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Improved period of a slowly rotating cool magnetic CP star HD 188041

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Abstract. The ephemeris of variations of the cool magnetic CP star HD 188041 was newly determined using all photometric, magnetic and spectroscopic observations available. The improved period $P = (223.826 \pm 0.040)$ d is common for all types of variation observed, all previously mentioned periods were definitely eliminated. The origin of phase counting $M_0 = (2\,444\,981.8 \pm 0.6)$ was put in the centre of the v light minimum. The effective magnetic field maximum lies at phase 0.002 ± 0.019. The slightly asymmetric curve of Gd II line strength has its maximum at -0.031 ± 0.012.

Key words: CP stars – photometry – variability – period

1. Introduction

HD 188041 (HR 7575, V 1291 Aql, HIP 97871) is a well-known cool chemically peculiar (CP2) star spectroscopically classified as A6 SrCrEu. Its magnetic, light and spectrum variations have the same period which corresponds to the standard oblique rotator model. The variable longitudinal component of the magnetic field induction remains irreversible for all the period. The light variations are most remarkable at 400 nm and the spectrum variability is most conspicuous in the strength of lines of the rare earth elements. The period, $P \sim 224$ d, aligns with the relatively less numerous group of CP stars.

Babcock (1953) was the first who mentioned the period of the magnetic field variations. In Babcock (1954, 1958) variations of the effective magnetic induction, $H_{\rm eff}$, and intensities of spectral lines was thoroughly described using the following ephemeris

$$JD(H_{\rm min}) = 2\,432\,323 + 226\,E. \qquad (1)$$

Preston (1967) warned that majority of Babcock's observations were performed during full moon phases, which allows the arrangement of the data to give a period $P = 26.123\,\mathrm{d}$. Wolff (1969) obtained fifteen more Zeeman observations in order to check both the possibilities. She unambiguously endorsed the longer value of period and improved it to $P = 224.5\,\mathrm{d}$ accepting the epoch of the minimum given by Babcock (1953). However, she was not able to exclude the value 34 d, which is the other synodic month alias to the long period. The same elements were used later in photometric studies by Jones & Wolff (1973), Musielok et al.(1980), Musielok (1986) and Musielok & Madej (1988).

Panov & Schöneich (1975) and Schöneich (1975) came to the period $P = 224.93$ d and mentioned the possibility of a value 0.992788 d. Renson (1975) found $P = (224.3 \pm 0.5)\,\mathrm{d}$. Mathys (1991) found a slightly shorter period $P = (224.0 \pm 0.2)\,\mathrm{d}$ when he added his four new magnetic observations to older ones. A still shorter photometric period was derived by Hensberge (1993) from ESO photometry (Manfroid et al. 1991, Sterken et al. 1993), $P = (223.9 \pm 0.2)\,\mathrm{d}$.

Despite this star being observed since 1947, discords in the period of its variability still persist. As well, the most recently published value of the period (e.g. Hensberge 1993), $P = (223.9 \pm 0.2)\,\mathrm{d}$ is determined with a relatively high vagueness, thus somewhat casting doubts on the results of fine analysis of mutual relations of magnetic, light and spectroscopic variations derived from observations obtained over the time interval of fifty years (uncertainty of ± 0.07 in determination of the phase).

Abt & Morell (1995), however, found a value $v \sin i = 40\,\mathrm{km\,s^{-1}}$, which, of course, questions the 224 d period as well as the applicability of the generally accepted *oblique rotator model* for interpretation of the observed light, spectral and magnetic variations of CP stars.

In this work all the available photometric, magnetic and spectroscopic material is used to revisit the period determination as consistently as possible.

2. Observational data and its analysis

Table 1 contains the sources of the observational data, the measured quantity used for the period analysis, the number of the observations used n, epoch E of the beginning and the end of the time interval covered by particular sets of observations, the mean value of the epoch $\overline{E}$ and $\overline{(O-C)}$ for extremes of the corresponding variability curve relative to the new elements (3). The epochs are counted from the minimum in v contiguously preceding the first of all the observations available.

