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SS CANCRI: THE SHORTEST MODULATION-PERIOD BLAZHKO RR LYRAE

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1 Introduction

RR Lyrae stars play a crucial role in our understanding of astrophysics, providing both standard candles and tests for stellar evolution (Jurcsik et al. 2006). Some aspects of the physics governing their pulsation behaviour are still under investigation and discussion, in particular, the Blazhko effect. The Blazhko effect is a periodic modulation in the pulsation amplitude of light curves (Jurcsik et al. 2009, Kovács 2009).

This paper aims to contribute to a better understanding of the Blazhko effect by studying SS Cancri (SS Cnc). SS Cnc ($\alpha_{2000} = 08^{\rm h}06^{\rm m}25\overset{\rm s}{.}56$, $\delta_{2000} = +23^\circ15'05\overset{\prime}{.}8$) is a pulsating variable star belonging to the RRab-type star Lyrae, with a pulsation period of 0.367337 d and a metallicity corresponding to [Fe/H] $= -0.03$ (Elmasli et al. 2006, Jurcsik et al. 2006).

SS Cnc is characterised by the shortest known Blazhko period (Jurcsik et al. 2006), and hence may provide fundamental constraint for theoretical models of the Blazhko effect (Gillet 2013).

Models have been proposed to explain the Blazkho effect. They include resonance between a radial mode and a non-radial mode (Dziembowski and Cassisi 1999, Nowakowski and Dziembowski 2001) and the influence of a magnetic oblique rotator on the stellar pulsations (Cousens 1983, Shibahashi 2000). However, these require a regular variation in the light and radial velocity curves, yet the observations show more irregular variations (Smolec et al. 2011, Gillet 2013). Also, the magnetic oblique rotator model is not supported by any clear evidence of a strong magnetic field in RR Lyrae stars (Chadid et al. 2004, Kolenberg and Bagnulo 2009). Two other models have been recently proposed to explain short period Blazhko effect. Stothers (2010) suggested that the Blazhko modulation would be mainly caused by irregular changes of the magnetic field determining structural variations in the outer convective zone. In order to confirm this model, a quantitative model capable of reproducing the light modulation must be produced, in particular for the case of a very short modulation Blazhko period (Gillet 2013). Alternatively, Buchler and Kolláth (2011) suggested that the modulation can be caused by resonance coupling between a low order (typically fundamental) radial mode and a high order radial (the so-called strange) mode (Benkő et al. 2014). Having the shortest Blazhko period so far reported (Jurcsik et al.2006), SS Cnc represents an ideal object to investigate the validity of these two models.

In this paper, we report a study of the light curve modulation of SS Cnc in the B, V and R bands. We use the data to study the periodic modulation of the light curve, the variation in the maxima and search for periodic changes in the other regions of the light curve.

2 Observations

The observations were carried out with 14" telescopes, located in Durham, UK (Durham Astrolab 2015), and a 0.5 m in La Palma, Canary Islands (Hardy et al. 2015). Images are processed using standard correction and optimization techniques (Durham Astrolab 2015). Photometric measurements are made relative to two reference stars whose magnitude is reported by the AAVSO Photometric All-Sky Survey[1] (APASS, Henden and Munari 2014) and by VizieR catalogue (Ochsenbein et al. 2000, Zacharias et al. 2012). The two stars are: UCAC4 567-041675, located at $\alpha_{2000} = 08^{\rm h}06^{\rm m}24^{\rm s}$, $\delta_{2000} = 23°16'54''$; and UCAC4 567-041673, located at $\alpha_{2000} = 08^{\rm h}06^{\rm m}21^{\rm s}$, $\delta_{2000} = 23°12'16''$.

The observation interval is between 2015 January 04 and 2015 March 04 in 31 separate runs, each lasting 1–9 hours. Individual exposures are 30 s. In total 10,250 frames have been obtained. After correcting images, the observational data are discarded if they are affected by an instrumental magnitude error twice larger than the average ($\pm$ 0.015 mag), or if they are collected under poor observing conditions (FWHM $> 5''$). Fig. 1 shows the portion of the greatest interest of the light curve in the B, V and R pass-bands within approximately the same observation time. Each of these light curves represents data taken during a single observational session. In order to improve readability, an offset of -0.5 and -1.5 mag has been applied to the V and B band data, respectively.

3 Results

3.1 Light Curve Minima and Maxima

Table 1 shows the values for maximum, minimum and average magnitude in the B, V and R bands; the last column shows the average magnitude values from the Simbad database (Wenger et al. 2000).

	Min Mag	Max Mag	Avg Mag	Avg Mag (Simbad)
B	13.35 $\pm$ 0.02	11.56 $\pm$ 0.03	12.48 $\pm$ 0.02	12.40 $\pm$ 0.16
V	12.76 $\pm$ 0.02	11.42 $\pm$ 0.01	12.21 $\pm$ 0.01	12.11 $\pm$ 0.15
R	12.64 $\pm$ 0.01	11.51 $\pm$ 0.02	12.15 $\pm$ 0.01	n.a.

Table 1: The values of maximum, minimum and average magnitude for each of the three band filters used, compared with the literature data from the Simbad database for the average magnitude.

