THE ALL-SKY GEOS RR Lyr SURVEY WITH THE TAROT TELESCOPES: ANALYSIS OF THE BLAZHKO EFFECT

J.-F. Le Borgne1,2,3, A. Klotz1,2,3,4, E. Poretti1,2,3,5, M. Boër8, N. Butterworth5, M. Dumont3, S. Dvorak7, F.-J. Hambisch3,7,8,9, F. Hund8, F. Kugel10, J. Vandenbergbroege3, and J. M. Vilalta11

1 Université de Toulouse, UPS-OMP, IRAP, 31400 Toulouse, France
2 CNRS, IRAP, 14 avenue Edouard Belin, 31400 Toulouse, France
3 Groupe Européen d’Observations Stellaire (GEOS), 23 Parc de Levesville, 28300 Bailleul l’Evèque, France
4 Observatoire de Haute-Provence (CNRS), Saint Michel l’Observatoire, France
5 INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate (LC), Italy
6 ARTEMIS, Université Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d’Azur, Nice, France
7 American Association of Variable Star Observers (AAVSO), 49 Bay State Rd., Cambridge, MA 02138, USA
8 Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V. (BAV), Munsterdamm 90, 12169 Berlin, Germany
9 Vereniging Voor Sterrekunde (VVS), Oude Bleken 12, 2400 Mol, Belgium
10 Observatoire Chante-Perdrix, 04150 Banon, France
11 Agrupació Astronòmica de Sabadell (AAS), Apartat de Correus, 50, 08200 Sabadell (Barcelona), Spain

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ABSTRACT

We used the GEOS database to study the Blazhko effect of galactic RRab stars. The database is continuously enriched by maxima supplied by amateur astronomers and by a dedicated survey by means of the two TAROT robotic telescopes. The same value of the Blazhko period is observed at different values of the pulsation periods and different values of the Blazhko periods are observed at the same value of the pulsation period. There are clues suggesting that the Blazhko effect is changing from one cycle to the next. The secular changes in the pulsation and Blazhko periods of Z CVn are anticorrelated. The diagrams of magnitudes against phases of the maxima clearly show that the light curves of Blazhko variables can be explained as modulated signals, both in amplitude and in frequency. The closed curves describing the Blazhko cycles in such diagrams have different shapes, reflecting the phase shifts between the epochs of the brightest maximum and the maximum \( O = C \). Our sample shows that both clockwise and counterclockwise directions are possible for similar shapes. The improved observational knowledge of the Blazhko effect, in addition to some peculiarities of the light curves, has yet to be explained by a satisfactory physical mechanism.

Key words: astronomical databases: miscellaneous – stars: evolution – stars: horizontal-branch – stars: variables: RR Lyrae

1. INTRODUCTION

In the early 20th century S. N. Blazhko pointed out cycle-to-cycle variations in the light curves of Var 87.1906 Draconis≡RW Dra, discovered by L. P. Tserasskaya at Moscow Observatory (Tseveich 1969). The periodic changes in the times of maximum brightness were fitted by adding a sinusoidal term to the linear ephemeris, as happened a few years later when the same effect was observed in the case of RR Lyr (Shapley 1916). After being discovered in several other RR Lyr stars, the variations of the times of maximum brightness \( T_{\text{max}} \) and of the magnitudes at maximum \( V_{\text{max}} \) were defined as the Blazhko effect since the list of maxima recorded from 1906 July 15 to August 25 on RW Dra (Blazhko 1907) constituted the first evidence of it. Klepikova (1956) reported on one of the first observational projects to study the Blazhko effect in a systematic way.

The characteristics of the Blazhko stars discovered in the 20th century (Szeidl 1976, 1988; Smith 1995) were determined by searching for periodicities in the \( V_{\text{max}} \) and/or \( O = C \) (observed minus calculated \( T_{\text{max}} \)) values and/or by performing a frequency analysis of the photometric timeseries. In the latter case the periodic variations of the shape of the light curve cause a multiplet centered on the pulsational frequency and with a separation equal to the Blazhko frequency.

The number of Blazhko stars did not increase significantly until the advent of CCD techniques. Stars much fainter than the threshold for photoelectric photometry could be discovered in large-scale surveys as MAssive Compact Halo (MACHO; Alcock et al. 2003) and Optical Gravitational Lensing Experiment (OGLE; Sozyski et al. 2010, and references therein). Moskalik & Poretti (2003) suggested that ~23% of the RRab stars in the galactic bulge shows a Blazhko effect. Collinge et al. (2006) substantially confirmed this incidence (27.6%) by performing an analysis on a larger sample and a longer baseline. A much larger incidence was found in the Konkoly Blazhko Surveys (KBSs): 14 out of 30 (47%) in the KBS I (Jurcsik et al. 2009b) and 45 out of 105 (43%) in the KBS II (Sódor et al. 2012). This is probably due to the very small modulations, which could be detected thanks to the multicolor CCD photometry performed with an automatic 60 cm telescope. The Konkoly surveys also provide information on the changes in the physical parameters during the Blazhko cycle.

The observational scenario changed with the continuous monitoring of Blazhko RR variables with the satellites CoRoT (Chadid et al. 2010; Poretti et al. 2010; Guggenberger et al. 2011) and Kepler (Kolenberg et al. 2010; Szabó et al. 2010). The lack of any relevant alias structure in the spectral windows of the space-based timeseries allowed us to obtain new results, as evidence of large cycle-to-cycle variations of the Blazhko effect (Guggenberger et al. 2011), of the excitation of additional modes (Poretti et al. 2010), and of the period doubling bifurcation (Szabó et al. 2010).
Figure 1. Spectral windows of three RR Lyr stars having different periods.

