## ORIGINAL ARTICLE



# Time-series analysis of long-term photometry of BM Canum Venaticorum<sup>†</sup>

L. Siltala<sup>1\*†</sup> | L. Jetsu<sup>1</sup> | T. Hackman<sup>1</sup> | G. W. Henry<sup>2</sup> | L. Immonen<sup>1</sup> | P. Kajatkari<sup>1</sup> | J. Lankinen<sup>1</sup> | J. Lehtinen<sup>1</sup> | S. Monira<sup>1</sup> | S. Nikbakhsh<sup>1</sup> | A. Viitanen<sup>1</sup> | J. Viuho<sup>1</sup> | T. Willamo<sup>1</sup>

<sup>1</sup>Department of Physics, University of Helsinki, Helsinki, Finland <sup>2</sup>Center of Excellence in Information Systems,

Tennessee State University, Nashville, Tennessee

#### \*Correspondence

L. Siltala, Department of Physics, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland. Email: lauri.siltala@helsinki.fi

<sup>†</sup>The analyzed photometry and numerical results of the analysis are both published electronically at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via

http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/yyy/ Axxx. Long-term photometry is commonly used to monitor chromospheric activity of late-type stars. We study standard Johnson differential V photometry of the RS CVn binary BM Canum Venaticorum (BM CVn) spanning over a quarter of a century. Our main aims are to determine the activity cycles, the rate of surface differential rotation, and the rotation period of the active longitudes of BM CVn. The continuous period search (CPS) algorithm is applied to the photometry. The changes of the mean and amplitude of the light curves are used to search for activity cycles. The rotation period changes give an estimate of the rate of surface differential rotation. The Kuiper method is applied to the epochs of the primary and secondary minima to search for active longitudes. The photometry reveals the presence of a stable mean light curve (MLC) connected to the orbital period  $P_{orb} = 20^{d}.6252$  of this binary. We remove this MLC from the original V magnitudes, which gives us the corrected V'magnitudes. These two samples of V and V' data are analyzed separately with CPS. The fraction of unreliable CPS models decreases when the MLC is removed. The same significant activity cycle of approximately 12.5 years is detected in both V and V' samples. The estimate for the surface differential rotation coefficient,  $k \ge 0.10$ , is the same for both samples, but the number of unrealistic period estimates decreases after removing the MLC. The same active longitude period of  $P_{al} = 20^4511 \pm 0^4005$ is detected in the V and V' magnitudes. This long-term regularity in the epochs of primary and secondary minima of the light curves is not caused by the MLC. On the contrary, the MLC hampers the detection of active longitudes.

#### KEYWORDS

methods: data analysis, stars: activity, binaries, starspots, individual (BM CVn)

#### **1** | INTRODUCTION

Bidelman (1983) noticed the strong Ca(II) K line emission of the BM Canum Venaticorum (CVn (HD116204, BD+39 2635). Hall (1983) suspected photometric variability. This was confirmed by Boyd, Genet, and Hall (1984), who discovered a period of  $P_{phot} = 21^{d}$ 3 from a light curve having an amplitude of 0<sup>m</sup>07. Furthermore, Boyd et al. (1984) suggested that BM CVn is an RS CVn binary. Among other published  $P_{phot}$  values are 21<sup>d</sup>9 (Mohin & Raveendran, (1987)), 20<sup>d</sup>66 ± 0<sup>d</sup>03 (Strassmeier, Hall, Boyd, & Genet, (1989)), and  $20^{1}2 \pm 0^{1}5$  (Erdem et al., (2009)). However, Koen and Eyer (2002) detected no periodicity in the Hipparcos photometry of n = 169 observations.

Griffin and Fekel (1988) showed that BM CVn is a binary with  $P_{orb} = 20!6252 \pm 0!0018$ , and noted that the secondary companion could not be detected spectroscopically. BM CVn is currently classified as a single-lined eclipsing binary with  $v \sin i = 15$  km/s in the Third catalogue of chromospherically active binaries (Eker et al., (2008)). The suggested spectral types of the primary are K3 III (Simon & Fekel, (1987)), KI III (Sato & Kuji, (1990)), and G8 III (Boffin, Cerf,



**FIGURE 1** Photometric data. Upper panel: All  $\Delta V_{S-C}$  data. Lower panel: All  $\Delta V_{K-C}$  data in the same magnitude scale as in the upper panel.

& Paulus, (1993)). Mohin and Raveendran (1987) arrived at a lower limit estimate,  $R \ge 6R_{\odot}$ , for the primary. Stawikowski and Glebocki (1994) argued that the inclination of the orbital plane,  $i_{orb} = 26^{\circ}$ , is nearly equal to the inclination of the rotation axis of the primary,  $i_{rot} = 24^{\circ}$ . Their estimate for the primary radius was  $15 \pm 2R_{\odot}$ .

Activity-induced chromospheric or coronal emission of BM CVn has been detected in the optical Ca(II) H&K and H $\alpha$  lines, as well as in UV and X-ray wavelengths (Dempsey, Linsky, Fleming, & Schmitt, (1993); Fekel, Moffett, & Henry, (1986); Frasca & Catalano, (1994); Montes et al., (2000); Pérez Martínez, Schröder, & Cuntz, (2011); Sato & Kuji, (1990); Strassmeier, Fekel, Bopp, Dempsey, & Henry, (1990)). Radio and IR emission have also been detected (Haakonsen & Rutledge, (2009); Helfand, Schnee, Becker, White, & McMahon, (1999); Mitrou, Doyle, Mathioudakis, & Antonopoulou, (1996)).