2.1. Photometric elements

Initially we chose the photometric observations as their ratio of the mean uncertainty of determination of the brightness to the amplitude of the variations at about 400 nm ($\sim 9\%$) is many times less than the ratio for variations of the effective magnetic field ($\sim 35\%$). The periodograms (Stellingwerff 1978, code by JZ) clearly displayed the best arrangement centred around ~ 224 d.To derive the

Table 1. List of observations

Source	Quantity	n	epochs	$\overline{E}$	$\overline{(O-C)}$ [d]	Mean value [G], [mag]
1	H_{eff}	68	$0.6-15.2$	8.3	-0.1 ± 4.4	774(25)
2	H_{eff}	15	$26.9-31.5$	29.8	3 ± 10	810(55)
3	$B-$Walraven	10	$31.6-32.1$	31.8	-1.3 ± 2.5	-0.8809(24)
4	$v-$Stroemgren	30	$38.1-41.9$	39.6	0.9 ± 1.4	6.0834(14)
5	$X-$10 col.phot.	40	$41.7-48.3$	46.4	-0.3 ± 1.3	-0.8762(13)
6	H_{Z}	4	$64.0-67.3$	66.1	-1 ± 17	1330(100)
7	$v-$Stroemgren	111^{*}	$58.2-77.6$	69.2	-0.2 ± 0.0	6.0957(8)
8	$B_{\mathrm{T}}-$Tycho phot.	13^{*}	$70.3-74.7$	72.6	-0.6 ± 2.1	5.9035(18)

Notes: 1–Babcock (1954,1958), 2–Wolff (1969), 3–van Genderen (1971), 4–Jones & Wolff (1973), 5–Musielok et al.(1980), 6–Mathys (1991), 7–ESO 1-4 (1991-1995), 8–TYCHO Catalog (1997). * – The observations were obtained in short-time sequences containing 2 or more measurements, we used their medians. In parentheses, last column, the error of a mean value is given.

period more precisely and to get the parameters of the v light curve we used our own robust gradient method based on the least square method (LSM) enabling us to eliminate the influence of outliers (see Appendix). The light curve was found to be practically symmetrical and was described with the following function:

$$m \cong \overline{m(c)} + A_1\cos(2\pi\varphi) + A_2\cos(4\pi\varphi), \quad \varphi = \frac{JD - M_0}{P}. \qquad (2)$$

Free parameters are the mean values of magnitudes in the individual set of observations, $\overline{m(c)}$, the coefficients of the shape and amplitude of the light curve, A_{i}, the period, P, and the time of minimum, M_0. The epochs are counted starting from the minimum of light immediately preceding the first of Babcock's observation of effective magnetic field. We assumed that the shapes and amplitudes of the light curves at about 400 nm are alike. The B_{T} was rescaled by a factor of 1.4 relatively to v. Although these presuppositions appear to be remarkably simplifying it can be proved that the detailed shape and amplitude of the regression model influence on light elements determination is only marginal. On the contrary, the application of the robust regression method showed it to be more important, as the quality of the observations is strongly affected with a massive occurrence of outliers mainly coming from the ESO photometry. After eliminating outlier's errors the standard deviation turned out to be only 0.0081 mag. The ephemeris obtained is as follows:

$$JD_{\mathrm{vmin}} = (2\,444\,981.8\pm0.6) + (223.826\pm0.040)(E-57), \qquad (3)$$