Figure 2. Light curves of the non-Blazhko stars BC Dra (top panel) and AR Per (middle panel). The residuals of the BC Dra data after a fit with harmonics up to 12f (lower panel) show the irregular repetitivity of the shoulder on the rising branch.
Despite these new observational results, the physical explanation of the Blazhko effect still remains controversial. Very different mechanisms were invoked: the oblique-pulsator model (Kurtz 1982; Shibahashi 2000), the resonant pulsator model (Dziembowski & Mizerski 2004), and the action of a turbulent convective dynamo (Stothers 2006). None of these models are able to provide a close match between theory and observations (Kovács 2009) and then it seems that we are still far from a satisfactory theoretical explanation.

The Groupe Européen d’Observations Stellaires (GEOS) RR Lyr Database12 aims at collecting the times of maximum brightness of RR Lyr stars, exclusively galactic RRab (fundamental radial pulsators) and RRc (first overtone radial pulsators). The project was started in 2000 by archiving recent and historical publications of \( T_{\text{max}} \) in the literature. It now contains 61,000 maxima of 3600 stars and it is regularly fed by the valuable inputs from amateur astronomers (BAV, AAVSO, GEOS...). We already used the GEOS database to obtain relevant results in the study of the evolutionary changes of the pulsational periods of RRab stars (Le Borgne et al. 2007). The same data can be used to study period variations for a wide sample of galactic RR Lyr stars on a much shorter timescale, in order to bring out new tiles necessary to compose the puzzle of the Blazhko effect.

2. THE GEOS RR RR Lyr SURVEY WITH TAROT TELESCOPES

The main contribution to the GEOS RR Lyr database comes from the GEOS RR Lyr Survey and particularly from the observations of the two robotic telescopes Télèscope à Action Rapide pour les Objets Transitoires (TAROT; Klotz et al. 2008, 2009) located in France (Calern Observatory) and in Chile (La Silla Observatory). These 25 cm automated telescopes are dedicated to the capture of the optical afterglows of gamma-ray bursts. Several programs are scheduled in the idle time, as the one on galactic RR Lyr stars. Indeed, RR Lyr stars are very suitable targets for small robotic telescopes due to their short-period and large-amplitude variability, which allow the observation of several \( T_{\text{max}} \) and \( V_{\text{max}} \) on a single night. TAROT telescopes have produced about 840 max/year since the beginning of the observations in 2004. This is about half the total production of 1640 max/year from ground-based observations on the same period. This performance appears more relevant when compared with an average of about 500 max/year over the 110 years elapsed since the discovery of RR Lyr stars.

RRab stars have periods in the 0.37–0.65 day range and we could collect from each TAROT site no more than 1 maximum/night for each given star. A few equatorial stars could be observed both from Calern and La Silla, but observing two consecutive maxima is an exceptional event due to weather conditions.

12 The GEOS database is freely accessible on the internet at http://rr-lyr.ast.obs-mip.fr/dbrr/.
Figure 4. Blazhko effect of BD Dra. Left panels: power spectra of \( O - C \) and \( V_{\text{max}} \) values (top) and curves of the \( O - C \) and \( V_{\text{max}} \) values (bottom). Right panels: TAROT CCD measurements (top) and residuals after the 24-frequency fit (bottom).

differences. Since the main goal is the monitoring of as many RR Lyr stars as possible, the scheduling software tries to secure points for all the program stars and hence gives a lesser priority to a star that has already been observed on a previous night. The telescopes are continuously moved from one star to the next during the night and the measurements consist of two consecutive 30 s exposures taken every 10 minutes. They are performed around the predicted \( T_{\text{max}} \) and the ephemerides are continuously updated to avoid missing the real maximum. The mean error bar of the observed \( T_{\text{max}} \) is about 0.003 days (4.3 minutes). We obtain an average of 50 measurements in 4.8 hr for each maximum.

The resulting spectral window clearly shows alias peaks at \( \pm 1 \text{ yr}^{-1} = \pm 0.0027 \text{ day}^{-1} \) (Figure 1, inserted boxes), due to the pointing limitations when stars are too close to the Sun, and different alias structures appear as a function of the period. The maxima of the shorter-period RR Lyr stars could be observed very frequently and their spectral windows are quite clear, as shown by that of AH Cam (Figure 1, top panel). Stars with a period close to 0.50 days could not be observed for a long time when the maxima occur around sunset or sunrise and the gaps in the timeseries produced alias peaks in their spectral window (RZ Lyr, middle panel). If the period is around or longer than 0.6 days the next observable maximum after a positive determination occurs a few days later (at least two). Therefore, the pseudo-Nyquist frequency is around 0.25 day\(^{-1}\), as shown by the case of ST Boo (lower panel). This extreme case is still largely satisfactory for our purposes, since the shortest known Blazhko period (\( P_{B} \)) is that of SS Cnc, 5.309 days (Jurcsik et al. 2006), corresponding to \( f_{B} = 0.188 \text{ day}^{-1} \). Therefore, we performed our frequency analyses in the interval 0.0–0.2 day\(^{-1}\) by means of the iterative sine-wave least-squares method (Vaniček 1971).

