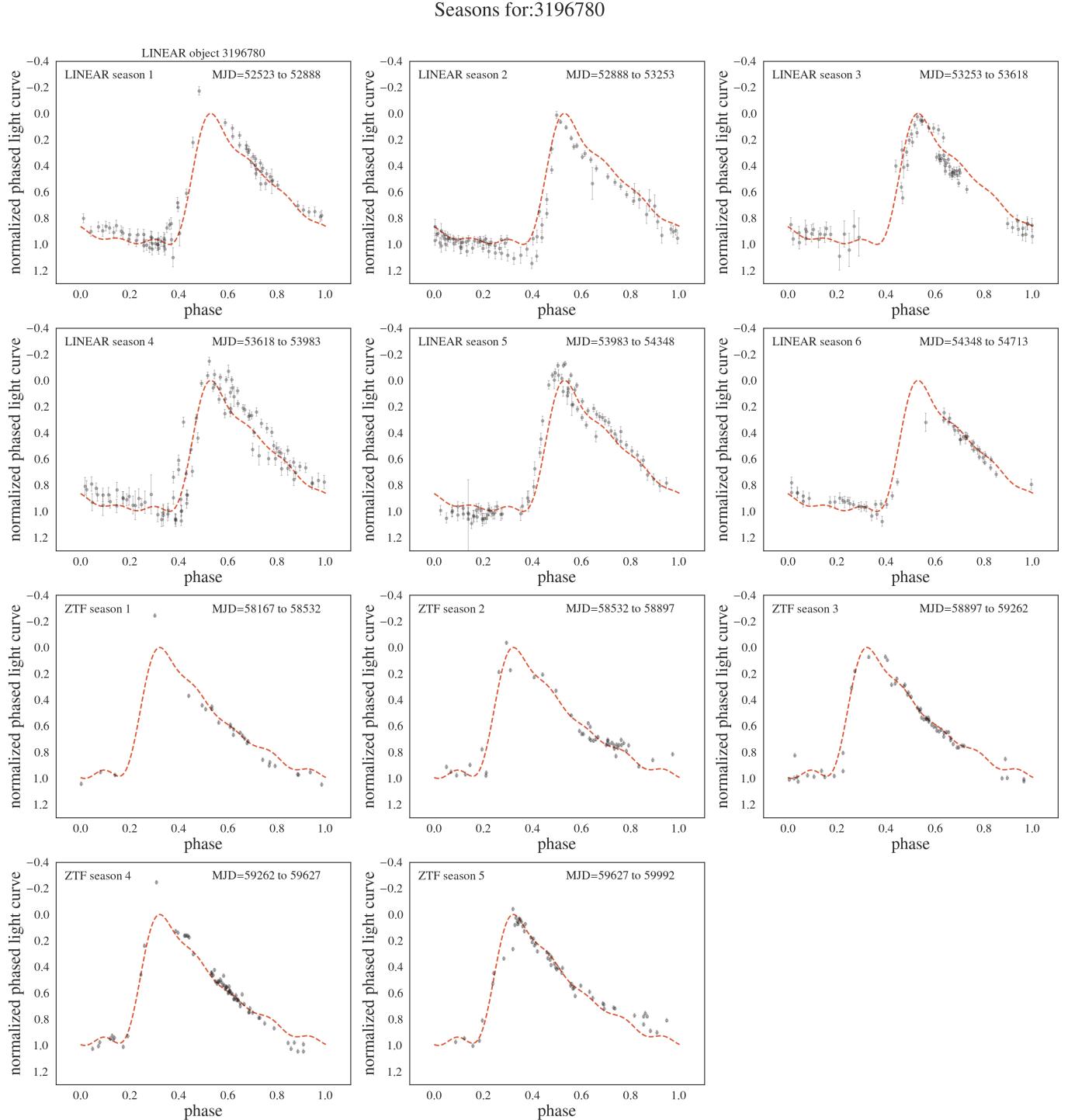
516

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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