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The Ap spectroscopic binary HD 59435 revisited[⋆,⋆⋆]

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Abstract. HD 59435 is a double-lined spectroscopic binary, one component of which is a magnetic Ap star and the other a G8 or K0 giant (Wade et al. 1996). Both components are very slowly rotating, and the Ap star exhibits spectral lines resolved into their magneti cally-split components. Herein we report additional measurements of the mean magnetic field modulus of the Ap star, measurements of the radial velocities of both components, and Geneva photometry of the system, and discuss their impact upon conclusions drawn previously.

Key words: stars: binaries: spectroscopic – stars: chemically peculiar – stars: evolution – stars: individual: HD 59435 – stars: magnetic fields

1. Introduction

HD 59435 is one of only 3 confirmed double-lined spectroscopic binaries (SB2s) known to contain a magnetic Ap star[1] (North 1994; Wade et al. 1996). In contrast to the other 2 SB2 systems, in the spectrum of HD 59435 the lines of both components are quite sharp and are of similar strength, making HD 59435 particularly amenable to detailed study. Wade et al. (1996) investigated the orbit characteristics, the nature of the components, and the mean magnetic field modulus variation of the Ap star. They determined from spectroscopic and photometric observations that the component masses are remarkably similar ($\mathcal{M}_1/\mathcal{M}_2 = 1.075 \pm 0.04$), but that the primary (the more massive and non-Ap star) is significantly more evolved than the secondary. They concluded that the Ap star secondary is a main sequence star with spectral type A4, while the primary is a G8 or K0 giant, which has likely just descended the Red Giant Branch. They also found that the mean magnetic field modulus (also referred to as the field modulus) of the secondary varies with a remarkably large relative amplitude, and implies a rotational period of the Ap star which is at least of the order of 3 years.

In this paper we report new spectroscopic and photometric measurements of HD 59435, obtained in order to better determine the field modulus variation of the Ap star, to continue monitoring the photometric variability of the system and especially to detect a possible photometric eclipse at orbital phase 0.0.

2. Observations

2.1. Optical spectroscopy

Between 1995 December and 1998 September, 9 new spectra were recorded at the European Southern Observatory (ESO) and at the Canada-France-Hawaii Telescope (CFHT), within the framework of a study of magnetic fields in Ap stars.

One observation was obtained in 1995 December using the CFHT 3.6 metre telescope, the $f/4$ Gecko spectrograph, the 316 grooves mm^{-1} grating and Loral 3 CCD. The spectral region covered was about 45 Å, centred at about 6150 Å. The resol ving power was 1.2×10^5, and a signal-to-noise ratio (S/N) of 240:1 was obtained.

Eight observations were furthermore obtained at ESO using the 1.4 metre Coudé Auxiliary Telescope (CAT) and Coudé Echelle Spectrograph (CES). The spectral region covered was about 50 Å, centred at 6150 Å. The resolving power was 1.0×10^5, and a S/N of about 150:1 was typically obtained.

While this represents the first publication of these data, a more detailed description of their acquisition and reduction is provided by Mathys et al. (1997).

2.2. Geneva photometry

Additional photometry was obtained between 1996 December and 1998 February, especially by Mr. Marc Künzli (in 1996) and Dr. Michel Burnet with the purpose of detecting a possible eclipse at phase 0.0. The observations were made with the

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⋆ Based on observations collected at the European Southern Observatory (La Silla, Chile; ESO Programme Nos. 56.E-0688, 58.E-0159, 60.E-0565)

⋆⋆ Table 3 is available only in electronic form at the CDS via anonymous ftp 130.79.128.5

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[1] Many HgMn and Am stars belong to SB2 systems, and some may even exhibit magnetic fields. However, they are not magnetic Ap star s in the classical sense, and the two groups seem physically different.

