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Time, spatial, and spectral resolution of the Hα line-formation region of Deneb and Rigel with the VEGA/CHARA interferometer

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ABSTRACT

Context. BA-type supergiants are amongst the most optically-bright stars. They are observable in extragalactic environments, hence potential accurate distance indicators.

Aims. An extensive record of emission activity in the Hα line of the BA supergiants β Orionis (Rigel, B8Ia) and α Cygni (Deneb, A2Ia) is indicative of presence of localized time-dependent mass ejections. However, little is known about the spatial distribution of these apparent structures. Here, we employ optical interferometry to study the Hα line-formation region in these stellar environments.

Methods. High spatial- (∼0.001") and spectral- (R=30 000) resolution observations of Hα were obtained with the visible recombiner VEGA installed on the CHARA interferometer, using the S1S2 array-baseline (34m). Six independent observations were done on Deneb over the years 2008 and 2009, and two on Rigel in 2009. We analyze this dataset with the 1D non-LTE radiative-transfer code CMFGEN, and assess the impact of the wind on the visible and near-IR interferometric signatures, using both Balmer-line and continuum photons.

Results. We observe a visibility decrease in Hα for both Rigel and Deneb, suggesting that the line-formation region is extended (∼1.5-1.75 R∗). We observe a significant visibility decrease for Deneb in the Siβ, Siγ, and Siδ lines of the BA supergiants β Orionis (Rigel, B8Ia) and α Cygni (Deneb, A2Ia) which indicates that the star’s atmosphere is extended (∼100-200 R∗). The decrease in the Hα visibility is caused by an inhomogeneous and unsteady circumstellar environment, while no such variability is seen in differential visibilities. Radiative-transfer modeling of Deneb, with allowance for stellar-wind mass loss, accounts fairly well for the observed decrease in the Hα visibility. Based on the observed differential visibilities, we estimate that the mass-loss rate of Deneb has changed by less than 5%.


1. Introduction

Supergiants of spectral types B and A (BA-type supergiants) are evolved massive stars of typical initial mass of 25-40 M⊙ and high luminosity (≥10⁵ L⊙). Their luminosity and temperature place them among the visually brightest massive stars. Therefore, they are particularly interesting for extragalactic astronomy (Puls et al. 2008). Moreover, they represent attractive distance indicators by means of the identified wind-momentum-luminosity relationship (WMLR) (Kudritzki et al. 2008, Evans & Howard 2003, Kudritzki et al. 1999). As a consequence, nearby BA supergiants have been analyzed with sophisticated radiative-transfer tools. Two subjects of intense scrutiny, both observationally and theoretically, have been Deneb (α Cygni, HD 197345, A2 Ia) and Rigel (β Orionis, HD 34085, B8 Ia) (Schiller & Przybilla 2008, Aufdenberg et al. 2006, 2002 for Deneb).

Intensive spectroscopic monitoring of the activity of wind-forming lines, such as Hα, suggests that the stellar-wind variability of luminous hot stars is associated with localized and
co-rotating surface structures. The pioneering work of Lucy (1976) based on a period analysis of radial-velocity curves of Deneb obtained in 1931/32 by Paddock (1935) revealed the simultaneous excitation of multiple non-radial pulsations (NRPs). This effort was followed by the extended optical Hérs campaigns (Kaufer 1998), monitoring for ~100 consecutive nights late B-type/A-type supergiants (Kaufer et al. 1997, 1996a) and early B-type hypergiants (Rivinius et al. 1997). Attempts to associate this activity with large-scale surface magnetic fields have so far been unsuccessful (Schnerr et al. 2008, Verduzo et al. 2003, Henrichs et al. 2003, Bychkov et al. 2003). However, the appearance of thin surface convection zones at the supergiant stage may favor the formation and emergence of magnetic fields (Cantiello et al. 2009), and may also have a significant impact on potential NRPs.

BA-type supergiants such as Rigel (B8 Ia) and Deneb (A2 Ia) exhibit observational evidence of the random and pseudo-cyclic activity of the stellar wind. A pulsation-driven mechanism has often been proposed, although the associated micro-variability is observed for a wide range of luminosities and log Teff. Gautschy (1992) argued for the presence of strange modes. Gautschy (2009) tentatively proposed that Deneb’s micro-variability is caused by a thin convection zone efficiently trapping the non-radial oscillations, and significant progress has been made in determining the mechanism leading to mass ejection (Cranmer 2009). The collective effect of multiple NRPs was also proposed as a promising means of explaining the large value of the macro-turbulence parameter; NRPs also represent an attractive mechanism for the formation of Be-star disks (Aerts et al. 2009, Neiner et al. 2009).

