The historical vanishing of the Blazhko effect of RR Lyr from GEOS and Kepler surveys

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ABSTRACT

RR Lyr is one of the most studied variable stars. Its light curve has been regularly monitored since the discovery of the periodic variability in 1899. Analysis of all observed maxima allows us to identify two primary pulsation states defined as pulsation over a long ($P_0$ longer than 0.56684 d) and a short ($P_0$ shorter than 0.56682 d) primary pulsation period. These states alternate with intervals of 13-16 yr, and are well defined after 1943. The 40.8 d periodical modulations of the amplitude and the period (i.e. Blazhko effect) were noticed in 1916. We provide homogeneous determinations of the Blazhko period in the different primary pulsation states. The Blazhko period does not follow the variations of $P_0$ and suddenly diminished from 40.8 d to around 39.0 d in mid-2009 and extended the time coverage of the Kepler observations, thus recording a maximum O-C amplitude of the Blazhko effect at the end of 2008, followed by the historically smallest O-C amplitude in late 2013. This decrease is still ongoing and VTT instruments are ready to monitor the expected increase in the next few years.

Key words: techniques: photometric stars: individual: RR Lyrae stars: oscillations stars: variables: RR Lyr.

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1 INTRODUCTION

The modulation of the amplitude in luminosity and the pulsation period, known as Blazhko effect, is observed in numerous RR Lyr stars (Le Borgne et al. 2012). Although its theoretical explanation has not yet been determined, a considerable breakthrough in its interpretation has been realized because of recent space observations. As a matter of fact, CoRoT (Poretti et al. 2010; Guggenberger et al. 2011) and Kepler (Guggenberger et al. 2012) results have shown that the Blazhko mechanism is not acting as a clock, thus undermining both the competing models based on a strict regularity: the oblique pulsator and the resonant nonradial pulsator. In our previous work on galactic Blazhko stars (Le Borgne et al. 2012), we did not consider the eponym of the class, i.e., HD 182989 ≡ RR Lyr. We know that its pulsational period shows some apparent erratic changes (Le Borgne et al. 2007). Indeed, we thought that the observation of RR Lyr through the ages deserved a detailed study and, furthermore, dedicated projects.

The variability of RR Lyr was discovered by Mrs. Willemina P. Fleming (see Cannon 1911 for a short but complete biography) on the photographic plates of the Henry Draper Memorial in 1899 (Pickering et al. 1910), Wendell (1905) reports that the first observation dates back to July 20, 1899 and the first maximum to September 23, 1899 (HJD 2414921.675, calculated by Schütte 1923), Prager (1916) and Shapley (1916) were the first to show the correlated photometric and spectroscopic variations. Fig. 5 of Shapley (1916) constitutes the ante litteram representation of the Blazhko effect. Note that this definition was introduced later in the astronomical literature because it shows the oscillation of the median magnitude of the ascending branch with a period of 40 d and an amplitude of 37 min. Detre (1943) compiled the first long list of observed maxima and reported a detailed investigation of the Blazhko effect (Baláz & Detre 1943). Preston, Smak & Paczynski (1965) found that spectroscopic and photometric parameters were strongly variable in the Blazhko cycles of 1961 and 1963, but essentially constant in those of 1962. The idea of irregularities in the Blazhko period gradually grew and later extended photoelectric observations suggested a 4-year cycle in the Blazhko effect, with a minimum variability in 1971 June and a new maximum variability in 1972 April (Detre & Szeidl 1973). A hundred years after the discovery of the RR Lyr variability, Szeidl & Kolláth (2000) have reported that attempts at representing the Blazhko variations by longer periods have failed because they are not strictly repetitive. Extensive photoelectric and CCD observations obtained over a 421-day interval in 2003-2004 fixed a shorter Blazhko period of 38.8±0.1 d (Kolenberg et al. 2004). Finally, RR Lyr ≡ KIC7198959 was included in the field of view of the Kepler space telescope (Borucki et al. 2010). Thus, high-precision, continuous observations could be secured, first in the long cadence (29.4 min) mode and then in the short cadence (1.0 min) observing mode. Kolenberg et al. (2011) have reported the results in the long cadence mode, while Molnár et al. (2012) and Stellingwerf, Nemec & Moskalik (2013) have reported the results in the short cadence mode. RR Lyr shows no particularities in metallicity, abundances and physical characteristics when compared with the other Kepler RR Lyræ stars, Blazhko and non-Blazhko, observed by means of homogeneous high-resolution spectroscopy (Nemec et al. 2013).