Due to the scheduling procedure of the TAROT telescopes, photometric measurements are concentrated around the maxima. The rising branch of the light curves is well covered including the shoulder in some stars, currently interpreted as the effect of a hypersonic shock wave propagating in the atmosphere (Chadid et al. 2008). Our analysis detected such a feature in the light curves of the non-Blazhko stars BC Dra and AR Per (Figure 2). BC Dra is a long-period RRab star (\( P = 0.72 \text{ days} \)), AR Per a short-period one (\( P = 0.42 \text{ days} \)). The almost complete phase coverage of the BC Dra curve allowed us to determine a pulsational period of \( 0.71958083 \pm 0.00000015 \text{ days} \). The amplitudes of the harmonics decrease up to 7\( f \) and then they show small fluctuations before the final decline at 12\( f \). The residual rms is 0.033 mag and the residuals still show the sudden change in the light curve occurring on the rising branch (Figure 2, lower panel). The frequency analysis of the TAROT timeseries and the 105 observed maxima did not detect any signature of the Blazhko effect. We applied the same procedure to the AR Per data, thus obtaining \( P = 0.42555060 \pm 0.00000010 \text{ days} \) in the 2004–2011 interval. This accurate determination is particularly useful since the period of AR Per is subject to secular changes (Le Borgne et al. 2007). As a drawback of the TAROT
scheduling procedure, the phase coverage of the light curves of many program stars is often incomplete, with large gaps on the descending branch.

3. THE TEST BENCH: STARS WITH A KNOWN BLAZHKO EFFECT

Due to pointing accuracy and small seasonal effects affecting it, the reduction software could select different stars for the ensemble photometry (Damerdji et al. 2007). This translates into small systematic differences that in some cases could prevent the frequency analysis of the \( V_{\text{max}} \) values. The \( T_{\text{max}} \) values are free from this effect, since it is independent from the choice of the reference stars. However, the \( O - C \) values depend on the stability of the main pulsational period, which could also vary on a time interval as short as seven years. A linear or parabolic ephemeris could locally fit the \( T_{\text{max}} \) values in an unsatisfactory way (Le Borgne et al. 2007), leaving some residual peaks at very low frequencies. In such cases we corrected this secular effect by calculating a linear ephemeris in the interval covered by the \( T_{\text{max}} \) values. Finally, we considered both \( O - C \) and \( V_{\text{max}} \) values to detect and characterize the Blazhko effect, giving full confidence to the results only if they were in agreement with each other. With the exception of just a couple of cases that will benefit from a longer time baseline covered by accurate maxima determinations, this double-check ruled out the possibility that the periodicity observed in the \( O - C \) values was caused by a light-time effect (i.e., an RR Lyr variable in a wide binary), since \( V_{\text{max}} \) values are not expected to show any appreciable variation due to the orbital motion. We have a couple of cases where a long-period, light-time effect is plausible: TAROT telescopes are monitoring them for a decisive confirmation.

First, we analyzed the stars for which the Blazhko effect was already known. Figure 3 gives an overview of the tools applied to some stars that will be discussed later: power spectra of \( O - C \) and \( V_{\text{max}} \) values (for RR Gem and AH Cam), the folded curves of \( O - C \) and \( V_{\text{max}} \) values (for RR Gem and SZ Hya), the folded curves of original measurements (for SZ Hya), and the folded curves of residuals (for AH Cam). As shown in the upper part of Table 1, our independent analysis confirmed most of the previously known results. For instance, the very small amplitude Blazhko effect of RR Gem (Jurcsik et al. 2005a) was correctly identified and characterized (Figure 3, top panels). This not only strengthened the confidence in our approach, but also allowed us to build the first \( O - C \) versus \( V_{\text{max}} \) plots for these stars.

Without entering in a detailed discussion of the well-established cases, we emphasize here some methodological and scientific items.

3.1. The Light Curves and the Periods of BD Dra and AH Cam

The dispersion in the residual plot was also observed on the rising branch of the Blazhko stars BD Dra and AH Cam. Regarding BD Dra, the analysis of 44 old photographic and
visual maxima did not show any significant periodicity. On the other hand, the frequency analysis of the 136 CCD maxima collected from 2005 to 2011 immediately pointed up a very clear periodicity of 24.1 days in both the $O - C$ and $V_{\text{max}}$ values (left top panel in Figure 4). The $O - C$ and $V_{\text{max}}$ values folded with the Blazhko period ($P_{\text{B}} = 24.107 \pm 0.001$ days) show a full amplitude of 0.043 days and 0.40 mag, respectively (left-bottom panel in Figure 4). The Blazhko effect is clearly noticeable in the folded light curve ($P_0 = 0.58900964 \pm 0.00000010$ days; right top panel in Figure 4). Very sharp triplets were also detected around $f_0$ and harmonics up to $7f_0$. It was not possible to investigate the existence of a quintuplet structure, since such peaks do not stand out clearly over the noise level of 0.003 mag (e.g., the component $f_0 + 2$ has an amplitude of 0.009 mag only). The plot of the residuals after a fit with 24 terms ($n f_0 \pm f_{\text{B}},$ with $n = 1, \ldots, 8$) shows a large spread in the values at the phases corresponding to such part of the light curve (right-bottom panel in Figure 4).