[1]https://www.aavso.org/apass

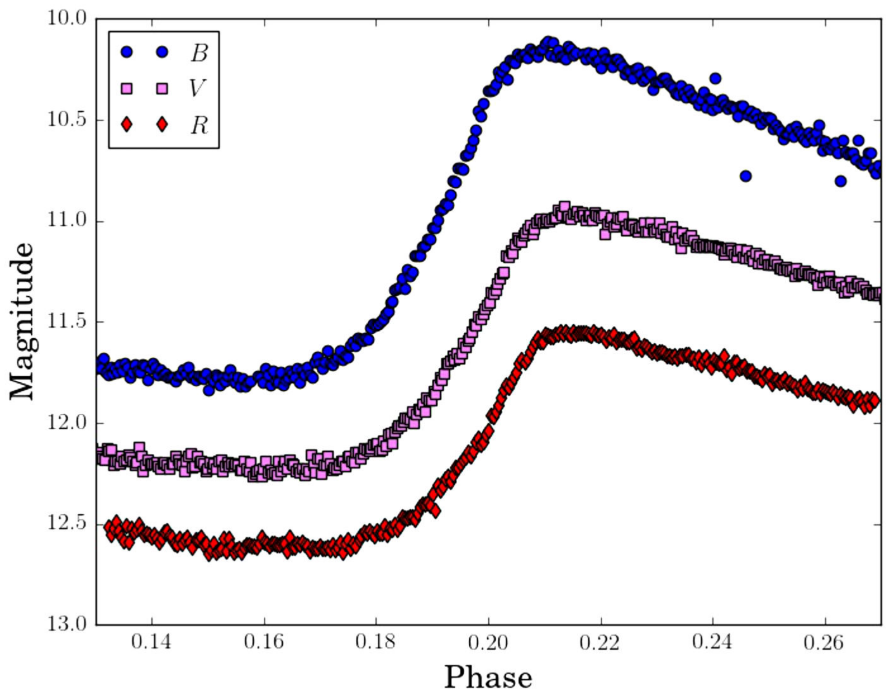

Figure 1. Light curves observed in the B, V and R bands. In order to improve readability, an offset of -0.5 and -1.5 has been applied to the V and B data, respectively. V and B band observational data were taken on 2015 February 07 using Draco-2 telescope and East-14 telescope, respectively. R-band observational data were taken on 2015 February 08 using West-12 telescope. All telescopes are in Durham, UK.

3.2 Period

The period is obtained using *VSTAR* software which uses Date Compensated Discrete Fourier Transform (DCDFT)[2]. The error on the period is computed using the jackknife method (Efron 1982). *VSTAR* software returns a period of 0.367405 ± 0.000002 d, which is within 0.02% of that of 0.367337 d reported by Jurcsik et al. (2006).

The period is also determined using *Period04* software which performs multiple-frequency fits with a combination of least-squares fitting and the Discrete Fourier Transform algorithm. The uncertainty is calculated using a Monte Carlo simulation (Lenz and Breger 2005, Hughes and Hase 2010). The algorithm returns the error on the frequency, α_f, and that on the amplitude; the error on the period, α_P, is calculated using the functional approach (Hughes and Hase 2010). *Period04* algorithm returns a value of 0.36731 ± 0.00004 d, which is in good agreement with that of 0.367337 d reported by Jurcsik et al. (2006), the difference between the former and the latter being smaller than 0.01%. It also confirms the value obtained from the *VSTAR* algorithm.

Using *Period04* algorithm, 9 harmonics of the pulsation frequency are detected, as shown in Table 2.

Harmonics	Frequency (cycles/d)	Period (d)	Amplitude (mag)
f_0	2.7225 ± 0.0003	0.36731 ± 0.00004	0.420 ± 0.010
$2f_0$	5.4443 ± 0.0002	0.18368 ± 0.00001	0.242 ± 0.002
$3f_0$	8.1700 ± 0.0200	0.12250 ± 0.00030	0.140 ± 0.010
$4f_0$	10.8870 ± 0.0010	0.09185 ± 0.00001	0.096 ± 0.008
$5f_0$	13.6090 ± 0.0090	0.07348 ± 0.00005	0.060 ± 0.004
$6f_0$	16.3000 ± 0.2000	0.06120 ± 0.00080	0.043 ± 0.009
$7f_0$	19.0560 ± 0.0030	0.05248 ± 0.00001	0.035 ± 0.003
$8f_0$	21.7800 ± 0.0200	0.04592 ± 0.00004	0.026 ± 0.003
$9f_0$	24.4970 ± 0.0030	0.04080 ± 0.00001	0.021 ± 0.003

Table 2: 9 harmonics of the pulsation frequency are detected. The table shows the frequency components and corresponding periods and amplitudes for each harmonic.

The period is compared with the available literature data to search any long-term change in the times of the light curve maxima. This is done using an observed-minus-calculated (O–C) diagram. The observed maximum peak times, $t_{maxpeak}$, are obtained from the GEOS RR Lyr database[3] (Boninsegna et al. 2002) and the calculated ones are given by:

$$t_{max\_calc} = t_0 + nP, \tag{1}$$

where t_0 is the time of a chosen reference observed maximum, n is an integer and P is the period, which is taken to be value of 0.367337 d reported by Jurcsik (2006). No change in period is discernible over the last 80 years (Fig. 8 in Appendix A). There is a significant scatter, probably due the Blazhko effect: an O–C variation of 0.011 ± 0.003 d is, indeed, observed over the Blazhko period of 5.313 d (Fig. 9 in Appendix A). Further pieces of information are available in the Appendix.

[2]https://www.aavso.org/vstar-overview
[3]http://www.ast.obs-mip.fr/users/leborgne/dbRR/

3.3 The Blazhko effect

For each V-band light curve, the maximum and the minimum are calculated by fitting a 3^{rd} degree polynomial curve to the region around the peak $\pm$ 0.5 hours. The fitting procedure is performed at least 5 times, and shifting the area of interest. Amplitude and time values are calculated as the mean of the repeated measurements. The standard errors are taken to be the associated uncertainties (Hughes and Hase 2010).

Table 3 shows the V-band maxima and the relative times when they are observed. Time is expressed as Modified Julian Date (MJD = JD − 2400000.5).