Recent studies have shown that for some RS CVn binaries the light curve is heavily biased by the ellipsoidal shape of the primary (Roettenbacher et al., (2015), (2015)). Furthermore, other physical processes, for example, mass transfer between close binaries, could distort the light curve. These kinds of distortions would always follow the periodicity of the orbital period. Long-term active longitudes, on the other hand, may follow a different periodicity (Hackman et al., (2011)). Thus, if the difference between these periods is large enough, we can separate the spot activity from other variability connected to the orbital period. One way to attempt this is to subtract a mean light curve (MLC) fit calculated with the orbital period. This approach is, in a sense, similar to the pre-whitening used in detecting stellar differential rotation (Reinhold, Reiners, & Basri, (2013)).

In the current study, we apply the continuous period search (CPS) (Lehtinen, Jetsu, Hackman, Kajatkari, & Henry, (2011)) to the photometry of BM CVn spanning over a quarter of a century. One of our aims is to look for active longitudes. Therefore, we check whether the binary has any orbital period MLC, which could distort the detection of active longitudes.

## **2** | **OBSERVATIONS**

Our differential photometry was obtained with the T3 0.4-m automated photoelectric telescope (APT) at Fairborn Observatory, Arizona. The observations were made between April 6, 1990 (HJD = 2447987.9) and June 15, 2015 (HJD = 2457188.8). The comparison and check stars of our target star, S = BM CVn, were C = HD 116010 (Yoss & Griffin, (1997), K2II-III, V=5.60) and K = HD 115271 (Rover, Zorec, & Gómez, (2007), A7V, V = 5.78). The mean (*m*) and the standard deviation (s) of standard Johnson differential magnitudes,  $\Delta V_{S-C}$  (Figure 1, upper panel: n = 2930), were  $m \pm s = 1^{\text{m}}_{\cdot}721 \pm 0^{\text{m}}_{\cdot}096$ . The respective values for the  $\Delta V_{\text{K-C}}$ differential magnitudes (Figure 1, lower panel: n = 2744) were  $m \pm s = 0^{\text{m}}_{.} 1797 \pm 0^{\text{m}}_{.} 0064$ . Hence, C = HD 116010 was a reliable comparison star, the accuracy of our photometry was approximately  $\sigma_{\rm V} = 0^{\rm m}.0064$ , and the observed variations of S = BM CVn were certainly real. The photometric data reduction procedures and the operation of the T3 0.4-m APT have been described in detail, for example, by Henry (1999) and Fekel and Henry (2005). The differential  $\Delta V_{S-C}$  magnitudes are hereafter referred to as the original V magnitudes.

# **3** | CPS METHOD

We analyzed the original V magnitudes of BM CVn with the CPS method formulated by Lehtinen et al. (2011). This method is described here only briefly, because we have already applied it to the photometry of numerous stars (Hackman et al., (2011), (2013); Lehtinen et al., (2011); Lehtinen, Jetsu, Hackman, Kajatkari, & Henry, (2012), (2016); Kajatkari, Hackman, Jetsu, Lehtinen, & Henry, (2014), Kajatkari et al., (2015)). We divided the observations into datasets having a maximum length of  $\Delta T_{\text{max}} = 1.5P_{\text{orb}} =$ 30!94. The modelled datasets contained at least  $n \ge n_{\text{min}} = 14$ observations. CPS uses a sliding window with a length of  $\Delta T_{\text{max}}$  and models all datasets having at least  $n_{\text{min}}$  observations within such a window. The notation for the mean of the n observing times  $t_i$  of a dataset is  $\tau$ . The CPS model is

$$\hat{y}(t_i) = \hat{y}(t_i, \bar{\beta}) = M + \sum_{k=1}^{K} [B_k \cos(k2\pi f t_i) + C_k \sin(k2\pi f t_i)],$$

where *K* is the model order and  $\overline{\beta} = [M, B_1, ..., B_K, C_1, ..., C_K, f]$  is vector of free parameters. The best modelling order *K* for each dataset is chosen by using a Bayesian criterion (Lehtinen et al., (2011), eq. 6). Here, the tested orders for this best model were  $0 \le K \le 2$ . These models gave the following physically meaningful light curve parameters: the period  $P(\tau)$ , the mean brightness  $M(\tau)$ , the peak to peak amplitude  $A(\tau)$ , and the epochs of the primary and secondary minima in time,  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$ . The error estimates for these light curve parameters were determined with the bootstrap method

TABLE 1 V magnitudes: CPS results and symbols of Figs 3-6

	$IND(\tau) = 1$	$IND(\tau) = 1$	$IND(\tau) = 0$	$IND(\tau) = 0$
	$R(\tau) = 0$	$R(\tau) = 1$	$R(\tau) = 0$	$R(\tau) = 1$
$M(\tau)$	<i>n</i> = 107 [ <b>■</b> ]	n = 12 [[]]	n = 1,098 [X]	$n = 102 [\times]$
$A(\tau)$	<i>n</i> = 107 [ <b>■</b> ]	n = 12 [	$n=1,098[\times]$	$n = 102 [\times]$
$P(\tau)$	<i>n</i> = 107 [ <b>■</b> ]	n = 12 [	$n=1,098[\times]$	$n = 102 [\times]$
$t_{\min,1}(\tau)$	<i>n</i> = 107 [ <b>■</b> ]	n = 12 [	$n=1,098[\times]$	$n = 102 [\times]$
$t_{\min,2}(\tau)$	$n = 23  [\blacktriangle]$	$n = 6 \left[ \bigtriangleup \right]$	$n = 293 [\times]$	$n = 42 [\times]$

