# The Konkoly Blazhko Survey: is light-curve modulation a common property of RRab stars?

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**ABSTRACT**

A systematic survey to establish the true incidence rate of Blazhko modulation among short-period, fundamental-mode, Galactic field RR Lyrae stars has been carried out. The Konkoly Blazhko Survey (KBS) was initiated in 2004. Since then, more than 750 nights of observation have been devoted to this project. A sample of 30 RRab stars was extensively observed, and light-curve modulation was detected in 14 cases. The 47 per cent occurrence rate of the modulation is much larger than any previous estimate. The significant increase of the detected incidence rate is mostly a result of the discovery of small-amplitude modulation. Half of the Blazhko variables in our sample show the modulation with such a small amplitude that they would definitely have been missed in previous surveys. We have found that the modulation can be very unstable in some cases; for example, RY Com showed regular modulation during only one part of the observations, and had a stable light curve with abrupt, small changes in the pulsation amplitude during two observing seasons. This type of light-curve variability is hard to detect in the data from other surveys. The higher frequency of the light-curve modulation of RRab stars makes it even more important to find an explanation for the Blazhko phenomenon.

The validity of the [Fe/H]($P$, $\varphi_{31}$) relationship using the mean light curves of Blazhko variables is checked in our sample. We found that the formula gives accurate result for small-modulation-amplitude Blazhko stars, and this is also the case for large-modulation-amplitude stars if the light curve has complete phase coverage. However, if the data for large-modulation-amplitude Blazhko stars are not extended enough (e.g. fewer than 500 data points from fewer than 15 nights), the formula may give false result owing to the distorted shape of the mean light curve used.

**Key words:** methods: data analysis – techniques: photometric – stars: horizontal branch – stars: oscillations – stars: variables: other.

## 1 INTRODUCTION

The light-curve modulation of RR Lyrae stars, the so-called Blazhko effect, is a hundred-year-old puzzle of stellar pulsation. The Fourier spectra of the light curves of Blazhko variables are characterized by the appearance of modulation-frequency series in the vicinity of the pulsation frequency ($f_0$) and its harmonic frequencies ($k f_0, k >$ 1). Based on the location and number of independent modulation-frequency components, some attempts have been made to introduce subtypes of the modulation ($\nu_1$, $\nu_2$, BL1, BL2, BL2x2, etc.; Alcock et al. 2003; Moskalik & Poretti 2003); these classification schemes, however, do not shed light on the unknown triggering mechanism of the modulation, which is probably common to each Blazhko star. Both observational and theoretical efforts are needed to gain an understanding of the modulation of RR Lyrae stars. Although the incidence rate of the modulation was estimated to be about 25–30 per cent based on visual, photographic and photoelectric observations of Galactic field and globular cluster variables (Smith 1981, 1995; Szeidl 1988), in a summary paper on RR Lyrae stars Preston (1964) wrote: 'There is no sharp distinction between singly and multiply periodic variables. When observed with

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sufficient precision or for long enough intervals of time, all RR Lyrae may be or may become multiply periodic' – quoting Balázs-Detre & Detre (1962).

More recently, large CCD surveys, for example Massive Compact Halo Objects Project (MACHO) (Alcock et al. 2003) and Optical Gravitational Lensing Experiment (OGLE) (Moskalik & Poretti 2003; Mizerski 2003; Soszyński et al. 2003; Collinge, Sumi & Fabrycky 2006), found a fraction of variables exhibiting light-curve modulation similar to or even smaller than that determined by photographic and photoelectric observations. The incidence rates of the modulation in the Large Magellanic Cloud (LMC) and in the Galactic bulge were estimated to be 12–15 per cent and 23–27 per cent, respectively. These statistics on Blazhko variables may, however, be biased owing to the limits of the photometric accuracy and/or the deficiencies in data sampling. Observation in a longer-wavelength band, where the amplitude of the modulation signal is small, may also reduce the detection rate of the modulation. According to Collinge et al. (2006), the incidence rates determined so far are only lower limits for the occurrence of the modulation. The metal deficiency of the variables has been suggested to explain the small fraction of Blazhko stars in the LMC, but Smolec (2005) could not detect any significant difference between the metallicities of RR Lyrae stars in the LMC and in the Galactic bulge.

*Hipparcos* (ESA 1997), NSVS (Woźniak et al. 2004) and ASAS (Pojmanski 2005) data bases also provide a large number of RR Lyrae observations, but these data are not suitable for estimating the true percentage of variables showing light-curve modulation. Based on the NSVS and ASAS data, Wils, Lloyd & Bernhard (2006) and Szczygieł & Fabrycky (2007) found modulations in an unrealistically small fraction, about 5 per cent of RRab stars (RRab stars, also called RR0, are RR Lyrae stars pulsating in the fundamental mode). Many of the well-known Blazhko variables do not even have detectable light-curve modulation in the *Hipparcos*, NSVS and ASAS data.

No systematic survey aimed at determining the frequency of light-curve modulation of RRab stars in the Galactic field had previously been performed. These variables are bright enough that accurate light curves can be obtained with even small telescopes. Earlier photometric programs concerning field RRab stars focused either on the light-curve variations of known Blazhko variables or on the multicolour light curves of large samples of variables (e.g. Sturch 1966; Fitch, Wisniewski & Johnson 1966; Bookmeyer et al. 1977; Lub 1977; Schmidt & Reiswig 1993) in order to determine their physical parameters (temperature, metallicity, reddening, etc.). Although these latter studies covered a large fraction of the brighter Galactic field variables, the time span, data number, phase coverage and photometric accuracy of the measurements were not suitable for detecting long-period and/or small-amplitude light-curve variations.

A knowledge of the true incidence rate of Blazhko stars is very important for finding the correct explanation of the phenomenon, as it shows how common the circumstances that favour the appearance of the modulation are. Exploiting the potential of our full access to an automated photometric telescope, we initiated a systematic study of RRab stars to obtain an estimate of the incidence rate of modulation. Although our survey concerns a much more limited sample of variables than were measured in the MACHO and OGLE projects, the photometric accuracy and the denseness of our data sampling allow us to detect the occurrence of light-curve modulation more reliably than in those surveys. The main results concerning the incidence rate of the modulation of the Konkoly Blazhko Survey (KBS) are summarized in this paper.

Results for variables with unstable light curves observed in the KBS that do not have data suitable for discussion in separate papers (RY Com, BD Her and FK Vul) are also published here.

By comparing the photometric and spectroscopic metallicities of Blazhko RRab stars of the KBS sample we also draw some conclusions on the correctness of the photometric metallicity (Jurcsik & Kovács 1996) derived from the mean light curves of Blazhko variables.

## 2 OBSERVATIONS AND TARGET SELECTION

The observations of the KBS began in 2004 using an automated 60-cm telescope (Budapest, Svábhegy) equipped with a Wright Instruments $750 \times 1100$ CCD camera (FoV $17 \times 24$ arcmin$^2$) and standard $BVR_CI_C$ filters. Data were corrected for atmospheric extinction and were transformed to the standard $BVR_CI_C$ photometric system. We obtained accurate, extended, multicolour light curves of fundamental-mode RR Lyrae stars with pulsation periods shorter than half a day. About 4000 h of measurements have been gathered for 30 variables on ~750 nights over the past five years. Each variable was observed for at least as long as it took to decide unambiguously whether the light curve was stable on a time base of about 20–100 days or was modulated. The typical accuracy of the observations was about 5–20 mmag, depending mainly on the brightness of the object and on weather conditions. The apparent maximum $V$ brightness of the observed variables was in the range 10.5–13.5 mag. The accuracy, extension and denseness of the data enabled us to detect light-curve modulations with small maximum brightness variations (some hundredths of a magnitude), that is, with Fourier amplitudes of the modulation-frequency components in the mmag regime. Data are utilized in two ways; either accurate multicolour light curves of mono-periodic RRab stars or detailed analyses of individual Blazhko variables have already been and are going to be published.

When selecting stars to observe, special care was taken to choose variables with good comparison stars (close to the variable in projected distance, brightness and colour) in order to gain the most accurate photometry possible with our instrument. Magnitude differences of the variable relative to a single comparison star were determined and analysed for most of the stars. The constancies of the comparison stars were verified by measuring several relatively bright stars in the fields. Details for the constancies of the comparison stars are given in the papers discussing the light-curve variability of the individual objects (see e.g. fig. 7 in Jurcsik et al. 2008c). The ensemble mean brightnesses of five, three and two neighbouring stars were calculated, and used as comparison star magnitudes for UZ UMa, SS Cnc and DM Cyg, respectively. We applied the image subtraction method (ISIS; Alard 2003) for the photometry of CZ Lac in order to eliminate the additional light of its close companion.