Time (day)	Amplitude (mag)
57051.035 ± 0.005	11.482 ± 0.020
57052.867 ± 0.001	11.462 ± 0.008
57053.970 ± 0.080	11.444 ± 0.007
57055.072 ± 0.003	11.436 ± 0.008
57058.010 ± 0.004	11.466 ± 0.007
57062.055 ± 0.004	11.461 ± 0.009
57070.132 ± 0.004	11.430 ± 0.008
57073.072 ± 0.003	11.466 ± 0.010
57074.909 ± 0.002	11.444 ± 0.006
57077.844 ± 0.004	11.454 ± 0.020
57080.045 ± 0.002	11.459 ± 0.008
57082.991 ± 0.003	11.436 ± 0.009
57084.824 ± 0.002	11.465 ± 0.020
57085.927 ± 0.002	11.445 ± 0.009

Table 3: Observed V-band peaks and relative times. Time is expressed as Modified Julian Date (MJD = JD − 2400000.5).

The model, which describes the maximum brightness variation, is given by:

$$P_{var}(t) = A\sin(\frac{2\pi t}{T} + \phi) + A_0, \tag{2}$$

where A is the amplitude, t is the time, T is the period and ϕ is the phase. A_0 is a fixed offset given by the mean of the peaks, which is not varied; hence, it is not a free parameter. The errors on the free parameters of the model, that are, amplitude, period and phase, are obtained minimising χ^2 (Hughes and Hase 2010).

Figure 2 shows the change of the V-band maximum magnitude over time. This confirms Jurcsik's study (2006), according to which SS Cnc exhibits Blazhko modulation period. In Fig. 2, the fitting model used to characterise the peak variation is given by Eq. 2. The numerical values of the free parameters in the model are: $A = 0.019 \pm 0.014$ mag, $T = 5.41 \pm 0.06$ d, and $\phi = 1400 \pm 700$. Our Blazhko period of 5.41 ± 0.06 d is in good agreement with the value calculated by Jurcsik et al. (2006) of 5.309 d, the difference being about 2 standard errors. The amplitude is also in agreement with that reported by Jurcsik (2006); considering the peak to peak variation, our amplitude differs, by about 2 standard deviations, from the value of about 0.1 mag found by Jurcsik. The discrepancy may depend on the very extreme values of the Blazhko cycle not taking place during the times of observation.

The fitting model is tested using χ^2 as a hypothesis test, the error bars on the data being heteroscedastic (Hughes and Hase 2010). χ^2_{min}, that is, the minimised sum of the

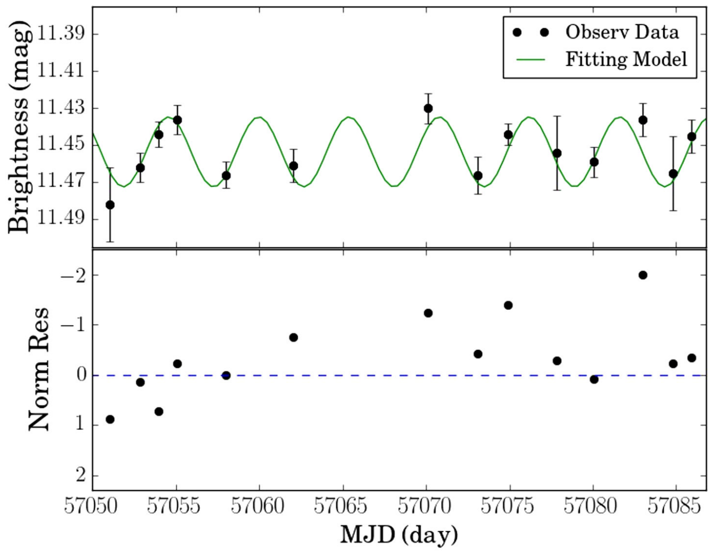

Figure 2. Blazhko modulation period is calculated to be 5.41 ± 0.06 d. Observational data correspond to the V-band light curve peaks. Errors on the time are too small to be clearly seen. In the bottom subplot, the normalised residuals are shown. MJD stands for Modified Julian Date. Given the convention of a decreasing scale for increasing brightness, normalised residuals are plotted on an inverse y-scale, in order to improve readability and visual comparison between the two subplots.

squared normalised residuals, is 9.86; ν, that is, the number of degrees of freedom of the system, is 11 (14 data points minus the 3 free parameters, A, T, and ϕ in Eq. 2); dividing the former by the latter, χ^2_ν is calculated to be 0.90, which is very close to the ideal value of 1, suggesting that the null hypothesis, which is that the model holds true, should not be rejected. The associated probability density function, $\mathrm{P}(\chi^2_{min}; \nu)$, is calculated to remove any ambiguity in whether or not to reject the null hypothesis. P(9.86; 11) is 0.54, which is slightly greater than the ideal value of 0.5; hence, it is confirmed that the null hypothesis should not be rejected (Hughes and Hase 2010).

The difference in the peaks being small, the data are also fitted using a flat line model. This returns a value of χ^2_ν of 2.29 and $\mathrm{P}(\chi^2_{min}; \nu)$ of 0.005. Both these two values indicate a poor fit. Furthermore, the Bayesian information criterion (BIC) for model selection is applied to confirm the hypothesis that the sinusoidal model is a better fit in comparison with a flat line model. BIC is defined as

$$BIC = \chi^2 + k \ln(n), \tag{3}$$

where k and n are the model free parameters and the data points, respectively (Kass and Raftery 1995). For the flat line model, BIC is 32.37, whereas the sinusoidal model is characterised by a BIC of 17.78. The difference between the two BICs being larger than 10, there is a very strong evidence against the model with the highest BIC, that is, the flat line model (Kass and Raftery 1995).