(Lehtinen et al., (2011)). The reliable and unreliable parameter estimates were identified from these bootstrap results. The parameter estimates were considered reliable if the distribution of the bootstrap estimates for all model parameters and the model residuals followed a Gaussian distribution (Lehtinen et al., (2011)). Two concrete examples of the use of this reliability criterion can be found in Jetsu and Pelt (1999), figs. 2 and 4. We use the notation  $R(\tau) = 0$  for the reliable light curve parameter estimates and  $R(\tau) = 1$  for the unreliable ones. The modelling results correlate for temporally overlapping subsets containing common data. We selected a sequence of independent datasets that did not overlap. The notation for these independent datasets is  $IND(\tau) = 1$ , while that for the remaining overlapping datasets with common data is  $IND(\tau) = 0$ .

# 4 | ANALYSIS OF V MAGNITUDES

# 4.1 | CPS results for the original V magnitudes

We detected periodicity in all 1,319 original V magnitude datasets. The order of the best model was K = 1 in 205 datasets and K = 2 in 1,114 datasets. CPS gave the numbers of different types of  $M(\tau)$ ,  $A(\tau)$ ,  $P(\tau)$ ,  $t_{\min,1}(\tau)$ , and  $t_{\min,2}(\tau)$  estimates in Table 1.

Note that the symbols given in the brackets are those used in Figures 3–6 for the modelling results of the original V magnitude data. All CPS analysis results for the independent Vdatasets are published electronically at the CDS.

The data and the CPS models of the 119 independent datasets are shown in Figure 2. We first computed the phases  $\phi_1 = \text{FRAC}[(t - t_{\min,1}(\tau))/P(\tau)]$ , where FRAC[x] removes the integer part of its argument x. Then, the phases  $\phi_{al,1}$  of the primary minima  $t_{\min,1}(\tau)$  were computed with the active longitude ephemeris of Equation 2. The photometry and the CPS models are plotted as a function of the phase  $\phi = \phi_1 + \phi_{al,1}$  in Figure 2.

# 4.2 | Activity cycles in V photometry

Horne and Baliunas (1986) formulated the power spectrum method (hereafter PSM) which was applied by Baliunas et al. (1995) to search for activity cycles in the chromospheric Ca(II) H&K emission line data. For example, Rodonò, Astronomische 455 Nachrichten

Messina, Lanza, Cutispoto, and Teriaca (2000) and Kajatkari et al. (2015) have applied PSM to the following light curve parameters:  $M(\tau)$  (axisymmetric part of spot distribution),  $A(\tau)$  (non-axisymmetric part of spot distribution),  $M(\tau) + A(\tau)/2$  (maximum spottedness) or  $M(\tau) - A(\tau)/2$  (minimum spottedness). These four parameters are also analyzed here, although there are actually only two independent variables,  $M(\tau)$  and  $A(\tau)$ . Furthermore, the amplitude of the light curve does not depend only on the area of the spots, but there are also other causes, for example, variations of the temperature of the spots or the connection between their projected area and their latitude.

The  $M(\tau)$  and  $A(\tau)$  changes of BM CVn are shown in Figure 3. PSM detected the following activity cycles  $P_c$  in the n = 107 independent and reliable estimates of the above four parameters of BM CVn, where *F* is the false alarm probability (Horne & Baliunas, (1986)):

	$P_{\rm c} \pm \sigma_{P_{\rm c}}$	F
M( au)	$13.1 \pm 0.2$	$5 \times 10^{-11}$
$A(\tau)$	$12^{y}.0 \pm 0^{y}.3$	$2 \times 10^{-4}$
$M(\tau) + A(\tau)/2$	$12^{y}.8 \pm 0^{y}.2$	$5 \times 10^{-10}$
$M(\tau) - A(\tau)/2$	$18.2 \pm 0.4$	$7 \times 10^{-9}$

All *F* values indicate that these cycles are very significant. Considering the  $\sigma_{P_c}$  errors, the first three parameters may follow the same activity cycle of approximately 12<sup>!</sup>.5 which has been repeated twice between 1990 and 2015. However, the parameter  $M(\tau) - A(\tau)/2$  appears to follow another cycle of 18<sup>!</sup>.2.

#### **4.3** | Differential rotation in V photometry

The  $P(\tau)$  changes of BM CVn are shown in Figure 4. Numerous unrealistic period estimates were obtained for low-amplitude light curves, for example, in the years 1992, 1993, 1995, and 1998. Our estimate for the differential rotation of BM CVn is based on the n = 107 reliable  $P(\tau)$ estimates of independent datasets. We compute the value of the parameter

$$Z = 6\Delta P_{\rm w} / P_{\rm w} = 0.10 \equiv 10\%, \tag{1}$$

where  $P_i \pm \sigma_{P,i}$  is period of *i*:th dataset,  $w_i = \sigma_{P,i}^{-2}$  is the weight,  $P_w = [\sum_{i=1}^{107} w_i P_i] / [\sum_{i=1}^{107} w_i]$  is the weighted mean of  $P_i$ , and  $\Delta P_w = \{[\sum_{i=1}^{107} w_i (P_i - P_w)^2] / [\sum_{i=1}^{107} w_i]\}^{1/2}$  is the error of this weighted mean  $P_w$  (Lehtinen et al., (2011), eq. 14). The numerical values for BM CVn are  $P_w \pm \Delta P_w = 20^4.67 \pm 0^4.36$ . We use the multiplying constant value of 6 in Equation 1, because parameter Z is the  $\pm 3\Delta P_w$  upper limit for the period variations.

