Astron. Astrophys. 323, 881–885 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Research Note

The variations of the Bp star HD 137509*,**

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Received 12 December 1996 / Accepted 20 January 1997

Abstract. A refined value P = (4.4916 $\pm$ 0.0002) d is derived for the rotation period of the Bp star HD 137509, from the simultaneous consideration of photometric data recorded in the Geneva system and of measurements of the mean longitudinal magnetic field and of the crossover. The variations of the magnetic field (one of the most intense fields known in an Ap or Bp star) show the signature of a strong quadrupolar component. This remarkable property is reflected in the brightness and line equivalent width variations.

Key words: stars: chemically peculiar – stars: magnetic fields – stars: rotation – stars: individual: HD 137509

1. Introduction

Bidelman & MacConnell (1973) have classified HD 137509 (= CPD $-70°2069$) as a peculiar A star of the Si type. Cowley & Houk (1975) stressed the interesting character of this star, of spectral type near B9, which is rich in Si, Fe, Cr, and Ti, and deficient in He. HD 137509 is also extremely peculiar in photometry, both in the Geneva system: $\Delta(V_1 - G)$ = 0.041 (Hauck & North 1982), and according to Maitzen's peculiarity index: Δa = 0.070 (Maitzen & Vogt 1983). Pedersen (1979) found some hint of spectrum variability and suggested that the star should be included in future programmes to study this aspect more in detail. The photometric variability of HD 137509 has first been reported by Lodén & Sundman (1989) from the consideration of 10 photometric measurements in the UBV system. A first attempt to determine the rotation period was made by Mathys (1991), from 9 determinations of the mean longitudinal magnetic field $\langle H_z \rangle$ and of the crossover $v \sin i \,\langle x\, H_z \rangle$ (see Mathys 1995a for the definition of the latter). Not surprisingly, given the small number of measurements, this attempt was plagued by severe ambiguities. The latter could be resolved by considering simultaneously the magnetic data of Mathys (1991), two additional determinations of the longitudinal field of Bohlender et al. (1993), and 36 photometric measurements in the Geneva seven-colour system. This had allowed us to establish unequivocally that HD 137509 rotates with a period P = (4.4912 $\pm$ 0.0010) d (Lanz & Mathys 1991).

2. New data and period analysis

In this paper, we report about the derivation of a refined value of the rotation period of HD 137509, achieved thanks to the acquisition of new photometric and magnetic data.

20 new photometric measurements have been performed in the Geneva system. Like the data discussed by Mathys & Lanz (1991), they were obtained using the P7 photometer attached to the 0.7 m Swiss telescope located on La Silla (Chile) and reduced within the general reduction framework at the Geneva Observatory. Both the old and the new photometric measurements (56 observations in total) are presented in Table 1, which is available only in electronic form. The magnitude and colour weights (Rufener 1988) are also given in that table.

The mean longitudinal magnetic field and crossover measurements analysed by Mathys (1991) were revised to deal more adequately with the errors in the procedure of determination of those field moments (Mathys 1994; 1995a). Mathys (1995b) also diagnosed the mean quadratic magnetic field $(\langle H^2 \rangle + \langle H_z^2 \rangle)^{1/2}$, which revealed that HD 137509 has one of the strongest magnetic fields of any Ap or Bp star. Five additional determinations of the longitudinal field, of the crossover, and of the quadratic field, were recently reported by Mathys & Hubrig (1996). All these magnetic data were derived from observations performed with the ESO 3.6 m telescope, the spec-

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$\star$ Based on observations collected at the European Southern Observatory (La Silla, Chile; ESO programmes Nos. 37.7-017, 39.7-089, 41.7-061, and 49.7-029)

$\star\star$ Table 1 is available only in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