It is clear that the full comprehension of the RR Lyr variability is very time demanding since the star has to be observed over decades with time series having a high temporal resolution, in order to survey the pulsation period (Pω) of 13 h, the Blazhko period (Pff) of 40 d, and the long-term changes of both.

Table 1. Observers and observing instruments.

| Observer                  | Telescope          | Detector |
|---------------------------|--------------------|----------|
| Maurice Audejean          | Reflector 320mm    | CCD      |
| Christian Buil            | Reflector 280mm    | CCD†     |
| Emmanuel Conseil          | Reflector 150mm    | DSLR     |
| Laurent Corp              | Photographic lens  | CCD      |
| Eric Denoux               | VTT                | CCD      |
| Christian Drillaud        | Refractor 70mm     | DSLR     |
| Thibault de France        | Refractors 60mm and 80mm | CCD     |
| Thibault de France        | Reflector 130mm    | CCD      |
| Keith Graham              | Reflector 200mm    | CCD      |
| Kenji Hiroswa             | Photographic lens  | DSLR     |
| Alain and Adrien N. Klotz | VTT                | CCD      |
| F. Kugel and J. Caron     | Photographic lens  | CCD      |
| F. Kugel and J. Caron     | Refractor 80mm     | CCD      |
| Jean-François Le Borgne   | VTT                | CCD      |
| Des Loughney              | Photographic lens  | DSLR     |
| Kenneth Menzies           | Reflector 317mm    | CCD      |
| Miguel Rodríguez          | Refractor 60mm     | CCD      |
| Paolo Maria Ruscitti      | Reflector 130mm    | DSLR     |
| Horace A. Smith and coll. | Reflector 600mmab  | CCD      |

*Synthetic photometry from low resolution spectra using Shelyak Alpy 600 spectrograph.
*Telescope at the Michigan State University campus Observatory (East Lansing, Michigan, USA) operated by H. Smith, with the help of Michigan State University students Charles Kühn, James Howell, Eileen Gonzales, and Aron Kilian.

With the goal of making the ground-based survey of the Blazhko effect of RR Lyr as effective as possible, we decided to devise small, autonomous, and transportable photometric instruments. The basic idea was that these instruments are able to follow RR Lyr continuously, in order to obtain a reliable time of maximum brightness (Tmax), on as many clear nights as possible. Since the calibration of a photometric system would have required a major refinement and would have increased the costs of the instrument (e.g. filters, standard stars observations, cooling, etc.), both ill-suited for the requirements of simplicity and duplicability, the determination of a standard, calibrated magnitude of the maximum was not pursued as a goal. The first observations were performed in 2008 and these are expected to continue for many years to come. The instruments are composed of a commercial equatorial mount (Sky-Watcher HEQ5 Pro Goto), an AUDINE CCD camera (512x768 kaf400 chip) and a photographic 135-mm focal, f/2.8 lens with a field of view of 2’x3’. We gave them the nickname, Very Tiny Telescopes (VTTs). Three such instruments have been built and used mainly in 3 different places near Toulouse, Castres and Caussades (Région Midi-Pyrénées, France). However they have been occasionally moved to several other places in France, Spain, and Italy.

The observations of the VTTs are controlled from a computer using the program AudeLa. VTT images were obtained with no filter with an exposure time of 30 s. Science images have been corrected with mean dark images obtained during the night to compensate the absence of cooling. A dark frame was obtained every five images on the target and the mean dark image of five individual
dark frames was subtracted from the 25 target images concerned. From June 2008 to November 2013, 332 maxima were measured by VTTs with about 360 000 images collected on 829 nights. The photometry of RR Lyr and of the comparison star HD 183383 was performed with the SExtractor software (Bertin & Arnouts 1996). The times of maximum brightness were determined by means of cubic spline functions with a non-zero smoothing parameter which depends on the number of measurements to fit and on their scatter (Reinsch 1965). The smoothing parameter was chosen to be large enough to avoid local maximums and so that the fitting curve goes through the points with zero mean residuals over a characteristic time interval of 5 min. The uncertainty on the time of the maximum was the difference between the two times corresponding to the intersection of the spline function with the line $y = m_{\text{max}} + \sigma / \sqrt{N - 1}$, where $m_{\text{max}}$ is the instrumental magnitude at maximum, $\sigma$ is the standard deviation of the fit and $N$ is the number of measurements used in the light curve.