The TAROT maxima collected on AH Cam in the recent years clearly indicate that the true Blazhko frequency is $f_{\text{B}} = 0.092341$ day$^{-1}$ (Figure 3, middle panels), i.e., the alias at $+1$ yr$^{-1}$ of the previous value (Le Borgne et al. 2007). This improvement in the analysis is due to the long coverage ensured by the automatic telescope during each year, able to strongly damp the aliases at $\pm 1$ yr$^{-1}$. The Blazhko frequency was also found in the analysis of the TAROT original measurements as triplets centered around $f_0 = 2.71211$ day$^{-1}$ and harmonics up to $5f_0$. The residuals show a large scatter in the rising branch (right-middle panel in Figure 3), although not as large as in the case of BD Dra. The periods obtained from the frequency analysis are $P = 0.36871596 \pm 0.00000006$ days and $P_B = 10.8289 \pm 0.0002$ days.

### 3.2 The $O - C$ and $V_{\text{max}}$ Amplitudes of the Blazhko Effect

The star with the most spectacular Blazhko effect is XY Eri (Figure 5). The $V_{\text{max}}$ values vary in a range of 0.75 mag, more than half the full amplitude of the peak-to-peak amplitude, and the $O - C$ values vary in a range of 91 minutes. The Blazhko effect of IK Hya is very similar, since the $O - C$ values have the same range, but the $V_{\text{max}}$ amplitude is probably around 0.5 mag. Since we only observed nine maxima, IK Hya deserves further investigation in the future. Most of the stars show a $V_{\text{max}}$ amplitude between 0.20 and 0.40 mag and only RS...
Boo, SS Oct, and RR Gem have amplitudes smaller than 0.20 mag. These large variations explain why the Blazhko effect was sometimes referred to an amplitude modulation (see also the introductory remarks in Szeidl 1988). Note how the $O - C$ values show variations only in a narrow phase of the Blazhko period of SZ Hya (Figure 3, bottom panels). SS CVn shows a similar variation of the $O - C$ values, but its Blazhko period is 3.6 times longer.

### 3.3. Long Blazhko Periods and Long-term Modulations

Blazhko periods longer than 100 days are less common than shorter ones. In our sample, we have the cases of RS Boo, ST Boo, RZ Lyr, RX Cet, and UV Oct. The longest Blazhko period is that of RS Boo (533 days). The modern CCD observations provide a spectacular confirmation of the second longest Blazhko period, that of ST Boo (Figure 6), whose features were never presented before. The analysis of the TAROT CCD timeseries of RZ Lyr supplies $P = 0.511241 \pm 0.000005$ days and $P_B = 120.19$ days, thus confirming the trends reported by Jurcsik et al. (2012) on a longer time baseline. In the case of RX Cet, the 15 maxima spread over 7 years did not allow a precise determination of the Blazhko period, characterized by the second largest amplitude (0.061 days) of the $O - C$ values after that of XY Eri. We detected a tentative period of 273 days superimposed on a slight secular variation of the period. On the other hand, UV Oct shows a low $O - C$ amplitude of only 0.012 days.

Long, additional modulations were also claimed as secondary periodicities superimposed on short Blazhko periods. For instance, Kholopov (1985) report on a composite Blazhko effect for RW Dra. The $O - C$ values in the GEOS database clearly indicate the Blazhko period of 41.4 days (Figure 6). The power spectrum and the folded light curve of the residual $O - C$ values are not supporting the action of other strictly periodic cycles. On the other hand, the $V_{\text{max}}$ values show some scatter, thus suggesting changes in the amplitude from one cycle to next (Figure 6). XZ Dra is perhaps the extreme case of changes in the Blazhko cycle. We did not detect any reliable periodicity around 75 days in the recent maxima collected in the GEOS database. The dampening of the Blazhko variation has been noticed for more than 50 years in the 20th century (Jurcsik et al. 2002). Since still more rapid variations are clearly detected in the continuous space timeseries (e.g., CoRoT 105288363; Guggenberger et al. 2011), we argue that the composite Blazhko effect and, more generally, the long-term variations could be a spurious effect of such cycle-to-cycle changes, irregularly or poorly sampled from ground-based monitoring.

### 3.4. Change in the Blazhko Period with Changes in the Pulsational Period: Z CVn

We detected the Blazhko effect in the CCD data of Z CVn, together with a well-defined secular change of the pulsation period. The pulsational period was $0.653942 \pm 0.000007$ days around JD 2,439,000. The more recent CCD data were obtained in a time interval where the pulsational period has undergone a sudden change to $0.6538907 \pm 0.0000003$ days after JD 2,454,200 (Figure 7, top panel). The Blazhko period around JD 2,439,000 was 22.75 days (Kanyo 1966). This value is

**Figure 6.** Blazhko effect of RW Dra and ST Boo. Power spectra and folded curves of the $O - C$ and $V_{\text{max}}$ values of RW Dra (left panels) and ST Boo (right panels).
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confirmed by our re-analysis of the $T_{\text{max}}$ values, even if we have to note that the power spectrum shows a broad peak. When analyzing the CCD data we immediately noticed that the amplitude of the $O-C$ variation was 0.021 days after JD 2,454,200, while it was 0.033 days in Kanyo’s data. This is the first remarkable change in the Blazhko modulation. More important, the frequency analysis of the two sets of $O-C$ and $V_{\text{max}}$ values supplied a Blazhko period of 22.95 ± 0.03 days after JD 2,454,200 (Figure 7, left-bottom panels). The amplitude of the $O-C$ values, corrected for the period change, decreased to 0.021 days, while the amplitude of the CCD $V_{\text{max}}$ values remained constant at 0.32 mag (Figure 7, right-bottom panels).