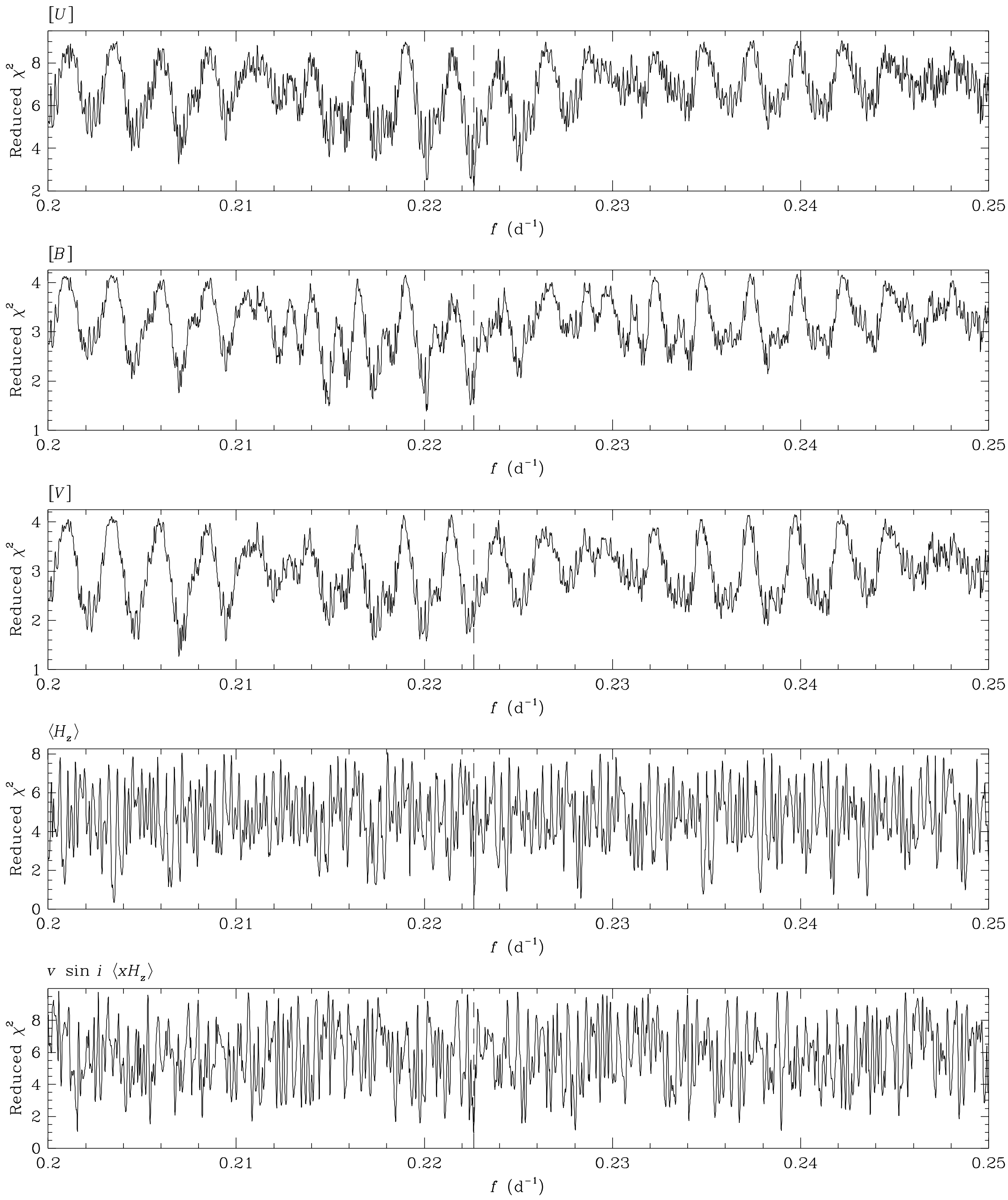

Fig. 1. Periodograms of the data obtained for HD 137509 for the Geneva colours $[U]$, $[B]$, and $[V]$, for the mean longitudinal magnetic field $\langle H_z \rangle$, and for the crossover $v \sin i \, \langle x \, H_z \rangle$ (*from top to bottom*). The ordinate is the reduced χ^2 of the fit of the corresponding observational data by a cosine wave with the frequency given in abscissa and its first harmonic. The dashed vertical line in each panel marks the position of the only frequency that simultaneously matches all observations

Table 2. Coefficients of the fits of photometric data by a cosine wave and its first harmonic