Although VTT observations are most numerous during the 2008-2013 campaign (829 night runs compared to 938 in total), observations with other instruments are also included in the present study (Table 1). Most of these additional observations where carried out with classical telescopes, refractors or reflectors, with diameters from 55 mm to 320 mm, equipped with CCD cameras. Among these, $BVI$ measurements were obtained with the 60-cm telescope at the Michigan State University campus observatory. However, some observations were carried out with digital photographic cameras (DSLR). As a new approach to spectrophotometry, synthetic photometry was performed on low-resolution spectra using a Shelyak Alpy 600 spectrograph mounted on a 280-mm diameter reflector. Low-resolution spectra ($R=600$) were obtained through a wide slit and calibrated in flux by means of spectrophotometric standard stars. Photometry is then performed by integrating the spectra in Johnson filter bandpasses.

### 3 GEOS DATA BASE

The Groupe Européen d’Observations Stellaires (GEOS) RR Lyr data base (Le Borgne et al. 2007) is a collection of published maxima of galactic RR Lyr stars which contains 2245 maxima of RR Lyr itself (up to 2013 December 5). In Appendix A, we give the list of references used to build the GEOS data base for RR Lyr. In our analysis, we did not consider uncertain maxima and those noted by the authors as normal, created from observations drawn from many different individual maxima. This is because they could be referred to a wrong epoch if an inaccurate $P_0$ value were to be used. The normal maximum could also be the arbitrary epoch of an ephemeris. This is the case of the first ephemerides of RR Lyr (Prager 1916; Shapiro 1916; Sanford 1928) that were calculated using JD 2414856, i.e., the date of the first observation, rather than JD 2414921, i.e., the date of the first maximum. Moreover, a normal maximum masks the Blazhko effect because it averages observations on a large interval of time.

We added 692 new photographic and photoelectric maxima observed by L. Detre in the years 1944-1981. The list of ~7000 measurements reported by Szeidl et al. (1997) was scanned and digitized by means of a semi-automatic procedure. These measurements are now available on electronic form on the Konkoly Observatory web site. We also evaluated the differences between 278 $T_{\text{max}}$ observed simultaneously in $B$ and $V$ filters. No systematic effect was detected: 67 per cent of the $T_{\text{max}}$ differences are within the interval from $-0.0016$ to $+0.0016$ d, symmetrically distributed with respect to 0.000 d. The frequency analysis did not detect any periodicity in the $T_{\text{max}}$ differences. Finally, we measured 25 $T_{\text{max}}$ values from the original observations collected at Michigan University in the framework of the 2003-04 campaign (Kolenberg et al. 2008).

### 4 $P_0$ VARIATIONS OF RR LYR OVER MORE THAN ONE CENTURY

We analysed 3975 $T_{\text{max}}$ (obvious outliers were removed) spanning 114 yr and we calculated the linear ephemeres from a least-squares fitting of all them:

$$\text{HJD Max} = 2414921.7746 + 0.566835616 \cdot E$$

(1)

In Appendix B, we give the list of $T_{\text{max}}$ used to calculate equation (1) and used in the subsequent analysis. The purpose of using the above ephemeres was to detect large changes in the $P_0$ value. Indeed, the plot of the O-C (observed minus calculated $T_{\text{max}}$) values clearly pointed them out (Fig. 1). Therefore, we subdivided the 114 yr of observations of RR Lyr into several time intervals, following the $P_0$ changes regardless of the observing technique. Table 2 lists the actual $P_0$ values in each interval.

The Blazhko period contributes greatly to an increase in the O-C scatter beyond that attributable to the observing technique alone. The varying thickness in Fig. 1 also suggests a variable amplitude. To study the behaviour of $P_0$, we calculated a linear ephemeres in each interval of Table 2 this time by dividing the $T_{\text{max}}$ on the basis of the observing technique (visual, photographic, photoelectric, or CCD) or instrument (VTTs, Kepler). These subsets supplied independent values of $P_0$ (Table 3) in good agreement with those of the whole time interval (Table 2). The uncertainties on $P_0$ (as well as those on the Blazhko period $P_b$, see below) are the formal error bars derived from the least-squares fittings. About the first long time interval, we preferred to use the visual maxima instead of the photographic maxima because the visual technique implied the survey of the star for several hours, while the photographic technique often recorded a few measurements only. The visual maxima are very useful to fill the long gap between 1982 and 2000, not covered by photoelectric observations before many amateur astronomers upgraded their instrumentation to CCD detectors. In addition to the time intervals listed in Table 2, we note that visual maxima provided $P_0$ values in excellent agreement with the photoelectric and CCD ones in the intervals JD 2439000-2442500, 2442500-2445000, and 2455000-2456200.