Our analysis shows that the pulsational period affects the Blazhko one. In particular, the decrease of the pulsational period resulted in a longer Blazhko period, i.e., the two changes are anticorrelated. The same behavior was observed in the cases of XZ Cyg (LaCluyzé et al. 2004), RV UMa (Hurta et al. 2008), RW Dra (Firmanyuk 1978), and RZ Lyr (Jurcsik et al. 2012). However, this does not seem to be a strict rule, since correlated changes were observed in the case of XZ Dra (Jurcsik et al. 2002).

4. NEW BLAZHKO STARS

Corroborated by the results obtained on stars with a known Blazhko effect, we applied the same tools to stars poorly observed in the past. TAROT photometry was able to detect the signatures of the Blazhko effect in the timeseries of the stars listed in the lower part of Table 1.

The Blazhko frequencies are determined without ambiguity in the cases of SS CVn, TY Aps, BI Cen, AF Vel, and SV Vol. The Blazhko effect of ST Vir is very small, similar to that of RR Gem, and its detection is another good example of the effectiveness of the TAROT survey. In the case of BI Cen, the uncertain value reported by Smith (1995; 70 days) is slightly different from what we determined. The light curve was well covered by TAROT observations and we could determine $P = 0.45319439 \pm 0.00000007$ days and $P_B = 79.75 \pm 0.02$ days from the frequency analysis of the timeseries. BI Cen shows very sharp $O-C$ and $V_{\text{max}}$ variations and the Blazhko variability looks like the most regular in our sample.

The fact that most of the timeseries are single site introduced some uncertainties on the determination of the true Blazhko frequencies, which could be actually the aliases at $\pm 1 \text{yr}^{-1}$ or $\pm 2 \text{yr}^{-1}$ of the highest peak in the power spectra. This ambiguity results in a real period shorter or longer by about 10 days for a Blazhko period of 40 days (BS Aps and UU Hya) and 4 days for a period of 23 days (U Cae). The situation is quite different for the stars showing a long Blazhko period, i.e., RX Col and RY Oct. At frequencies of 0.008 day$^{-1}$ (corresponding to a period of 130 days, as that of RX Col) or lower (RY Oct) the
Figure 8. Stars with the brightest $V_{\text{max}}$ (ordinate) corresponding to the maximum positive $O-C$ (abscissa). The closed curves are run counterclockwise.
Figure 9. Same as Figure 8, but the closed curves are run in the clockwise direction.

Figure 10. Stars with the brightest $V_{\text{max}}$ (ordinate) corresponding to the maximum negative $O-C$ (abscissa). The closed curves are run in the counterclockwise direction.

alias at $-1$ yr$^{-1}$ points to an almost twice longer period. The extreme case is that of RU Cet. The $O-C$ and $V_{\text{max}}$ values and the folded light curve suggest the possibility of a long period, probably much longer than 100 days, but the strong aliasing effect prevented us from proposing a reliable value.

In addition to those listed in Table 1, other RRab stars in the GEOS database show cycle-to-cycle variation that could be ascribed to a Blazhko effect, but we could not propose a reliable value for the period due to the strong alias uncertainty. The scientific discussion of the Blazhko effect could be sharpened if new values for $T_{\text{max}}$ are collected on these stars.

5. DISCUSSION

5.1. Varieties in the Phenomenology of the Blazhko Effect

With respect to the frequency analysis of ground- or space-based photometric timeseries, the GEOS database enriched with the maxima observed with the TAROT telescopes offers the possibility of investigating the relation between amplitude and phase changes, described by the $O-C$ versus $V_{\text{max}}$ diagram. Benkő et al. (2011) recently interpreted the Blazhko light curves as modulated signals and provided theoretical predictions of these diagrams (see their Figures 17 and 18).

To exploit this possibility, we used the $O-C$ and $V_{\text{max}}$ folded with the Blazhko period (see bottom left panels in Figure 4 for an example). We calculated the least-squares fits of these folded data, thus obtaining an $O-C$, $V_{\text{max}}$ couple at any given Blazhko phase. We drew the closed curve that describes the shape of the Blazhko effect by connecting the consecutive couples. A quick analysis immediately reveals how such closed curves can assume different shapes and can be run in opposite directions. We have 20 cases of counterclockwise directions and nine cases of clockwise ones. The most numerous category is formed by Blazhko cycles where the $O-C$ and $V_{\text{max}}$ curves are roughly in phase and the closed curves are run in the counterclockwise directions (13 cases, Figure 8). The $\Delta\phi$ shifts range from
−0.06\(P_B\) (RS Boo) to −0.26\(P_B\) (TT Cnc). The curves of ZCVn (\(\Delta \phi = -0.79P_B\)) and UU Hya (−0.83\(P_B\)) have the same orientation, but run clockwise (two cases, Figure 9).

The \(O-C\) and \(V_{\text{max}}\) curves are roughly in anti-phase and the closed curves are run counterclockwise for six stars (Figure 10). The \(\Delta \phi\) shifts range from −0.30\(P_B\) (RX Col) to −0.42\(P_B\) (UV Oct). For this orientation of the closed curve the number of stars running clockwise is nearly the same (seven cases, Figure 11) and the phase shifts range from −0.52\(P_B\) (DD Hya) to −0.66\(P_B\) (RZ Lyr).