We observed only short-period RRab stars ($P < 0.5$ d) in order to obtain a sample with fairly homogeneous physical parameters, as most of the physical properties of RRab stars relate, to some degree, to the period of the pulsation. The restriction of our survey to short-period variables also made the observations effective, as it ensured a good coverage of the entire possible sample within a few years of observations. No star with declination below 5° was selected to be observed, in order to obtain extended data sets.

The philosophy of the target selection was to choose variables with poor-quality photometric observations and to clear up some questionable cases. We endeavoured to obtain the most unaffected sample possible in order to gain an unbiased estimate of the incidence rate of the modulation. None of the observed stars was

definitely known to show Blazhko modulation. In three cases (RR Gem, MW Lyr and DM Cyg), light-curve modulation was reported based on photographic or visual observations, but these results were in conflict with further observations and/or a reanalysis of the original data could not confirm the formerly detected modulation (Sódor & Jurcsik 2005; Sódor, Szeidl & Jurcsik 2007b). Our observations revealed that these stars do indeed show light-curve modulation, but with significantly different modulation period, amplitude and type (amplitude or phase modulation) from values found previously. RY Com was suspected to show Blazhko modulation (Jurcsik & Kovács 1996); however, the scatter around minimum brightness shown by the available observations (Jones 1966; Bookmeyer et al. 1977) might have arisen from photometric inaccuracy. Four of the targets (TZ Aur, SS Cnc, RR Gem and FH Vul) were used by Jurcsik & Kovács (1996) to calibrate the relationship between metallicity and light-curve parameters assuming that the light curves were stable. Our accurate measurements show that, in fact, two of these stars, SS Cnc and RR Gem, are Blazhko variables.

The 30 RRab stars for which extended photometric data were obtained in the KBS account for about 60 and 80 per cent of the possible targets of the Northern Hemisphere summer and winter season RRab stars matching our selection criteria.

## 3 THE KONKOLY BLAZHKO SURVEY

About half of the 30 observed RRab stars (14 variables, 47 per cent) were found to exhibit light-curve modulation. This is a much larger percentage than obtained by any previous survey. None of the discovered Blazhko variables could have been unambiguously identified from the *Hipparcos*, NSVS, ASAS or any other previous photometry as showing light-curve modulation. As examples, in Figs 1 and 2 our observations are compared to the published light curves for two RR Lyrae stars discovered to show Blazhko modulation in our survey.
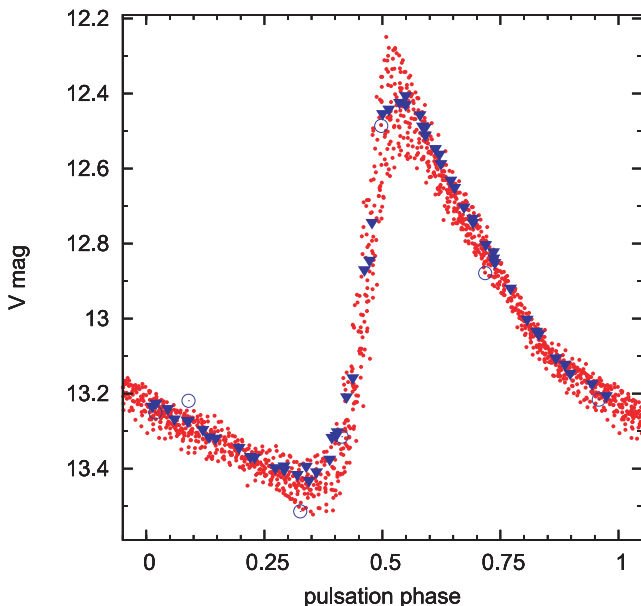


**Figure 1.** Comparison of the Konkoly and previous photoelectric and CCD observations of AQ Lyr. The Konkoly observations are shown by dots, the CCD observations of Castellani et al. (1998) by triangles, and the photoelectric data of Sturch (1966) by circles. Based on the previous observations, no light-curve modulation of AQ Lyr could be detected.

AQ Lyrae, one of the stars measured in the survey, was previously supposed to have a stable light curve. Castellani et al. (1998) observed AQ Lyr on six consecutive nights in 1995 and found no light-curve modulation. The earlier photoelectric observations of Sturch (1966) matched the CCD light curve observed by Castellani et al. (1998) within the limits of the photometric accuracy. Our extended data have revealed, however, that AQ Lyr shows large-amplitude modulation. Although the variation in its maximum *V* brightness is ∼0.3 mag, its light curve does not change significantly on the time base of a few days owing to the 65-d length of its Blazhko period. In Fig. 1 our *V* light curve of AQ Lyr is compared with the previous observations.

In Fig. 2, the Konkoly photometry is compared with the ASAS-3 and NSVS light curves of UZ Vir. The Konkoly light curve shows about 0.3-mag variation in maximum brightness, and corresponding to the $P_{Bl} = 68$-d period of the modulation many triplet components can be identified with 0.015 cd$^{-1}$ (cycle per day) separation from the pulsation components in the pre-whitened spectrum. Despite its strong maximum brightness variation, UZ Vir has not been found to be a Blazhko variable either from the ASAS or from the NSVS data. These data show scattered light curves and a very high noise level of the residual spectra. Although the $f_0 - f_m$[1] modulation side-frequency appears in the residual spectrum of the ASAS data, this is not the largest-amplitude frequency, and there is no other signal in the residual spectrum with the same separation from any of the other pulsation components.

Table 1 summarizes the observations and the results of the 30 RRab stars measured in the KBS. The identification of the comparison stars is given in the second column. The third, fourth and fifth columns list the filters, the number of nights and the time interval of the observations, respectively. Previous photometric light-curve information on the targets is given in the 'light-curve history' column. Pulsation periods are taken either from the GCVS (Kholopov et al. 1985) or from our works (7th column in Table 1). The references given in the final column give information on access to the Konkoly photometric data.[2]

The basic parameters of the modulation of the 14 Blazhko stars discovered in the KBS are listed in Table 2. The modulation periods and amplitudes were determined from our observations. The modulation amplitudes listed in Table 2 give different measures of the strength of the modulation. The full amplitude of the maximum-light variation ($A(V)_{max}$) and the Fourier amplitude of the largest modulation peak in the *V* band ($A(V)$) are listed. For comparison with the OGLE-II results, the final column gives the $I_C$ amplitude of the highest modulation peak in the vicinity of the main pulsation frequency ($A(I_C)$). This frequency is not always identical with the highest-amplitude modulation-frequency component, as our sample shows that the highest-amplitude modulation component appears in the vicinity of the first or second harmonic component of the pulsation ($2f_0$ and $3f_0$) in about half of the Blazhko variables.

The observations of the 16 mono-periodic RRab stars of the sample were published by Jurcsik et al. (2006a, 2008a,b); Kun et al. (2008) and Sódor et al. (2007a). These stars were observed

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[1] The modulation frequency $f_m = 1/P_{Bl}$. The primary modulation features in the Fourier spectra of Blazhko stars are triplets at $kf_0 - f_m$; $kf_0$; $kf_0 + f_m$ frequencies.