Based on intensive monitoring of spectroscopic lines, many observational campaigns have attempted to discriminate between these models. Monitoring of Deneb and Rigel is still ongoing (Danetis et al. 2009, Morrison et al. 2008, Rzaev 2008, Markova et al. 2008, Markova & Puls 2008, Morel et al. 2004, Rivinius et al. 1997, Kaufer et al. 1996b), for a non-exhaustive list). The uniform-disk (UD) angular diameters of Deneb and Rigel are 2.4 mas and 2.7 mas, respectively (Aufdenberg et al. 2008, Mozurkewich et al. 2003), making them good targets for accurate long-baseline optical interferometry. An extensive study of Deneb was performed by Aufdenberg et al. (2002), using different radiative-transfer models (with allowance for the presence of a wind), and constraints from optical interferometry data. Deneb’s wind should enhance the limb darkening relative to hydrostatic models that neglect it. However, this can only be constrained observationally by using long baselines in the near-IR (longer than 250m) or by observing in the visible, thus relaxing the constraints on the baselines by a factor of about 3-4. The Hα line is particularly interesting in that context. Its large opacity makes it very sensitive to changes at the stellar surface and above, in particular through modulations in stellar-wind properties. Its extended line-formation region is therefore more easily resolved than the deeper-forming continuum. Dessart & Chesneau (2002) investigated the possibility of monitoring the mass-loss activity in wind-forming lines by means of optical interferometers equipped with spectral devices of sufficient dispersion.

BA supergiants rotate slowly ($v \sin i$ of about 25–40 km s$^{-1}$), at least relative to their terminal wind-velocity of ~200–400 km s$^{-1}$. Spectrally resolving the Doppler-broadened Balmer lines thus requires a resolving power as high as $R \approx 10000$. At optical wavelengths, the most conspicuous indicator of mass-loss in early-type supergiants is Hα, which exhibits the distinctive P-Cygni profile morphology and has often been a crucial estimator of the mass-loss rate in spite of its documented variability. While Aufdenberg et al. (2002) was successful in reproducing many observables obtained for Deneb, the modeling of the Hα line proved difficult. The most significant and persistent discrepancy between the synthetic and observed profiles has been the depth of the absorption component, which is significantly weaker in the observed spectrum (residual intensity ~0.6). Furthermore, while the velocity of the absorption component minimum is quite variable, it is rarely, if ever, shifted blueward by more than ~50 km s$^{-1}$, which is ~20% of the terminal velocity. Schiller & Przybilla (2008) used a different strategy, using the Hα profile as a reference for a detailed modeling of the wind characteristics, and reached a more satisfactory solution. Nevertheless, they also reported some remaining discrepancies in matching the Hα absorption, and proposed additional effects that may need to be considered in the modeling, such as wind structure or the influence of a weak magnetic field.

The VEGA recombiner of the CHARA array is a recently commissioned facility that provides spectrally dispersed interferometric observables, with a spectral resolution reaching $R \approx 30,000$, and a spatial resolution of less than one mas. The instrument recombines currently the light from two telescopes, but 3-4 telescope recombination modes are foreseen in a near future. The Hα line of bright, slow rotators such as Deneb or Rigel can be isolated from the continuum, and the spatial properties of the line-forming region can thus be studied with unprecedented resolution. Using the smallest baseline of the CHARA array (baseline of 34m), we conducted a pioneering temporal monitoring of Deneb uncovering a high level of activity in the Hα line-forming region. Rigel was also observed a few times.

The paper is structured as follows. In Sect. 2 we present the optical interferometry data and their reduction, in addition to complementary spectra obtained by amateur astronomers. We then review in Sect. 3 the previous interferometric measurements aiming to more tightly constrain the diameter of Rigel and Deneb. We then apply this extensive record of measurements in the visible and near-IR continuum to interpret semi-quantitatively the spectrally-dispersed measurements in Sect. 3.2, and to elaborate a radiative-transfer model of the stars in Sect. 4.