Lehtinen et al. ((2011), their eq. 15) introduced the relation  $Z_{phys} = Z^2 - Z_{spu}^2$ , where Z measures the observed period changes of Equation 1, while  $Z_{phys}$  and  $Z_{spu}$  measure the real physical and unreal spurious period changes. The mean of the half amplitude  $A(\tau)/2$  of the above-mentioned 107 models of BM CVn is  $A_{half} = 0$ . 068. The data precision is  $N = \sigma_V =$ 0. 0064. This yields a "signal to noise" ratio of  $\epsilon = A_{half}/N \approx$ 10. Together with the mean number of data points per dataset,



**FIGURE 2** Data and the light curves of 119 independent *V* magnitude datasets (IND( $\tau = 1$ )). The reliable and unreliable models a re denoted with  $R(\tau) = 0$  and 1, respectively. The *x*-axis is the phase  $\phi$  and the *y*-axis is the magnitude *V*. The computation of the phases  $\phi$  is explained in the last paragraph of Section 4.1.

 $n_{\text{data}} = 19.9$ , and the ratio of the mean rotation period to the dataset length,  $n_{\text{rot}} = 1.45$ , this predicts spurious changes of  $Z_{\text{spu}} \approx 0.08$  (Lehtinen et al., (2016), eq. 10). This is a major fraction of the raw estimate Z = 0.10, although the physically originating component of the period changes may still be estimated at  $Z_{\text{phys}} \approx (Z^2 - Z_{\text{spu}}^2)^{1/2} = 0.06$ .

One approximation for the solar law of differential rotation is  $P(b) = P(b = 0)/[1 - k_{\odot}(\sin b)^2]$ , where *b* is the latitude and  $k_{\odot} = 0.2$  is the solar differential rotation coefficient. If this law were valid for BM CVn and its  $P(\tau)$  were reliable tracers of surface differential rotation, the differential rotation coefficient of BM CVn would be  $|k| = Z_{\text{phys}}/h$ ,



**FIGURE 3** (a) Mean  $M(\tau)$  for the original V magnitudes, (b) amplitude  $A(\tau)$  for the original V magnitudes. The symbols are explained in the first paragraph of Section 4.1.



**FIGURE 4** Period  $P(\tau)$  for the original V magnitudes. The  $P_w$  and  $P_w \pm 3\Delta P_w$  levels are denoted with horizontal continuous and dotted lines, respectively.

where  $b_{\min}$  and  $b_{\max}$  are the minimum and maximum latitudes of spot activity, and  $h = \sin^2 b_{\max} - \sin^2 b_{\min}$  (Jetsu, Pelt, & Tuominen, (1993)). The exact latitudes of the spots cannot be determined from photometric observations, and thus the numerical value of *h* remains unknown. For example, if spots form at all latitudes between the equator and pole of BM CVn, this coefficient reaches its maximum value h = 1. Thus, the relation  $|k| > Z_{phys} \approx 0.06$  is valid for all possible  $b_{\min}$  and  $b_{\max}$  values.

#### 4.4 | Active longitudes in V photometry

The spots on the surface of rapidly rotating giants have been observed to concentrate on long-lived active longitudes (e.g., Jetsu et al., (2000)). Such structures have been detected, for example, with the non-weighted or weighted Kuiper test formulated in Jetsu and Pelt ((1996), section 3.1). In this test, the phases  $\phi_i$  of *n* time points  $t_i$  are first computed with the tested period P. These phases are then arranged into increasing order (i.e., rank order). The monotonously increasing sample distribution function  $F_n(\phi_i) = i/n$  of these phases is compared to the sample distribution function of an even distribution  $F(\phi) = \phi$ , that is, a random distribution. The Kuiper test statistic is  $V_n = D^+ + D^-$ , where  $D^+ = F_n(\phi) - F(\phi)$  and  $D^- = F(\phi) - F_n(\phi)$ . A large  $V_n$  value indicates that the phases  $\phi_i$  do not represent a sample drawn from a random distribution, that is, the phases  $\phi_i$  are not evenly distributed and there is periodicity in time points  $t_i$  with the tested period P.



**FIGURE 5** (a)  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$  for the original *V* magnitudes with the active longitude ephemeris of Equation 2. (b) Histogram of the number of values  $n(\phi)$  within 0.1 bins in phase. The dark and shaded areas denote the reliable  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$  estimates of independent datasets, respectively.

We applied the non-weighted Kuiper test to the reliable  $t_{\min,1}(\tau)$  estimates of all independent datasets (n = 107). The tested period range was between  $0.85P_W = 17^46$  and  $1.15P_W = 23^48$ . The best rotation period for the active longitudes of BM CVn was  $P_{al} = 20^4511 \pm 0^4005$ . This periodicity reached an extreme significance of  $Q_K = 1 \times 10^{-7}$  (Jetsu & Pelt, (1996), eq. 24). We also applied the same test to the reliable  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$  estimates of all independent datasets (n = 130). The result was exactly the same,  $20^4511 \pm 0^4008$  ( $Q_K = 4 \times 10^{-7}$ ).