[2] All the publications of the Konkoly Blazhko group and the Konkoly photometric data can be downloaded from the website http://www.konkoly.hu/24/publications.
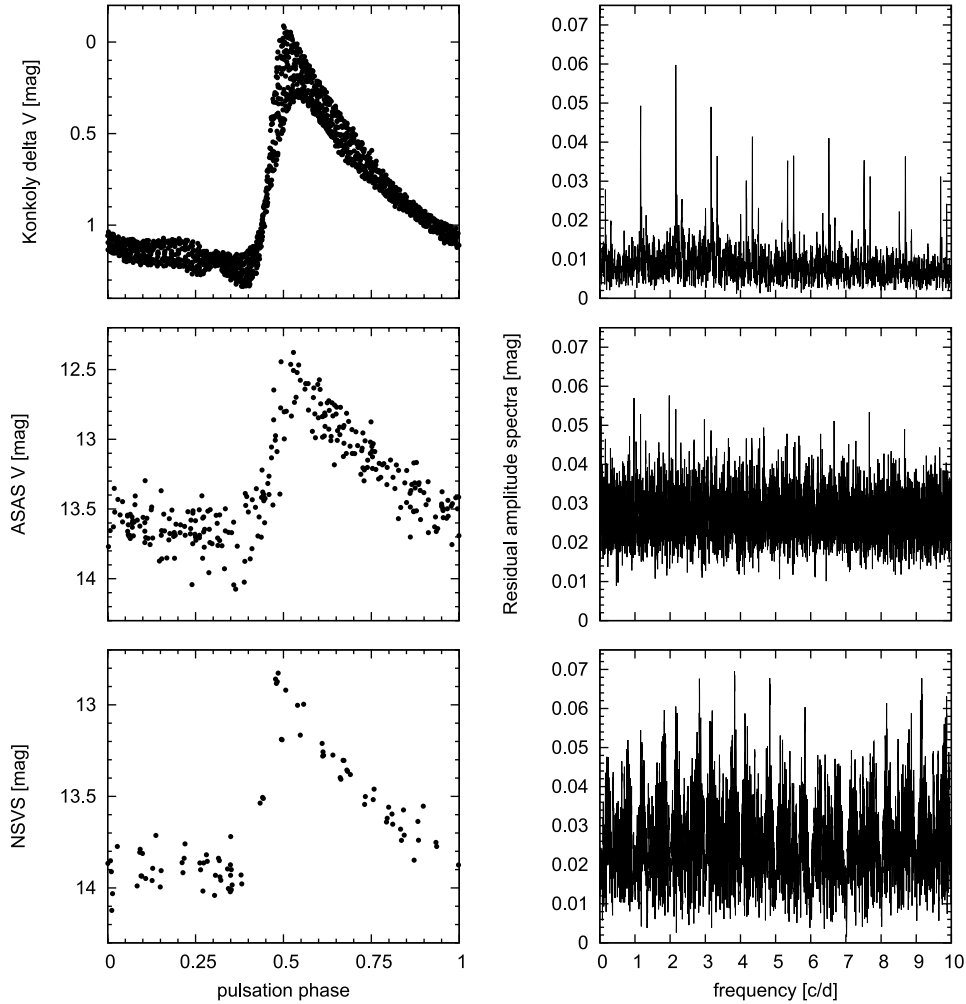
**Figure 2.** Comparison of the Konkoly and previous CCD light curves of UZ Vir. The residual spectra of the data pre-whitened for the pulsation light variation are shown in the right-hand panels. The largest-amplitude signals in the residual spectrum of the Konkoly data are modulation components at 0.015 cd$^{-1}$ separation from the pulsation-frequency components and $\pm 1$ cd$^{-1}$ alias frequencies of these modulation components. Although one of the modulation components ($f_0 - f_m$) appears in the residual spectrum of the ASAS data, too, this is not the largest-amplitude signal and no other significant peak with the same separation from the pulsation components can be identified. The scarce NSVS data show a scattered light curve.

on 8–26 nights, spanning time intervals of 19 to 443 d. Within the limits of our observational accuracy, the light curves of these stars were stable. However, we cannot exclude the possibility that these stars may also show short- or long-period 'micro-modulation' with amplitude of the modulation side-frequencies of 1–2 mmag, which is below our limit of detectability. According to the compilation of Blazhko stars by Smith (1995), about half of the short-period Blazhko stars have modulation periods longer than 50 d. Therefore, it cannot be excluded either that some of the stars claimed here to be mono-periodic have long modulation periods, longer than 3–4 times the time interval of the observations. Moreover, there is a third possibility for the non-detection of the modulation of these stars, namely the temporal behaviour of the modulation as shown for RR Gem by Sódor et al. (2007b) and for RY Com in the next section of this paper. These stars can be regarded as mono-periodic only with these restrictions in mind.

Detailed analyses of RR Gem, SS Cnc and DM Cyg, three Blazhko variables showing small-amplitude light-curve modulation that was not detected previously, were published by Jurcsik

et al. (2005a, 2006b, 2009b). The doubly periodic modulation of UZ UMa was shown by Sódor et al. (2006), and the first really detailed analysis of the light curve and colour behaviour of a large-modulation-amplitude Blazhko variable, MW Lyrae, was presented by Jurcsik et al. (2008c, 2009a). The observations of AQ Lyr, V759 Cyg, BR Tau, XY And, CZ Lac and UZ Vir are extended enough to enable detailed analyses of their Blazhko behaviour to be performed, and these analyses will be the subjects of further individual papers. Results for the remaining three modulated stars, RY Com, FK Vul and BD Her, are presented in this paper.

Only half of the new Blazhko variables (XY And, BD Her, CZ Lac, AQ Lyr, MW Lyr, UZ Vir and FK Vul) have modulation amplitudes that are large enough to be detectable with less accurate and/or less extended observations. However, even though the variation in maximum $V$ brightness is larger than 0.15 mag and the largest-amplitude modulation-frequency component has an amplitude larger than 0.02 mag for these stars, they were not found to show Blazhko modulation in the *Hipparcos*, ASAS and NSVS data.

**Table 1.** Summary of the Konkoly RR Lyrae Survey. Blazhko and mono-periodic variables are typeset in boldface and italics, respectively.

| Star | Comparison star | Filters | No.[a] | Time[b] | Light-curve history[c] | $P_0$ [d] | Ref.[d] $P_0$ | data |
|---|---|---|---|---|---|---|---|---|
| **AQ Lyr** | GSC2.3 N21I000423 | $BV(I)_C$ | 55 | 460 | Stable | 0.357134 | 1 | 1 |
| **V759 Cyg** | GSC2.3 N2IA000839 | $V(I)_C$ | 74 | 152 | n/a | 0.360014 | 1 | 1 |
| **SS Cnc** | Ensemble mean of 3 stars | $BV(RI)_C$ | 35 | 79 | Stable | 0.367337 | 2 | 2 |
| *EZ Cep* | GSC 4521-00784 | $BV(I)_C$ | 26 | 202 | n/a | 0.3790035 | 3 | 3 |
| *BK Cas* | GSC 4025-01395 | $V(I)_C$ | 11 | 337 | n/a | 0.3902700 | 3 | 3 |
| **BR Tau** | NA45000305 | $BV(I)_C$ | 115 | 843 | n/a | 0.3905928 | 1 | 1 |
| *TZ Aur* | BD +41 1609 | $BV(RI)_C$ | 13 | 29 | Stable | 0.3916746 | 4 | 5 |
| *ET Per* | GSC 3671-01241 | $BV(RI)_C$ | 12 | 23 | n/a | 0.3940135 | 3 | 3 |
| **RR Gem** | BD +31 1547 | $BV(RI)_C$ | 63 | 111 | Stable/contradictory | 0.3972893 | 6 | 6 |
| **MW Lyr** | GSC2.3 N0223233663 | $BV(I)_C$ | 177 | 361 | Contradictory | 0.3976742 | 7 | 7 |
| *V378 Per* | GSC2.3 NCGO000977 | $V(I)_C$ | 15 | 96 | n/a | 0.3987208 | 9 | 9 |
| **XY And** | GSC2.3 NBXO000560 | $V(I)_C$ | 64 | 467 | n/a | 0.398725 | 1 | 1 |
| *FH Vul* | GSC2.3 N2P8000417 | $BV(I)_C$ | 8 | 108 | Stable | 0.405413 | 10 | 10 |
| *CN Lyr* | GSC2.3 N24S000237 | $BV(I)_C$ | 8 | 59 | Stable | 0.4113823 | 4 | 10 |
| **DM Cyg** | GSC2.3 N0330220980; N03302207371 | $BV(I)_C$ | 81 | 446 | Contradictory | 0.419863 | 11 | 11 |
| *BK And* | GSC2.3 N078000076 | $BV(I)_C$ | 20 | 99 | n/a | 0.4216093 | 9 | 9 |
| **CZ Lac** | Image subtraction method | $BV(RI)_C$ | 116 | 465 | n/a | 0.432174 | 1 | 1 |
| *GI Gem* | GSC2.3 N8N9000652 | $BV(I)_C$ | 22 | 92 | n/a | 0.4332664 | 12 | 12 |
| **FK Vul** | GSC2.3 N2P8000417 | $BV(I)_C$ | 14 | 83 | n/a | 0.4340529 | 4 | 13 |
| *SW CVn* | BD +37 2310 | $BV(I)_C$ | 10 | 58 | n/a | 0.441671 | 12 | 12 |
| *BH Aur* | GSC 02397-00378 | $V(RI)_C$ | 12 | 19 | n/a | 0.4560898 | 4 | 5 |
| *UU Boo* | GSC2.3 N6AZ000508 | $BV(RI)_C$ | 16 | 396 | n/a | 0.4569339 | 9 | 9 |
| **UZ Vir** | GSC2.3 N5IZ000213 | $BV(I)_C$ | 70 | 474 | n/a | 0.4593925 | 1 | 1 |
| *CG Peg* | GSC2.3 N2MC000574 | $BV(I)_C$ | 11 | 95 | Stable | 0.4671382 | 4 | 10 |
| *UZ UMa* | Ensemble mean of 5 stars | $V$ | 30 | 115 | n/a | 0.4668413 | 8 | 8 |
| **RY Com** | GSC2.3 N5CI000130 | $BV(I)_C$ | 98 | 768 | n/a[e] | 0.468951 | 13 | 13 |
| *SU Leo* | GSC2.3 N6WV000233 | $V(I)_C$ | 12 | 123 | n/a | 0.4722633 | 12 | 12 |
| **BD Her** | GSC2.3 N2BS000412 | $BV(I)_C$ | 16 | 69 | n/a | 0.4739064 | 4 | 13 |
| *RZ Cam* | GSC2.3 N7T2000280 | $BV(I)_C$ | 17 | 75 | n/a | 0.4804514 | 12 | 12 |
| *TW Lyn* | GSC 02971-00853 | $BV(RI)_C$ | 17 | 26 | n/a | 0.4818600 | 4 | 5 |

[a]Number of nights of observations.