After an initial change, which the few observed maxima place around 1910, the period of RR Lyr was constant for about 36 yr. Then, around 1946, it started a series of sudden changes, on a timescale of few years. The O-C pattern shows jumps from long values (O-C’s from negative to positive values, with maxim values reached on 1946.5, 1965.7, 1982.1, 1994.4, and 2009.5) to short values (O-C’s from positive to negative values, with maxim values reached on 1958.8, 1975.2, 1989.8, and 2004.0). Table 2 lists the computed values of $P_0$ after any observed change and the last three digits of $P_0$ are also noted in Fig. 1. The minimum difference between a long and a short value is between JD 2445000 and 2455000. One of the changes of state is well covered by VTT observations: when considering the $T_{\text{max}}$ before JD 2455000 the period is a long one (0.56686 d), after a short one (0.56680 d, see Table 3).
Figure 1. Historical behaviour of the period variations of RR Lyr. The numbers are the last three digits of the pulsational period calculated in each interval.

Table 3. Pulsation $P_0$ and Blazhko $P_B$ periods calculated from homogenous subsets. Error bars on the last digits are between brackets.

| Julian Days [JD-2400000] | Method | Number of $T_{max}$ | Pulsation period [d] | Blazhko period [d] | Blazhko O-C amplitude [d] |
|---------------------------|--------|---------------------|----------------------|---------------------|--------------------------|
| 19635-27313 visual        |        | 75                  | 0.5668 470(5)        | 40.89(3)            | 0.018(3)                 |
| 32062-33455 photog.       |        | 27                  | 0.5668 193(45)       | 40.86(28)           | 0.014(3)                 |
| 33505-36457 photoel.      |        | 39                  | 0.5668 200(9)        | 40.94(28)           | 0.005(2)                 |
| 36674-38996 photoel.      |        | 160                 | 0.5668 734(17)       | 40.83(10)           | 0.018(2)                 |
| 39008-42405 photoel.      |        | 342                 | 0.5668 205(4)        | 41.14(3)            | 0.014(1)                 |
| 42504-44822 photoel.      |        | 162                 | 0.5668 583(13)       | 38.95(12)           | 0.013(2)                 |
| 45493-47779 photoel.      |        | 14                  | 0.5668 271(26)       | Too few points      |                          |
| 45131-47982 visual        |        | 193                 | 0.5668 239(13)       | 39.02(20)           | 0.007(3)                 |
| 48012-50000 visual        |        | 98                  | 0.5668 427(18)       | 39.03(10)           | 0.018(3)                 |
| 50224-52926 visual        |        | 126                 | 0.5668 1703(10)      | 39.06(11)           | 0.012(2)                 |
| 52915-54733 CCD           |        | 40                  | 0.5668 621(28)       | 39.00(5)            | 0.024(2)                 |
| 54652-55000 VTTs          |        | 69                  | 0.5668 589(14)       | 39.39(5)            | 0.026(2)                 |
| 55276-56390 Kepler        |        | 1815                | 0.5668 953(4)        | 38.84(2)            | down to 0.009            |
| 55000-56624 VTTs          |        | 264                 | 0.5668 024(11)       | 38.91(7)            | down to 0.006            |

We also note that there is a sort of semiregular cadence separating two consecutive O-C maxima or two consecutive O-C minima, about 13–16 years and that the $P_0$ is still decreasing: if we consider the maxima after the change at JD 2455000 only, the period is below 0.5668000 d (Tables 2 and 3).