2. Observations and data processing

2.1. VEGA observations

Deneb and Rigel were observed with the Visible spEctroGraph And Polarimetr (VEGA instrument, Mourard et al. 2009) integrated within the CHARA array at Mount Wilson Observatory (California, USA, ten Brummelaar et al. 2005). Deneb obser-
Table 1. VEGA/CHARA observing logs.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>SCI/CAL</th>
<th>Projected Baseline Length [m]</th>
<th>PA [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008.07.28</td>
<td>06:04</td>
<td>Deneb</td>
<td>33.4</td>
<td>6.2</td>
</tr>
<tr>
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<td>Deneb</td>
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<td>-18.8</td>
</tr>
<tr>
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<td>-46.7</td>
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<td>10.3</td>
</tr>
<tr>
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<td>32.3</td>
<td>-9.9</td>
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<tr>
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<td>30.1</td>
<td>-37.6</td>
</tr>
<tr>
<td>2009.07.27a</td>
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<td>CAL1</td>
<td>31.8</td>
<td>-19</td>
</tr>
<tr>
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<td>-11.1</td>
</tr>
<tr>
<td>2009.07.27b</td>
<td>08:28</td>
<td>CAL1</td>
<td>31.4</td>
<td>-23</td>
</tr>
<tr>
<td>2009.08.26</td>
<td>06:51</td>
<td>CAL1</td>
<td>31.1</td>
<td>-26.8</td>
</tr>
<tr>
<td>2009.08.26</td>
<td>07:06</td>
<td>Deneb</td>
<td>33.0</td>
<td>-18.5</td>
</tr>
<tr>
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<td>07:25</td>
<td>CAL1</td>
<td>30.5</td>
<td>-31.0</td>
</tr>
<tr>
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<td>Deneb</td>
<td>33.2</td>
<td>-14.3</td>
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<tr>
<td>2009.10.01</td>
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<td>CAL1</td>
<td>33.2</td>
<td>-14.3</td>
</tr>
<tr>
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<td>-27.3</td>
</tr>
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<td>Rigel</td>
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<tr>
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<td>-26.2</td>
</tr>
<tr>
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<td>32.8</td>
<td>-20.4</td>
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<tr>
<td>2009.11.17</td>
<td>09:48</td>
<td>Rigel</td>
<td>27.1</td>
<td>-20.5</td>
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</tbody>
</table>

a CAL1: HD 184006, A5V, V=3.7, estimated diameter 0.6±0.05mas from SearchCal@JMMC
b Observations performed remotely from France

determination of the absolute visibility which implies a large observing strategy using the medium-resolution mode, larger baselines coupled with a fringe tracking performed in the near-IR. This possibility is foreseen in the future. Therefore, calibrator observations were not performed systematically, but only to ensure that the instrument was behaving well.

The data reduction method is fully described in Mourard et al. (2009) and we only summarize it shortly here. The spectra are extracted using a classical scheme, of collapsing the 2D flux in one spectrum, wavelength calibration using a Th-Ar lamp, and normalization of the continuum by polynomial fitting. We note that the photon-counting cameras saturate when the rate of photons is too high locally. Because of the brightness of the sources, neutral density filters of 0.6 to 1 magnitudes had to be applied, depending on the atmospheric conditions and the spread of the speckle images on the slit. Spectra with a signal-to-noise ratio (SNR) of 300-400 were routinely obtained, although clear signs of saturation were found in a few of them. After careful testing, we checked that the saturation had only a very limited effect on the interferometric measurements. When the quality of the spectra was such that telluric lines are observable, these are used to refine the wavelength calibration, although most of the time the VEGA spectral calibration was checked against the reference spectra obtained by amateur astronomers. A series of spectra for Deneb is shown in Fig. I.

The raw squared visibilities (V^2) were estimated by computing the ratio of the high frequency energy to the low frequency energy of the averaged spectral density. The same treatment was applied to the calibrators, whose angular diameter was computed using the software SearchCal (Bonneau et al. 2009). The expected absolute visibilities of VEGA in the continuum from the short baselines do not provide strong constraints on the angular diameter and a calibrator was not systematically observed. When such an observation is available, we carefully checked that the observed visibilities were compatible with the expected ones. A contemporary measurement obtained with the medium resolution mode is presented in Mourard et al. (2009).

The information in a line was extracted differentially by comparing the properties of the fringe between a reference channel centered on the continuum of the source, and a sliding science narrow channel, using the so-called cross-spectrum method (Berio et al. 1999). The absolute orientation of the differential phase was established by considering the change in the spectral slope of the dispersed fringes (Koechlin et al. 1996) when changing the delay line position. Thus a positive value corresponds to a photocenter displacement along the S1S2 projected baseline in the south direction.