Table 1. Radial velocities of the components of HD 59435 and field modulus $\langle H \rangle$ of the Ap component. Orbital phases are computed according to the revised orbital ephemeris described in the text. Rotational phases refer to the Ap star, and are computed according to the rotational ephemeris described in the text

HJD -2440000	Orbital phase	$V_r \pm \sigma_V$ primary (km/s)	$V_r \pm \sigma_V$ secondary (km/s)	Rotational phase	$\langle H \rangle$ (G)
10057.101	0.729	26.87 ± 0.27	53.63 ± 0.21	0.616	2327
10084.685	0.749	25.61 ± 0.61	54.71 ± 0.49	0.636	2307
10110.708	0.768	24.65 ± 0.80	55.53 ± 0.42	0.655	2333
10132.633	0.784	24.54 ± 0.87	55.98 ± 0.38	0.671	2454
10149.613	0.796	23.57 ± 0.94	56.37 ± 0.32	0.684	2585
10171.539	0.812	23.56 ± 0.70	57.15 ± 0.32	0.700	2522
10522.625	0.065	53.33 ± 0.87	29.42 ± 0.29	0.958	3989
10817.800	0.278	55.53 ± 0.35	26.99 ± 0.63	0.175	3417
11085.870	0.472	42.90 ± 0.50	40.02 ± 0.22	0.372	2320

Table 2. Orbital parameters of the binary. For each component, the second line gives the estimated standard deviations of the parameters. This is an updated version of Table 3 of Wade et al. (1996)

Star name	P (days)	$T_\circ$ (HJD -2440000)	e	$V_\circ$ ($\mathrm{km\,s^{-1}}$)	ω_1 ($^\circ$)	$K_{1,2}$ ($\mathrm{km\,s^{-1}}$)	$\mathcal{M}_{1,2}\sin^3 i$ ($\mathcal{M}_\odot$)	$a_{1,2}\sin i$ 10^6 km	N	(O−C) $\mathrm{km\,s^{-1}}$
HD 59435	1386.1	46274.0	0.285	40.40	89.4	16.86	2.809	307.95	78	0.75
	1.6	6.2	0.005	0.06	1.4	0.13	0.049	2.37		
					269.4	18.12	2.614	331.00	78	
					1.4	0.14	0.045	2.55		

double-beam "P7" photometer attached to the 0.7 metre Swiss telescope at ESO La Silla, Chile. This photometer allows the quasi-simultaneous measurement of stellar magnitudes through all seven bandpasses of the Geneva system. The 41 new measurements (for a total of 152 photometric observations in the Geneva system) were made in the all-sky mode, and are not differential.

3. Radial velocity measurements and orbital characteristics

The new spectra (reduced to the heliocentric frame) were measured in order to obtain the radial velocities (RVs) of both components of the binary. The inferred velocities were obtained from typically 4–6 position measurements of spectral lines of each of the components. The new RV measurements are reported in Table 1.

We have recomputed the orbit of HD 59435, taking into account the new RV measurements. The new orbital parameters are shown in Table 2. They are quite compatible with the previous ones and slightly more precise. In particular, the revised mass ratio of the components is effectively identical to that reported by Wade et al. (1996), and the conclusions drawn in that paper are fully supported by these results. We do note that the average RV of the Ap star is slightly larger (by about 0.8 $\mathrm{km\,s^{-1}}$) than that of the giant component, implying a slightly greater systemic velocity. The reason for this systematic difference remains unclear, although we immediately see two possible sources which may contribute. First, the gravitational redshift expected for lines of the primary is about 0.11 $\mathrm{km\,s^{-1}}$, while that expected for those of the secondary is about 0.37 $\mathrm{km\,s^{-1}}$. This should result in an increase in the inferred RV of the secondary relative to the primary of 0.26 $\mathrm{km\,s^{-1}}$. Secondly, the large difference in T_{eff} between the two components (perhaps the largest difference in the entire CORAVEL database of binaries), as well as the peculiar chemical composition of the secondary, may have resulted in a differential systematic error in the radial velocities inferred for each of the stars. This is perhaps all the more likely when we consider that the CORAVEL line template has been built on the basis of the red giant Arcturus, and so will provide a far better match to the spectrum of the primary than to that of the secondary.

4. Component characteristics

The new data are fully consistent with the component characteristics determined by Wade et al. (1996). However, Dr. P. Renson has pointed out an arithmetic error in that paper which could potentially impact those results. Wade et al. state in Sect. 4, based on the expected magnitude difference of the components in the V band (0.035 magnitudes), that the flux ratio at 6150 Å should be approximately unity. This is incorrect. Because the primary is significantly cooler than the secondary, the flux ratio at 6150 Å should in fact be larger. The correct flux ratio at this wavelength, determined using empirical energy distributions (Sviderskiene 1988), is $L_1/L_2 = 1.4$, or $\Delta m = 0.37$. This method is somewhat more accurate than using the bolometric corrections as was done in the first paper.