All  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$  estimates of BM CVn are shown in Figure 5. The phases are calculated from the active longitude ephemeris

$$HJD_0 = 2\ 447\ 987.8762 + 20^4.511E,$$
 (2)

where the zero epoch is the time of the first photometric observation. The majority of the reliable primary minima of independent datasets concentrate between phases 0.1 and 0.6 (Figure 5a: closed squares and Figure 5b: dark areas). The corresponding simultaneous secondary minima are usually about half a rotation apart from these primary minima (Figure 5a: closed triangles). The light curves had only one minimum in the years 1991–1992, 1997, 2001–2006, 2011–2013, that is, two minima were present for half of the time. When the activity was present on both longitudes, the longitude with stronger activity determined the phase of  $t_{\min,1}(\tau)$  (Figure 5a: closed squares). Sometimes the activity shifted abruptly nearly to the opposite side of the stellar hemisphere, like in the years 2003-2004. This type of the "flip-flop" events have previously been observed, for example, on the rapidly rotating single G4 III giant FK Comae (Jetsu et al., (1993)).

If the inclination of the primary were indeed only  $i_{rot} = 24^{\circ}$  (Stawikowski & Glebocki, (1994)), then extreme spot coverage would be required to explain the high amplitudes of  $A(\tau) \approx 0.5^{\text{m}}$  in the year 2013 (Figure 3).

Using the Barnes–Evans relation as formulated by Lacy (1977), we can derive an alternative estimate of the stellar radius with the formula

$$\log R/R_{\odot} = 7.4724 - 0.2V_0 - 2F_V + \log d, \qquad (3)$$



**FIGURE 6**  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$  for the original *V* magnitudes with the orbital period ephemeris of Equation 4. Otherwise as in Figure 5.

where  $F_V = 3.977 - 0.429(V - R)_0$  and [d] = pc. The Hipparcos parallax of 8.86 mas (van Leeuwen, (2007)) combined with the V magnitude and  $V - R \approx 0.81$  (Eker et al., (2008)) indicates a primary radius of  $\sim 8R_{\odot}$ . This would mean that that the rotational inclination of the primary is in fact  $i_{rot} \sim 50^{\circ}$ . This value would still require a high, but not extreme spot coverage. Furthermore, assuming approximately the same orbital inclination would result in a secondary mass of  $\sim 0.3M_{\odot}$ . Thus, it is no surprise that its spectral lines have not been observed.

Recently, Roettenbacher et al. (2015) showed that the ellipsoidal shape of the primary of another RS CVn binary  $\sigma$  Gem (Duemmler, Ilyin, & Tuominen, (1997),  $P_d = 19^{4}604471 \pm 0^{4}000022$ ) offered an alternative explanation for the active longitude hypothesis presented by Kajatkari et al. (2014). For BM CVn, the active longitude period  $P_{al} = 20^{4}511 \pm 0^{4}005$  is only 0.55% smaller than the orbital period  $P_{orb} = 20^{4}6252 \pm 0^{4}0018$ . This period difference causes a  $\Delta \phi = 2.48$  phase difference during the whole time span of data. The three periods of BM CVn increase in the order  $P_{al} < P_{orb} < P_{w}$ . The  $P_{w} = 20^{4}67$  error,  $\Delta P_{w} = 0^{4}36$ , does not exclude the cases  $P_{w} < P_{orb}$  or  $P_{w} < P_{al}$ . However, the accuracy of the other two periods excludes the case  $P_{al} > P_{orb}$ .

We decided to test the ellipsoidal primary shape hypothesis for BM CVn. The orbital period ephemeris in Griffin and Fekel (1988) was

$$HJD_0 = 2\ 445\ 252.12 + 20^{4}6252E.$$
(4)

The  $t_{\min,1}(\tau)$  and  $t_{\min,2}(\tau)$  phases of BM CVn computed with this ephemeris are shown in Figure 6. These phases show no clear concentrations at  $\phi = 0.25$  or 0.75, which could be one signature of ellipticity. The minima of the binned *B* and *V* magnitude light curves of  $\sigma$  Gem were at these particular orbital phases in Roettenbacher et al. ((2015), their fig. 5). The results of a similar binning of the *V* magnitudes of BM CVn are shown in Figure 7a. This 0<sup>m</sup>.042 peak-to-peak amplitude MLC shows only one minimum and one maximum, while there were two maxima and minima in the MLC of  $\sigma$  Gem.

The MLC of BM CVn would also have two minima and maxima if the real  $P_{orb}$  of BM CVn were 2 times larger than the one reported in Griffin and Fekel (1988) (Figure 7b).



**FIGURE 7** (a) The mean light curve (MLC) of BM CVn with the ephemeris of Equation 4. The bin width was 0.050 in phase  $\phi$ . The error bars show the mean error within each bin. The continuous line shows the best fit with the model of Equation 5. The dashed and the dotted lines show the MLC for the binned data before and after the mid epoch 2002.85. (b) The MLC for the period  $2P_{orb}$  in Equation 4. (c) Radial velocities  $v_r$  in Griffin and Fekel (1988) with the ephemeris of Equation 4. (d) Same data for the period  $2P_{orb}$  in Equation 4.

However, this double period hypothesis must be rejected because the radial velocity measurements from Griffin and Fekel (1988) follow a single and double sine wave with  $P_{orb}$  and  $2P_{orb}$ , respectively (Figure 7c, d). These results do not support the ellipsoidal shape hypothesis, because the MLC of BM CVn does not have two minima and maxima. We will later discuss the possible cause of this sinusoidal MLC of BM CVn in the end of Section 6. Whatever the real cause may be, it is certain that this regular  $0^{m}_{..}042$  variation has been misleading our CPS analysis of the original V magnitudes.