5 $P_B$ VARIATIONS OF RR L YR OVER MORE THAN ONE CENTURY

Because the pulsation period of RR Lyr was undergoing changes from two different states, the question of whether these changes effect the Blazhko effect immediately arose. This point could be very
Table 2. Pulsation periods $P_0$ in the intervals of Fig. 1. Error bars on the last digits are between brackets.

| Years     | Julian Days [JD-2400000] | $N_{\text{max}}$ | Pulsational period $P_0$ [d] |
|-----------|---------------------------|------------------|-----------------------------|
| 1899-1908 | 14921-18000               | 5                | 0.5668 (1)                  |
| 1908-1946 | 18000-32000               | 138              | 0.5668 481(3)               |
| 1946-1958 | 32000-36500               | 70               | 0.5668 116(9)               |
| 1959-1965 | 36500-39000               | 164              | 0.5668 721(17)              |
| 1965-1975 | 39000-42500               | 418              | 0.5668 204(4)               |
| 1975-1981 | 42500-45000               | 324              | 0.5668 585(10)              |
| 1982-1989 | 45000-47800               | 205              | 0.5668 224(12)              |
| 1989-1995 | 47800-50000               | 103              | 0.5668 427(17)              |
| 1995-2003 | 50000-53000               | 132              | 0.5668 174(10)              |
| 2004-2009 | 53000-55000               | 188              | 0.5668 619(14)              |
| 2009-2013 | 55000-57000               | 2228             | 0.5667 975(4)               |

6 THE Kepler DATA

Kepler data allowed us to combine the analysis of $T_{\text{max}}$ variations with another specific Blazhko characteristic, i.e., the changes of the magnitude at the maximum brightness ($K_{p_{\text{max}}}$). We determined $T_{\text{max}}$ and $K_{p_{\text{max}}}$ from the original Kepler data by means of the same procedure used for VTT data. We used the Q5-Q16 short-cadence data acquired from 2010 March 20 to 2013 April 3. The analysis of the almost continuous succession of observed maxima already pointed out a totally new and prominent feature, i.e., the alternation of higher and lower maxima (i.e. period doubling; see Fig. 4 in Szabó et al. 2010, for a clear example). A theoretical background has been proposed for this new phenomenon (Kolláth, Molnár, & Szabó 2011). We investigated the regularity of this effect along all the time interval of the Kepler observations (Fig. 3). The scatter due to the period doubling effect is always noticeable (top panel). The amplitudes are variable and the largest amplitudes are not related to a particular phase of the Blazhko effect, because the related large scatter is observed at both the maximum and at the minimum values of $K_{p_{\text{max}}}$. Moreover, there are Blazhko cycles where the period doubling effect is always very noticeable, as that from BJ 2455710 to 2455750. There is also a damping of the effect toward the end of observing time, when also $K_{p_{\text{max}}}$ variations have a small amplitude.

As a new contribution to the characterization of the period doubling effect, we calculated the differences between the $K_{p_{\text{max}}}$ value of an even $(2n)$ epoch and that of an odd $(2n-1)$ epoch. These differences are both positive and negative (middle panel) and this implies that the highest $K_{p_{\text{max}}}$ changes from an odd epoch to an even one. In this plot the highest maxima or the deepest minima are separated by a time interval corresponding to the characteristic period of the switching from an odd epoch of high $K_{p_{\text{max}}}$ to an even one. Moreover, more rapid fluctuations are also visible. It is worth analysing these time series to search for periodicities in the switching process. The iterative sine-wave fitting method (Vaniček 1971) is well suited to disentangle such periodicities because it allows the detection of the components of the light curve one by one. Only the values of the detected frequencies (known constituents) are introduced in each new search, while their amplitudes and phases are recalculated for each new trial frequency. In such a way, the exact amount of signal for any detected frequency is always subtracted. In the first power spectrum of the $K_{p_{\text{max}}}$ differences (bottom-left panel), the highest peak was at a low frequency, $f_2 = 0.018$ d$^{-1}$, corresponding to $P \approx 55.6$ d, i.e., about 98 $P_0$. After introducing it as a known constituent, we could identify a higher frequency, $f_2 = 0.062$ d$^{-1}$ (bottom-right panel), corresponding to $P \approx 16.1$ d, i.e., about 28.5 $P_0$. The peak close to $f = 0.0$ d$^{-1}$ appearing in both spectra is a result of the very long-term effect (see below).