We have renormalised the spectrum of the primary assuming this new luminosity ratio (see Sect. 4 of Wade et al. 1996), and performed a improved synthesis (using both an updated code and a greater number of lines) of Fe I and Fe II lines in the primary's spectrum. We find a spectroscopic effective temperature for the primary $T_{eff} = 5100 \pm 200$ K, slightly hotter than that obtained by Wade et al. but fully consistent with their results.

5. Magnetic field of the Ap star

The secondary component of HD 59435 displays spectral lines resolved into their magnetically-split components. Taking advantage of this, its field modulus $\langle H \rangle$ could be repeatedly inferred by measuring the wavelength separation (by multiple gaussian fitting) of the components of the Fe II $\lambda 6149.2$ Zeeman doublet. This technique is described in detail by Mathys et al. (1997).

At some orbital phases, Fe II $\lambda 6149.2$ of the secondary was blended with lines of the primary. In order to "clean" the secondary's Fe II $\lambda 6149.2$ of the lines of the primary, a mask spectrum was constructed using spectra at unblended phases, containing all apparent lines of the primary in the region 6147.5–6149.5 Å. Then, at each blended phase, this mask was shifted to the heliocentric radial velocity of the primary and subtracted out of the blended spectrum. The field modulus was then inferred from the "cleaned" Fe II $\lambda 6149.2$ line. This technique appears to be quite robust against relative velocity uncertainties with magnitudes typical of our RV measurements (of order 0.01 Å). We do however expect that the uncertainty associated with the field modulus measurements obtained from such "cleaned" spectra is probably slightly greater than that when no "cleaning" was required (such as at orbital phases when no line of the primary is blended with the secondary's Fe II $\lambda 6149.2$). The new $\langle H \rangle$ measurements are reported in Table 1, and all measurements (including those reported by Wade et al. 1996) are plotted versus HJD in Fig. 1. An examination of Fig. 1 suggests that the period of the field modulus variation is about 1300 days.

Indeed, a period search of the $\langle H \rangle$ measurements conducted using a Lomb-Scargle algorithm (Press & Rybicki 1989) results in a single strong, significant peak at 1360^{+70}_{-40} days. This period is remarkably similar to the orbital period of the system of 1386 days, re-determined in Sect. 3. However, Wade et al. (1996) point out that even when the primary was at the tip of the Red Giant Branch it was far from filling its Roche lobe, and that the components evolved as single stars. Therefore tidal synchronisation could not have occurred in this system, and we are led to conclude that the similarity between the orbital and rotational periods is most likely coincidental.

When the $\langle H \rangle$ measurements are phased according to this period (Fig. 2), they describe a smooth variation with little scatter. A least-squares first-order Fourier series fit to these measurements (assuming uniform error bars of 75 G, a value reasonable for such measurements [Mathys et al. 1997]) results in a reduced χ^2 of 4.9, and clearly only approximately describes the variation (dashed curve in Fig. 2). On the other hand, a second-order Fourier series results in a reduced χ^2 of 2.3, and results in a much better match to the data. The $\langle H \rangle$ variation of HD 59435 therefore appears to depart from a pure sinusoid. Such behaviour is observed in a large number of stars for which the field modulus variation has been recorded (Mathys et al. 1997).

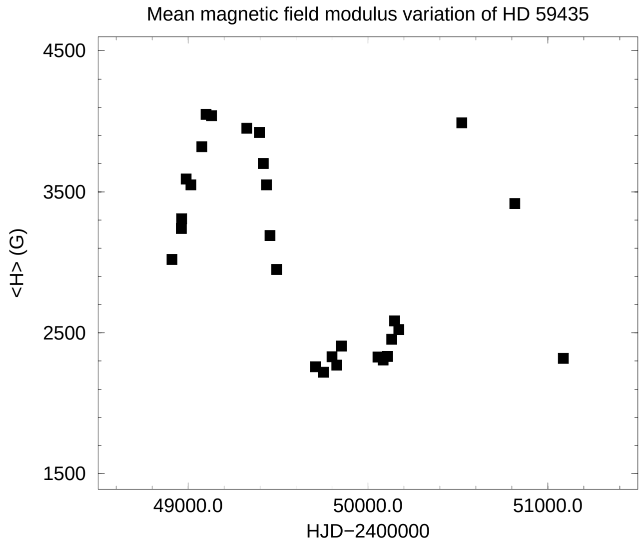

Fig. 1. Field modulus $\langle H \rangle$ variation of the Ap component of the SB2 HD 59435, shown versus Heliocentric Julian Date. This is an updated version of Fig. 5 of Wade et al. (1996)