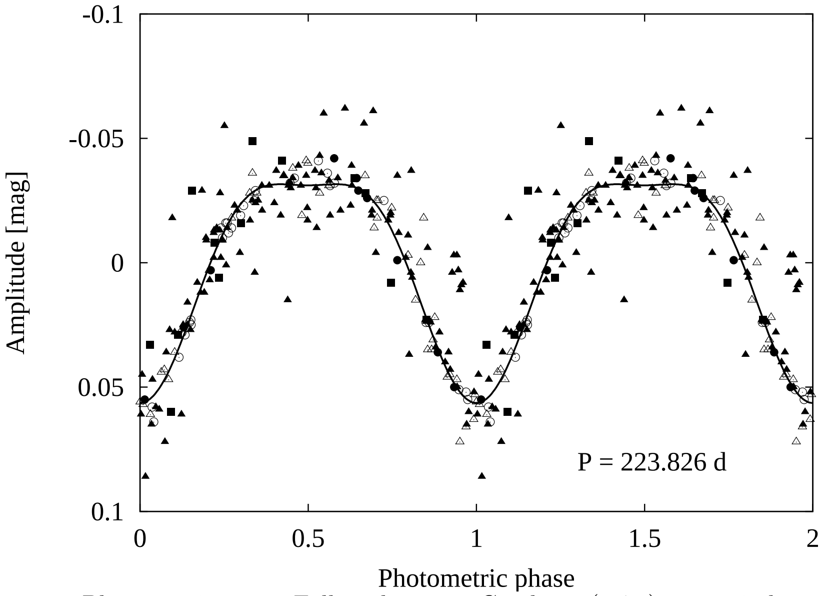

Figure 1. Photometric curve. Full circles – van Genderen (1971), open circles – Jones & Wolff (1973), open triangles – Musielok et al. (1980), full triangles – ESO 1-4 (1991-1995), full squares – ESA (1997).

where E is the serial number of the cycle.

The model light curve shows a symmetric minimum passing to a flat maximum in which the brightness changes only a little. The coefficients determining its amplitude and shape are

$$A_1 = (0.0438 \pm 0.008)\text{mag},\ A_2 = (0.0126 \pm 0.008)\text{mag}. \tag{4}$$

The amplitude is amongst the largest of the CP stars.

2.2. Magnetic field

The magnetic field variability was studied independently of the conclusions obtained by virtue of photometry. We used the all magnetic data listed in Tab 1. A simple sine function was used as a regression model. We admitted that the mean values from various authors could be different. The period $P = (223.78 \pm 0.3)$ d found is in an excellent agreement with the photometric one. As the photometric period is an order of magnitude more precise, we will accept it as the rotational period of the star in the following. Thus, the ephemeris for magnetic variations is

$$JD(H_{\max}) = (2\,444\,982.2 \pm 4.0) + (223.826 \pm 0.040)(E - 57), \tag{5}$$

