Discovery of starspots on Vega *

First spectroscopic detection of surface structures on a normal A-type star.

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ABSTRACT

Context. The theoretically studied impact of rapid rotation on stellar evolution needs to be confronted with the results of high resolution spectroscopy-velocimetry observations. Early type stars present a perfect laboratory for these studies. The prototype A0 star Vega has been extensively monitored in the last years in spectropolarimetry. A weak surface magnetic field has been detected, potentially leading to a (yet undetected) structured surface.

Aims. The goal of this article is to present a thorough analysis of the line profile variations and associated estimators in the early-type standard star Vega (A0) in order reveal potential activity tracers, exoplanet companions and stellar oscillations.

Methods. Vega was monitored in high-resolution spectroscopy with the velocimeter Sophie/OHP. A total of 2588 high S/N spectra was obtained during 5 nights (August 2012) at R = 75000 and covering the visible domain. For each reduced spectrum, Least Square Deconvolved (LSD) equivalent photospheric profiles were calculated with a $T_{eq} = 9500$ and log $g = 4.0$ spectral line mask. Several methods were applied to study the dynamic behavior of the profile variations (evolution of radial velocity, bisectors, vsin, 2D profiles, amongst others).

Results. We present the discovery of a starspotted stellar surface in an A-type standard star with faint spot amplitudes $\Delta F/F_c \sim 5 \times 10^{-4}$. A rotational modulation of spectral lines with a period of rotation $P = 0.68$ d has clearly been exhibited, confirming the results of previous spectropolarimetric studies. Either a very thin convective layer can be responsible for magnetic field generation at small amplitudes, or a new mechanism has to be invoked in order to explain the existence of activity tracing starspots.

Conclusions. This first strong evidence that standard A-type stars can show surface structures opens a new field of research and asks the question about a potential link with the recently discovered weak magnetic field discoveries in this category of stars.

Key words. stars: starspots — stars: early-type – stars: rotation – stars: oscillations – stars: individual: Vega – asteroseismology

1. Introduction

The role rapid rotation plays on the stellar interior and its evolution represents a very challenging research topic as of today. Rapidly rotating stars reveal many unanswered questions in the domain of observations, theory and modeling. The only known way to study stellar interiors is through asteroseismology and its associated observational techniques, which are either based on photometry or high-resolution spectroscopy. In addition, the detection and observation of activity tracing structured stellar surfaces can also contribute significant constraints on stellar evolution models.

The recent detection of a very weak magnetic field in Vega was reported in Lignières et al. (2009). The $-0.6 \pm 0.3$ G the disk-averaged line-of-sight component of the surface magnetic field can reach peak values of 7 G (Petit et al. 2014). Lignières et al. (2009) and later Petit et al. (2010) concluded on the fact that a previously unknown type of magnetic stars exist in the intermediate-mass domain, and that Vega may well be the first confirmed member of a much larger, as yet unexplored, class of weakly-magnetic stars. The Zeeman-Doppler imaging of the magnetic field topology (Petit et al. 2010, 2014) showed that apart from a prominent polar magnetic region a few other magnetic spots are reconstructed at lower latitude. Petit et al. (2010) conclude that an important help for distinguishing between a potential fossil or dynamo origin of the magnetic field would be to investigate the long-term stability of the observed field geometry, as a dynamo-generated field is likely to show some temporal variability. Detecting surface structures in unpolarized light would largely contribute to a better understanding of the origin of magnetic fields in these stars, and the role the rotation could play.

Large scale surveys of A-type stars with the Kepler satellite revealed low frequency periodic variations in 28% of the sample interpreted as linked to the stellar rotation frequency and associated rotational modulation (Balona 2011). The author sug-
gests that the light variations in A-type stars may possibly be due to starspots or other corotating structures and that A-star atmospheres may not be quiescent as previously supposed. In a more recent article on Kepler data, Balona (2013) reports that in 875 A-type stars (40%), photometric indications for the period of rotation are detected. From the amplitude distribution he concludes that the sizes of starspots in A-type stars are similar to the largest sunspots. He concludes that A-type stars are active and, like cooler stars, have starspots and flares. Providing direct detection of starspotted surfaces in A-type stars is therefore a necessary next step in order to ascertain this thesis.