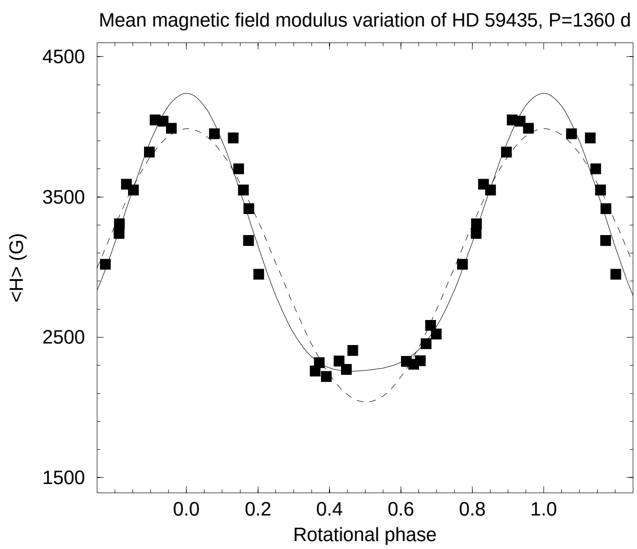

Fig. 2. Field modulus $\langle H \rangle$ variation of the Ap component of the SB2 HD 59435, phased according to the ephemeris described in Sect. 6. The dashed and solid curves are respectively least-squares first- and second-order Fourier fits to the data

6. Photometric variation

Thirty-two of our 41 new photometric observations were obtained over the course of 38 nights covering orbital phases 0.983 through 0.010. The largest gaps in the phase coverage occur at

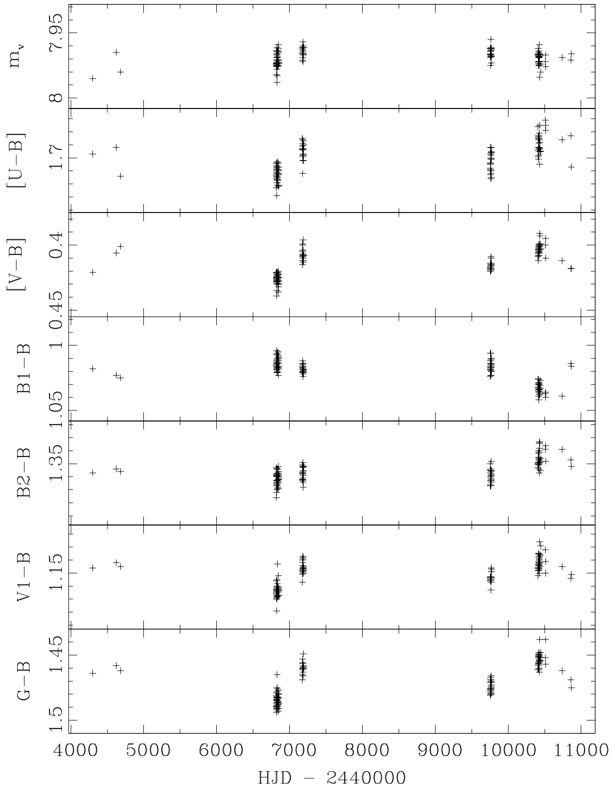

Fig. 3. Photometric variation of HD 59435 in the Geneva system. This figure is an updated version of Fig. 4 of Wade et al. (1996)

phases 0.9996–0.0025 (4 nights) and at phases 0.0039–0.0082 (6 nights). The duration of a central eclipse at phase 0.0 is expected to be about 4 days (0.003 cycles), and the total uncertainty associated with the phase of the eclipse is 7.8 days (less than 0.006 cycles). If the eclipse did not occur during one of the two phase gaps, the lack of a photometric eclipse at orbital phase 0.0 implies that the orbital inclination is not larger than $\sim 88^{\rm o}$ (see Wade et al. 1996 for a detailed discussion of the conditions required for an eclipse). On the other hand, there are significant photometric variations, not so much in the V magnitude but rather in the $[V-B]$ and $[G-B]$ indices. Such variations are typical of cool Ap stars, and would appear approximately twice as large if the Ap star was single.

