Historical vanishing of the Blazhko effect of RR Lyr from the 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 its periodic variability in 1899. The 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. the 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 1975. The monitoring of these periodicities deserved, and still deserves, a continuous and intensive observational effort. For this purpose, we have built dedicated, transportable and autonomous small instruments, Very Tiny Telescopes (VTTs), to observe the times of maximum brightness of RR Lyr. As immediate results, the VTTs recorded the last change of the P_0 state 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 the VTTs 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 Lyrae.

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1 INTRODUCTION

The modulation of the amplitude in luminosity and the pulsation period, known as the 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 competing models based on strict regularity: the oblique pulsator and the resonant non-radial pulsator. In our previous work on galactic Blazhko stars (Le Borgne et al. 2012), we did not consider the eponym of the class, HD 182989 ≡ RR Lyr. We know that its pulsation 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. 1901). Wendell (1909) reports that the first observation dates back to 1899 July 20, and the first maximum to 1899 September 23 (HJD 241 4921.675, 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 (Balázs & 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-yr 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-d interval in 2003–2004 fixed a shorter Blazhko period of 38.8 ± 0.1 d (Kolenberg et al. 2006). 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 Lyr 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 because the star has to be observed over decades with time series having a high temporal resolution, in order to survey the pulsation period (P_0) of 13 h, the Blazhko period (P_B) of 40 d and the long-term changes of both.

2 OBSERVATIONS

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 (T_{max}) on as many clear nights as possible. Because 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 (512 × 768 kaf400 chip) and a photographic 135-mm focal, *f*/2.8 lens with a field of view of 2° × 3°. We have given these the nickname, Very Tiny Telescopes (VTTs). Three such instruments have been built and used mainly in three different places near Toulouse, Castres and Caussades (Région Midi-Pyrénées, France). However, these 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 are obtained with no filter using an exposure time of 30 s. Science images have been corrected with mean dark images obtained during the night to compensate for 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 2008 June to 2013 November, 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 1967). 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 $y = m_{max} + \sigma/\sqrt{N-1}$, where m_{max} is the instrumental magnitude at maximum, σ 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 were carried out with classical telescopes, refractors or reflectors, with diameters from 55 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 (DSLRs). As a new approach to spectrophotometry, synthetic photometry was performed on low-resolution spectra using a Shelyak

Table 1. Observers and observing instruments.

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

Note. [a]Synthetic photometry from low-resolution spectra using a Shelyak Alpy 600 spectrograph.
[b]Telescope at the Michigan State University campus observatory (East Lansing, MI, USA) operated by H. Smith, with the help of Michigan State University students, Charles Kuhn, James Howell, Eileen Gonzales and Aron Kilian.

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 was 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[1] (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 the online Appendix A (available only in the electronic version), 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 these 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; Shapley 1916; Sanford 1928) that were calculated using JD 241 4856 (i.e. the date of the first observation) rather than JD 241 4921 (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 period 1944–1981. The list of ~7000 measurements reported by Szeidl et al. (1997) was scanned and digitalized by means of a semi-automatic procedure. These measurements are now available in electronic form on the Konkoly Observatory web site. We also evaluated the differences between 278 T_{max} observed simultaneously in B and V filters. No systematic

[1] http://rr-lyr.irap.omp.eu/dbrr/dbrr-V1.0_08.php?RR%20Lyr

effect was detected. We have found that 67 per cent of the T_{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_{max} differences. Finally, we measured 25 T_{max} values from the original observations collected at Michigan University in the framework of the 2003–2004 campaign (Kolenberg et al. 2006).

4 P_0 VARIATIONS OF RR LYR OVER MORE THAN ONE CENTURY

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

$$\text{HJD Max} = 241\,4921.7746 + 0.566\,835\,616\ E. \tag{1}$$

In the online Appendix B (available in the electronic version only), we give the list of T_{max} used to calculate equation (1) and used in the subsequent analysis. The purpose of using the above ephemeris was to detect large changes in the P_0 value. Indeed, the plot of the O − C (observed minus calculated T_{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 ephemeris in each interval of Table 2, this time by dividing the T_{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 3, we note that visual maxima provided P_0 values in excellent agreement with the photoelectric and CCD values in the intervals JD 243 9000–244 2500, 244 2500–244 5000 and 245 5000–245 6200.