Band	$m_0 \pm \sigma$	$m_1 \pm \sigma$	$\phi_1 \pm \sigma$	$m_2 \pm \sigma$	$\phi_2 \pm \sigma$
$[U]$	6.5249 ± 0.0027	0.0294 ± 0.0037	0.207 ± 0.022	0.0197 ± 0.0039	0.854 ± 0.031
$[B]$	5.7624 ± 0.0023	0.0156 ± 0.0033	0.180 ± 0.036	0.0140 ± 0.0034	0.839 ± 0.038
$[V]$	6.8995 ± 0.0025	0.0176 ± 0.0035	0.167 ± 0.034	0.0067 ± 0.0036	0.873 ± 0.087
B_1	6.5732 ± 0.0023	0.0172 ± 0.0032	0.178 ± 0.032	0.0141 ± 0.0033	0.838 ± 0.037
B_2	7.3297 ± 0.0024	0.0158 ± 0.0033	0.206 ± 0.037	0.0141 ± 0.0035	0.847 ± 0.038
V_1	7.5995 ± 0.0026	0.0183 ± 0.0036	0.173 ± 0.034	0.0063 ± 0.0038	0.858 ± 0.094
G	8.0595 ± 0.0026	0.0200 ± 0.0037	0.169 ± 0.032	0.0087 ± 0.0038	0.867 ± 0.070

trograph CASPEC and its Zeeman analyzer. A full description of those observations is given in the cited references.

All the datasets mentioned above were taken into account in the period determination described here. For the latter, we used the same method of minimization of the residuals of the observations with respect to a least-squares fit of the variations as Manfroid & Mathys (1985). More specifically, we fitted the data by a cosine wave and its first harmonic, for a series of rotation frequencies. Periodograms were then built by plotting the reduced χ^2 of the fit against the frequency.

This approach was applied to the photometric data in each of the seven Geneva bands separately, and to the $\langle H_z \rangle$, $\langle x\, H_z \rangle$, and $(\langle H^2 \rangle + \langle H_z^2 \rangle)^{1/2}$ measurements. Only those photometric data having weights larger than or equal to 2 in both magnitude and colour were used for the period search: 36 of the 56 measurements of Table 1 met this condition. For the magnetic data, the least-squares fit were weighted by the measurement uncertainties, as explained e.g. in Mathys (1994). In the case of the longitudinal field, the 2 measurements of Bohlender et al. (1993) were also used for the period derivation.

In this way, 10 independent periodograms were obtained. Comparing them and requiring the same period to represent the variations of all the considered quantities, we could resolve the remaining aliasing ambiguities and rule out spurious period values appearing in some of the periodograms. In a first run, the periodograms were computed over the frequency range 0.1–1.0 d^{-1}, at equidistant frequencies separated by $2\,10^{-4}$ d^{-1}. This allowed us to check the absence of any plausible value of the frequency outside the interval 0.2–0.25 d^{-1}. Our next periodograms sampled this interval at frequency steps of 10^{-5} d^{-1}. The result is shown in Fig. 1 for the 3 wide colour bands $[U]$, $[B]$, and $[V]$, and for the longitudinal field and the crossover. The aliasing ambiguity and the presence of spurious peaks in the periodograms (especially for the magnetic data, due to the relatively small number of data available and to their limited accuracy) are quite apparent in the figure. However, a careful intercomparison of the periodograms (including those for the other 4 colour bands and for the quadratic field) reveals that there is only one value of the frequency which is consistent with all the observations. This value is identified in Fig. 1 by a dashed vertical line in each panel. To determine its value accurately, we repeated the period search around it, using a smaller frequency step, 10^{-6} d^{-1}. Again, all the periodograms so obtained were confronted with each other to derive the final value of the rotation frequency and to estimate its uncertainty.

As a result, we found that the rotation frequency of HD 137509 is

$$f = (0.222637 \pm 0.000010)\ \mathrm{d}^{-1},$$

corresponding to a period

$$P = (4.4916 \pm 0.0002)\ \mathrm{d}.$$

This value of the period is quite consistent with the one that we had previously derived (Lanz & Mathys 1991), within the uncertainty of the latter. The accuracy of the new determination is about 5 times better than the old one.

3. Variation curves

The photometric, magnetic, and spectroscopic variations of HD 137509 with the period derived in the previous section are illustrated in Fig. 2.