The updated V magnitudes and colour indices are listed in Table 3 (only available in electronic form at the CDS) and shown versus HJD in Fig. 3.

A period search using Renson's (1978) θ_1 test finds a possible period at 1341 days in the $[B-V]$ index, very close to that found on the basis of the magnetic field variations. Another possible period shows up at 576 days, however this period is entirely inconsistent with the $\langle H\rangle$ measurements. The number of independent photometric data (i.e. rotational phases observed) remains too small to strongly constrain the period, so the magnetic data are clearly more useful in this regard. Based on these results, we adopt the following rotational ephemeris for the Ap component of HD 59435:

$$P_{rot} = 2450580 + 1360 \cdot {\rm E}, \qquad (1)$$

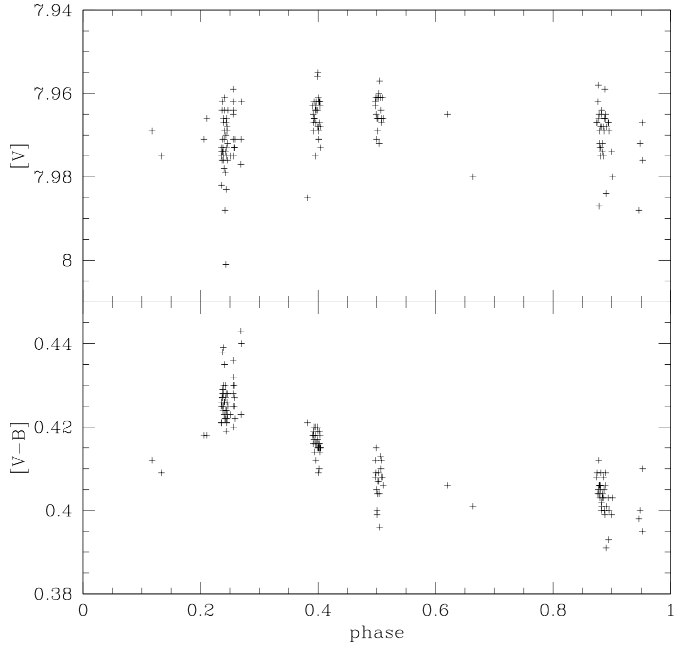

Fig. 4. $[V]$ and $[V-B]$ variation of HD 59435, phased according to the ephemeris described in Sect. 6

where the zero-point refers to the epoch of $\langle H\rangle$ maximum. The Geneva $[V]$ magnitude and $[V-B]$ colour index have been phased according to this ephemeris, and are shown in Fig. 4. No fit of a Fourier series has been attempted, owing to the relatively small number of independent data. However, the shape of the curves is quite typical of magnetic Ap stars. While the number of data is limited, we note that the apparent photometric extrema (seen most clearly in the $V-B$ index) do not seem to coincide with the magnetic extrema (which occur at phases 0.0 and 0.5). This could imply that the chemical abundance inhomogeneities of HD 59435 are not distributed symmetrically about the magnetic axis of the star. Continued monitoring is clearly required in order to more usefully compare the magnetic and photometric variations.

7. Summary and conclusions

We have obtained new spectroscopic and photometric measurements of the SB2 HD 59435, one of only 3 such systems known to contain a magnetic Ap star. The new data presented in this paper allow us to confirm and to refine significantly the results derived in an earlier study (Wade et al. 1996).

Radial velocities of both components were obtained from the high-resolution spectra, and a revised orbital solution was computed which is consistent (although slightly more precise) than that obtained by Wade et al. (1996). New measurements of the mean magnetic field modulus of the Ap star allow us to conclude that this quantity varies non-sinusoidally, with a remarkably large relative amplitude, throughout a period of 1360^{+70}_{-40} days which we interpret to be the rotational period of the Ap star. The Geneva photometric measurements show no evidence of an eclipse at orbital phase 0.0, indicating that the inclination of the system is probably smaller than $\sim 88^{\rm o}$ (Wade et al. 1996). Significant $[V - B]$ variations are however observed, and are probably due to rotational modulation by surface structure on the Ap star. The photometric variations are consistent with the magnetic field period, and display a roughly sinusoidal variation when phased accordingly. While such a conclusion should be considered tentative due to the limited photometric data, the photometric extrema do not appear to coincide with the magnetic extrema.

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