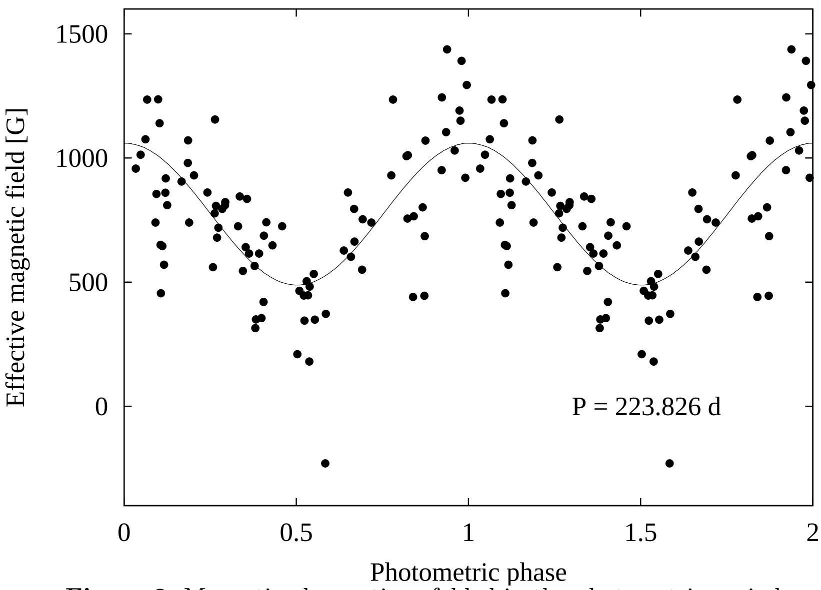

Figure 2. Magnetic observations folded in the photometric period

As follows from (3) and (5) the maximum of the magnetic field occurs only by (0.4 ± 4.1) d in date and by 0.002 ± 0.019 in phase later than the light minimum. The coincidence of the minimum light in the blue region and the maximum magnetic field is evident. The difference between Babcock's and our predictions for the center of Babcock's observations time interval is insignificant: (3.9 ± 4.5) d in date or 0.017 ± 0.020 in phase. The amplitude of variations of the longitudinal component of the magnetic induction is (575 ± 60) G and the ratio of the maximum to the minimum magnetic induction, reduced to Babcock's measurements, amounts to 0.46 ± 0.04.

2.3. Lines of rare earth elements

Babcock (1954) also pointed to significant changes in the strength of lines of Gd II, Eu II and Sr II. Comparing with the close, practically invariable Fe I 425.09 nm line, he estimated the strength of the Gd II $\lambda\,425.17$ nm line on all his Zeeman spectrograms. Displaying the strengths of the Gd II on a phase diagram, one notes a strict periodicity and a slight asymmetry of the fitting curve. Its maximum is at the phase 0.969 ± 0.012 while the minimum is at 0.405 ± 0.012 , thus preceding the minimum of effective magnetic field by 0.1. This difference has a;ready been pointed out by Babcock (1954), the asymmetry of the curve, however, Babcock did not mention.

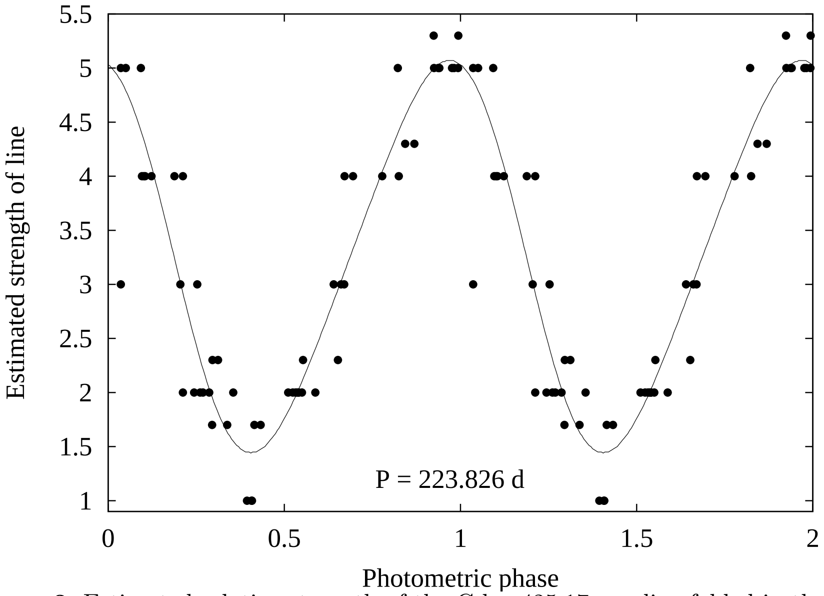

Figure 3. Estimated relative strength of the Gd II 425.17 nm line folded in the photometric period

3. Discussion

Simultaneous treatment of all the available data on the variability of HD 188041 resulted in a solution of the period close to 224 d. Data acquired at different ground-based observatories (La Silla, Mauna Kea, Shemakha, MtPalomar and Leiden Southern Center in South Africa) was properly supplemented with Hipparcos satellite data, which is not biased by seasonal observational runs, the lunar phase, etc. In particular we were able to eliminate all the periods around 1 sidereal day (namely 0.993 d), the periods aliased by the synodic month, and the sidereal year. The double value of 223.826 d indicated by photometries is reliably excluded by magnetic observations.