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 time-scale of a few years. The O − C pattern shows jumps from long values (O − C values from negative to positive values, with maxima values reached on 1946.5, 1965.7, 1982.1, 1994.4 and 2009.5) to short values (O − C values from positive to negative values, with minima 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 244 5000 and 245 0000. One of the changes of state is well covered by VTT observations: when considering the values of T_{max} before JD 245 5000, the period is a long one (0.56686 d), after a short one (0.56680 d; see Table 3).
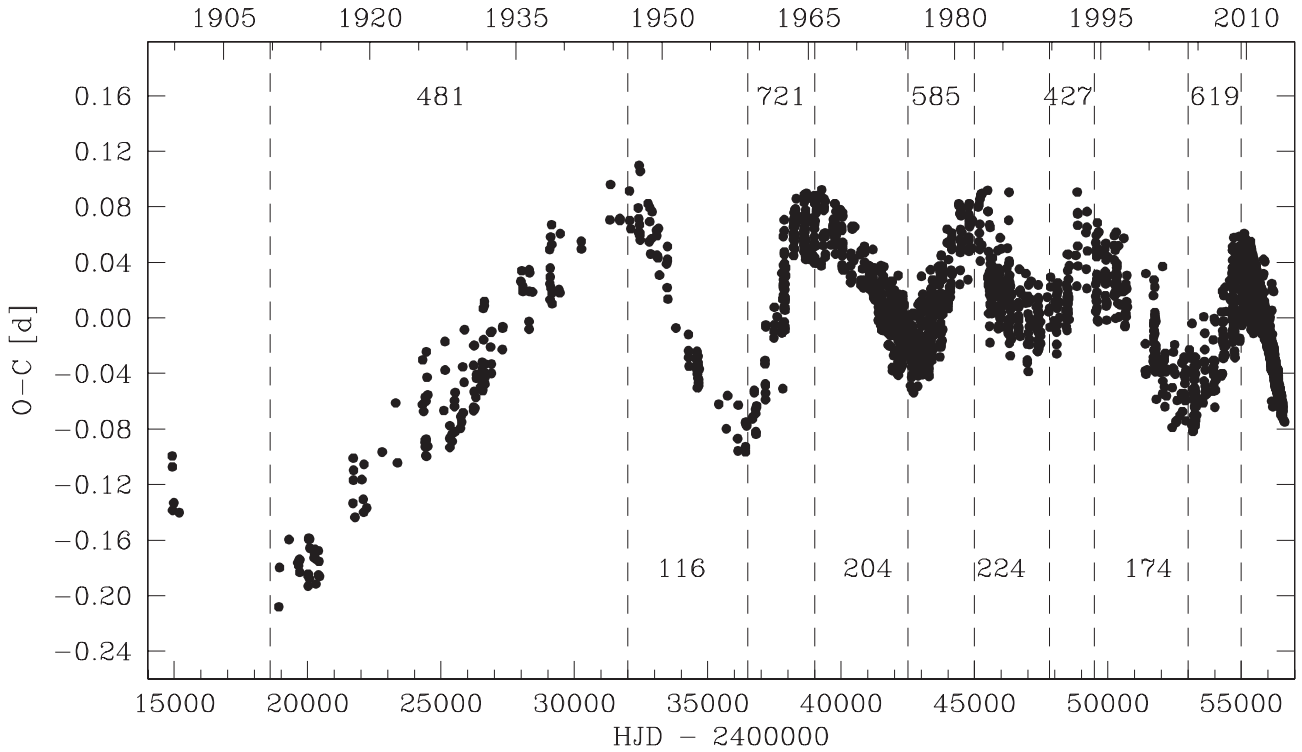
Figure 1. Historical behaviour of the period variations of RR Lyr. The numbers are the last three digits of the pulsation period calculated in each interval.

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 240 0000)	N_{max}	Pulsation 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)

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 yr, and that the P_0 is still decreasing: if we consider the maxima after the change at JD 245 5000 only, the period is below 0.5668000 d (Tables 2 and 3).