It should be noted that, both here and in the data analysis presented in the following sections, the errors on the brightness are taken into account, as they have a significantly larger influence on the corresponding variable in comparison with the errors on time; this assumption is also tested comparing ordinary least-squares algorithms and orthogonal

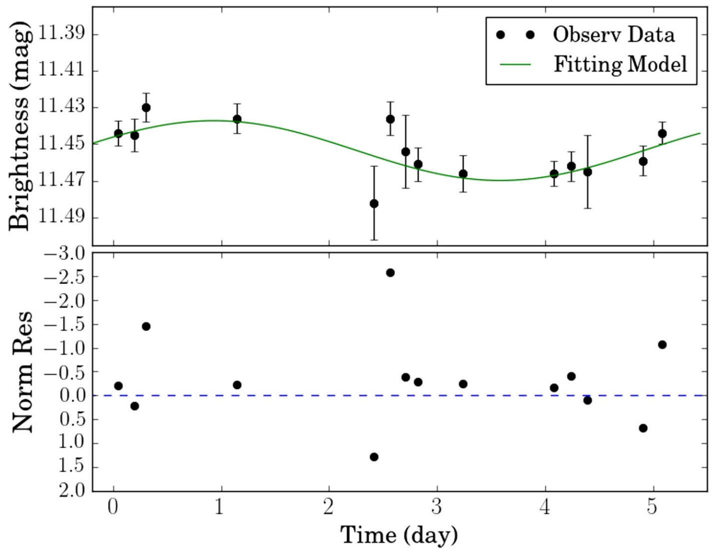

Figure 3. Blazhko modulation period: phase folded data. V-band light curve peaks are phase-folded. In the bottom subplot, the normalised residuals are shown. The phase-folded plot confirms the sinusoidal nature of the Blazhko effect, and returns a value for the Blazhko period of 5.313 ± 0.018 d.

distance regression ones (Hughes and Hase 2010). The differences between the outputs of the two fitting procedures tend to be small, if not negligible.

Figure 3 shows the Blazhko effect in the phase-folded plot: the data points are folded, and after a period the next peak is plotted at day zero. The phase-folded plot confirms the sinusoidal nature of the Blazhko effect, and returns a more precise value for the Blazhko period, that is, 5.313 ± 0.018 d ($\chi^2_\nu = 1.15$ and P(12.63; 11) = 0.32). The amplitude of the modulation is 0.016 ± 0.003 mag. Furthermore, the phase-folded data analysis shows no clear structure in the distribution of the normalised residuals, which fluctuate randomly around the zero. This suggests that even if the normalised residuals in Fig. 2 do not appear to be completely randomly distributed, this could be due to chance rather than any actual structure. The period used to phase-fold the data is taken to be 5.3 d, as it allows obtaining the most precise period and a value for χ^2_ν very close to the ideal one of 1.

An analysis is performed to assess whether V-band minimum magnitude exhibits any significant change over time and any correlation with the maximum variation. No clear evolution is found in the modulation of the minima, and no correlation seems to be present between the maxima and the minima variations (see Appendix B).

3.4 Periodic modulation in the ascending and descending gradients

As shown in Fig. 1, the light curve exhibits two almost linear gradients, where particular features, such as humps, bumps or changing slope tend to be absent. The first gradient is ascending and starts after the quadratic like curve following the minimum, and finishes before the inflection point leading to the maximum region. The second gradient is descending and follows the straight line after the maximum region. The two gradients are fitted with a straight line. The values of the gradients for each light curve, and the associated standard errors are computed using the same procedure described in the previous section with regards to the maxima and minima. The light curves, where the ascending gradient is calculated, have to meet the condition that both the maximum and the minimum are present in the same observation.

The time evolution of the two gradients is analysed, as shown in Fig. 4 and Fig. 5. The model, used to describe the observational data, is represented by Eq. 2. The ascending gradient varies with a periodicity of 3.80 ± 0.01 d, an amplitude of 0.09 ± 0.03 mag h^{-1} and a phase $\phi = 3.5 \pm 0.1$. Statistical analysis of the model is performed. P(10.98; 4) returns a value of about 0.03, suggesting that the model should not be rejected. Furthermore, χ^2_ν is 2.75, which is smaller than the largest acceptable value for a system with $\nu \leq 5$, that is, 2.9 (Hughes and Hase 2010).

The descending gradient shows a periodicity of 4.01 ± 0.07 d and an amplitude of 0.01 $\pm$ 0.08 mag h^{-1}, with $\phi = 7000 \pm 2000$. In this case, Eq. 2 is a good model to fit the data, as χ^2_ν is 1.60 and P(χ^2_ν; ν) 0.11 (Hughes and Hase 2010). The residuals, however, are not completely randomly distributed with respect to the zero line (bottom subplot of Fig. 5), but there is a slight tendency to have negative values for the values relative to the last observations.

Further studies performed on a larger data set and with more sensitive instruments are needed to confirm the behaviour of the gradients.

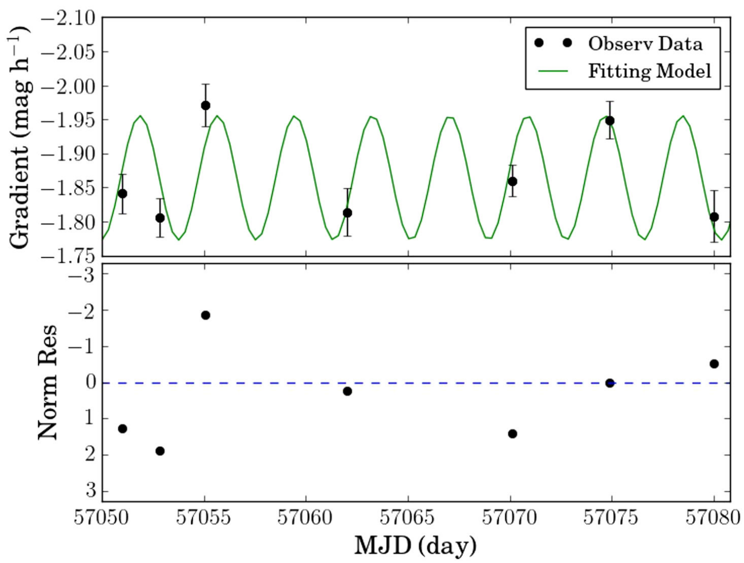

Figure 4. Modulation period of the V-band light curve ascending gradient: 3.80 ± 0.01 d. In the bottom subplot, the normalised residuals are shown. MJD stands for Modified Julian Date.