The Kepler data make it possible for us to study in detail the cycle-to-cycle variations of the Blazhko effect in RR Lyr. To do this, we calculated a least-squares fit of the observed O-C and $K_{p_{\text{max}}}$ values on sliding boxes of 56 d shifted from each other by 8 d. This procedure returns the values of the amplitudes of the O-C and $K_{p_{\text{max}}}$ variations for each box (Fig. 3). The general trend for both amplitudes is a slow decrease. In particular, the O-C curve does not seem to have reached the final minimum at the end of Kepler observations (middle panel), while the $K_{p_{\text{max}}}$ amplitude curve seems to start to increase again after a shallow minimum at JD 2459000.
Figure 3. The period doubling effect in the magnitudes at maximum brightness of RR Lyr observed with Kepler. Top panel: $K_{p,\text{max}}$ values. Consecutive values are connected. Middle panel: plot of the differences between two consecutive cycles in the sense odd-epoch (2n) minus even-epoch (2n-1). Bottom panels: power spectra of the values of the middle panel, with no known constituent (left) and with $f_1=0.018$ d$^{-1}$ (right) as known constituent. (bottom-left panel). The extreme changes in the Blazhko effects are sketched by the shrinking of the close curve connecting O-C and $K_{p,\text{max}}$ values (bottom-right panel). The alternation of low and high maxima also twists the regular shape of the close curve, adding a new model to the already variegated collection [Le Borgne et al. 2012]. Modulations are clearly visible both in the O-C and in the $K_{p,\text{max}}$ amplitudes (Fig. 4). Combined with the long-term trend, they produce the cycle-to-cycle variations of the Blazhko effect.

We performed the frequency analysis of the time series of the O-C and $K_{p,\text{max}}$ amplitudes to search for periodicities by means of a sinusoidal fit and a parabolic trend. The two power spectra are characterized by broad structures with different highest peaks at low frequencies. The inconsistency between the two results does not support a reliable identification of real periodicities in the changing shape of the Blazhko effect.

7 VTT DATA

The first VTT $T_{\text{max}}$ was observed on 2008 July 4 simultaneously with two instruments. Since then the regular survey of RR Lyr has yielded 55, 78, 42, 56, 75, and 27 $T_{\text{max}}$ from 2008 to 2013, respectively. To analyse VTT data we performed a least-squares fit of the O-C values determined each year. Indeed, ground-based observations of RR Lyr are concentrated in a few months of each year, covering about two consecutive Blazhko cycles. The variations between the Blazhko cycles in a given year are very small and consequently the folded curves of O-C over the Blazhko cycle are quite representative of the behavior in each year. Indeed, the continuous decline in amplitude and the changing shape of the O-C curve is well reproduced and variations have already become noticeable from one year to the next already (Fig. 5). In particular, note how

Figure 4. The changes in the Blazhko effect of RR Lyr from 2008 to 2013. Top panel: VTT (red filled circles) and Kepler (grey circles) O-Cs showing the strong decrease in amplitude. Middle panel: O-C half amplitude, same symbols. VTT values are taken from the yearly mean curves (Fig. 5). Bottom panel (left): $K_{p,\text{max}}$ (half) amplitude, Kepler data. Bottom panel (right): the first (big) and last (small) Blazhko cycles observed with Kepler.

Figure 5. The decreasing amplitude of the O-C curves in the VTT data from 2008 to 2013.
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The curve becomes more sinusoidal with the decreasing O-C amplitude.

By adding the VTTs to Kepler ones (Fig. 6, middle panel), we can state that the maximum O-C amplitude has been reached well before the space observations began. The CCD determinations preceding the VTT observations (40 T_max between JD 2452915 and 2454733) supply an O-C amplitude of 0.024 d (Fig. 6). While the visual T_max values collected before CCD ones supply smaller amplitudes, i.e., 0.018±0.003 d and 0.012±0.002 d (Table 3). From these values we can infer that a minimum O-C amplitude occurred when only visual T_max were available, in 1984-85 (tentatively around JD 2446000) followed by an increase that reached its maximum (0.031 d) at the beginning of the VTT observations, near the end of 2008 (JD 2454800, see Fig. 6 top panels). The subsequent decrease is still ongoing (bottom panels). Indeed, the O-C amplitude recorded by the VTTs until the end of 2013 (0.006 d) is even smaller than that of the last Kepler data (Fig. 6 middle panel).