[b]Time interval of observations.

[c]n/a: not enough photometric data.

[d]References: (1) forthcoming papers of the Konkoly RR Lyrae group; (2) Jurcsik et al. (2006b); (3) Sódor et al. (2007a); (4) Kholopov et al. (1985); (5) Jurcsik et al. (2006a); (6) Jurcsik et al. (2005a); (7) Jurcsik et al. (2008c); (8) Sódor et al. (2006); (9) Jurcsik et al. (2008a); (10) Kun et al. (2008); (11) Jurcsik et al. (2009b); (12) Jurcsik et al. (2008b); (13) this paper.

[e]Jurcsik & Kovács (1996) noted possible Blazhko modulation. The previous observations (Jones 1966; Bookmeyer et al. 1977) show, however, large scatter at minimum light that may be attributed to photometric inaccuracy. See also Fig. 3.

Based on the maximum timings collected in the GEOS data base[3] and our observations, we found that there is no indication for any strong, irregular period change in any of the mono-periodic RRab stars in the sample. UU Boo, SW CVn and probably EZ Cep show steady period increase, whereas the period of FH Vul is probably decreasing. The periods of the other 12 mono-periodic RRab stars are stable, with very small if any changes detected. In contrast, strong, irregular changes are evident in some of the Blazhko stars (e.g. AQ Lyr, RR Gem, BD Her, V759 Cyg). We thus conclude that the pulsation periods of Blazhko variables tend to be less stable than the periods of unmodulated RRab stars. A similar result was derived from the study of the period changes of RR Lyrae stars in M3 by Szeidl (1965).

## 3.1 The special case of RY Com

We followed the light-curve variation of RY Com in three consecutive seasons, in 2007, 2008 and 2009.

[3] http://rr-lyr.ast.obs-mip.fr/dbrr/dbrr-V1.0_0.php

The Konkoly light curve of RY Com between JD 2 454 205 and 2 454 283 (2007 season) is compared with the available photoelectric (Jones 1966; Bookmeyer et al. 1977) and CCD (NSVS, ASAS) observations in Fig. 3. The scatter of these latter measurements is much larger than the amplitude of the detected light-curve variation in the Konkoly observations. The residual spectra of the four data sets show different characteristics, after pre-whitening the data for the mean pulsation light curves. The highest peaks in the residual spectrum of the Konkoly data are modulation-frequency components at $f_0 \pm f_m$ ($f_m = 0.03$ cd$^{-1}$) with small, $\sim$0.01-mag amplitudes, whereas the residual spectra of the ASAS, NSVS and the old photoelectric data show peaks higher than 0.04 mag at different frequencies. Peaks close to integer frequencies dominate the spectra of the old photoelectric and the NSVS data, indicating long-term trends in the observations, whereas the residual spectrum of the 4-yr-long ASAS data shows multiple peaks in the close vicinity of the pulsation frequency components. This is a typical feature if the pulsation period is changing during the time base of the observations. In the ASAS data this is indeed the case: the pulsation period of the variable was 0.00001 d longer during the first 2 years of the ASAS observations than during the second part of the data. Any

**Table 2.** Summary of the modulation properties of the 14 Blazhko stars discovered in the Konkoly Blazhko Survey.

| Star | $P_{Bl}$ [d] | $A_{Bl}$ [mag][a] | | |
| | | $A(V)_{max}$ | $A(V)$ | $A(I_C)$ |
| --- | --- | --- | --- | --- |
| AQ Lyr | 64.9[b] | 0.30 | 0.032 | 0.022 |
| V759 Cyg | 16.0[b] | 0.12 | 0.014 | 0.009 |
| SS Cnc | 5.3 | 0.09 | 0.015 | 0.009 |
| BR Tau | 19.3 | 0.13 | 0.012 | 0.007 |
| RR Gem | 7.2 | 0.09 | 0.007 | 0.004 |
| MW Lyr | 16.5 | 0.45 | 0.090 | 0.056 |
| XY And | 41.4 | 0.20 | 0.050 | 0.031 |
| DM Cyg | 10.6 | 0.07 | 0.010 | 0.006 |
| CZ Lac | 14.6/18.6 | 0.46 | 0.027 | 0.016 |
| FK Vul | ~56 | 0.3 | 0.06 | 0.04 |
| UZ Vir | 68.2 | 0.36 | 0.053 | 0.036 |
| UZ UMa | 26.7/143: | 0.14 | 0.020 | – |
| RY Com[c] | 32: | 0.06 | 0.008 | 0.005 |
| BD Her | ~22 | 0.5 | 0.12 | 0.08 |

[a] $A(V)_{max}$: full amplitude of the maximum light variation in the $V$ band; $A(V)$: Fourier amplitude of the largest-amplitude modulation-frequency component in the $V$ band; $A(I_C)$: Fourier amplitude of the largest-amplitude modulation-frequency component in the vicinity of $f_0$ in the $I_C$ band.
[b] Complex multiperiodicity of the modulation is detected.
[c] Modulation properties in 2007.

light-curve modulation of RY Com was definitely hidden in the noise and other biases in all previous observations.

Hoping to refine the modulation properties of RY Com, we continued its observation in 2008. However, in this season we could not find any sign of a regular modulation: instead, the maximum brightness of the pulsation light curve dropped by about 0.08 mag in a very short period (about a week) at about JD 2 454 530. Although the scatter of the phased light curves before and after JD 2 454 530 was larger than typical for our observations, especially around minimum light, we could not find any definite modulation period in the data. The star behaved similarly in 2009 – a sudden jump was again detected in maximum brightness in this season, at about JD 2 454 905, and no clear modulation was evident. The observed light-curve variations were consistent in the $B$, $V$, $I_C$ bands in each season. Fig. 4 documents the light-curve history of RY Com between 2007 and 2009.

Fig. 5 shows the O−C variation of RY Com based on archive data collected in the GEOS data base and on our recent observations. The plots indicate that the pulsation period of RY Com varies irregularly, showing both abrupt and continuous changes. During the Konkoly observations, a period increase of 0.00007 d occurred. Unfortunately, it cannot be resolved from our data whether the period change occurred abruptly at around the drop of maximum brightness (JD 2 454 530) or whether it was continuous.

RY Com is the second star in our sample with temporarily occurring modulation. For RR Gem it was found that during the 70 years of the observations the modulation properties of the star changed significantly, and that the modulation was not detectable in the 1970–80s (Sódor et al. 2007b). The photographic data of RR Gem showed that the change of the maximum brightness of the mean light curve was probably connected to an abrupt period change. A 0.00006-d period increase was followed by a 0.1-mag brightening of the $B_{pg}$ mean maximum magnitude of RR Gem, whereas the 0.08-mag drop of the mean maximum $V$ brightness of RY Com was accompanied by a 0.00007-d pulsation period increase in 2008.

### 3.2 FK Vul and BD Her

FK Vul and BD Her were observed in the course of the KBS in 2008. Both stars were observed on more than 10 nights. According to these observations, large-amplitude modulations of the light curves are evident (see Fig. 6). The observations indicate that the modulation periods of FK Vul and BD Her are about 56 and 22 days, respectively. As we do not plan to continue to observe these stars, and the obtained data are not extended enough to allow us to perform detailed analyses of these Blazhko variables, their observations are presented here.

The photometric observations and maximum timings of RY Com, FK Vul and BD Her are available in the online version of the journal as Supporting Information (see Tables 3 and 4 as samples of the electronic data).