There are close similarities with the curves predicted by the amplitude and frequency modulations (Benkő et al. 2011). In particular, the extreme cases of the Blazhko diagrams shown by BD Dra, SZ Hya (Figure 8), and VW Dor (Figure 11) confirm the complicated shapes predicted in case of simultaneous non-sinusoidal amplitude and phase modulations. They are characterized by strongly elongated shapes, with some cusps and loops, due to the peculiar plots of the \(O-C\) and/or \(V_{\text{max}}\) values. The \(\Delta \phi\) shifts reflect this peculiarity in the case of SZ Hya (Figures 3 and 8), which is different from the others of the same group of stars.

These subdivisions reflect the mathematical differences in the signal modulations stressed by Benkő et al. (2011). The phase shifts \(\Delta \phi\) (Table 1) can be transformed in the phase parameter \(\phi_m\) (Equation 45) and Figure 17 in Benkő et al. (2011) by the relation \(\phi_m = \Delta \phi + k \times 180\), where \(k = 1\) for the counterclockwise direction and \(k = -1\) for the clockwise direction. It is noteworthy that Benkő et al. (2011) obtained their diagrams by a mathematical representation of the light curve, while ours were built by using the observed \(T_{\text{max}}\) and \(V_{\text{max}}\) values, without any assumption on the form of the light curve. We can argue that our observational results are a rather solid confirmation that the Blazhko effect can be described by amplitude and frequency modulations, though the physical reasons of these modulations still remain unknown.
5.2. Distribution of the Blazhko Periods

The characteristics of the all-sky galactic Blazhko RR Lyr stars could be compared with those obtained in the galactic bulge by OGLE (Collinge et al. 2006) and in the Magellanic Clouds by MACHO (Alcock et al. 2003). The results of the OGLE and MACHO surveys were obtained by performing a frequency analysis of the photometric timeseries and the Blazhko periods were measured from the separation of the multiplets in the amplitude spectra, without having the possibility to determine individual $T_{\text{max}}$ and $V_{\text{max}}$. We analyzed the OGLE stars considering the different subclasses introduced by Collinge et al. (2006) on the basis of the appearance of their amplitude spectra: BL1 (a single peak close to the main pulsational frequency), BL2 (an equidistant triplet), and BL2+? (equidistant triplet plus an additional peak) stars. The distributions of the Blazhko periods versus the pulsational ones are not very different in the plots of each subclass. The same applies for the similar categories used in the MACHO classification. Figure 12 allows a direct comparison, although the all-sky Blazhko variables are much less numerous than those in the galactic bulge and in the Large Magellanic Cloud (LMC). Blazhko periods longer than 400–500 days are not very common (see inserted boxes). The lack of such long periods in the all-sky survey could be an observational bias due to the impossibility of following an isolated star along many years.

The range of pulsational periods is quite similar and the very few Blazhko variables below 0.40 days and above 0.67 days reflect the lesser number of RRab stars having these periods. The long Blazhko periods for stars with $P < 0.40$ days (RS Boo and of a couple of stars in the galactic bulge) are quite rare. Note how the limited all-sky sample enhances an apparent linear increase of the Blazhko period from 0.40 to 0.55 days, accompanied by a rather flat distribution starting from 0.47 days toward longest pulsational periods. This peculiarity is less discernible in the OGLE sample, but disappears in the MACHO one. We are not very confident of the reality of such structures. Indeed, the histograms of the Blazhko periods did not reveal any significant peak after the highest at 45 days in the MACHO sample and at 25 days in the OGLE one.

We prefer to consider Figure 12 as evidence that the Blazhko period could be very different for the same pulsational period (vertical scatter) and that the same Blazhko period could be observed in a large range of pulsational periods (horizontal scatter). In such a context, the Blazhko effect of AH Cam (Section 3.1) is very similar to that of V1127 Aql (Chadid et al. 2010) for the amplitudes of the magnitudes and phases of the maxima, for the shape of the Blazhko cycle in the $O - C$ versus magnitudes plot. The pulsational periods are very similar too. But the two Blazhko periods are very different, although both are short ($P_B = 10.829$ days for AH Cam, $P_B = 26.88$ days for V1127 Aql).
The analysis of the LMC stars in the MACHO sample allows another comparison. Alcock et al. (2003) report a higher incidence (74%) for frequency patterns in which the modulation amplitude on the higher frequency side peaks is larger than its lower frequency counterpart. The mathematical formalism (Benkő et al. 2011) tells us that larger modulation on the higher frequency side indicates counterclockwise direction in the $T_{\text{max}}$ versus $O-C$ plots. As in the case of our galactic sample, this direction is the preferred one for LMC RRab stars.

6. CONCLUSIONS

The GEOS database and the TAROT survey provided a treasure of information on the Blazhko effect. TAROT light curves revealed that the non-repetitive nature of the shoulder on the rising branch is a common feature in both Blazhko and non-Blazhko stars. This immediately translates into a model constraint, since the physical cause creating the shoulder must work in both types of stars and the Blazhko effect is not damped by this cause. The hydrodynamical models should take into account several features (the bump at minimum, the shoulder on the rising branch, and also the double maximum observed in RRc stars) that accurate photometry is putting in evidence on non-Blazhko stars, too. In this context, the new models explaining the period doubling bifurcation (Szabó et al. 2010) should be used to test these features also.