To assess whether there is any relationship between the descending and ascending gradients, only the light curves, where both the gradients are observed within the same night, are studied. Even if the analysis is based on a small number of points, the two gradients do not seem to be proportional, as shown in Fig. 6. When the descending gradient has low values, the ascending gradient may have high or low values. Similarly, when the ascending gradient has low values, the descending gradient may have high or low values. The magnitude variations of the two gradients being ambiguously related to

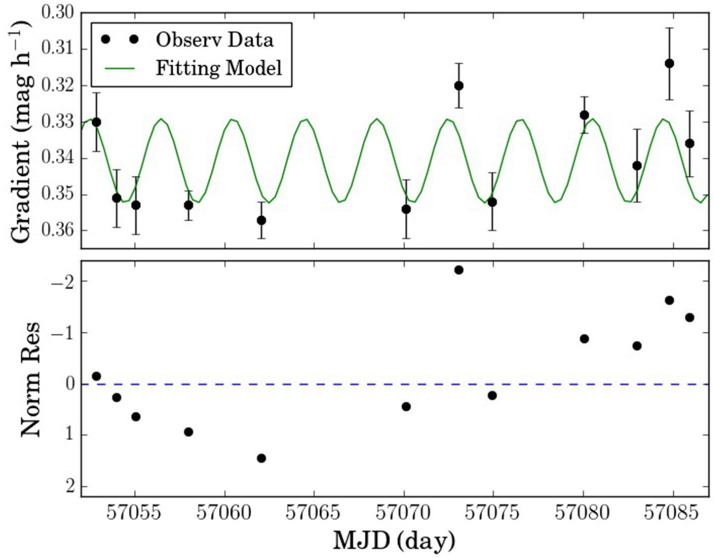

Figure 5. Modulation period of the V-band light curve descending gradient: 4.01 ± 0.07 d. In the bottom subplot, the normalised residuals are shown. MJD stands for Modified Julian Date.

each other, a hysteresis mechanism may be present. If this were the case, they would change in different points on the Blazhko phase.

To assess the validity of this hypothesis, the two gradients are analysed with respect to the maxima in the Blazhko curve (Fig. 8). The ascending gradient seems to be greater when closer to the peak in the Blazhko maxima curve. The minimum values for the ascending gradient are, instead, reached close to the mimimum value in the Blazhko maxima curve. The descending gradient increases its value only after the minimum in the Blazhko maxima sine curve. The descending gradient tends to remain the same when considering the other parts of the Blazhko maxima curve. A hysteresis behaviour may characterise the modulation of the two gradients. As the data set is limited, this investigation should be, however, considered only as a pilot study and hence further analyses are needed to validate the pattern presented here.

4 Discussion

As mentioned in the Introduction, physical models for the Blazhko effect have been under intense discussion in the literature.

With the main period being observed to be stable over time, the pulsating mechanism in SS Cnc is unlikely to be produced by the light travel time effect of a binary, or by tides generated by the binary system, as proposed by Elmasli et al. (2006). Alternatively, models explaining the Blazhko effect as due to the resonance between radial and non-radial modes predict that the light curve would have specific features in the frequency spectra (a triplet structure). These features, however, have not been detected in satellite data. In addition, observations have found higher order components than those predicted by this model (Smolec et al. 2011). New advances in explaining the phenomenon have been proposed by Buchler & Kolláth (2011) using the amplitude equation formalism.

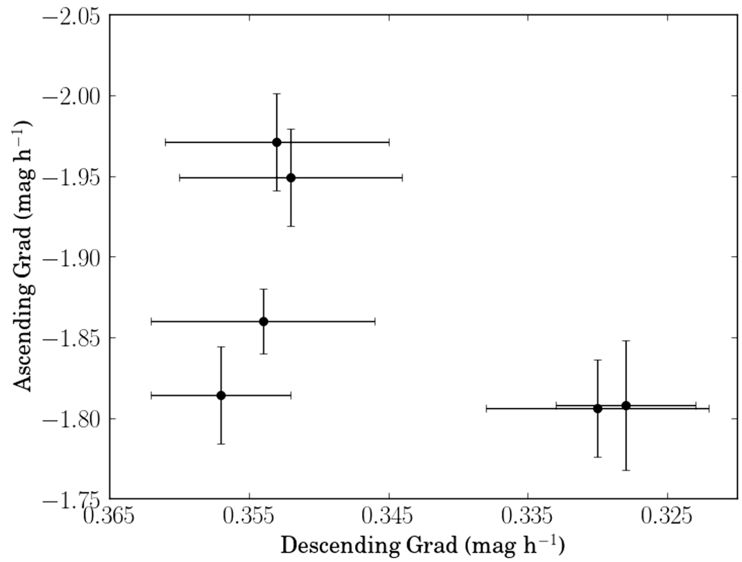

Figure 6. The V-band light curves, where both the gradients are observed within the same night, are studied. No linear relationship seems to be present between the ascending and the descending gradients. For low values of the descending gradient, the ascending gradient may take both high and low values. The ascending gradient is unambiguously characterised by low values only for high values of the descending gradient.