8 DISCUSSION

The VTT observations started 624 d before the first Kepler observation in short-cadence mode, and they are still continuing, while the last Kepler T_max was obtained in 2013, in early April. The re-analysis of the T_max epochs listed in the GEOS data base allowed us to reconstruct the changes in the pulsational period of RR Lyr. We could establish the existence of two states characterized by the pulsation over a long P_0 (longer than 0.56684 d) and over a short P_0 (shorter than 0.56682 d). The history begins with a long P_0 status that lasted from 1910 to 1943. After this, the two states alternate more frequently and usually long states last much less than the short states. Since 1943 the same state seems to re-appear after a time interval of 13-16 yr (Fig. 6). The frequency analysis of the O-C values since 1950 shows the highest peak at 14 yr. The last cycle began in 2003 with a long P_0 and the VTTs recorded that it switched into a short (the shortest, actually) one in 2009, and that is still running. The cyclic shift of P_0 amounts on average to ΔP_0 = 4 × 10^{-5} d (Table 2) and hence ΔP_0/P_0 = 7 × 10^{-5}.

We also determined the periods of the Blazhko effect by means of an homogenous technique. We can provide a new reliable chronological set of values since the beginning of the twentieth century, replacing the values reported by each author on the basis of different methods of analysis or simply adopting values reported in the literature (see Table 6 in Kolenberg et al. 2006, for a detailed list). The alternate states of P_0 do not have a counterpart in the variations of P_B (Fig. 6). Actually, when comparing the whole set of the new determinations of P_B we can argue that P_B suddenly changed in 1975 (around JD 2442500, Fig. 5, much earlier than that reported by Kolenberg et al. 2006). It was around 41 d until 1975 and since then shortened to 39 d; the shift from one side to the other of the 40 d mark is also visible in Fig. 6. The corresponding rate ΔP_B/P_B = 0.05 is three orders of magnitude larger than that observed for P_0. Correlated and anticorrelated changes of P_B and P_0 were observed in Blazhko RRab stars: RW Dra (Firmanyuk 1978), XZ Dra (Jurcsik, Benkó & Szeidl 2002), XZ Cyg (LaCluyze et al. 2004), RR Gem (Sándor, Szeidl & Jurcsik 2007), RV UMa (Hurt et al. 2008), MS stars (Szeidl et al. 2011), RZ Lyr (Jurcsik et al. 2012), and Z CVn (Le Borgne et al. 2012). RR Lyr shows alternate states of long and short P_0, combined with the decreasing P_B. Taking into account that changes of P_0 and P_B also occurred at different epochs, it seems that RR Lyr adds another kind of relation between the two periods describing the light curves of Blazhko stars.

The combination of Kepler and VTT data supplies us with a clear picture of the vanishing of the Blazhko effect. The space telescope continuously monitored the monotonic long-term decrease, proving that small-scale modulations, lasting from 2 to 4 P_B, are also visible in the O-C values. The VTTs have allowed us to assess that the decline in amplitude started in 2008 and is still ongoing. The plot of the O-C amplitude (Fig. 6, middle panel) reveals about 5 yr and it shows the continuous decrease. Hence, it does not support the action of a 4-yr modulation cycle of the Blazhko effect (Detre & Szeidl 1973). We also note that the minimum full-amplitudes of the T_max and K_max variations observed with VTTs and Kepler (0.012 d and 0.04 mag, respectively) are about half those recorded in the 1971 minimum (0.020 d and 0.07 mag). Therefore, it seems evident that we are observing the historical minimum level of the Blazhko effect. Such a small value was observed perhaps only during the sharp decrease after the O-C maximum in 1950 (Fig. 5), but the event is poorly covered because of the small numbers of T_max. Another minimum O-C amplitude was perhaps observed around 1985, but on this occasion we only obtain very scattered visual T_max. We note that these three minimum O-C amplitudes occurred when P_0 was in the short state.

Combined with the Blazhko effect, the period doubling is making RR Lyr still more intriguing. The analysis of the Kepler short-cadence data was helpful in understanding this new effect. We can verify that this effect does not seem to be related to any particular Blazhko phase and can be observed at any time in the data. We find two clear periodocities describing a long-time (55.6 d) and a short-time (16.1 d) switch between the epochs (odd or even) of the higher K_p,max. Both these periodocities are not obviously related with P_B. We can just note that 55.6/38.8=1.43, roughly similar to the occurrence of half-integer values, but the 1.5 value is not matched. Moreover, here we are dealing with periods, while the

Figure 6. Uncorrelated variations of the pulsation period P_0 (top panel) and of the Blazhko period P_B (bottom panel). Time interval are the same as in Fig. 4.
period doubling effect can be represented by means of half-integer
values of the pulsational frequency \((f/2, 3/2f, 5/2f, \ldots)\).