5 P_B VARIATIONS OF RR LYR 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 affect the Blazhko effect immediately arose. This point could be very important for understanding the relation between the two periods. It required the analyses of all the previous observations by a homogeneous procedure, because often the P_B values were determined in different ways or were simply assumed from previous works.

Therefore, we performed the frequency analysis of the O − C values obtained from the linear fits used to determine the P_0 in each subset (Table 3). We have used the iterative sine-wave fitting method (Vaniĉek 1971) and we present the results as amplitude spectra for the sake of clarity. Fig. 2 shows the application of the method to several subsets covering a time interval of one century. We can clearly see that the amplitude is variable and that P_B jumps from left to right of the mark at 0.025 d^{-1} (i.e. 40.0 d) around 1975. The P_B values obtained from the highest peaks were refined by means of the MTRAP code (Carpino, Milani & Nobili 1987) and the final values are listed together with error bars and amplitudes in the last two columns of Table 3. It is quite evident that P_0 and P_B changed in a way completely uncorrelated with each other (see Section 8).

6 *Kepler* DATA

The *Kepler* data allowed us to combine the analysis of T_{max} variations with another specific Blazhko characteristic, the change of the magnitude at the maximum brightness ($K_{p, max}$). We determined T_{max} and $K_{p, max}$ 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 has already pointed out a totally new and prominent feature, 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 all along 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

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

Julian days [JD 240 0000]	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)	40.88(10)	0.018(2)
39008–42405	Photoel.	342	0.5668 205(4)	41.15(3)	0.014(1)
42504–44822	Photoel.	162	0.5668 583(13)	38.92(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	0.5667 953(4)	38.84(2)	Down to 0.009
55000–56624	VTTs	264	0.5668 024(11)	38.91(7)	Down to 0.006
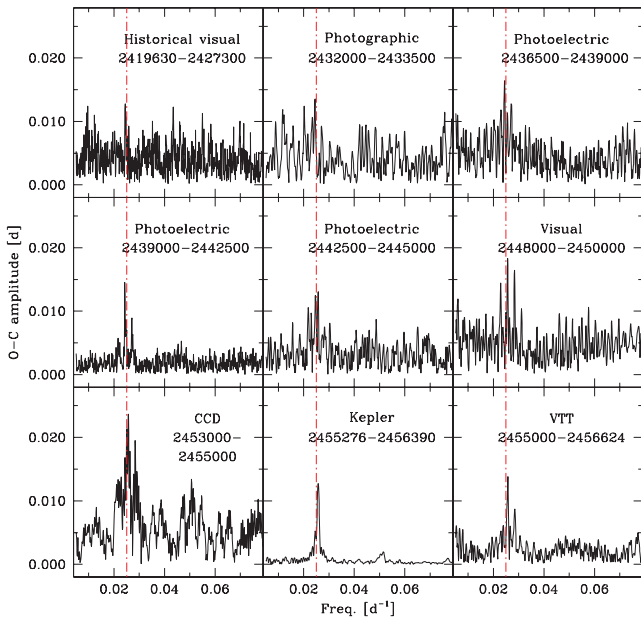
Figure 2. The spectra show the amplitudes and the frequencies of the Blazhko effect in the O − C values of RR Lyr as measured with different techniques through the ages. The (red) vertical line is at $f = 0.025$ d^{-1} ($P = 40.0$ d).

Figure 3. The period-doubling effect in the magnitudes at maximum brightness of RR Lyr observed with *Kepler*. Top panel: $K_{p,max}$ values (consecutive values are connected). Middle panel: plot of the differences between two consecutive cycles in the sense of 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 a known constituent.

minimum values of $K_{p,max}$. Moreover, there are Blazhko cycles where the period-doubling effect is always very noticeable, such as BJD 245 5710–245 5750. There is also a damping of the effect towards the end of observing time, when $K_{p,max}$ variations also have a small amplitude.