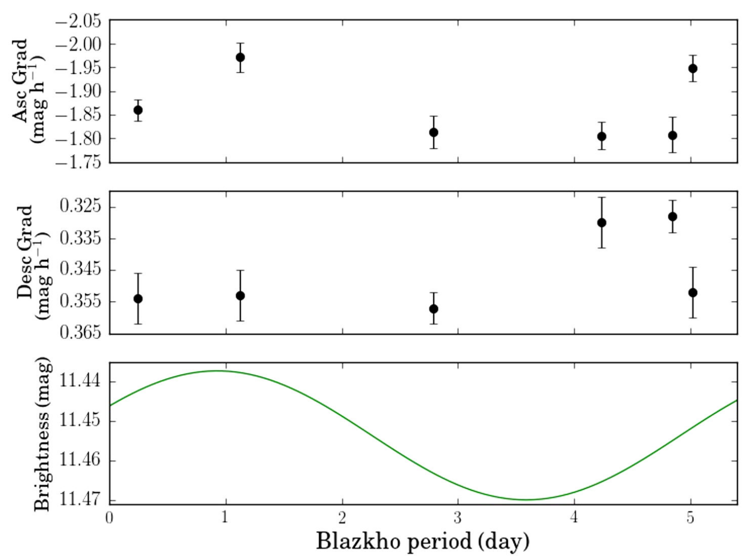

Figure 7. Phase folded observational data of the V-band light curve ascending and descending gradients, taken during the same day, are compared to the Blazhko modulation period of the V-band light curve maxima. The ascending gradient seems to mirror the behaviour of the maxima. The descending gradient period may be characterised by a hysteresis pattern with respect to the maxima modulation.

According to this model, the mechanism responsible for the modulation period would be a resonance coupling between a low order and a high order radial mode. This model has been also supported by Kepler space telescope data for 15 Blazhko RR Lyrae stars (Benkő et al. 2014). On the other hand, it has been suggested that the Blazhko effect is connected to the cyclic strengthening and weakening of turbulent convection in the outer stellar layers, caused by a transient magnetic field, which would have an irregular amplitude. When the magnetic field decays, the turbulent convection would become more vigorous. The magnetic field would decay cyclically and be substituted by a new one, produced by the turbulent-rotational dynamo (Smolec et al. 2011, Gillet 2013). However, this theory is unlikely to be the sole mechanism behind the Blazhko effect as it would be only effective for long modulation periods, typically for more than 100 d, in agreement with the thermal time-scales of the pulsation in RR Lyrae stars (Molnár et al. 2012). Therefore, it does not adequately describe the observed short-period Blazhko modulation such as that found in SS Cnc. Indeed, using hydrodynamic simulations, it was not possible to reproduce the Blazhko phenomenon through changes in convection unless implausible variations in the convective parameters on short time-scales take place (Molnár et al. 2012). Instead, numerical hydrodynamical simulations (Szabó et al. 2010, Kolláth et al. 2011) point to the Blazhko effect being associated with the half-integer (9:2) resonance between the fundamental pulsation mode and a destabilizing overtone. Further studies have also pointed out that irregular amplitude modulations can occur as a result of the nonlinear, resonant mode coupling between the 9th overtone and the fundamental mode. Hence, some of the irregular features observed in this paper may be due to irregular destabilization of the fundamental pulsation (Buchler & Kolláth 2011, Benkő et al. 2014). Furthermore, Buchler & Kolláth model presents some advantages in comparison with other resonance coupling models, such as the one proposed by Gillet (2013). The latter model is based on the interaction between the shocks generated by the fundamental mode and the first overtone. The first overtone is, however, observed only in a minority of RR-ab type star Lyrae, even with the precision of Kepler (Benkő et al. 2014, Molnár et al. 2017). Our observations highlighting the hysteresis-like variation in the ascending and descending gradients and the lack of any significant variation in the magnitude of the minima over the Blazhko period provide an additional test of the competing models for the mechanisms driving the Blazhko effect. Further observations are needed to confirm the results presented in this paper and investigate if a resonance between the fundamental pulsation mode and a destabilizing overtone is present.

5 Conclusions

The characteristics of SS Cnc have been studied in order to better understand the Blazhko effect. The Blazhko effect has been studied in the V-band. The Blazhko period is found to be 5.313 ± 0.018 d; the amplitude of the Blazhko effect is 0.016 ± 0.003 mag. The peak variation exhibits a sinusoidal pattern. The ascending and descending gradients show a sinusoidal periodic modulation. The variation in the maxima, within some limitations, seems to be associated with a corresponding variation in the ascending and descending gradient behaviour. The minimum magnitude seems to be constant over time. The findings may support the theory of resonance coupling between a low order radial mode and a high order radial mode, which would give rise to a regular, either single or multiperiodic, variation.

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A Appendix. O–C

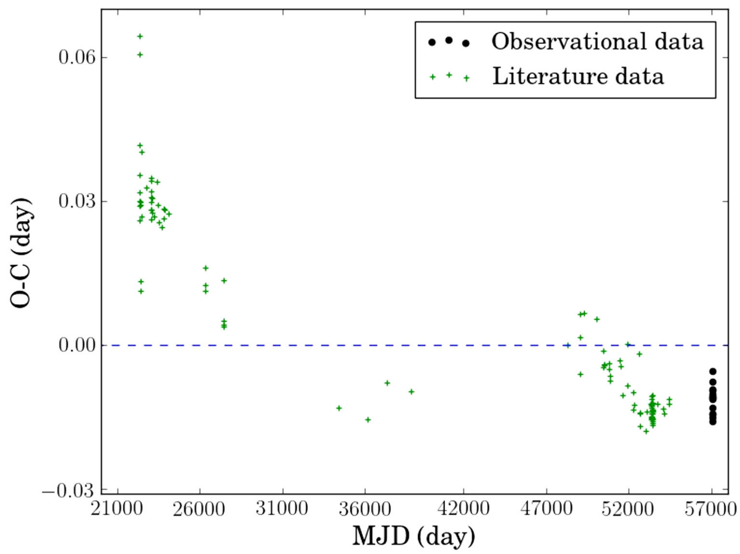

Figure 8. Observed minus calculated (O–C) diagram. Black points correspond to the observational data collected by the authors. Excluding the data before MJD 27000, no significant change overt time would be clearly observable.