The width of the science channel was 0.02 nm in good atmospheric conditions, and degraded to 0.08 nm in poor weather conditions. The rms of the spectrally dispersed visibility in the 654-655 nm continuum ranges from 3-4% at visibility 1 in the highest quality nights (2008.07/28, 2008.07/30, 2009.10/01) to about 7-8% in medium nights (2009.07/27, 2009.08.26) and more than 10% in poor nights (2009.11/17). The rms of the differential phases follows the same trend ranging from 1-2° in good conditions, to 3-4° in medium conditions, and 5-6° in poor conditions. 

http://www.jmmc.fr/searchcal/
Fig. 1. Top: Montage of Hα observations at various epochs for Deneb and Rigel. We also include one observation of the calibrator (HD17643). The dashed lines indicate the spectra recorded by amateur astronomers. Bottom: Normalized multi-epoch Hα observations of Deneb. The color coding is the same as that used in the top panel.

poor conditions. Figures 3 illustrate the best observations of Deneb secured in 2008. A Gaussian fit was applied to the differential visibilities and phase to retrieve accurate information about the spectral FWHM and position of the interferometric signal. The spectral location of the differential visibility and differential phase dips are stable at a level of 0.005 nm (~3 km s⁻¹). Information from the blue camera was also used, as some important lines, e.g. Si 6343–6371Å can be investigated (see Fig. 3 and Sect. 3.3).

2.2. Spectroscopy from amateur astronomers

Several Hα spectra were obtained during the same period with the 0.28 m amateur telescope (Celestron 11) located in Castanet-Tolosan (France) equipped with the eShel spectrograph and a QSI532 CCD camera (CCD KAF3200ME). These spectra were used in this study as an indication of the emission level and variability of the stars. The typical resolution of these spectra is ~11 000.

The reduction of these data was performed using the standard echelle pipeline (Reshel software V1.11). H2O telluric lines are removed by means of division by a synthetic H2O spectrum using Vspec software - the telluric-line list was taken from GEISA database (LMD/CNRS). We corrected for the diurnal and annual earth velocity are corrected for (spectral wavelengths are given in a heliocentric reference for a standard atmosphere). Systematic differences were found in the VEGA/CHARA and amateur continuum correction producing the differences seen in Fig. 1 between the solid (VEGA) and dashed lines (eShel).

3. Results

3.1. The diameters of Deneb and Rigel

For the most accurate estimates to date of the diameters of Rigel and Deneb, we refer to Aufdenberg et al. (2008, 2006a), in which CHARA/FLUOR observations in the K band with baselines reaching 300 m are described. These observations infer a UD angular diameter of 2.76±0.01 mas, and 2.36±0.002 mas, for Rigel and Deneb, respectively. To first order, no significant change in these diameters inferred from the visible or the near-IR is expected, the wind being too tenuous to shift the continuum-formation region (see Sect. 4). This value of the Deneb UD angular diameter agrees with the optical measurements of Mozurkewich et al. (2003) obtained with the MarkIII interferometer using multiple observations with baselines ranging from 3m to 28m with 2.34±0.05 mas at 0.8 µm, 2.26±0.06 mas at 0.55 µm, and 2.25±0.05 mas at 0.41 µm. The few V² measurements secured from the present observations with a very limited spatial frequency range agree with the MarkIII measurements. We estimated the uniform disk diameter of Deneb using only the red camera to be 2.31±0.04 mas at 0.65 µm, and using both cameras found the diameter to be 2.34±0.03 mas. Only the best observations could be used, as the visual magnitude of the calibrator (V=3.7) was too faint to often obtain a reliable estimate of the absolute visibility, even using the broadest possible spectral band (i.e. 5 nm).
The Hα line-formation region

The Hα line is one of the most optically thick of all lines seen in the optical and near-IR spectra of hot stars, hence represents an excellent tracer of their winds. This line has mostly been observed by means of spectroscopy at various spectral resolution, and in some dedicated campaigns with a very intensive time coverage aimed at recovering the time variability of the line-forming region. We refer to Rzaev (2008) and Morrison et al. (2008) for the latest reports on Deneb and Rigel. This conspicuous line-profile variability suggests that the wind itself, where the Hα line forms, is variable in its properties. For example, variations may take place in the ionization, the morphology, or the density structure of the wind. The significant changes in the line-profile shape with time indicates that the Hα line-formation region is asymmetric, and that this asymmetry changes with time.