The A0 photometric standard star Vega is a rapid rotator. Vega is seen pole-on with an inclination angle of $i=5-7^\circ$, a result ascertained by photometric (Gray 1983), spectroscopic (Gulliver et al. 1994) and interferometric (Aufrébourg et al. 2006; Peterson et al. 2006; Monnier et al. 2012) observations. While spectroscopic analysis and modeling by Takeda et al. (2008) and Hill et al. (2010) slightly differ in equatorial velocities ($\approx 175$ km s$^{-1}$ versus $211\pm 4$ km s$^{-1}$, respectively), first interferometric studies by Peterson et al. (2006) and Aufrébourg et al. (2006) conclude on a much higher equatorial velocity of $\approx 275$ km s$^{-1}$.

Petit et al. (2010) announced that the short-term evolution of polarized signatures in Vega is consistent with a rotational period of $0.732 \pm 0.008$ d, the error bar being underestimated (private com.). Alina et al. (2012) worked on the NARVAL/TBL 2010 data set (Alina et al. 2012; Bohm et al. 2012) and detected a period of $0.678 \pm 0.002$ d. Budkowska (2013) analyzed the results of 1312 longitudinal magnetic field measurements obtained during 15 years of observations performed at the Crimean Astrophysical Observatory and proposed that the magnetic field variations are caused by stellar rotation; their derived stellar rotation period corresponds to 0.6225503 days. Both determined periods are significantly longer than values expected from earlier interferometry-based models, but compatible with the results of spectroscopic modeling of gravity darkened photospheric lines in Vega (Takeda et al. 2008). Based on new interferometric CHARA/MIRC observations, Monnier et al. (2012) concluded that a more slowly rotating model was compatible with the new interferometric data, thereby reconciling these new results with those determined by spectroscopy.

As reviewed by Gray (2007), Vega was used since more than 150 years as a photometric and spectrophotometric standard. Still, very low photometric variability was occasionally reported at the 1-2% level. Hill et al. (2010) report low level variations of Ti II 4529 AA profiles on the time basis of several years. First evidence of pulsations in Vega was suspected in three data sets (3 nights NARVAL/TBL 2008 - 3 nights ESPADONS/CFHT 2009 - 5 nights TBL 2010) corresponding to a total of 4478 quasi-continuous high-resolution ($R > 65000$) echelle spectra (Bohm et al. 2012). Least square deconvolved (LSD) profiles (Donati et al. 1997) were obtained for each spectrum representing the photospheric absorption profile potentially deformed by the presence of pulsations, and telluric lines were used as a velocity reference. All three data sets revealed the presence of residual periodic variations with the following frequencies and amplitudes: 5.32 and 9.19 d$^{-1}$ (A $\approx$ 6 ms$^{-1}$) in 2008, 12.71 and 13.25 d$^{-1}$ (A $\approx$ 8 ms$^{-1}$) in 2009 and 5.42 and 10.82 d$^{-1}$ (A $\approx$ 3-4 ms$^{-1}$) in 2010. However, due to a lack of intrinsic stability of the employed spectropolarimeters it was too early to conclude that the variations were due to stellar pulsations, and it was concluded that their confirmation with a highly stable spectrograph was the necessary next step. The results of a 5 night survey with the highly stabilized spectrograph SOPHIE/OHP is presented in this article.
Table 1. Log of the spectroscopic observations of Vega. (1) Date of the observation (UT). (2) and (3) Barycentric Julian date (mean observation, 2,450,000 + \Delta\text{BJD}) of the first and the last stellar spectrum of the night, respectively; (4) Number of high resolution Vega spectra obtained; (5) exposure time (sec); (6) total hours covered on the sky; (7) nightly average and standard deviation of signal to noise ratio per resolved element at 520 nm.

| Date   | BJD<sub>first</sub> | BJD<sub>last</sub> | N<sub>spec</sub> | \(t_{\text{exp}}\) (sec) | \(t_{\text{cov}}\) (hrs) | S/N   |
|--------|---------------------|-------------------|---------------|-----------------|-----------------|------|
| Aug. 2 2012 | 6142.3308 | 6142.6238 | 425 | 17-30 | 7.0 | 884\pm202 |
| Aug. 3 2012 | 6143.3528 | 6143.6436 | 629 | 10-15 | 7.0 | 925\pm145 |
| Aug. 4 2012 | 6144.3412 | 6144.6423 | 628 | 10-17 | 7.2 | 850\pm121 |
| Aug. 5 2012 | 6145.3788 | 6145.6442 | 402 | 13-17 | 6.4 | 766\pm103 |
| Aug. 6 2012 | 6146.3444 | 6146.6423 | 504 | 17-25 | 7.1 | 808\pm115 |