## 4 COMPARISON WITH THE MACHO, OGLE-I AND OGLE-II STATISTICS

We compare our results with the MACHO LMC (Alcock et al. 2003), OGLE-I (Moskalik & Poretti 2003) and OGLE-II (Collinge et al. 2006) Galactic bulge statistics, as only these publications give enough details on the variables for a reliable comparison. These surveys are based on the observations of 6158, 150 and 1888 fundamental-mode RR Lyrae stars, among them 944, 51 and 544 have periods shorter than half a day. The detected incidence rates of the modulation of these short-period variables are 16, 27 and 30 per cent, whereas 47 per cent of the stars in the Konkoly sample exhibit the Blazhko effect.

We do not make any distinction between the different types of modulation according to the location of the detected modulation-frequency components ($\nu_1$, $\nu_2$, BL1, BL2, BL2x2, etc.), which were used in the other surveys. Our previous results showed that the $\nu_1$ and BL1 variables, which are characterized by only one modulation-frequency component close to the main pulsation frequency, exhibit, in fact, Blazhko-type modulation (BL2 showing equidistant triplet frequencies) with high asymmetry in the amplitudes of the side-lobe frequencies (Jurcsik et al. 2005b). We have also shown that the side-lobe frequencies of an amplitude and phase-modulated harmonic signal can naturally have highly asymmetric amplitudes (Szeidl & Jurcsik 2009). Collinge et al. (2006) obtained a significantly higher ratio of BL2 stars to BL1 stars than that found in previous surveys. This was attributed mainly to the robustness and sensitivity of the method they applied to detect additional symmetrical frequency components. Their result also indicates that the detection of equidistant frequency components on both sides of the pulsation frequency depends on the accuracy of the data and the efficiency of the analysis performed. It seems that characterizing the modulation with frequency doublets instead of triplets does not reflect real differences of the modulation. The $\nu_2$ and BL2x2 variables show multiperiodic modulation, which is probably also a common feature of Blazhko stars.

The distribution of the modulation amplitude of short-period ($P_{puls} < 0.5$ d) Blazhko variables is shown for the MACHO, OGLE-I, OGLE-II and Konkoly data in Fig. 7. The amplitude corresponds to the largest-amplitude modulation-frequency component in the $V$ band. In order to have homogeneous data, the $I_C$-band amplitudes of the OGLE-I and OGLE-II data are transformed to $V$ amplitudes according to the formula $A(V)/A(I_C) = 1.58$ (Jurcsik, Sódor & Váradi 2005c). Here we stress again that only amplitudes of modulation-frequency components in the vicinity of the main pulsation frequency were published for the OGLE-II data, but the
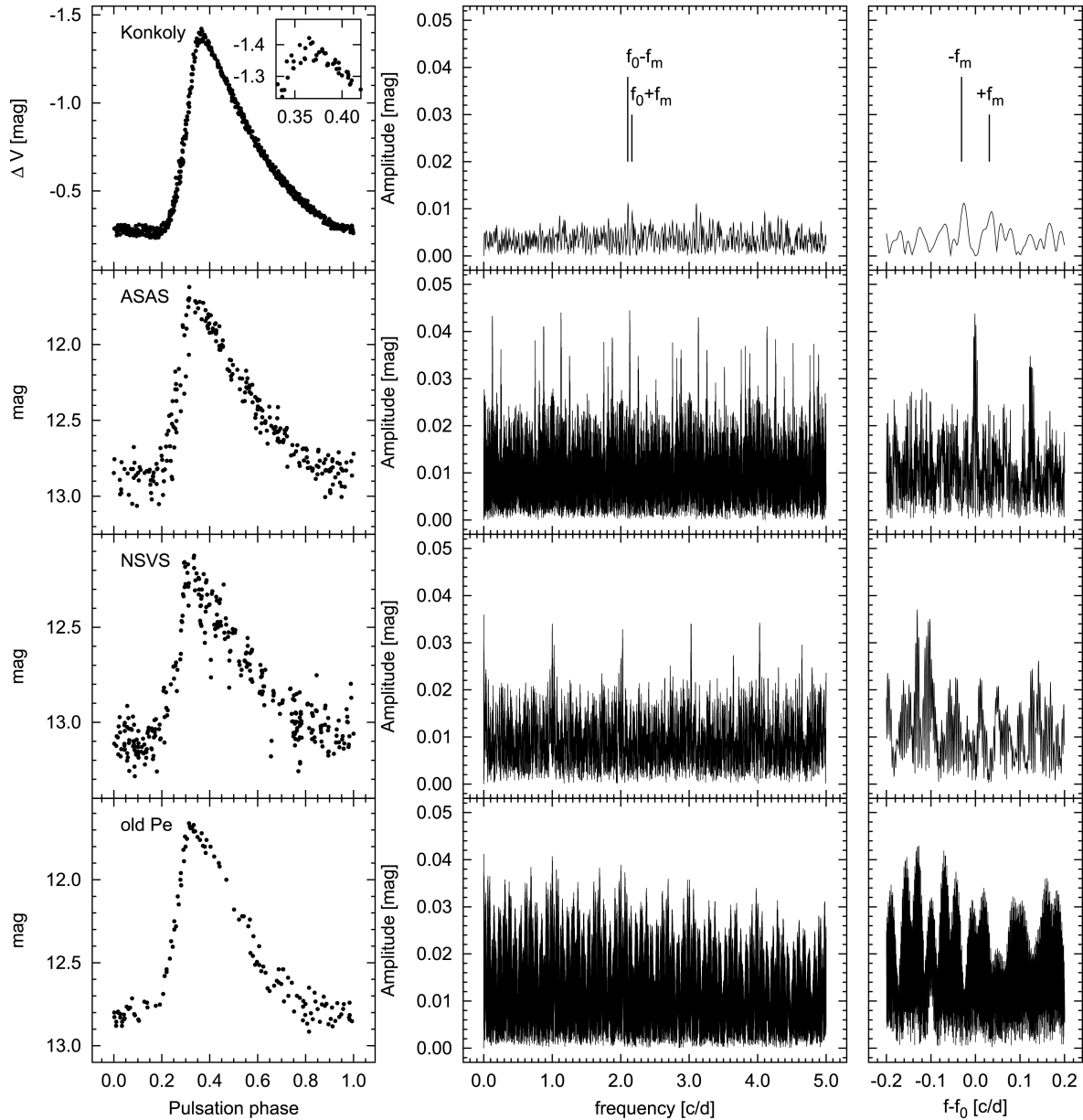
**Figure 3.** Comparison of the Konkoly 2007 light curve and previous photoelectric and CCD observations of RY Com (left-hand panels). The residual spectra of the data pre-whitened for the pulsation period in the $0$–$5\,\mathrm{cd}^{-1}$ frequency range and in the $\pm 0.2\,\mathrm{cd}^{-1}$ vicinity of the main pulsation frequency are shown in the middle and right-hand panels, respectively. The residual spectra of the Konkoly observations show small-amplitude ($<0.01$ mag) modulation-frequency components corresponding to a modulation period of 32 d. The residual spectra of the other data are dominated by noise and large-amplitude signals resulting from long-term trends in the data and from pulsation-period changes of the star.

largest-amplitude modulation-frequency component occurs in the vicinity of the higher harmonics of the pulsation frequency in some Blazhko variables.

Whereas the MACHO and OGLE data show similar modulation-amplitude distributions, with the most frequent amplitude of the modulation being between 0.050 and 0.075 mag, small-amplitude modulations ($A(V) < 0.025$ mag) are the most frequent in the Konkoly sample. Blazhko variables with such small modulation amplitudes constitute only 1, 7 and 10 per cent of the MACHO, OGLE-I and OGLE-II Blazhko samples, respectively, but 50 per cent of the modulated RRab stars discovered in the Konkoly Survey belong to this group.

The $V$ and $I_\mathrm{C}$ Fourier amplitudes given in the last two columns in Table 2 can be directly compared with the modulation am-

plitudes measured in the MACHO and OGLE-II surveys. In our sample of 14 Blazhko stars, six variables have $A(V) \leq 0.015$-mag and $A(I_\mathrm{C}) \leq 0.009$-mag modulation amplitudes. Modulations with similarly small amplitudes were not detected in the MACHO and OGLE-I surveys at all, and were detected in only 2 per cent of the short-period RRab stars of the OGLE-II data.