In the panels of the bottom row of this figure, the measurements of the mean longitudinal magnetic field $\langle H_z \rangle$ and of the crossover $v\ \sin i\, \langle x\, H_z \rangle$ are plotted against phase. The curves are least-squares fits to the data by a cosine wave and its first harmonic. The corresponding fit coefficients have been given in Tables 4 and 5 of Mathys & Hubrig (1996). Note that the longitudinal field measurements of Bohlender et al. (1993), although they are shown in the figure, were not taken into account to compute the best fit. The remarkable double-wave character of the variations of both $\langle H_z \rangle$ and $\langle x\, H_z \rangle$ has already been stressed by Mathys & Hubrig (1996). It indicates that the magnetic field of HD 137509 includes an unusually large quadrupolar component. Such a strong quadrupolar character of the magnetic field structure was known so far only in two other stars, HD 37776 (Thompson & Landstreet 1985) and HD 133880 (Landstreet 1990). This unusual feature strengthens even more the interest of studying HD 137509.

The quadrupolar character of the field of HD 137509 is reflected in its photometric and spectroscopic variations. Examples of the photometric variations are shown in the upper three panels of the left column of Fig. 2, where the $[U]$, $[B]$, and $[V]$ measurements are plotted against rotation phase. All the data of Table 1 appear in the figure, where open symbols are used to distinguish the points that were not used in the period search