In a next step, we worked on the line profile variations themselves (as a function of velocity). Vspan was calculated for each profile, measuring the difference of the upper and lower part of the bisector (a kind of skewness); for this, we worked in relative profile height, the bottom of the profile set at 0., the continuum at 1. Vspan was calculated as the difference of the medians of upper [0.35, 0.5] and lower [0.1, 0.25] bisector ranges. Ranges were defined checking out different combinations in order to produce the most clear periodograms. Optimal ranges are lying rather low in the profile, which can be understood having in mind the nearly pole-on position of the star, since equatorial contributions are barely seen (those which cross the full line profile from \(-v\sin i\) to \(+v\sin i\)).

Fig. 1 shows the corresponding mean rescaled LSD profile. The variation of vspan with time is shown in Figs. 2 and 3, the latter one showing the low frequency variations.

Radial velocity (RV) can be determined in several ways: cross-correlation with an average profile, fitting of gaussians or rotationally broadened profiles, first moment determination and median determination of the lower part of the line bisector, amongst others. Having computed the different methods on our data set, we present in this study the radial velocities determined by i) the first moment of the profile and ii) the median of the lower part of the line bisector range [0.15, 0.3], the bottom of the line being particularly sensitive to potential spot signatures crossing the line profile. As can be seen in Tables 3 and 4, for a given frequency, the amplitude of the radial velocity variation strongly varies between the two estimators (first moment, bisector). This fact is not really surprising taking into account that both determinations are significantly different, and that a 10 m s\(^{-1}\) value corresponds to only 2 \times 10^{-3} of the overall width of the profile (\(\approx 2 \, v\sin i\), i.e. 44 km s\(^{-1}\)).

In a next step, we worked on the line profile variations themselves (as a function of velocity). The very small variations we discovered never exceeded 10^{-3} of the continuum. In traditional spectroscopic data sets such small variations are in generally not seen, mostly due to insufficiently precise data reduction or continuum normalization, amongst other issues. At these tiny levels of variation a particular care has to be taken in order to avoid misinterpretation due to residual instrumental effects (see e.g. Sect. 3.2).

3. Results and discussion

3.1. Periodicity analysis of vspan and radial velocity

We started the search for periodicities in our line profile estimators by analyzing the vspan data, which are insensitive to radial velocity calibration data (since they measure profile asymmetries to some extent, and no shifts). This asymmetry measurement reveals to be robust and provides similar frequency values, independently of the precise depth boundaries chosen.

The Lomb Scargle periodogram of vspan is shown in Fig. 4. In a recent paper, [Alina et al. (2012)] had determined for Vega a \(P_{\text{rot}} = 0.678 \pm 0.036\) d based on spectropolarimetric observations. We overplotted in grey bars at 0.3 height the corresponding rotational frequency of 1.47 d\(^{-1}\), as well as its harmonics (multiple of this frequency), the width of the bars corresponding to the reported error bars. The lower bars at 0.15 and 0.02 height indi-
Fig. 3. Low frequency vspec variations of Vega (SOPHIE/OHP) 2012. Superimposed (continuous line) is the result of the corresponding frequency analysis as listed in Tables. Time is expressed in BJD = 2450000 + ΔBJD. The period of rotation can clearly be seen in this figure.

Fig. 4. Lomb Scargle periodogram of vspec, including the window function of the data set. The grey bars at 0.3 height indicate the rotational frequency of the star as determined by Alina et al. (2012), i.e. 1.47 d$^{-1}$, as well as its harmonics (multiple of this frequency), its width corresponds to the error bar. The lower bars at 0.15 and 0.02 height indicate the position of the ±1 and 2 day aliases with respect to the rotational frequency comb, respectively. The thin vertical black line indicates the same kind of frequency grid for a frequency of 1.77 d$^{-1}$ (see Sect. 3.3).

An important result is the fact that many detected periodicities in the range 0 - 15 d$^{-1}$ correspond to the stellar rotation frequency (and its harmonics and aliases), and are in perfect agreement with the rotation period as published by Alina et al. (2012). This provided us with a first evidence that surface structures should cross the photospheric equivalent line profile, leading to a rotational modulation of the vspec parameter.