We also computed the MLC for the first and second part of the data, that is, before and after the mid epoch of 2002.85. These two MLCs are denoted with dashed and dotted lines in Figure 7a. Both these curves show one maximum and minimum. The maximum deviation of both curves from the MLC of all data is only 0<sup>m</sup>.014. The phase and the height of the MLC maximum of BM CVn have remained very stable, but the depth and the phase of the MLC minimum have varied. These MLC minimum variations are at least partly caused by the high-amplitude light curves of the years 2012 and 2013. However, the MLC of BM CVn in Figure 7a (continuous line) must be a real phenomenon, because the erratic changes of the light curve mean, amplitude, and period, and especially those of the minimum and maximum phases, should cause a constant long-term MLC. The MLC was computed with  $P_{orb}$ . This induces a phase difference of  $\Delta \phi = 2.48$  with  $P_{\rm al}$  during the whole time span of data. Hence, the observed MLC phase coherence is not caused by active longitudes.

## 4.5 | MLC-corrected V' magnitudes

We used the Bayesian criterion from Lehtinen et al. ((2011), eq. 6) to determine the best modelling order K for the binned

*V* magnitudes of Figure 7a. The tested orders were  $0 \le K \le 4$ . The best order was K = 2. Hence, we modelled these binned *V* magnitudes with

$$g_2(\phi, \beta_{\text{MLC}}) = a_0 + a_1 \cos(2\pi\phi) + b_1 \sin(2\pi\phi) \quad (5) + a_2 \cos(4\pi\phi) + b_2 \sin(4\pi\phi),$$

where the free parameters were  $\bar{\beta}_{MLC} = [a_0, a_1, b_1, a_2, b_2]$ , and the orbital phases  $\phi$  were calculated from the ephemeris of Equation 4. The best fit had  $a_0 = 1.721 \pm 0.002$ ,  $a_1 = 0.011 \pm 0.002$ ,  $b_1 = -0.017 \pm 0.003$ ,  $a_2 = 0.000 \pm 0.002$ , and  $b_2 = 0.003 \pm 0.002$ . The continuous line outlines this model in Figure 7a. The Bayesian criterion from Lehtinen et al. ((2011), eq. 6) revealed that a second-order component was present in the MLC, although the amplitude of this second order part was low, that is, constant  $a_2$  was zero and constant  $b_2$  was very close to zero. We used this same criterion to determine the best K value for the CPS models of *all* V and V' datasets.

This best fit of Equation 5 was used to remove the MLC from the V magnitudes of BM CVn. The corrected magnitudes were computed from

$$V'(t_i) = V(t_i) - g_2(\phi, \bar{\beta}_{\text{MLC}}) + a_0, \tag{6}$$

where  $V(t_i)$  were the original data, and the values of the free parameters  $\bar{\beta}_{MLC}$  were those of this best fit of Equation 5. The CPS analysis results do not depend on subtracting a constant value from differential photometry. Therefore, we did not subtract the MLC mean, that is, the constant  $a_0 = 1.721$ , from the  $V(t_i)$  data. In other words,  $a_0$  was "added back" in Equation 6.

One example of this correction procedure of Equations 5 and 6 is displayed in Figure 8. The original V data are denoted with closed squares (SEG = 1, SET = 1). The continuous line shows the light curve for these original data, that is, the first light curve from Figure 2. The MLC values  $g_2(\phi, \bar{\beta}_{MLC})$  computed with Equation 5 are scattered (Figure 8: crosses). The reason for this scatter is that these MLC values are computed with the period  $P_{\rm orb} = 20^{4}.6252$ , but the correct period for these data is much shorter  $P(\tau) = 20^{d}.14 \pm 0^{d}.31$ . This mixes the MLC phases when these phases are computed "incorrectly" with  $P(\tau)$ , that is, not with the correct period  $P_{orb}$ . The upward peak in the MLC values (crosses) close to phase 0.35 provides a nice example of the correction procedure. When this peak is subtracted from the original V data (closed squares), the corrected V' data show a dip at the same phase (open diamonds).

#### 5 | ANALYSIS OF V' MAGNITUDES

# 5.1 | CPS results for the MLC-corrected V' magnitudes

We use a prime (') to denote all CPS analysis results for the V' magnitudes, for example,  $M'(\tau)$  for the mean. For  $\tau$ , this notation is not required, because the observing times  $t_i$  of the



**FIGURE 8** Example of the mean light curve (MLC) correction procedure. The data (closed squares) and the continuous period search (CPS) model (continuous line) are from Figure 2 (SEG=1, SET=1). The crosses denote MLC magnitudes computed from Equation 5. The diamonds show the MLC corrected V' magnitudes (Equation 6).