If only Blazhko variables with at least one large-amplitude modulation-frequency component ($A(V) > 0.025$ mag) were considered in the Konkoly data, the incidence rate of the modulation would be 23 per cent, similar to the MACHO and OGLE results. Consequently, the differences in the observed incidence rates of the modulation between our and the MACHO and OGLE statistics do not arise from the small number of objects and/or from
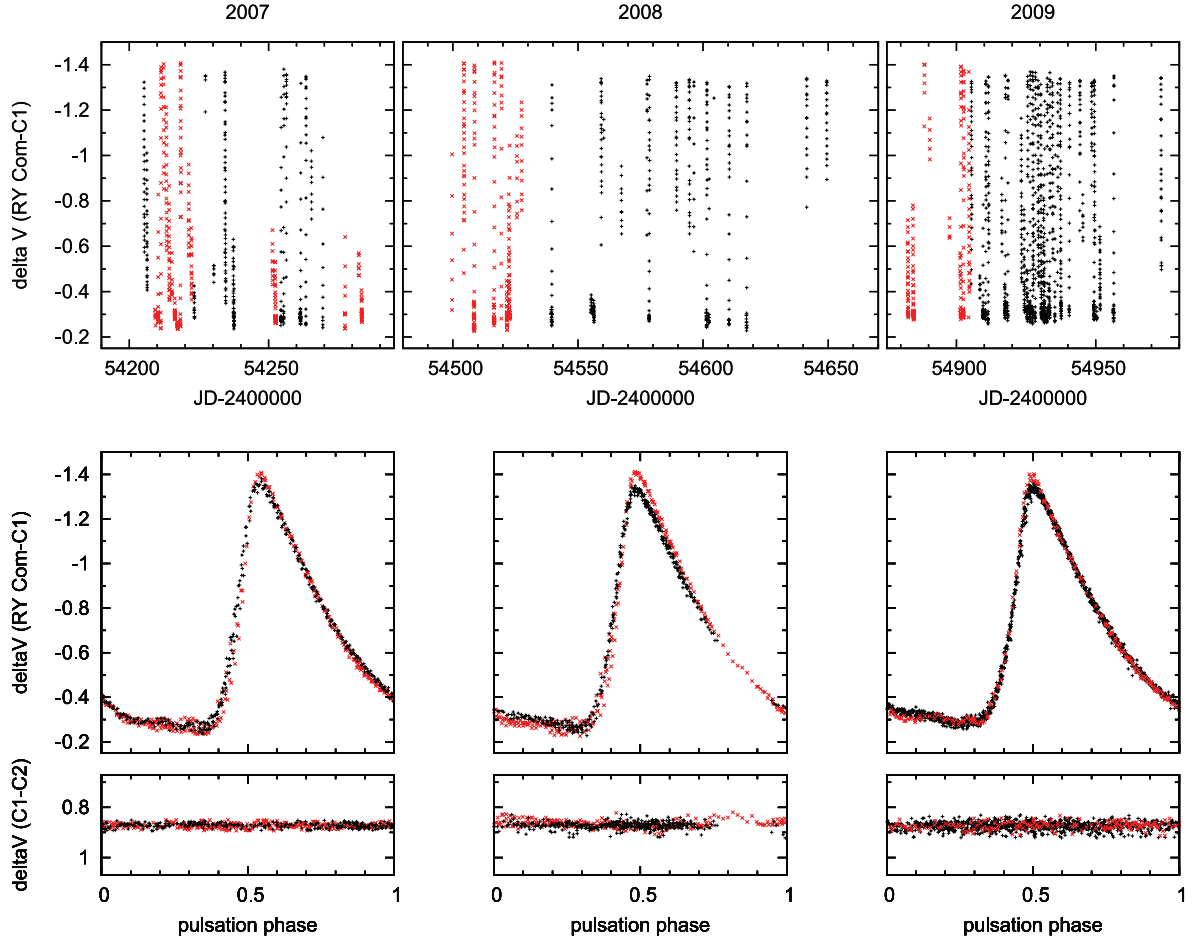
**Figure 4.** The Konkoly *V* light curves of RY Com in the 2007, 2008 and 2009 observing seasons. Crosses denote data belonging to the larger pulsation-amplitude phase of the 32-d modulation detected in the 2007 season and data from the first parts of the 2008 and 2009 observations. Plus signs denote data for which the maximum brightness of the star was fainter. The bottom panels show the comparison − check stars magnitude differences (GSC N5CI000130 − GSC3.2 N5CI000137). These data are phased with the pulsation period of RY Com, in order to demonstrate that the maximum-brightness variation of RY Com does not arise from any variation of the comparison star's magnitude.
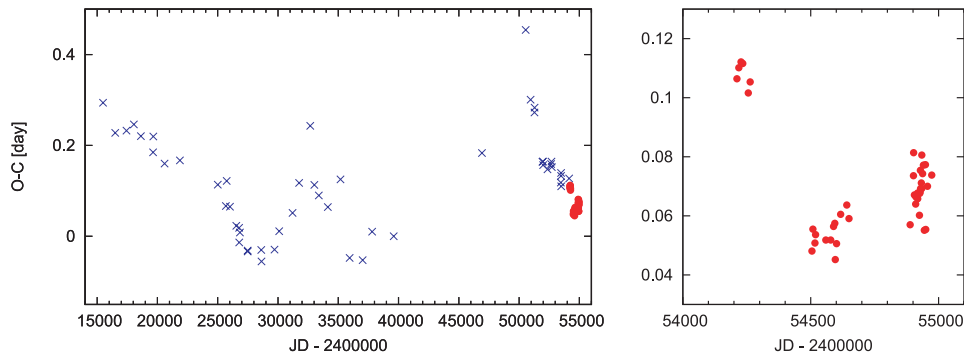


**Figure 5.** O−C plot of the maximum timing data of RY Com. Crosses denote data published in the GEOS data base, and dots show the recent Konkoly data. The right-hand panel is an enlarged part of the O−C diagram for the last three years using the Konkoly data. The O−C value is calculated using 2439598.806 initial epoch and 0.468951-d pulsation period values.

any bias in the target selection of our survey, but from the fact that the latter surveys could not detect small-amplitude light-curve modulations.

As our survey concerns only 30 objects, which is statistically a small number, it is important to verify the significance of the results obtained from this sample. In the OGLE-II data used by Collinge et al. (2006) there were 544 RRab stars with $P_{puls} < 0.5$ d, and among them 30.5 per cent, 166 variables, had detectable light-curve modulation. Assuming that the true incidence rate of modulation among RRab stars is equal to this ratio, the likelihood
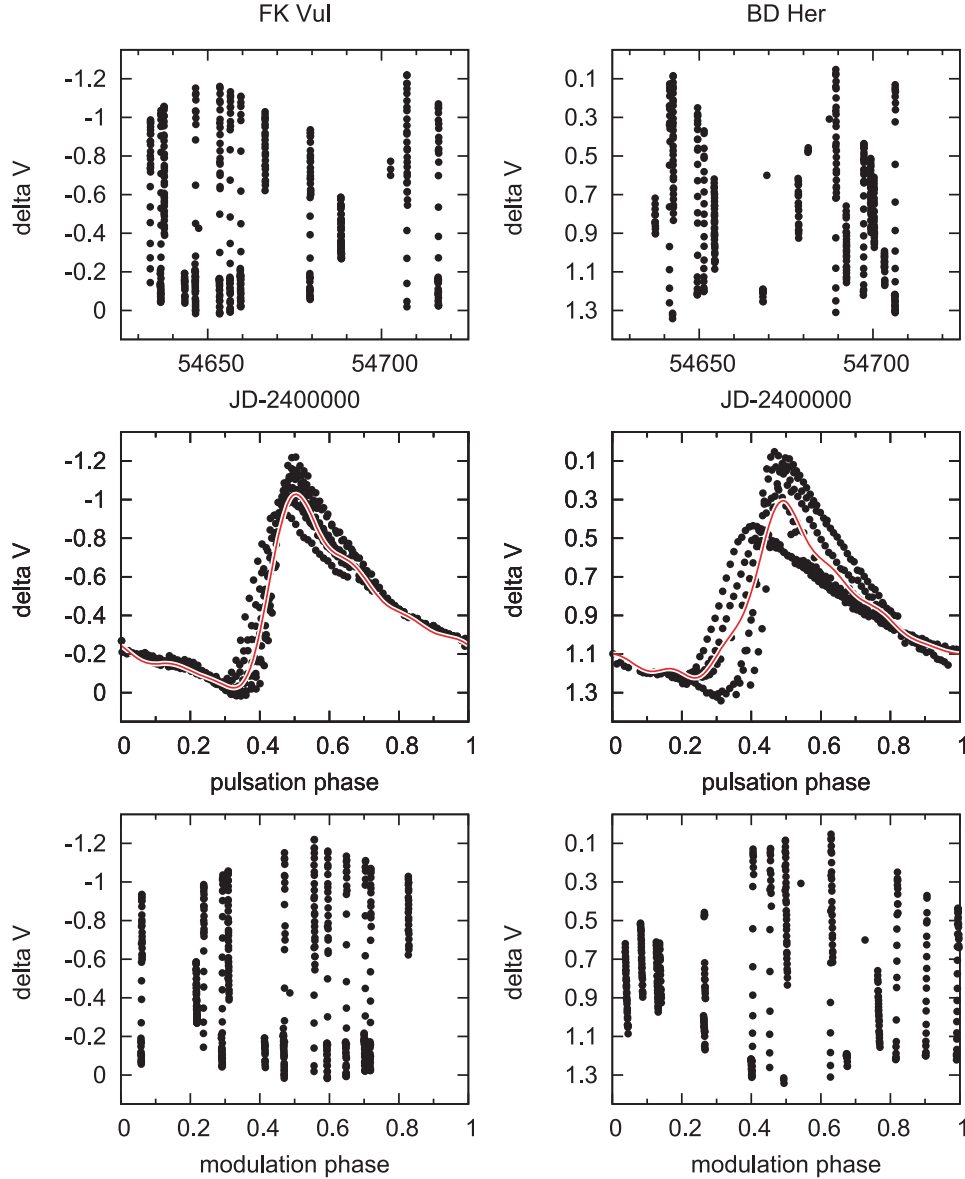
**Figure 6.** Relative *V* magnitudes of FK Vul and BD Her versus Julian Date and phased with the pulsation and modulation periods are plotted in the top, middle and bottom panels, respectively. In the middle panels the mean light curves, determined as appropriate-order Fourier fits with the pulsation frequency to the data, are also shown.