Table 2 present the corresponding periodicity analysis of this vspec time series based on the SigSpec tool (Reegen 2007). SigSpec calculates the spectral significance of an amplitude $A$ by:

$$\text{sig}(A) = -\log[\Phi_{FA}(A)],$$

where $\Phi_{FA}$ indicates the false alarm probability. The sig threshold for the determination of the prewhitening sequence was equal to 4, which indicates that the considered amplitude level is due to noise in less than one out of $10^4$ cases. Kurtz & Müller (1999) estimate the uncertainty in the frequency to be approximately $1/(4\Delta T)$, where $\Delta T$ is the time span of the data set. In our case this would yield an uncertainty of 0.05 d$^{-1}$. The last column of the table proposes some identification with the rotation comb (the star’s rotation frequency $F_{rot}$, its harmonics, and ±1d window function aliases only). For each frequency combination we assumed that we correctly identified them, and calculated the distance to the expected position. The
average distance is only 0.043 d\(^{-1}\) and tends therefore to confirm our identification.

| ID   | freq. d\(^{-1}\) | A m s\(^{-1}\) | Comment |
|------|-----------------|--------------|---------|
| F1   | 1.457           | 69.32        | \(F_{\text{rot}}\) |
| F2   | 2.02            | 22.93        | 2 \(F_{\text{rot}}\) - 1. |
| F3   | 0.40            | 47.52        | |
| F4   | 8.34            | 13.30        | 5 \(F_{\text{rot}}\) + 1. |
| F5   | 11.31           | 14.17        | 7 \(F_{\text{rot}}\) + 1. |
| F6   | 5.78            | 14.09        | 4 \(F_{\text{rot}}\) |
| F7   | 8.04            | 12.59        | |
| F8   | 16.21           | 8.23         | 11 \(F_{\text{rot}}\) |
| F9   | 5.43            | 9.05         | 3 \(F_{\text{rot}}\) + 1 |
| F10  | 10.70           | 8.92         | 9 \(F_{\text{rot}}\) |

A possible coincidence, but nevertheless striking, is the fact that in the vspan periodogram not all harmonics are equally seen. \(F_{\text{rot}}\), 2 \(F_{\text{rot}}\), 3 \(F_{\text{rot}}\), 5 \(F_{\text{rot}}\) and 7 \(F_{\text{rot}}\) are seen, while 4 \(F_{\text{rot}}\), 6 \(F_{\text{rot}}\) and 8 \(F_{\text{rot}}\) are absent. If vspan represents a cleaned radial velocity measurement, concentrating only on the activity within the line and not on its global shift, a simple simulation as shown in Fig. [5] can provide some explanation. Adopting the inclination of Vega’s rotation axis with respect to the line of sight \((i = 7^{\circ})\), i.e. an star seen almost pole-on, we simulated using the basic trigonometric equations the impact of a spot on the radial velocity, depending on its latitude. We normalized radial velocity and power in the Lomb Scargle periodogram for the spot at +60°, and omitted any consideration on limb and gravitational darkening, true spot contrast and extension. The model is purely trigonometric but shows nicely that spots located close to the pole are seen permanently and provide an almost purely sinusoidal variation, yielding a single peak in the periodogram. Once the spot is at significantly lower latitudes a first harmonic appears. A spot location exactly at the equator will yield, due to the absence of spot structure during half the rotation period, the canceling of the 4 \(F_{\text{rot}}\), 6 \(F_{\text{rot}}\), 8 \(F_{\text{rot}}\) harmonics. Does this provide an indication on the location of potential surface spots close to the equator? At even lower latitudes the spot is only seen for a very short time during the rotation period, yielding therefore all harmonics without canceling of any harmonics.

In a next step, we performed a frequency analysis of the variation of the two different radial velocity estimators. Fig. [7] shows the result of a Lomb Scargle periodicity analysis of the variation of both radial velocity estimators with time. The corresponding frequencies are listed in Tables [3] and [4].

As can be seen in Fig. [5] vspan is slightly anticorrelated to the radial velocity (first moment), which reinforces the idea of a starspotted surface (see Boisse et al. [2011]). During our analysis of the data set we did computations with different line masks, and some masks yielded a much more obvious anticorrelation. Since we concentrate on one specific line mask in this article we prefer showing the corresponding figure.