It can be claimed the newly found period, 223.826 d, is the rotational period of the star and the period is reliably stable with a high accuracy rate. It is also evident that the oblique rotator model is fully applicable for HD 188041. Considering the radius of this cool CP star is not greater than $2.5\,R_\odot$ we estimate the upper limit for $v \sin i = 0.6\,\mathrm{km\,s^{-1}}$. This is far less than the $40\ \mathrm{km\,s^{-1}}$ given by Abt & Morell (1995). Obviously, their estimation is in error, as Babcock (1954) presented the components of the Mg II 448.1 nm doublet were distinctly resolved. Also our assessment of $v \sin i$ from our spectra, obtained in the frame of our project *Lithium in CP stars* (Hack et al. 1997) with the 2.6 m telescope of the Crimean Astrophysical Observatory, confirm the extremely low projected rotational velocity.

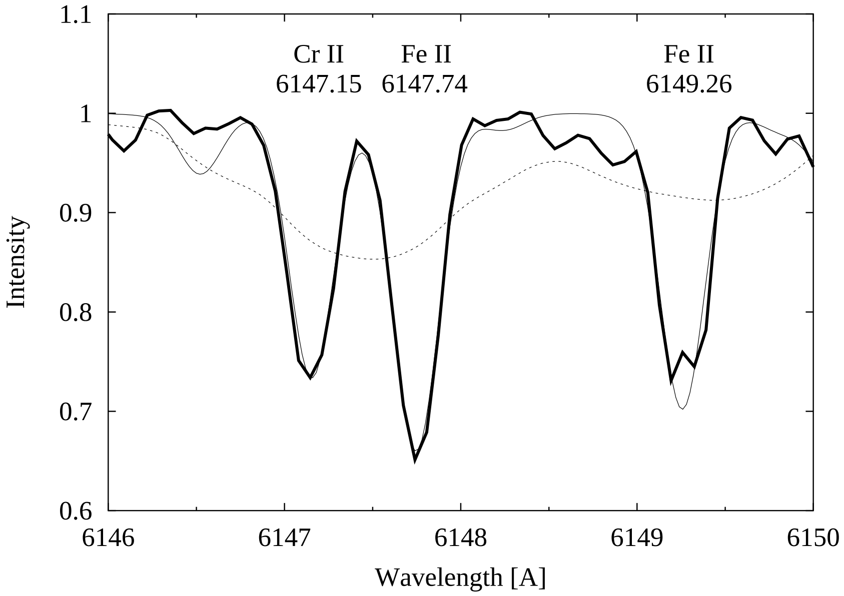

Figure 4. A section of the high-dispersion spectrum confirming the low projected rotational velocity value. Thick line – observed spectrum, thin line – computed with $v \sin i = 0.6\,\mathrm{km\,s^{-1}}$, broken line – computed with $v \sin i = 40\,\mathrm{km\,s^{-1}}$. The theoretical spectrum was computed with SYNSPEC code (Hubeny 1987, Krtička 1998) for $T_{\mathrm{eff}} = 8500\,\mathrm{K}$, $\log g = 3.5$.

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A. Appendix: The robust regression used

Solving many astrophysical problems one needs to fit a model function $F(\boldsymbol{\beta}, x)$ to measured or observed data. The most favorite is the least square method (LSM). It is supposed in the LSM, that errors of measurement comply with the normal distribution, in particular, the extreme deviations, so called *outliers*, occur rarely. Fitting by the LSM is based on minimizing of the sum of squares of deviations and so the result is extraordinarily responsive to the outliers which are more frequent in real astrophysical data. To avoid the biasing, weighted squares of deviations are summed, while the weight of each individual measurement is a product of its own (e. g. internal) weight, $w_{\rm i}$, and an appropriately chosen weighting function, $f_{\rm i}$, e. g.:

$$S(\boldsymbol{\beta}) = \sum_{i=1}^{n} [y_i - F(\boldsymbol{\beta}, x_i)]^2 w_i f_i = \sum_{i=1}^{n} \Delta y_i^2 w_i f_i, \quad \frac{\partial S(\boldsymbol{\beta})}{\partial \boldsymbol{\beta}} = 0. \tag{A1}$$

The non-negative weighting function $f_{\rm i}$ reaches its maximum for points close to the presupposed fitting curve and decreases monotonically to zero for extremely distant points. The robust fitting is performed in a few steps with the weights of individual points being iteratively changed until the solution converges to a stable one.