The Blazhko effect appears to be multifaceted. We observe very different shapes of the $O-C$ versus $V_{\text{max}}$ plots and the described paths (circular, elongated, almost linear, with loops, and hooks, . . . ) can be run in a clockwise or counterclockwise direction also in stars with similar periods, both pulsational and Blazhko. Our observational results confirm the variety of shapes predicted by a mathematical formalism involving amplitude and phase variations (Benkő et al. 2011). As a further feedback to theoretical works, the physical cause of the Blazhko mechanism must be able to explain both such a large variety and the preferred counterclockwise direction. The very long photometric monitoring also suggests that the Blazhko effect shows cycle-to-cycle changes (also in the case of RR Lyr itself; Preston et al. 1965; J. F. Le Borgne et al. 2012, in preparation) and this further variability has still to be implemented in the formalism. We could say that perfect regularity is the exception (i.e., BI Cen) rather than the rule.

We emphasize the occurrence of different Blazhko periods at the same pulsational periods and of the same Blazhko period at very different pulsational periods. We could be tempted to consider that the oblique-pulsator model combined with the randomly distributed line of sights and (very) different rotational periods could produce the variety of the observed $O-C$ versus $V_{\text{max}}$ plots. However, the non-detection of relevant magnetic fields and the large cycle-to-cycle variations in the Blazhko effect pose insoluble problems to this explanation.

Since RRab stars are located in a narrow strip on the horizontal branch, their physical conditions are not expected to vary too much. Le Borgne et al. (2007) showed how both redward and blueward shifts are observed in the evolutionary paths of RRab stars and perhaps the evolutionary stage (i.e., contraction or expansion) could introduce relevant differences in the Blazhko mechanism. In the case of Z CVn we could verify that the variation of the pulsational period resulted in changes in the Blazhko effect, both in terms of period and amplitude, and that they are anticorrelated. Since the variations of the pulsational period reflect changes in the star’s radius, the Blazhko effect seems very sensitive to this stellar parameter. In this context, the unique case of correlated changes between the Blazhko and pulsational periods (i.e., XZ Dra), the few stars with $P < 0.40$ days showing a very long Blazhko period and those showing complicated Blazhko plots can be considered promising laboratories in which to test future improvements in the theoretical models of the Blazhko effect.

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APPENDIX

THE INVENTORY OF GALACTIC BLAZHKO STARS

The inventory of Blazhko stars located in the galactic field has been proposed and revised several times. The first comprehensive list was published by Szeidl (1976, 1988) and then adapted by Smith (1995) for his book. Wils et al. (2006) discovered new Blazhko RR Lyr stars by analyzing the Northern Sky Variability Survey (Woźniak et al. 2004). Wils & Sógor (2005) did the same by analyzing the All Sky Automated Survey (ASAS; Pojmanski & Maciejewski 2004). Sógor & Jurcsik (2005) corrected some uncertain results and Jurcsik et al. (2005b) added some complementary stars, partially overlapping those proposed by Wils et al. (2006). The Blazhko effect was discovered on many RRab stars located in the Kepler field of view (Benkő et al. 2010). Table 2 lists the Blazhko RRab stars complementing Table 1. New entries are expected from the KBS II, e.g., V397 Her and ASAS 212034+1837.2 (Sógor et al. 2012), the Sloan Digital Sky Survey (Süveges et al. 2012), and from other specific projects, as SATINO13 and FARO (Le Borgne et al. 2010).

Table 2 does not include the Blazhko stars in the galactic bulge discovered in the OGLE project, for which we refer the reader to the classification paper (Collinge et al. 2006). Moreover, the stars listed by Wils et al. (2006), Jurcsik et al. (2009b), and Benkő et al. (2010) with an uncertain Blazhko period are not considered as well. This is justified by the 59 day period suggested for RZ Lyr, while the true period is 120 days (Jurcsik et al. 2012). Other cases are controversial: FM Per (20 days after Wils et al. 2006, 122 days after Lee & Schmidt 2001), AR Ser (63 days after Wils et al. 2006, 110 days after Lee & Schmidt 2001), and X Ret (45 days after Smith 1995, 161 days after Wils & Sógor 2005). These uncertainties are not surprising since sometimes it is very difficult to have clear evidence: the Blazhko effect of DM Cyg was announced by Lysova & Firmanyuk