The rotation period is again well represented in both data sets (F1b, F4c), and many harmonics and respective aliases of the window function are present. Amplitudes are different, which is due to different estimators. In the frequency analysis of the radial velocity (first moment) SigSpec extracts as highest amplitude frequency 0.77 d\(^{-1}\). We concluded however that SigSpec selected the -1d alias of F1c, which should be F1c = 1.77 d\(^{-1}\) (and probably F2b = 1.89 d\(^{-1}\), despite the rather large difference in frequency). We compared two complete frequency grids (fundamental frequency at 0.77 d\(^{-1}\) or 1.77 cd, plus harmonics and window function aliases) with the observed periodogram and concluded based on the frequency distribution that the true frequency must be F1c = 1.77 d\(^{-1}\), the grid for 0.77 is much narrower and provides a significantly less good fit. The discussion of a potential origin of this frequency, which is not detected in vspan, is discussed in section 3.3.

| ID   | freq. d\(^{-1}\) | A m s\(^{-1}\) | Comment |
|------|-----------------|--------------|---------|
| F1b  | 1.44            | 20.20        | \(F_{\text{rot}}\) |
| F2b -1 | 0.89         | 22.79        | \(F_{\text{rot}}\) |
| F3b  | 9.34            | 13.91        | 7 \(F_{\text{rot}}\) - 1? \(F_{2008}\) ? |
| F3b  | 13.32           | 9.52         | \(F_{2009}\) |
| F5b  | 4.15            | 9.08         | |
| F6b  | 5.71            | 11.46        | |
| F7b  | 10.69           | 8.74         | 8 \(F_{\text{rot}}\) - ? \(F_{2009}\) - 2 ? \(F_{2010}\) ? |
| F8b  | 24.49           | 5.57         | 16 \(F_{\text{rot}}\) + 1 ? |
| F9b  | 9.94            | 6.17         | |

Fig. 8. Anticorrelation of vspan versus vrad (first moment).

Table 4. Frequencies and amplitudes of vrad (first moment) variations measured on the LSD-profiles (median value of lower part 0.15-0.3).

| ID   | freq. d\(^{-1}\) | A m s\(^{-1}\) | Comment |
|------|-----------------|--------------|---------|
| F1c -1 | 0.77           | 6.16         | \(F_{\text{rot}}\) |
| F2c  | 3.34            | 4.32         | 3 \(F_{\text{rot}}\) - 1? \(F_{2008}\) + 2? \(F_{2010}\) - 2 ? |
| F3c  | 4.97            | 3.78         | 4 \(F_{\text{rot}}\) - 1 ? |
| F4c  | 1.48            | 4.01         | \(F_{\text{rot}}\) |
| F5c  | 24.47           | 2.17         | 16 \(F_{\text{rot}}\) + 1 |
| F6c  | 14.24           | 2.42         | \(F_{2009}\) + 1 ? |
| F7c  | 8.29            | 2.12         | 5 \(F_{\text{rot}}\) + 1 ? |
| F8c  | 5.53            | 2.30         | |
| F9c  | 11.78           | 2.61         | \(F_{2009}\) - 1 ? \(F_{2010}\) + 1 ? |
| F10c | 14.67           | 2.68         | 10 \(F_{\text{rot}}\) |

Table 3. Frequencies and amplitudes of vrad (bisector) variations measured on the LSD-profiles (median value of lower part 0.15-0.3).

Fig. 8. Anticorrelation of vspan versus vrad (first moment).
3.2. Spot-like trails in dynamic spectra

We propose to investigate further the nature of photospheric features responsible for the 0.678 d variability showing up in the time-series of radial velocities and velocity spans, and gather further evidence of the rotational origin of this periodical signal.

Fig. 5 shows a D-shaped bisector, typical for early type stars. As can be seen in this figure, enhanced "bisector activity" (as indicated by the spread in the left part of the figure, but also on the standard deviation as represented on the right side) of the bisector variations is seen around the bottom of the profile, but also near continuum. The variability of the bisector in the lower part is easily understood if surface structures cross the projected stellar disk during rotation. An easy explanation for the upper variations can not be provided at this stage. Very tiny LSD profile variations were seen in a thorough inspection.

To highlight the tiny spectral features responsible for the periodic signal, we first cleaned up the data set by getting rid of LSD equivalent photospheric profiles affected by the lowest S/N, therefore discarding about 1.4% of all available data (files with less than 95% of the mean S/N were rejected). As a next step, we corrected the LSD profiles from changes of their EW (equivalent width), observed as a systematic increase of the EW during each observing night. The daily repeatability of this effect suggests an effect linked to the airmass of observations (Fig. 11). It should be noted that the periodogram of the equivalent width variations (Fig. 12) does not match any of the other periodograms (except
Fig. 6. Radial velocity variations of Vega (SOPHIE/OHP) 2012 measured by the median of a lower bisector range (top) and first moment (bottom). Superimposed (continuous line) is the result of the corresponding frequency analysis as listed in Tables 3 and 4, respectively. Time is expressed in $\text{BJD} = 2450000 + \Delta \text{BJD}$. Both RV determinations follow the same trend without being identical.