The weighting function acquires various shapes, we, however, accepted after long experience our own one, as follows:

$$f(\Delta y_i, s) = 1.060 \; exp \left[- \left(\frac{\Delta y_i}{2.5 \; s} \right)^4 \right], \tag{A2}$$

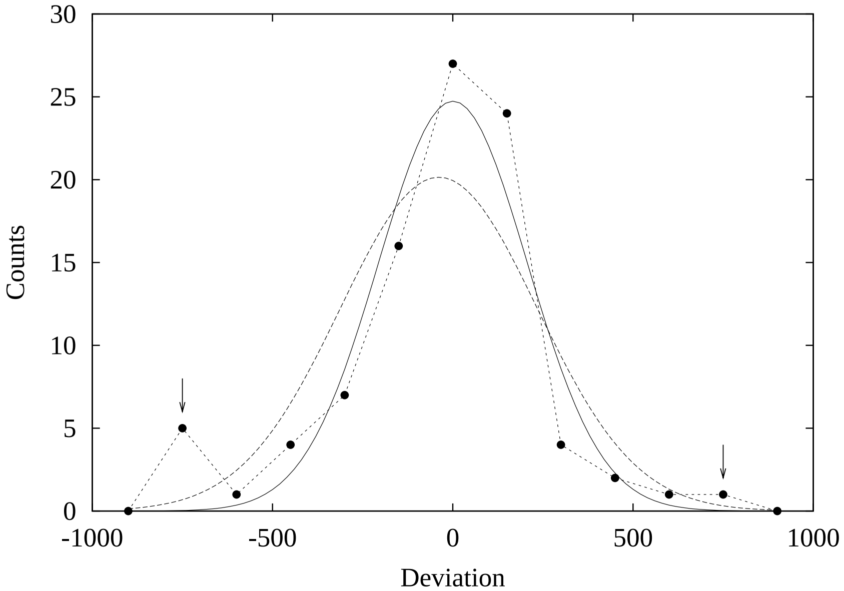

Figure 5. Comparison of the *robust* and the *standard* LSM. Full circles and dotted line – data, dashed line – standard LSM, full line – robust method. The arrows indicate the *outliers*.

where s is the weighted measure of deviation, which, in the case of normal distribution, numerically equals the standard deviation:

$$s = 1.108 \sqrt{\frac{n_r}{n_r - g} \frac{\sum_{i=1}^{n} \Delta y_i^2 w_i f_i}{\sum_{i=1}^{n} w_i f_i}}, \tag{A3}$$

where g is a degree of freedom (the lengths of the vector of $\boldsymbol{\beta}$), n_r is the estimate of the number of points purified of outliers and other points out of the normal distribution:

$$n_r = n \frac{\sum_{i=1}^{n} w_i f_i}{\sum_{i=1}^{n} w_i}. \tag{A4}$$

The iteration starts with a zero solution with the parameters of the function $F(\boldsymbol{\beta}, x)$ found by standard regression, and s set to standard deviation, or better still to a robust estimate of the measure of deviation, s_r, which depends on the occurrence of outliers only marginally,

$$s_r = 1.483 \sqrt{\frac{n}{n - g}} \text{ wmedian}(|\Delta y_i|). \tag{A5}$$

wmedian is a weighted median. As a rule, the convergence is swift and only a few iterations are needed to come to the ultimate solution.