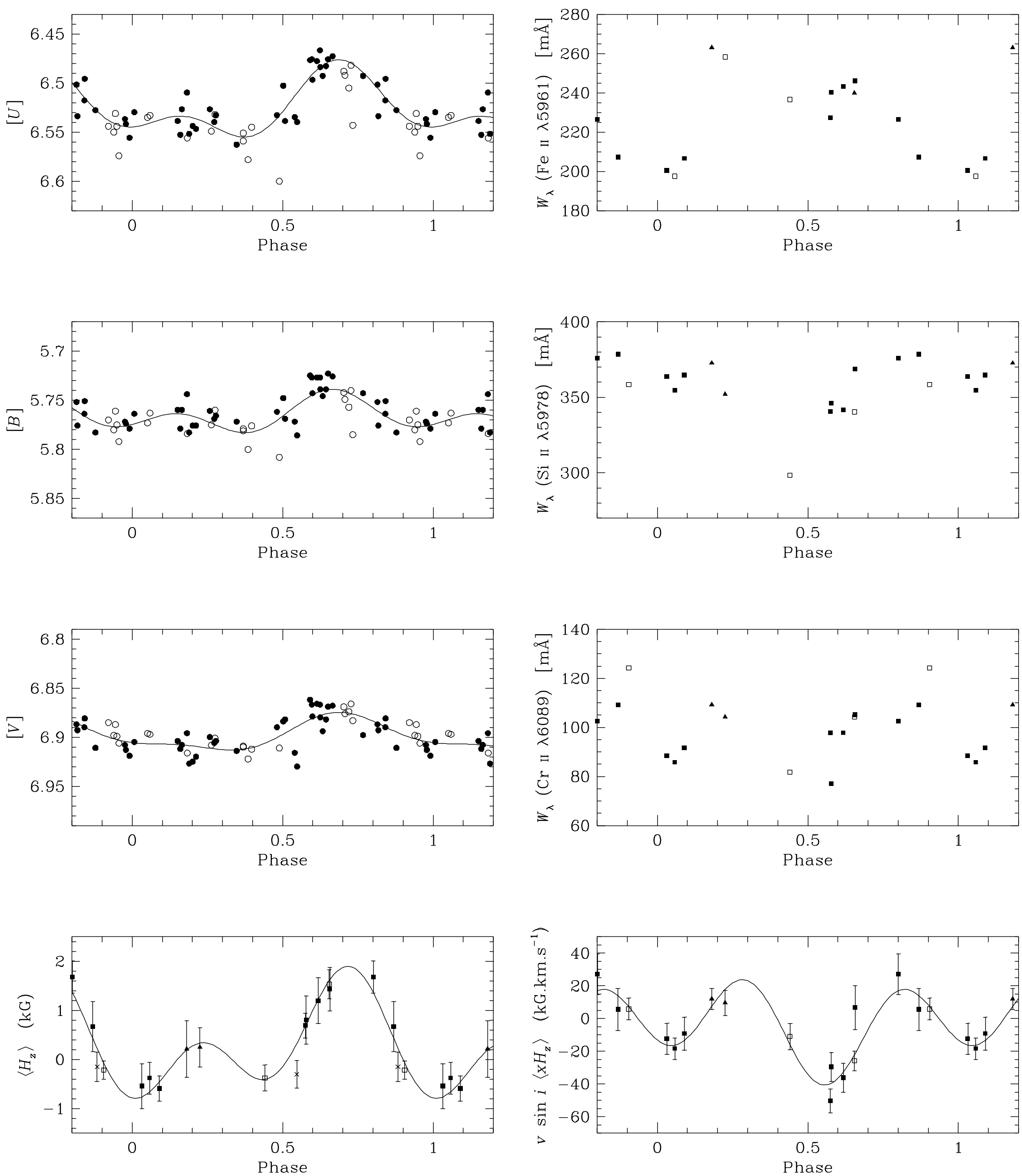

Fig. 2. Phase diagrams of the variations of HD 137509 in the Geneva photometric bands $[U]$, $[B]$, and $[V]$, of its mean longitudinal magnetic field $\langle H_z \rangle$ and of its crossover $v \sin i \, \langle x\, H_z \rangle$, and of the equivalent width of the lines Fe II $\lambda\,5961$, Si II $\lambda\,5978$, and Cr II $\lambda\,6089$. *Filled dots* represent photometric data with weights greater than or equal to 2 in both magnitude and colour; the remaining photometric measurements appear as *open circles*. The longitudinal field and crossover data are from Mathys (1994, 1995a; *filled squares*), Mathys & Hubrig (1996; *open squares* and *filled triangles* depending on the instrumental configuration used – see the cited reference for details), and Bohlender et al. (1993; *crosses*). The symbols used in the equivalent width plots distinguish different series of observations in the same way as for the magnetic field. The solid curves are least-squares fits of the photometric and magnetic data by a cosine wave and its first harmonic (see resp. Table 2 and Mathys & Hubrig 1996)

on the account of weight lower than 2 in either magnitude or colour (or both). These points were not taken into account either to compute the least-squares fits to the data that appear as solid curves in the figure. The fitting function used is of the form:

$$m(\phi) = m_0 + m_1 \cos[2\pi(\phi - \phi_1)] + m_2 \cos[2\pi(2\phi - \phi_2)]\,.$$

The fit parameters m_0, m_1, ϕ_1, m_2, and ϕ_2, and their respective standard errors, are given in Table 2 for the 7 colours of the Geneva system. One sees in Fig. 2 and in Table 2 that the variation curves are similar in all the photometric bands, with a marked double-wave character reminiscent of that of the magnetic variations. The primary brightness maximum roughly coincides in phase with the stronger positive extremum of the longitudinal field, while the secondary brightness maximum occurs close to the phase of the secondary maximum of $\langle H_z\rangle$.

Mathys (1991) had pointed out that HD 137509 also undergoes quite conspicuous spectroscopic variations, which are illustrated here in the upper three panels of the right column of Fig. 2. The panels show phase diagrams of the variations of the lines Fe II $\lambda\,5961$, Si II $\lambda\,5978$, and Cr II $\lambda\,6089$. All spectral lines of HD 137509 are strongly distorted by the combination of Zeeman and rotational Doppler effect, and are accordingly difficult to measure. Only lines that are sufficiently strong can be measured, yet with a limited accuracy. Unrecognized weaker blends may furthermore affect the derived equivalent widths. These circumstances explain the rather large scatter seen in Fig. 2 in the equivalent width plots. For the same reasons, we did not attempt to fit a mathematical function to the equivalent width data. Nonetheless, definite variability is found for Fe II and Cr II. Again the variations mirror to a large extent those of the longitudinal field, with two minima per cycle close to the phases of the negative extrema of the latter. The case of Si II is less clearcut. The evidence for the occurrence of a minimum of the equivalent width near phase 0.45, where $\langle H_z\rangle$ also reaches a negative extremum, mostly rests on a single measurement, but the difference between this and other measurements is large enough to support its significance. The figure also gives some marginal hint of a secondary minimum of the Si II line equivalent width close to the phase of the other extremum of $\langle H_z\rangle$.

In summary, we have refined the determination of the rotation period of HD 137509, using new photometric and magnetic data. The star proves very interesting, with a magnetic field which is one of the strongest known in any Ap or Bp star and whose structure includes a large quadrupolar contribution, such as observed so far in only two other stars. HD 137509 is definitely an object deserving a more detailed study. The latter should in particular aim at modelling both the magnetic field and the surface distribution of the chemical elements.

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