Fig. 7. Lomb Scargle periodogram of the radial velocity evolution during the run, measured by (i) the lower part of the bisector (top) or (ii) the first moment of the profile (bottom). Definition of vertical bars and lines are identical to Fig. 4.
Fig. 10. Residuals after nightly shift correction and subtraction of average profile are plotted as a function of velocity and time modulo period, where the period is fixed at the formally estimated value of $P = 0.678 \text{ d}$. The coherent structures along the diagonals in this plot are evidence of activity zones (in emission or absorption) moving together with stellar rotation and crossing therefore the line profile. The good matching of starspot features across several nights is a strong indicator for a structured surface on Vega.

The resulting line residuals are plotted in Fig. 10, after attributing a phase to each observation according to the 0.678 d period, and choosing $\text{BJD} = 2456142.3308$ (first stellar spectrum of the run) as the phase reference. The dynamic spectra display a number of bright and dark trail-like features first showing up in the blue wing of the line profile, and progressively shifting towards the red wing, in excellent agreement with the typical spectral signature of brightness inhomogeneities carried across the visible stellar hemisphere during stellar rotation, as routinely observed in active solar-type stars (Collier Cameron et al. 2002). The amplitude of these subtle bumps and dips is of the order of $5 \times 10^{-4} - 10^{-3}$ of the continuum level. The typical width of each individual feature on the 2D phase plots of Fig. 10 corresponds to an angular size of the order of $20^\circ$, or a linear scale of roughly $0.3 \, \text{R}_\text{Vega}$ projected on the stellar surface. Spot sizes are resolved by the spectrograph (the resolved element being close to $4 \, \text{km s}^{-1}$), i.e. the observed surface plages have a large spatial extension, even larger in this case then concluded by Balona (2013) on a statistical sample of A-type stars. In a forthcoming work, Doppler imaging techniques will be applied and are expected to yield more constraining limits on spot sizes.

The main trails are repeatedly observed during different observing nights, demonstrating that they do follow the 0.678 d period and possess a lifetime of a few days at least. Note that a residual of EW variations is still visible in the dynamic spec-

Fig. 11. Nightly relative equivalent width variations of the LSD profiles of this run. Time is expressed in $\text{BJD} = 2450000 + \Delta \text{BJD}$. 

As this smooth evolution is observed to correlate with the S/N of LSD profiles, we can remove most of the systematic trend through the assumption that the equivalent width is a polynomial function of the S/N (each night being processed separately). We finally compute an averaged LSD profile for all the run, that we subtract from each LSD profile, to highlight fluctuations in the pseudo-line profiles.

The resulting line residuals are plotted in Fig. 10 after attributing a phase to each observation according to the 0.678 d period, and choosing $\text{BJD} = 2456142.3308$ (first stellar spectrum of the run) as the phase reference. The dynamic spectra display a number of bright and dark trail-like features first showing up in the blue wing of the line profile, and progressively shifting towards the red wing, in excellent agreement with the typical spectral signature of brightness inhomogeneities carried across the visible stellar hemisphere during stellar rotation, as routinely observed in active solar-type stars (Collier Cameron et al. 2002). The amplitude of these subtle bumps and dips is of the order of $5 \times 10^{-4} - 10^{-3}$ of the continuum level. The typical width of each individual feature on the 2D phase plots of Fig. 10 corresponds to an angular size of the order of $20^\circ$, or a linear scale of roughly $0.3 \, \text{R}_\text{Vega}$ projected on the stellar surface. Spot sizes are resolved by the spectrograph (the resolved element being close to $4 \, \text{km s}^{-1}$), i.e. the observed surface plages have a large spatial extension, even larger in this case then concluded by Balona (2013) on a statistical sample of A-type stars. In a forthcoming work, Doppler imaging techniques will be applied and are expected to yield more constraining limits on spot sizes.

The main trails are repeatedly observed during different observing nights, demonstrating that they do follow the 0.678 d period and possess a lifetime of a few days at least. Note that a residual of EW variations is still visible in the dynamic spec-
Fig. 9. The distribution of bisectors in the total dataset is represented in the left figure. The red lines enclose 95% credibility intervals for each depth. The right figure shows the standard deviation of the bisector variations as a function of renormalized profile depth. Note the enhanced activity of the bisector variations around the bottom of the profile, but also near the continuum.