TABLE 2 V' magnitudes: CPS results and symbols of Figs 10-12

	$IND'(\tau) = 1$ $R'(\tau) = 0$	IND' $(\tau) = 1$ $R'(\tau) = 1$	$IND'(\tau) = 0$ $R'(\tau) = 0$	$IND'(\tau) = 0$ $R'(\tau) = 1$
$M'(\tau)$	<i>n</i> ′ = 105 [ <b>■</b> ]	n' = 14 [[]]	$n' = 1,117 [\times]$	n' = 83 [X]
$A'(\tau)$	$n' = 105  [\blacksquare]$	n' = 14 [	n' = 1,117 [X]	n' = 83 [X]
$P'(\tau)$	n' = 105 [ <b>•</b> ]	n' = 14 [	n'=1,117[X]	$n' = 83 [\times]$
$t'_{\min,1}(\tau)$	$n' = 105  [\blacksquare]$	n' = 14 [	$n'=1,117[\times]$	$n' = 83 [\times]$
$t'_{\min,2}(\tau)$	$n'=24[\blacktriangle]$	$n' = 5 \left[ \bigtriangleup \right]$	$n' = 321 [\times]$	$n' = 33 [\times]$

 $V(t_i)$  and  $V'(t_i)$  magnitudes are the same. The total number of CPS models for the corrected V' magnitudes was 1,319. Again, CPS detected periodicity in all datasets. The order of the best model was K' = 1 in 220 datasets and K' = 2 in 1,099 datasets. The number of different types of CPS parameter estimates,  $M'(\tau)$ ,  $A'(\tau)$ ,  $P'(\tau)$ ,  $t'_{\min,1}(\tau)$ , and  $t'_{\min,2}(\tau)$ , were given in Table 2.

The symbols used for the modelling results of these parameters in Figures 10–12 are given above the brackets. The fraction of unreliable CPS models was 114/1319 = 8.6% for the original V magnitudes. This fraction decreased to 97/1319 = 7.4% for the V' magnitudes. Hence, the number of reliable models ( $R'(\tau) = 0$ ) increased when the MLC was removed from the original V magnitudes. The CPS analysis results of the corrected V' magnitudes are also published only electronically at the CDS.

The CPS models of 119 independent V' magnitude datasets are shown in Figure 9. The phases were first computed from  $\phi'_1 = \text{FRAC}[(t - t'_{\min,1}(\tau))/P'(\tau)]$ . Then, we computed the phases  $\phi'_{al,1}$  of the primary minima  $t'_{\min,1}(\tau)$  with the active longitude ephemeris of Equation 2. The V' magnitudes and the CPS models are plotted as a function of the phase  $\phi' = \phi'_1 + \phi'_{al,1}$  in Figure 9. The light curves of the original V and corrected V' magnitudes are nearly identical (Figures 2 460 Astronomische Nachrichten



**FIGURE 9** Light curves of 119 independent V' magnitude datasets (IND'( $\tau = 1$ )). The reliable and unreliable models are denoted with  $R'(\tau) = 0$  and 1, respectively. The *x*-axis is the phase  $\phi$  and the *y*-axis is the magnitude V'. The computation of phases  $\phi$  is explained the last paragraph of Section 5.1.

and 9). The largest change in the mean values  $M(\tau)$  and  $M'(\tau)$  is 0.<sup>m</sup>014. It occurs in SET=18 of SEG 11. The largest amplitude change, 0.<sup>m</sup>027, between  $A(\tau)$  and  $A'(\tau)$  occurs in SET=1, SEG=19 (Figure 10). The light curves of this latter dataset are displayed in Figures 2 and 9.

# 5.2 | Activity cycles in V' photometry

The amplitude of the MLC was low, that is, only 0<sup>m</sup>042. Hence, the correction of Equation 6 should not cause large changes in the mean and amplitude of the CPS light curves.



**FIGURE 10** (a) Mean  $M'(\tau)$  for the V' magnitudes. (b) Amplitude  $A'(\tau)$  for the V' magnitudes. The symbols are explained in the first paragraph of Section 5.1.



**FIGURE 11** Period  $P'(\tau)$  for the corrected V' magnitudes, otherwise as in Figure 4.

The maximum differences were  $\max(|M(\tau) - M'(\tau)|) = 0^{\text{m}}014$  and  $\max(|A(\tau) - A'(\tau)|) = 0^{\text{m}}027$ . When we applied PSM to the corresponding CPS parameters as in Section 4.2, the results were as follows:

	$P_{\rm c}^{\prime} \pm \sigma_{P_c}^{\prime}$	F'
M'( au)	$13^{1} \pm 0^{2}$	$1 \times 10^{-10}$
A'( au)	$12\%0 \pm 0\%3$	$5 \times 10^{-4}$
$M'(\tau) + A'(\tau)/2$	$12^{y}.9 \pm 0^{y}.2$	$2 \times 10^{-10}$
$M'(\tau) - A'(\tau)/2$	$18.2 \pm 0.4$	$5 \times 10^{-9}$

The best cycles were practically the same as those for the original V magnitudes. All this supported the presence of an activity cycle of approximately  $12^{y}$ .5.

#### 5.3 Differential rotation in V' photometry

The results for  $P'(\tau)$  are shown in Figure 11. The n' = 105independent and reliable period estimates had  $P'_{\rm w} \pm \Delta P'_{\rm w} =$  $20^{4}67 \pm 0^{4}37$ , which was equal to  $Z' = 0.11 \equiv 11\%$ . The signal-to-noise ratio A/N was practically the same as for the original V magnitude data, because there were no significant changes in the light curve amplitudes. Hence, the V' magnitude data gave close to the same differential rotation coefficient estimate  $k' \geq Z'_{\rm phys} = 0.08$  (with changes  $Z_{\rm spu} = 0.08$ ). Comparison of Figures 4 and 11 revealed that the MLC correction eliminated numerous unrealistic  $P(\tau)$  values obtained in the CPS analysis of original V magnitudes. Most of the remaining unrealistic  $P'(\tau)$  values were obtained during the year 1998 when the amplitude  $A'(\tau)$  of light curves was very close to zero.