**Table 3.** Konkoly CCD observations of RY Com, FK Vul and BD Her. Standard $BVI_C$ magnitude and $B - V$, $V - I_C$ colour differences are given relative to the GSC2.3 stars N5CI000130 (13 05 16.84 +23 16 54.0), N2PT000030 (20 52 40.50 +22 26 25.4) and N2BS000413 (18 h 50 min 32.84 s +16° 27′ 28.0″) for RY Com, FK Vul and BD Her, respectively. The full table is available as Supporting Information with the online version of this article.

| HJD 2400000 + | Delta mag. | Filter/colour | Star |
|---|---|---|---|
| 54205.28742 | −1.911 | B | RY_Com |
| 54205.29319 | −1.862 | B | RY_Com |
| 54205.29978 | −1.835 | B | RY_Com |
| . . . | . . . | . . . | . . . |

**Table 4.** Maximum timings derived from the Konkoly CCD *V* observations for RY Com, FK Vul and BD Her. The full table is available as Supporting Information with the online version of this article.

| Maximum time | Star |
|---|---|
| 54211.368 | RY_Com |
| 54218.404 | RY_Com |
| 54227.315 | RY_Com |
| . . . | . . . |

of detecting 14 out of 30 variables to show light-curve modulation would be only 4.6 per cent. Therefore, the small sample size of the KBS cannot account for the large percentage of Blazhko variables detected.
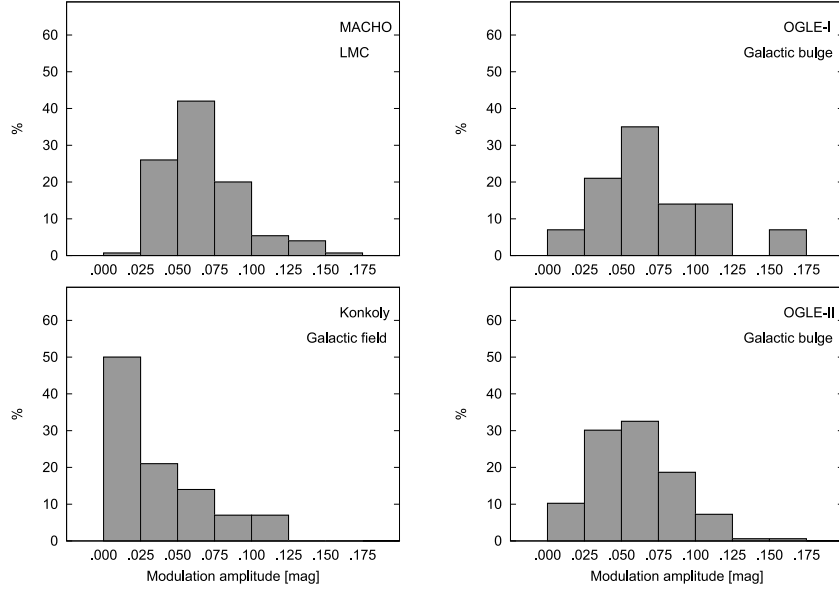
**Figure 7.** Modulation-amplitude distribution of the Blazhko variables with pulsation periods shorter than 0.5 d for the MACHO (Alcock et al. 2003), OGLE-I (Moskalik & Poretti 2003), OGLE-II (Collinge et al. 2006) and Konkoly surveys. There are 148, 14, 166 and 14 short-period Blazhko stars detected in the four surveys. The modulation amplitude corresponds to the *V* Fourier amplitude of the largest-amplitude modulation-frequency component. The OGLE $I_C$ amplitudes are multiplied by 1.58 in order to be comparable with the *V*-band amplitudes. The MACHO and OGLE-I,II data show similar distributions: the modulation with 0.050–0.075-mag amplitude is the most frequent according to these surveys. In contrast, the more densely sampled and more accurate Konkoly data show that the modulation is most frequently of small amplitude ($A_{mod}$ < 0.025 mag). The Konkoly results suggest that a large fraction of Blazhko stars, those with small-modulation amplitudes, has previously escaped detection.

We alsochecked whether or not the selection procedure that Collinge et al. (2006) applied to detect Blazhko variables could identify small-amplitude modulations. The last column in Table 2 lists the $I_C$ amplitudes of the highest modulation peaks in the vicinity of the main pulsation frequency of the Blazhko variables observed in the KBS. To classify a variable to BL1, this peak has to be as large as 2.4 times the noise level. For a BL2 variable, two peaks with symmetrical frequency separations are required, each with an amplitude larger than 1.1 times the noise level, according to the selection applied by Collinge et al. (2006). The average noise level of the light curves of the short-period Blazhko variables in the OGLE-II sample is 16.7 mmag $\pm$ 8.3 mmag. According to the data in Table 2, the $A(I_C)$ amplitudes of the small-modulation-amplitude variables are about half of the average noise level of the OGLE-II data.

The probability of detecting RR Gem-type, small-amplitude modulation in the OGLE-II survey was also tested using various subsets of our observations. The same number of data points (250) as contained in the OGLE-II light curves were randomly selected from the $I_C$-band light curve of RR Gem. Following the method of Collinge et al. (2006) we searched for modulation-frequency components in the vicinity of the main pulsation component in the test data sets. As RR Gem has a modulation period of 7.2 d, modulation-frequency components were searched for in a wider frequency range ($f_0 \pm 0.2\,cd^{-1}$) than used by Collinge et al. (2006). RR Gem was detected only twice from 1000 random selections to be a Blazhko variable according to the criteria of Collinge et al. (2006). Therefore, we conclude that weak modulations such as displayed by RR Gem were definitely missed in the OGLE-II survey.

Another reason for the underestimation of the number of Blazhko variables in the OGLE-II data lies in the detection criteria that Collinge et al. (2006) applied. They searched only for modulations with period $P_{mod} > 10$ d. Taking into account that in our survey two of the 14 new Blazhko stars have modulation periods shorter than 10 d, this selection limit also causes some fraction of the Blazhko variables to be missed.

Concerning the MACHO data, the standard deviations of the residuals after the removal of the pulsation and modulation components from the light curves are in the range 0.03–0.20 mag. This very high noise level makes the detection of small-amplitude modulations very unlikely. Using the light-curve solution of RR Gem and the timings of the MACHO observations we generated artificial time series to test the detection probability of RR Gem-like modulation in the MACHO data. To mimic the noise properties of the MACHO data, Gaussian noise was added with 0.03-, 0.06- and 0.09-mag rms statistics. Fourier analysis of the test data (pre-whitened for the pulsation) showed that the higher modulation peak in the vicinity of the main pulsation frequency had an amplitude larger than $2\sigma$ of the spectrum only if the smallest (0.03 mag) rms noise was added. If the rms was 0.06 mag, none among 500 test time series had a modulation peak reaching $2\sigma$ amplitude. For comparison, only 5 per cent of the MACHO light curves have an rms residual smaller than 0.06 mag.