Fig. 12. Lomb Scargle periodogram of the equivalent width variation during the run. Definition of vertical bars and lines are identical to Fig. 9.

If the trail amplitude is barely above noise level in the blue-red transit, the associated red-blue transit (visible in principle for spots that are not eclipsed during stellar rotation thanks to their high latitude) are even fainter, owing to the less favorable projection factor and limb darkening during the return transit. Still, a close look to the left and middle panel of Fig. 10 reveals clearly back-traveling spot signatures.

In addition, a close inspection of individual trails further shows that the trail inclination in the dynamic spectrum is not identical for all spot-like features. As an illustration, the bright trail crossing each night the line center at phase ≈0.2 looks steeper than the other bright trail crossing line center at phase ≈0.05. The most natural interpretation of the different trail inclinations is a difference in the stellar latitude of brightness features.

Fig. 13. Optimal coherence is searched for a time remapping of the data set presented in Fig. 10 around the pre-estimated rotational period. Optimality is based on the spread of the cloud in three dimensions (binned data in time modulo Prot, intensity, velocity). It can be seen that Prot = 0.678 d corresponds to the best matching period. To assess significance we used the same data set with randomly permuted time data set (green dots).

The earlier data sets from 2008, 2009 and 2010 (Böhm et al. 2012) were acquired with poorly stabilized spectrographs, and data reduction could only to some extend correct for these errors. Low frequency information was therefore totally lost, which is the reason why we did not directly detect the frequency of stellar rotation in their radial velocity data. Encouraged by our current results, we will try to present, in a forthcoming work, the results of a direct search for rotationally modulated LSD profiles in these data sets, a similar approach as presented in this section.

3.3. Stellar oscillations and a potential exoplanet signature?

In Böhm et al. (2012) we announced the presence of higher frequencies in the radial velocity periodograms of Vega, and suggested the possible detection of corresponding stellar oscillations. We only detected higher frequencies 5.32 and 9.19 d⁻¹ (A ≈ 6m s⁻¹) in 2008, 12.71 and 13.25 d⁻¹ (A ≈ 8m s⁻¹) in 2009 and 5.42 and 10.82 d⁻¹ (A ≈ 3-4m s⁻¹) in 2010. As mentioned in the last section, these data sets were acquired with instruments not optimized in the sense of radial velocity stabilization, making
any low frequency detection, such as stellar rotation, impossible.

As can be seen in tables 3 and 4 corresponding to our 2012 run, some energy in the periodograms is located in the higher frequency domain. Possible identifications with frequencies found in the former data sets are indicated. Still, the dense frequency spacing of the rotational harmonic comb and its different window function aliases, together with propagated error bars, do almost always allow to find a possible identification with rotationally linked frequencies. This tells us that rotation might be in all data sets responsible for the observed higher frequencies too. However, it still does not exclude the presence of oscillations in all these data sets, it just prohibits any conclusion at this stage.

The most striking difference between the periodicity analysis of vspan and the two different radial velocity determinations is the fact that the strong frequency at 1.77 d⁻¹ (or 1.89 d⁻¹) only appears in the latter ones. (See Fig. 14). Vspan measures an asymmetry within the profile and is totally insensitive to global radial velocity shifts. Should we therefore understand F1c = 1.77 d⁻¹ (or F2b) as the signature of a global, i.e. dynamical shift of the line profile? The presence of an exoplanet could be one possible source of such bulk RV variations. Activity induced radial velocity signature (starspots/ bumps traveling through the line profile) could not provide this type of global variations. In Fig. 7 one can see that F1c is most likely in presence of two harmonics at 2F1c and 3F1c. A low eccentricity orbit could explain a low number of harmonics. Since amplitudes differ significantly between both radial velocity measurements, only very gross deductions can be tempted. Applying Kepler’s laws and Vega’s fundamental parameters, using the global shift measuring radial velocity determined by the first moment, and assuming an exoplanet orbiting in the equatorial plane at a distance of 0.017 AU, a 0.34 M_Jupiter exoplanet could satisfy the observed parameters (stellar mass: 2.15 M_⊙, amplitude Vorb(Vega)sin i ≈ 6 m s⁻¹ derived from the first moment measurement, inclination angle of the system: 7° (pole-on), P = 0.56 d (corresponding to F1c = 1.77 d⁻¹), eccentricity e = 0). Using the values of vrad (bisector), i.e. P = 0.53 d and Vorb(Vega)sin i ≈ 22.9 m s⁻¹ an exoplanet mass of 1.24 M_Jupiter at 0.0165 AU would satisfy the equations. In both case studies, the interesting result is the proximity of the frequency to the rotation frequency. It indicates that the orbital radius of such an exoplanet would correspond to only 1.36 (or 1.31) R_Vega (calculated for e = 0 and using the concordance model as published by Monnier et al. [2012]), while the co-rotating radius/synchronous orbit corresponds to 1.5 R_Vega. If we have at this stage no further indication supporting this potential exoplanet presence, attention should be given to a recently published article by Balona [2014], announcing the fact that approximately 19% of A-type stars were potentially accompanied by a roughly Jupiter mass exoplanet on a synchronous orbit. The most interesting conclusion of our (still hypothetical) analysis is therefore that planetary material of a significant fraction of the Jupiter mass could be located close to the synchronous (or co-rotating) radius. This result seems to agree with Balona [2014] findings, and Vega could be one of this close-planet A-type stars. If confirmed, it would be very interesting to observe associated tidal effects of such a close in planet orbiting a “hot” star. Would these findings indicate that in A-type stars exoplanet migration stops at the corotating radius? Would that imply that dipolar magnetic fields act till the corotation radius and avoid any further migration?