As a new contribution to the characterization of the period-doubling effect, we calculated the differences between the $K_{p,max}$ value of an even ($2n$) epoch and that of an odd ($2n − 1$) epoch. These differences are both positive and negative (middle panel), which implies that the highest $K_{p,max}$ changes from an odd epoch to an even epoch. 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 $K_{p,max}$ to an even epoch. Moreover, more rapid fluctuations are also visible. It is worth analysing these time series to search for periodicities in the switch-
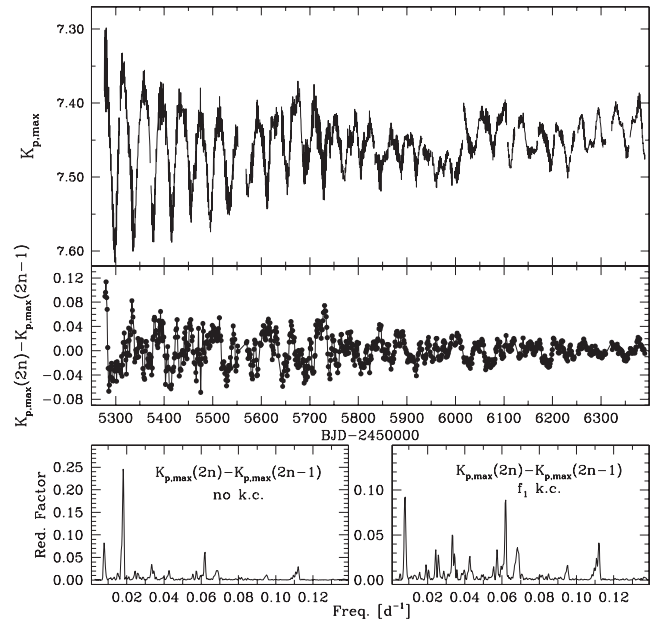
ing process. The iterative sine-wave fitting method (Vaniĉek 1971) is well suited to disentangle such periodicities, because it allows the detection of the components of the light curve one by one. Only the values of the detected frequencies (known constituents) are introduced in each new search, while 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 $K_{p,max}$ differences (bottom-left panel), the highest peak was at a low frequency, $f_1 = 0.018$ d^{-1}, corresponding to $P = 55.6$ 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 $P = 16.1$ d
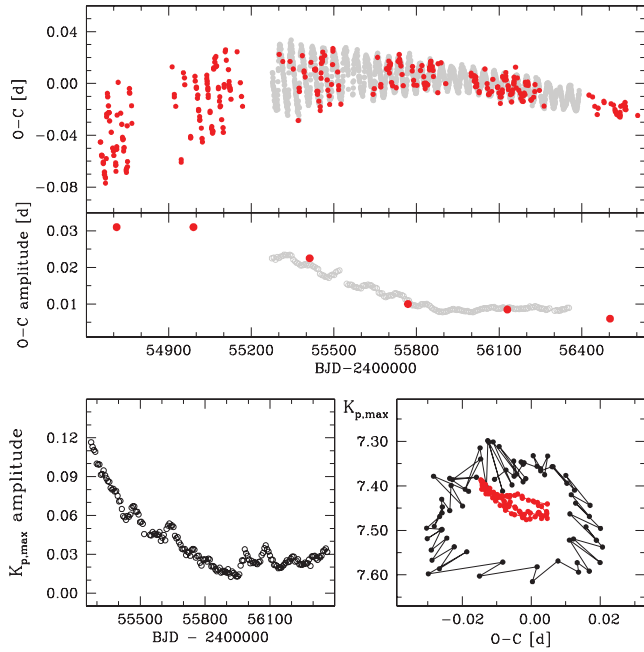
Figure 4. Changes in the Blazhko effect of RR Lyr from 2008 to 2013. Top panel: VTT (red filled circles) and *Kepler* (grey circles) O − C values showing the strong decrease in amplitude. Middle panel: O − C half amplitude (same symbols). The VTT values are taken from the yearly mean curves (Fig. 5). Bottom panel: (left) $K_{p, max}$ (half) amplitude, *Kepler* data; (right) the first (big) and last (small) Blazkho cycles observed with *Kepler*.