The O–C diagram (Fig. 8) shows a change of the pulsation period over time. When constructing the O–C diagram, t_0 is taken to be MJD 48289.40200 (i.e. 1991 A.D). The choice is based on the fact that the observed maxima, available in the literature immediately before MJD 48289.40200, were recorded in 1966 A.D. CCD devices being invented in 1969, instruments before this date were, probably, not so sensitive as the ones developed in the last 30 years.

It should be noted that the data taken before MJD 15000 (i.e. pre-1900 A.D.) are excluded due to the timing uncertainties of maxima from visual observations. The analysis of the reduced data set seems apparently to confirm Elmasli's hypothesis: the pulsation period shows a variation, which could be due to the light travel time variation expected in a binary system (Elmasli et al. 2006). However, given the large gaps in the O–C data, the analysis does not lead to completely reliable conclusions.

In addition, if the data before MJD 27000, that is, before ≈ 1934 A.D., were not considered, no change over time would be clearly observable. The decision not to include data from the beginning of the last century could be justified given the limited accuracy and precision of the detecting systems available at that time. Within this further reduced data set, the difference between the lowest and highest value of the O–C would give a variation of 0.031 d, that is, a negligible gradient in comparison with SS Cnc period. The measurement of this gradient has no corresponding error, as the two values used to compute it are retrieved from the GEOS RR Lyr database, where no errors appear available. The data after MJD 27000 are, however, not on a straight gradient, but seem to fluctuate with no definite structure. Fluctuations could be due to imprecision in the measurements. Hence, further studies of the pulsation period, alongside with radial velocity measurements, are needed to definitely reject the hypothesis of a companion star for SS Cnc. Further observations are needed also to assess whether the tendency of the values to lie below the zero is due to chance, or whether there is any sinusoidal structure, whose minima values the literature has so far highlighted.

Figure 9 shows a change of the pulsation period over time, considering the phase folded V-band maxima observed in the present study. The period of 5.313 d is used to phase fold the data. A sinusoidal modulation (Fitting model 1) may seem to be present. This hypothesis should not be rejected as χ^2_ν is 0.76, which is close to the ideal value of 1. $P(\chi^2_\nu;\nu)$ is, however, 0.68, that is, slightly higher than the ideal value of 0.5; hence, the null hypothesis may be questioned (Hughes and Hase 2010). It should be, also, noted that the O–C variation (-0.011 ± 0.003 d) is close to the average error on the observed peak times, that is, $\pm$ 0.003 d. In light of this and of the aforementioned value of $P(\chi^2_\nu;\nu)$ for the sinusoidal model, a flat line model is tested (Fitting model 2). χ^2_ν and $P(\chi^2_\nu;\nu)$ for this flat line model are 1.78 and 0.04, respectively. These values may suggest that the null hypothesis should not be rejected and the flat line model fits the data (Hughes and Hase 2010). Bayesian information criterion (BIC) is, then, used to compare the two fitting models. BIC is 25.81 for the flat line model and 16.29 for the sinusoidal one. The difference between the two BICs being 9.52, there is a strong evidence against the model with the highest BIC, that is, the flat line model (Kass and Raftery 1995).

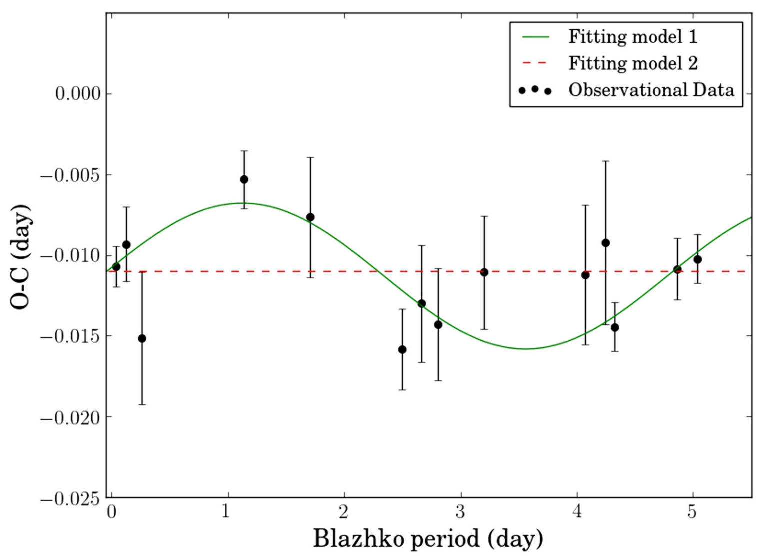

Figure 9. Observed minus calculated (O–C) diagram for the phase folded V-band maxima observed in the present study.

B Appendix. Minima

The fitting model, given by Eq. 2 and represented by the green curve in Fig. 10, is used to fit the data. The periodicity, T, is 5.40 $\pm$ 0.09 d. Statistical analysis of the model is performed. ν is 4, the data points being 7 and the free parameters 3, χ^2_ν is 0.17 and $P(\chi^2_\nu;\nu)$ returns a value bigger than 0.5, that is 0.95, suggesting that the null hypothesis should be, at least, questioned (Hughes and Hase 2010). The reason for this is mainly due to the fact that the magnitude variation is of the same order of magnitude as the errors on the data points. This is caused by the observations not being sensitive enough. Another limitation is represented by the analysis being based on a very small data set, which resulted in a low value of ν; this was due to long periods of bad weather. The two limitations can also explain the minima period being different from the maxima one. Further investigations appear necessary to assess whether also the light curve minima exhibit a modulation period. A flat line model is also tested (Fitting model 2). In this case, χ^2_ν is 0.74 and $P(\chi^2_\nu; \nu)$ is 0.62. These values suggest that the null hypothesis should be questioned, that is, the flat model does not fit the data perfectly. The lower value of P suggests, however, that the linear fit may be slightly better than the sinusoidal one (Hughes and Hase 2010).