Our survey is confined to short-pulsation-period variables, which tends to bias the sample in favour of metal-rich disc RR Lyraes. Therefore our conclusion that the true incidence rate of modulation is significantly larger than estimated in the previous surveys is valid only for this population of RRab stars. As the MACHO and OGLE surveys do not show, however, large differences in the occurrence rates of the modulation at different pulsation periods, it is a sound assumption that the situation is the same for longer-period variables, too. To confirm this supposition, accurate photometric data are needed for longer-period RRab stars.

## 5 THE PHOTOMETRIC METALLICITY OF BLAZHKO VARIABLES

The metallicity of RRab stars can be derived from the period of the pulsation and the $\varphi_{31}$ epoch-independent phase difference of the $V$ light curve with an accuracy similar to that determined from low-dispersion spectroscopic observations (Jurcsik & Kovács 1996; Kovács 2005). However, we do not know whether this relationship also holds for the mean light curves of Blazhko variables. If the phase coverage of both the pulsation and the modulation cycles is not sufficiently complete then the mean light curves of large-modulation-amplitude Blazhko variables can be seriously distorted, giving rise to spurious values of the Fourier parameters. For instance, using the ASAS data for SS For, Kovács (2005) found that the photometric metallicity deviates significantly from the spectroscopic value; however, the recent, extended photometric data (Kolenberg et al. 2008) define a mean light curve with Fourier parameters matching the [Fe/H]($P$, $\varphi_{31}$) relationship well.

The extended data we obtained for Blazhko variables enable us to check the accuracy of the photometric metallicities derived from the mean light curves of these variables. Among the 14 new Blazhko variables, nine have spectroscopic abundance determinations. Table 5 lists these variables and summarizes their spectroscopic and photometric metallicities. In this sample there are four and five stars showing small- and large-amplitude modulations, respectively. The photometric metallicities of the small-modulation-amplitude variables calculated from well-defined mean light curves are in very good agreement with the spectroscopic values. We thus conclude that the photometric metallicity of small-modulation-amplitude Blazhko variables is correct, and it has the same accuracy as for unmodulated RRab stars if the light variation is sampled properly.

The situation for Blazhko variables showing large-amplitude modulations is, however, not so clear-cut. Unfortunately, the spectroscopic information on these stars is less certain than that for the small-modulation-amplitude variables. For those variables that have good data coverage (AQ Lyr, XY And and CZ Lac), the spectroscopic and photometric metallicities agree reasonably well. A similar result was derived by Smolec (2005), using published photometric and spectroscopic data for five large-modulation-amplitude Blazhko stars. For the two large-modulation-amplitude variables in

our sample, which have only 400–600 measurements (FK Vul and BD Her), however, the discrepancy between the photometric and spectroscopic metallicities is large. The mean light curves used to calculate the [Fe/H]$_{phot}$ for FK Vul and BD Her are drawn in the middle panels of Fig. 6. It can be seen that the descending branch of the light curve of FK Vul is undersampled, which may result in an improper shape of the mean light curve. Furthermore, the mean light curve of BD Her, especially around minimum light, has an unusual shape, probably as a result of unequal data sampling. It is an open question, however, whether if the light curves of FK Vul and BD Her were better sampled their photometric [Fe/H] would or would not match their spectroscopic values better. The good agreement between the photometric and spectroscopic metallicities of those large-modulation-amplitude Blazhko variables that have good light-curve coverage indicates, however, that if the light variation is well sampled then the Fourier parameters of the mean light curve can be safely used to calculate the metallicity. However, to make this statement better grounded, both extended photometric data of other large-modulation-amplitude variables and spectroscopic metallicities of these variables (e.g. for MW Lyr) are needed.

## 6 SUMMARY

(i) We have shown that with the inclusion of small-amplitude modulations the incidence rate of modulation increases to about 50 per cent for short-period RRab stars. The KBS showed that, in fact, small-amplitude modulations are as frequent as large-amplitude ones. The distribution of the amplitudes of the modulation shows an increase towards smaller amplitudes according to our data. This suggests that the light curves of those RRab stars that are now supposed to be stable may be modulated but with very small amplitude, below our present detection limit. Moreover, we may have missed detecting small-amplitude modulations with long-modulation periods in our sample. Therefore, it is likely that the incidence rate of the modulation we detected is still a lower limit to the true fraction of RRab stars showing the Blazhko effect. Modulations with amplitudes of the maximum brightness variation in the milli-magnitude regime may have escaped detection. The observations of recent space missions (*MOST*, *CoRoT*, *Kepler*) will clarify this issue soon.

**Table 5.** Comparison of spectroscopic and photometric [Fe/H] values of Blazhko stars. Variables with small and large modulation amplitudes are typeset in italics and boldface, respectively.

| Star | No. of $V$ data | [Fe/H]$_{sp}$ (weight)[a] | | $\overline{[Fe/H]_{sp}}$ [b] | [Fe/H]$_{phot}$ |
|---|---|---|---|---|---|
| | | Suntzeff, Kraft & Kinman (1994) | Layden (1994) | | |
| *SS Cnc* | 1400 | −0.16 (4.0) | 0.13 (2.5) | −0.03 | −0.12 |
| *RR Gem* | 3000 | −0.14 (4.5) | −0.13 (2.0) | −0.14 | −0.16 |
| *DM Cyg* | 3000 | −0.16 (1.0) | 0.07 (2.0) | −0.01 | −0.01 |
| *RY Com* | 1000 | −0.64 (0.5) | −1.38 (1.0) | −1.13 | −1.16; −1.16; −1.08; −1.23; −1.16[c] |
| **AQ Lyr** | 1400 | −0.19 (2.0) | | | −0.05 |
| **XY And** | 2600 | | −0.68 (1.0) | | −0.68 |
| **CZ Lac** | 8000 | −0.13 (2.0) | | | −0.26 |
| **FK Vul**[d] | 500 | | −0.71 (1.0) | | −0.37 |
| **BD Her**[d] | 400 | −0.13 (2.0) | | | −1.05 |

[a]Spectroscopic data transformed to the metallicity scale of the photometric [Fe/H] and their weights.
[b]Weighted means as specified in Jurcsik & Kovács (1996).
[c]Derived from the mean light curves of the 2007 and 2008, 2009 data before and after JD 2454530 and JD 2454905, respectively.
[d]Scarce data.

(ii) There is another embarrassing feature of the Blazhko modulation, namely its temporal occurrence as documented recently in the study of the long-term behaviour of RR Geminorum (Sódor et al. 2007b) and in the case of RY Com in the present paper. The modulation of RR Lyrae is also known to cease for a short period in every fourth year (Szeidl 1988). Based on these results there is a good chance that modulation is a common feature of the pulsation of fundamental-mode RR Lyrae stars – it may even be a universal property of these variables. This possibility is an indication that an understanding of Blazhko modulation is crucial to an understanding of the pulsation of RR Lyrae stars.

(iii) Detection of the small-amplitude light-curve modulation of RRab stars is also relevant from a theoretical point of view. Kovács (1995) used the lack of small-amplitude modulations as an argument against the oblique magnetic rotator model of the Blazhko phenomenon (Shibahashi 2000). He says 'Assuming random distribution [of the aspect angle], we should see some small- and some large-amplitude modulations. This is apparently not the case'. The discovery of small-amplitude modulation contradicts this argument. Whatever the cause of the Blazhko modulation, it manifests itself in the full possible range of amplitudes. Besides, simultaneous multiperiodic modulation with similar modulation amplitudes was also detected in the KBS. The significantly different values of the modulation periods observed in these stars is a strong argument against those explanations of the Blazhko phenomenon that connect the modulation period to the rotation of the star.

(iv) Based on our photometric data and spectroscopic information on Blazhko stars we have found that the photometric metallicities determined from the mean light curves of Blazhko variables are correct if the light curve is properly sampled; that is, if the mean light curve is not distorted by uneven data sampling of the various Blazhko phases.

In the KBS we obtained extended data on 30 RRab stars with fundamental periods shorter than 0.5 d, 14 of them showing the Blazhko effect. This is a significantly larger incidence rate of modulation than found previously. We cannot exclude the possibility, however, that the large percentage of Blazhko stars in the sample of the KBS is related to the short pulsation period of these stars. If this were the case, the incidence rate of the modulation would also depend on the metallicity of the stars, as short-period RRab stars are, in general, less metal-poor than longer-period variables. In order to decide whether there is a period and/or metallicity dependence of the occurrence rate of the modulation we initiated a similar survey focusing on RRab stars of longer periods in 2009.

## ACKNOWLEDGMENTS

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table 3.** Konkoly CCD observations of RY Com, FK Vul and BD Her.
**Table 4.** Maximum timings derived from the Konkoly CCD *V* observations for RY Com, FK Vul and BD Her.

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