4. Conclusion

The discovery of corotating structures at the surface of a non-chemically peculiar A-type star provides new insights into the processes at work in the envelope of a typical intermediate-mass star. Long-lived large scale chemical spots are already known to exist on Ap/Bp stars, but this class of magnetic and chemically peculiar stars only represents 5-10% of stars in this mass range and the origin of their spots is attributed to the atomic diffusion of chemical elements in an atmosphere stabilized and structured by 300 Gauss or higher large scale fields.

This result could be different since the magnetic field of Vega is much too weak to stabilize its outer layers and generate strong chemical anomalies through atomic diffusion. But the magnetic field observed on Vega is still a natural explanation for corotating structures seen with Doppler Imaging. In this case, the property of these structures should help determine the enigmatic nature of Vega’s magnetic field.

Although the envelope of A-type stars is mainly radiative, small convective layers due to respectively the hydrogen, the first and the second helium ionizations are present. This layers can in principle host a dynamo driven by the convective motions. Due to their small thickness and low density, the energy contained in these motions is limited. Moreover, close the surface, the convective turnover time can be much smaller than the rotation rate, in which case the dynamo is inefficient. Nevertheless, Cantiello & Braithwaite [2011] found that in the hotter O and B stars the convective layer due to the opacity peak related with iron group elements can generate relatively strongly magnetic fields, assuming the equipartition between kinetic and magnetic energy and estimating the convective velocity from the mixing length model. In A-type stars, the convective layer induced by the second helium ionization might play a similar role. However, whether such a dynamo can generate the observed 7 Gauss nearly polar spot of Vega (Petit et al. [2014]) and also account for the observed corotating structures with typical ~ 0.3 R_Vega length scale remains to be verified. Furthermore, convective dynamos are intrinsically variable with a spot lifetime on the order of the rotation period. Such a variability is not detected in our data.

Other possible origins of Vega’s magnetic field, discussed by Lignières et al. [2009] and Cantiello & Braithwaite [2011], rather involve fields generated in the early phase of the star life and their subsequent evolution in the radiative envelope. In this context also, a key feature that would help distinguish between models is the intrinsic time variation of the field. Given the low-amplitude of the Stokes V profile, we expect that, if present, this variability will be easier to detect through spectroscopic studies similar to the present one.

Another question raised by the present study concerns the sign and the amplitude of the luminosity contrast induced by the co-rotating structure. For the weak magnetic field observed in Vega, bright rather than dark spots are expected because dark spot only occur when the field is strong enough to limit convective heat transport within the spot. As mentioned before, rotational modulations compatible with spots have been detected with Kepler’s light curves in a large fraction of A-type stars [Balona 2011]. If these modulations are the photometric counterpart of the present spectroscopic structures, this would strongly support the existence of a widespread Vega-like magnetism and activity among A-type stars.

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Fig. 14. Lomb Scargle periodogram showing the frequencies present in $v_{\text{span}}$, $v_{\text{rad}}$ (first moment) and $v_{\text{rad}}$ (bisector). Bars are identical to Fig. It can clearly be seen that all three estimators show the rotation frequency, but only the two radial velocities show the 1.77d$^{-1}$ frequency. Color codes are online.

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