(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 $K_{p, max}$ 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 $K_{p, max}$ variations for each box (Fig. 4). 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 $K_{p, max}$ amplitude curve seems to start to increase again after a shallow minimum at JD 245 9000 (bottom-left panel). The extreme changes in the Blazhko effects are sketched by the shrinking of the close curve connecting the O − C and $K_{p, max}$ 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 $K_{p, max}$ 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 $K_{p, max}$ 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_{max} was observed on 2008 July 4 simultaneously with two instruments. Since then, the regular survey of RR Lyr
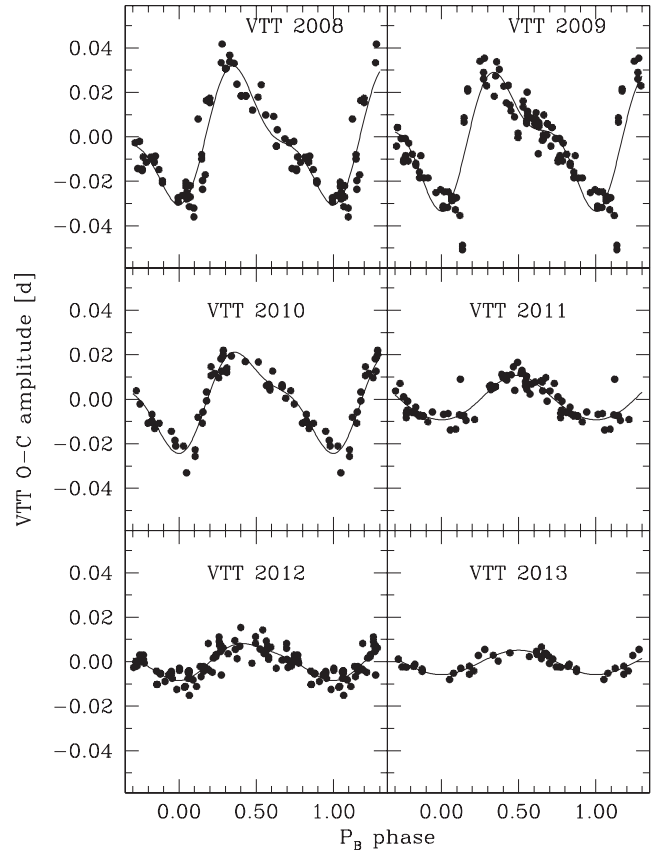

Figure 5. Decreasing amplitude of the O − C curves in the VTT data from 2008 to 2013.

has yielded 55, 78, 42, 56, 75 and 27 T_{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 behaviour 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 (Fig. 5). In particular, note how the curve becomes more sinusoidal with the decreasing O − C amplitude.

By adding the VTT points to *Kepler* ones (Fig. 4, middle panel), we can state that the maximum O − C amplitude was reached well before the space observations began. The CCD determinations preceding the VTT observations (40 T_{max} between JD 245 2915 and 245 4733) supply an O − C amplitude of 0.024 d (Fig. 2), while the visual T_{max} collected before the CCD values supply smaller amplitudes (i.e. 0.018 ± 0.003 d and 0.012 ± 0.002 d; see Table 3). From these values, we can infer that a minimum O − C amplitude occurred when only visual T_{max} values were available, in 1984–1985 (tentatively around JD 244 6000), followed by an increase that reached its maximum (0.031 d) at the beginning of the VTT observations, near the end of 2008 (JD 245 4800; see Fig. 5, 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. 4, 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} value was obtained in 2013, in early April. The reanalysis of the T_{max} epochs listed in the GEOS data base allowed us to reconstruct the changes in the pulsation 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 time than the short states. Since 1943, the same state seems to reappear after a time interval of 13–16 yr (Fig. 1). 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 P_0 (the shortest, actually) in 2009, and this is still running. The cyclic shift of P_0 amounts, on average, to $\Delta P_0 = 4 \times 10^{-5}$ d (Table 2) and hence $\Delta P_0/P_0 = 7 \times 10^{-5}$.