13 http://stiftung-astronomie.de/satino.htm
Table 2

RRab Stars Showing a Known Blazhko Effect and not Discussed in this Paper

| Star  | \(P_{\text{puls}}\) (day) | Known \(P_B\) (day) | Reference | Star  | \(P_{\text{puls}}\) (day) | Known \(P_B\) (day) | Reference |
|-------|-----------------|-----------------|-----------|-------|-----------------|-----------------|-----------|
| SW And | 0.442            | 36.8            | (1) V445 Lyr | 0.512 | 53.1            | (9),(10)       |
| XY And | 0.399            | 41.2            | (6) V450 Lyr | 0.504 | 125             | (9)            |
| DR And | 0.564            | 57              | (5) RS Oct  | 0.458 | 244             | (2)            |
| GV And | 0.528            | 32              | (4) DZ Oct  | 0.477 | 36.8            | (2)            |
| OV And | 0.471            | 27              | (5) V788 Oph | 0.547 | 115             | (1),(3)        |
| V1127 Aql | 0.356          | 26.86           | (7) V829 Oph | 0.569 | 165             | (1),(3)        |
| S Ara  | 0.451            | 49.5            | (2) V1280 Ori | 0.479 | 28              | (5)            |
| SW Boo  | 0.514            | 13              | (1),(3) FO Pav | 0.551 | 571             | (2)            |
| RW Cnc  | 0.547            | 87              | (1) AE Peg  | 0.497 | 23              | (5)            |
| SS Cnc  | 0.367            | 5.3             | (6) BH Peg  | 0.641 | 39.8            | (1)            |
| RV Cap  | 0.448            | 233             | (1) FM Per  | 0.489 | 122 20          | (8),(5)        |
| V674 Cen | 0.494            | 29.5            | (1) CS Phe  | 0.484 | 62.5            | (2)            |
| RT Gru  | 0.512            | 87              | (2) BT Sco  | 0.548 | 78              | (2)            |
| AR Her  | 0.470            | 31.6            | (1),(5) CoRoT 0101128793 | 0.472 | 18.66          | (7)            |
| BD Her  | 0.474            | 22              | (6) CoRoT 0101503544 | 0.605 | 25.6            | (7)            |
| DL Her  | 0.572            | 33.6            | (1),(5)     |       |                 |                |
| V365 Her | 0.613            | 40.6            | (1),(5) KIC 11125706 | 0.613 | 39.4            | (9)            |
| V434 Her | 0.514            | 26.1            | (1),(3) GSC 0275-0090 | 0.595 | 59              | (5)            |
| V442 Her | 0.442            | 700             | (4) GSC 0318-0905 | 0.447 | 48              | (5)            |
| V1124 Her | 0.551            | 39              | (4) GSC 0607-0591 | 0.456 | 55              | (5)            |
| SV Hya  | 0.478            | 63              | (2) GSC 1581-1784 | 0.591 | 23              | (5)            |
| CZ Lac  | 0.432            | 14.6            | (6) GSC 1667-1182 | 0.562 | 84              | (5)            |
| SZ Leo  | 0.534            | 179             | (2) GSC 1948-1733 | 0.502 | 42              | (5)            |
| AH Leo  | 0.466            | 29              | (4) GSC 4378-1934 | 0.519 | 46              | (5)            |
| Y LMi  | 0.524            | 33.4            | (1) GSC 5590-0758 | 0.540 | 41.7            | (2)            |
| FU Lup  | 0.382            | 42.4            | (2) GSC 5828-0847 | 0.627 | 54              | (2)            |
| PQ Lup  | 0.582            | 48.8            | (2) GSC 5885-0757 | 0.602 | 122             | (2)            |
| RR Lyr  | 0.566            | 39.6            | (1),(9) GSC 6619-1146 | 0.598 | 59              | (2)            |
| AQ Lyr  | 0.357            | 64.9            | (6) GSC 6672-0596 | 0.399 | 48.3            | (2)            |
| KM Lyr  | 0.500            | 30              | (1) GSC 6730-0109 | 0.448 | 26              | (4),(2)        |
| MW Lyr  | 0.398            | 16.5            | (6) GSC 6811-0414 | 0.461 | 22.2            | (2)            |
| NR Lyr  | 0.682            | 27              | (5) GSC 6964-0926 | 0.530 | 182             | (2)            |
| V349 Lyr | 0.507            | ≳127            | (9) GSC 7448-0418 | 0.379 | 45.7            | (2)            |
| V353 Lyr | 0.556            | 60.0            | (9) GSC 8297-1427 | 0.600 | 49.5            | (2)            |
| V354 Lyr | 0.561            | ≳127            | (9) GSC 8814-0696 | 0.605 | 133             | (2)            |
| V355 Lyr | 0.473            | 31.4            | (9) GSC 8826-0640 | 0.615 | 63              | (2)            |
| V360 Lyr | 0.557            | 51.4            | (9) GSC 8826-0640 | 0.615 | 63              | (2)            |
| V366 Lyr | 0.527            | 65.6            | (9) NSV 5200 | 0.502 | 63              | (2)            |

Notes. See Colllinge et al. (2006) for the OGLE stars in the galactic bulge.

References. (1) Smith 1995; (2) Wils & Sódor 2005; (3) Sódor & Jurcsik 2005; (4) Jurcsik et al. 2005b; (5) Wils et al. 2006; (6) Jurcsik et al. 2009b; (7) Szabó et al. 2009; (8) Lee & Schmidt 2001; (9) Benkó et al. 2010; (10) Guggenberger et al. 2012. New names are provided by the General Catalogue of Variable Stars for the newly discovered RRab Blazhko variables V1124 Her≡NSV 8170 (Jurcsik et al. 2005b), PQ Lup≡NSV 7330, DZ Oct≡NSV 4350, CS Phe≡NSV 420, and AL Pic≡NSV 1700 (Wils & Sódor 2005), V1280 Ori≡NSV 2724, and NS UMa≡NSV 4034 (Wils et al. 2006).
(1980), then questioned by Sódor & Jurcsik (2005), and finally confirmed by new observations (Jurcsik et al. 2009a).

Except for the stars too faint to be measured with 25 cm telescopes, we are planning to complete their monitoring in the next years. In such a way we could extend the TAROT homogenous sample of well-studied Blazhko stars.

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