**FIGURE 12**  $t'_{\min,1}(\tau)$  and  $t'_{\min,2}(\tau)$  for the corrected V' magnitudes with active longitude ephemeris of Equation 2.



**FIGURE 13** (a) Kuiper periodogram for the n = 107 independent and reliable  $t_{\min,1}(\tau)$  estimates of original *V* magnitudes. The thick horizontal lines denote the locations of the two best periods  $1 \equiv 20!51$  and  $2 \equiv 20!68$ . (b) Kuiper periodogram for the n' = 105 independent and reliable  $t'_{\min,1}(\tau)$  estimates of corrected *V'* magnitudes. The two best periods are  $1 \equiv 20!51$  and  $2 \equiv 20!70$ .

#### **5.4** | Active longitudes in V' photometry

The non-weighted Kuiper test was applied to the n' = 105 reliable  $t'_{\min,1}(\tau)$  estimates of independent datasets. The tested period range was the same as in Section 4.4. The best active longitude rotation period was  $P'_{al} = 20^{4}512 \pm 0^{4}005$  ( $Q_{\rm K} = 5 \times 10^{-8}$ ). The result for the n' = 129 reliable  $t'_{\min,1}(\tau)$  and  $t'_{\min,2}(\tau)$  estimates of independent datasets was the same,  $20^{4}512 \pm 0^{4}010$  ( $Q_{\rm K} = 6 \times 10^{-7}$ ). The  $P_{al}$  and  $P'_{al}$  values were also the same within their error limits. Therefore, the ephemeris of Equation 2 was also used in our Figure 12, which shows the phases of  $t'_{\min,1}(\tau)$  and  $t'_{\min,2}(\tau)$ . Most of the reliable  $t'_{\min,1}(\tau)$  estimates of independent datasets concentrate between phases 0.1 and 0.7.

The Kuiper test periodograms  $V_n$  for the primary minima of the original V magnitudes and the corrected V' magnitudes are shown in Figure 13. The two best active longitude periods for the original V magnitudes were 20<sup>4</sup>51 ( $Q_K = 1 \times 10^{-7}$ ) and 20<sup>4</sup>68 ( $Q_K = 1 \times 10^{-5}$ ). The  $V_n$  peak of the second best period value in Figure 13a was also very significant. The two best active longitude periods for the corrected V' magnitudes were 20<sup>4</sup>51 ( $Q_{\rm K} = 5 \times 10^{-8}$ ) and 20<sup>4</sup>70 ( $Q_{\rm K} = 4 \times 10^{-5}$ ) (Figure 13b). After the MLC correction, the significance of the best period increased while the significance of the second best period decreased. From this we could conclude that the MLC did not cause the active longitudes. On the contrary, the MLC hampered the detection of active longitudes.

#### 6 | CONCLUSIONS

We analyzed a quarter of a century of photometry of BM CVn. The original V magnitude data were binned as a function of phase computed with the orbital period ephemeris of Equation 4. This revealed that the photometry contained a MLC, having a peak-to-peak amplitude of  $0^{\text{m}}_{.}042$  (Figure 7a). The corrected V' magnitudes were computed by subtracting the MLC from the original V magnitudes (Equation 6)

The CPS algorithm was applied to the original V magnitudes and the corrected V' magnitudes. When we removed the MLC from the data, the fraction of unreliable CPS models decreased from 8.6% to 7.4%. The same activity cycle of approximately 12.5 years was detected with the power spectrum method from the V and V' magnitudes (Sections 4.2 and 5.2). The results for the differential rotation coefficient were nearly the same for the V and V' magnitudes,  $k \ge Z_{phys} = 0.06$ and  $k' \geq Z'_{\text{phys}} = 0.08$  (Sections 4.3 and 5.3). However, the number of unrealistic period estimates decreased after the MLC was removed (Figures 4 and 11). It has to be noted that the estimated level of spurious period changes at  $Z_{spu} = 0.08$ is significant because of the long rotation period of the star in relation to reasonable dataset lengths. Thus the estimated differential rotation values have considerable uncertainties. The same active longitude rotation period,  $P_{\rm al} = 20^{4}.511 \pm 0^{4}.005$ , was detected with the non-weighted Kuiper method from the primary minima of V and V' data (Equation 2). This result did not change when the secondary minima were also included into the analysis (Sections 4.4 and 5.4). We showed that the MLC hampered the detection of active longitudes. Hence, the MLC was certainly not the cause for observing such long-term regularities in the light curve minima of BM CVn.

The ellipticity of the primary component of another RS CVn star,  $\sigma$  Gem, causes a regular MLC as a function of the orbital period (Roettenbacher et al., (2015)). Because of projection effects, this MLC has two minima and maxima. Roettenbacher et al. (2015) argued that this MLC may be the reason for observing two active longitudes in  $\sigma$  Gem, that is, this phenomenon may not be connected to dark spots or to chromospheric activity in general. The MLC of BM CVn has only one minimum and one maximum (Figure 7) and ellipticity cannot therefore be the cause for this regularity. Innumerable different types of light curves have been observed in different classes of variable stars (e.g., Drake et al., (2014)). For example, a mass-transfer-induced bright spot in BM CVn could explain the observed MLC. If the rate of this mass transfer varies, the brightness changes caused

by the bright spot also vary, and our MLC correction of Equation 6 cannot remove such irregularity from the original V magnitude data. Nevertheless, we stress that the removal of the MLC increased the detectability of the active longitudes.

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unrelated to spot activity.

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This is an indication of the MLC being caused by physics

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