We have also determined the periods of the Blazhko effect by means of an homogeneous 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 the 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 244 2500; Fig. 6), much earlier than 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. 2. The corresponding rate $\Delta P_B/P_B = 0.05$ is three orders of magnitude larger than that observed for P_0. Correlated and anticorrelated changes of P_0 and P_B were observed in Blazhko RRab stars: RW Dra (Firmanyuk 1978), XZ Dra (Jurcsik, Benkő & Szeidl 2002), XZ Cyg (LaCluyzé et al. 2004), RR Gem (Sódor, Szeidl & Jurcsik 2007), RV UMa (Hurta et al. 2008), M5 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 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 that it is still ongoing. The plot of the O − C amplitude (Fig. 4, middle panel) covers 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 $K_{p, max}$ variations observed with the 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. 1), but the event is poorly covered because of the small number of T_{max} values. 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 makes RR Lyr still more intriguing. The analysis of the *Kepler* short-cadence data has been helpful for 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 periodicities 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 periodicities 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 period-doubling effect can be represented by means of half-integer values of the pulsation frequency ($f/2$, $3/2f$, $5/2f$, etc.).

9 CONCLUSIONS

The most promising mechanism that can explain the Blazhko effect is the $9P_9 = 2P_0$ 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 data sets 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 time constraints 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* survey 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 variations. The alternation of the long and short P_0 with a semiregular time-scale of 14 yr stresses the necessity to collect long series of light maxima in a continuous way. Because of the new *Kepler* orientation, VTTs are probably the only instruments that can monitor the expected
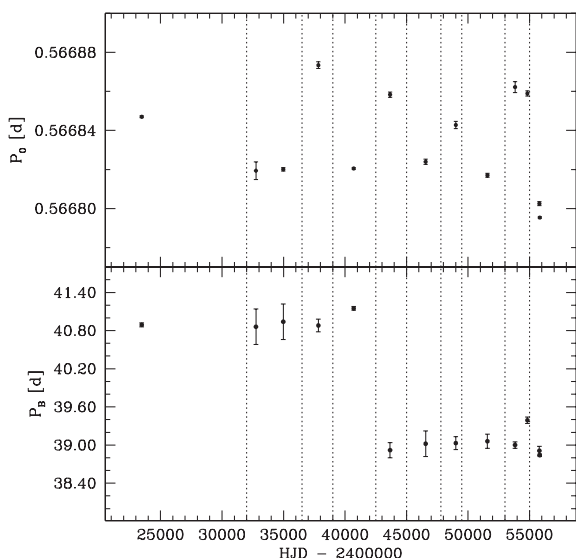
Figure 6. Uncorrelated variations of the pulsation period P_0 (top panel) and of the Blazhko period P_B (bottom panel). Time intervals are the same as in Fig. 1.

regrowth of the Blazhko effect and to measure the new P_0 in the coming years.

These insights have led to new contributions to the description of the pulsation of RR Lyr. They corroborate our decisions to maintain an updated data base of T_{max} of RR Lyr stars (Le Borgne et al. 2007), to monitor Blazhko stars with modern instruments (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. In this online appendix, we list the references of the publications available, to the best of our knowledge. As said in the text, Szeidl et al. (1997) does not contain determinations of times of maximum, but the measurements from which we have determined the individual times of maxima. The complete reference list is available online as supporting information.

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

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

HJD	Uncert.	O − C	*E*	Reference	Observer	Method	Comment
241 4921.6750	0.01	−0.0996	0	Wendell (1909, 1914)	O. C. Wendell	vis	
241 4925.6350	0.01	−0.1074	7	Wendell (1909, 1914)	O. C. Wendell	vis	
241 4938.6410		−0.1387	30	Wendell (1909, 1914)	O. C. Wendell	vis	
241 4984.5600		−0.1334	111	Wendell (1909, 1914)	O. C. Wendell	vis	
241 5184.6460		−0.1403	464	Wendell (1909, 1914)	O. C. Wendell	vis	
241 8919.4580	0.01	−0.2082	7053	Hertzsprung (1922)	E. Hertzsprung	pg	
241 8944.4270	0.01	−0.1800	7097	Hertzsprung (1922)	E. Hertzsprung	pg	

time of maximum; *E*, cycle number used in the linear ephemeris to obtain the calculated time of maximum; Reference, the paper where the tabulated time of maximum is reported; Observer, the name of the observer, if specified in the Reference; Method of observation, visual (vis), photographic (pg), pe (photoelectric), ccd (CCD) and dslr (digital photographic camera); Comment, supplementary information. The complete table is available online as supporting information.

SUPPORTING INFORMATION

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

Appendix A: References to published times of maximum
Appendix B: Historical maximum list (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu671/-/DC1).

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