9 CONCLUSIONS

The most promising mechanism that can explain the Blazhko effect
is the \(9P_0=2P_B\) resonance between the ninth overtone and the
fundamental mode, also capable of producing the period doubling
effect (Buchler & Kolláth 2011). A recent new explanation is based
on the transient excitation of the first overtone radial mode (Gillet
2013). The signature of this mode has already been found in the
Q5-Q6 Kepler data (Molnár et al. 2012) and the analysis of other
datasets is ongoing. The results described here supply a complete
overview of the behaviour of the Blazhko effect and of the pulsation
content of RR Lyr since its discovery 114 yr ago, thus putting
pressure on the Blazhko mechanism. In particular, the
completely different behaviours of the \(P_0\) and \(P_B\) changes suggest that
they are not coupled in a direct way.

The VTT monitoring complemented the Kepler one and allowed us to follow the historical minimum amplitude of the
Blazhko effect. The previously suggested 4-yr cycle does not
seem effective in fitting the cycle-to-cycle and the long-term vari-
ations. The alternation of the long and short \(P_0\) with a semiregular
timescale of 14 yr stresses the necessity to collect long series of
light maxima in a continuous way. Because of the new Kepler or-
tientation, VTTs are probably the only instruments that can monitor
the expected regrowth of the Blazhko effect and to measure the new
\(P_0\) in the coming years.

These insights lead new contributions to the description of the
pulsation of RR Lyr. They corroborate our decisions to maintain an updated data base of \(T_{\text{max}}\) of RR Lyr stars (Le Borgne et al. 2007), to monitor Blazhko stars with modern instru-
ments (Le Borgne et al. 2012), and to have started the project to continuously monitor RR Lyr itself. These facts support us in
our aim to continue and to improve the VTT project for several
more years.

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APPENDIX A: REFERENCES TO PUBLISHED TIMES OF MAXIMUM

The historical study of the variations of the pulsating period and of the Blazhko effect period of RR Lyr uses determinations of times of individual maxima reported in numerous publications since the early twentieth century. We list here the references of the publications available, to the best of our knowledge. As said in the text, the reference Szeidl et al. (1997) does not contain determinations of times of maximum, but the measurements from which we determined the individual times of maxima.

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Table B1 lists the times of maximum of RR Lyr used to determine the historical linear ephemeris.

| HJD          | Uncert. | O-C  | E   | Reference                  | Observer   | Method | Comment |
|--------------|---------|------|-----|-----------------------------|------------|--------|---------|
| 2414921.6750 | 0.01    | -0.0996 | 0   | Wendell,1909, Wendell,1914 | O.C. Wendell | vis    |         |
| 2414925.6350 | 0.01    | -0.1074 | 7   | Wendell,1909, Wendell,1914 | O.C. Wendell | vis    |         |
| 2414938.6410 | -0.1387 | 30   | Wendell,1909, Wendell,1914 | O.C. Wendell | vis    |         |
| 2414984.5600 | -0.1334 | 111  | Wendell,1909, Wendell,1914 | O.C. Wendell | vis    |         |
| 2415184.6460 | -0.1403 | 464  | Wendell,1909, Wendell,1914 | O.C. Wendell | vis    |         |
| 2418919.4580 | 0.01    | -0.2082 | 7053 | Hertzsprung,1922           | E. Hertzsprung | pg    |         |
| 2418944.4270 | 0.01    | -0.1800 | 7097 | Hertzsprung,1922           | E. Hertzsprung | pg    |         |

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APPENDIX B: HISTORICAL MAXIMUM LIST

Table B1 lists the times of maximum of RR Lyr used to determine the historical linear ephemeris.

The columns give the following:

- **HJD**: Heliocentric Julian Day
- **Uncert.**: Estimated uncertainty on the time of maximum
- **O-C**: Observed time of maximum minus calculated time of maximum
- **E**: Cycle number used in the linear ephemeris to obtain the calculated time of maximum
- **Reference**: Paper where the tabulated time of maximum is reported
- **Observer**: Name of the observer, if specified in the Reference
- **Method of observation**: visual (vis), photographic (pg), pe (photoloelectric), ccd (CCD), dslr (digital photographic camera)
- **Comment**: supplementary information

The complete table is available online as supporting information.