An analysis of the phase folded data is performed, confirming, for the flat line model, a value for $P(\chi^2_\nu; \nu)$ of 0.62, which is close to the ideal threshold of 0.5 (Hughes and Hase 2010). The $P(\chi^2_\nu; \nu)$ of 0.95 for the sinusoidal model is, also, confirmed, suggesting that this model should be rejected. The value of $P(\chi^2_\nu; \nu)$ for the sinusoidal model is, probably, due to the fact that the amplitude variation is of the same order of magnitude as the errors on the data points.

The analysis is suggestive of no significant change of the minima over time.

The modulation period of the minima seems independent from that of the maxima, as shown in Fig. 11 and in Fig. 12.

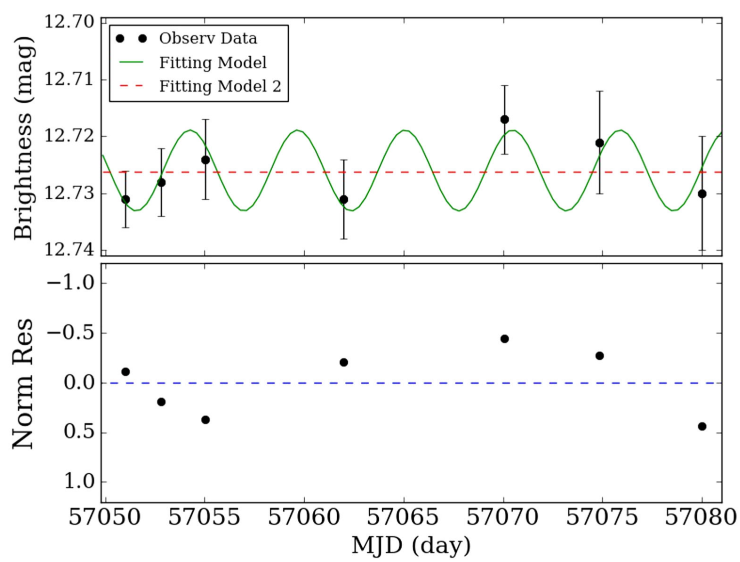

Figure 10. The modulation period of the V-band light curve minima. In the bottom subplot, the normalised residuals, with respecft to the sinusoidal fitting model, are shown. The minima do not seem to show any periodic modulation. The flat line model (Fitting model 2), with $P(0.74; 6) = 0.62$, seems to be slightly better than the sinusoidal one (Fitting model), characterised by $P(0.17; 4) = 0.95$ and with respect to which the normalised residuals are plotted in the bottom suplot.

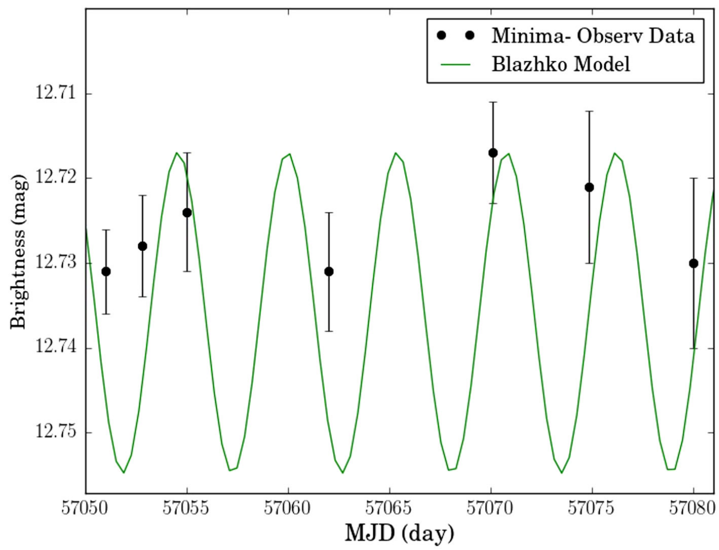

Figure 11. The V-band light curve minima are shown as dots and do not show any clear correlation with the modulation period of the maxima. The modulation period of the V-band light curve maxima (Blazhko Model) is plotted as a continuous green line. An offset of 1.28 mag has been applied to the Blazhko Model in order to improve readability.

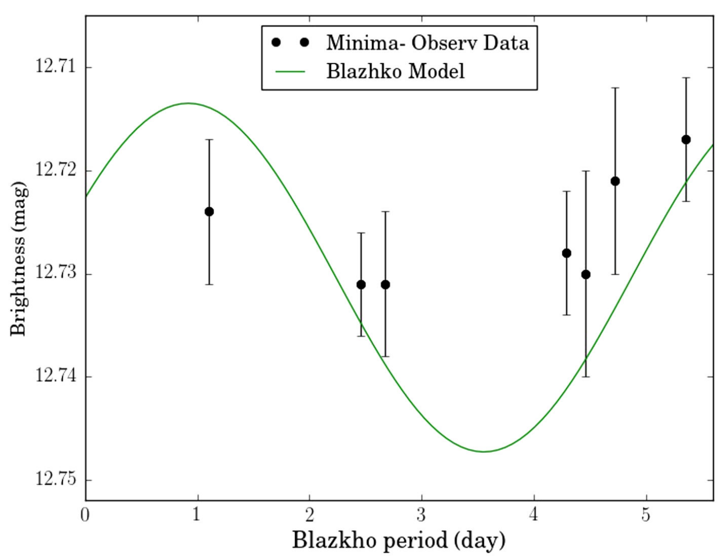

Figure 12. Phase folded data points of the V-band light curve minima are shown as dots. The period of 5.40 d is used to phase fold the minima. Phase folded modulation period of the V-band light curve maxima is the continuous green curve, labelled as Blazhko Model. No clear correlation seems to be present between the minima and the sinusoidal model obtained by fitting the maxima. An offset of 1.28 mag has been applied to the Blazhko Model in order to improve readability.