The Hα line observed in Deneb exhibited evidence of some activity during the 2008-2009 observations, but not of any dramatic change in mass-loss rate. The Rigel spectra were also obtained during what appears to have been quiet periods and differ from the “typical” spectrum shown in Fig. 1 of Morrison et al. (2008). As can be seen here in Fig. 2, the Hα line is as deep as the carbon Cii lines at 657.8 and 658.3 nm in Rigel. This is not an unusual state, as Hα often appears in pure absorption and to be symmetric about the line center (in the rest-frame) about 20% of the time (using Morrison et al. (2008) statistics).

Both the Deneb and Rigel dispersed visibilities exhibit a profound dip in the Hα line, suggesting that the line forms over an extended region above the continuum. These dips are symmetric about the line center (in the rest-frame) in both objects. The FWHM of the visibility dip was estimated by performing a Gaussian fit to data of the high quality nights in 2008. These measurements yield a FWHM of 0.215±0.007 nm, i.e. 98±3 km s⁻¹ for Deneb (Fig. 2). By comparison, the visibility...
signal is narrower for Rigel, with a FWHM of $70 \pm 5 \text{ km s}^{-1}$. One can estimate the visibility in the line by using a continuum derived from published values of the angular diameter. The corresponding UD estimates for the highest extension of the H\textsc{$\alpha$} line-forming regions are $4.1 \pm 0.2 \text{ mas}$ and $4.2 \pm 0.2 \text{ mas}$ for Deneb and Rigel, representing $1.75$ and $1.5 R_\ast$, respectively.

The differential phases are a direct indication of the position of the H\textsc{$\alpha$} line-forming regions at different radial velocities, by comparison to the continuum considered as the reference of phase. For the 2008 data, the Gaussian fits provide FWHMs that increase from the baselines oriented near $+10^\circ$ to $-40^\circ$ from $61 \pm 2 \text{ km s}^{-1}$ to $84 \pm 4 \text{ km s}^{-1}$. Sub-structures are also detected, with the highest peak near the zero velocity, and two satellites at about $40 \text{ km s}^{-1}$. The peak level reached by the differential phases follows a trend from a large photo-center shift at P.A. close to $5-10^\circ$ that decreases toward $-30-50^\circ$.

The differential phases recorded for Deneb between 2008 and 2009 are shown in Fig. 3. Dramatic changes are observed with periods of large phase signal alternating with periods containing no detectable signal.

The “calm” periods may potentially provide important information about the rotation of the star. This characteristic signal can be observed in the rotating circumstellar environment of Be-star disks (see Delau et al. in preparation; Berio et al. 1999, Nakhi et al. 1998, Stee 1996), and also directly on the photosphere of a rotating star (Le Bouquin et al. 2009). Approaching and receding regions of a rotating star experience different Doppler shifts and are thus spectrally separated. In the sky, the natural consequence is that the line-absorbing regions are seen by the interferometer at one or the other side of the continuum, generating the well-known S-shape signal in the differential phases. This signal might have been detected in Rigel data of the 2009-10-01 (see Fig. 3). The rms of the phase of these data is $7.7^\circ$, and the maximum and minimum of the signal are at $26^\circ$ and $-17^\circ$, respectively, at the blue and red sides at $\sim 15 \text{ km s}^{-1}$ from line center. The signal is kept at a similar level when extracted with a double binning of $0.04 \text{ nm}$, and the phase rms is decreased to $5.6^\circ$. This is on the order of the estimated $v \sin i$ of the source of about $36 \text{ km s}^{-1}$. We were unable to detect a similar signal for Deneb probably because of the limited spectral resolution, insufficient to resolve its low estimated $v \sin i$ of $20 \text{ km s}^{-1}$. As the signal is anti-symmetric, it cancels out if the spectral resolution is too low. One must also keep in mind that the quality of the data fluctuated and that the
induced by the inhomogeneous Hα of the light in the Hα curve), and the corresponding differential visibility, scaled to the expected absolute value of the continuum (lower curve). Bottom: Differential phase curve exhibiting a clear S-shape signal, indicative of rotating circumstellar material. A vertical dotted line is shown in both panels to indicate the location of the Hα rest-wavelength determined by a Gaussian fitting of the visibility curve.

binning could not be kept identical at all epochs. It is not impossible that weak signals are blurred (such a signal might be visible the 2009/11/17; Fig. 3). Given the large extension and the activity observed in the differential phases in Hα, this line is probably not ideally suited to inferring the rotation of the star.

To first order, and for marginally resolved sources, the differential phases can be considered to linearly depend on the photo-center position of the emitting source. This is no longer the case when the source is significantly resolved as in our case, but we consider this as a rough estimate. Assuming that the line emission represent a fraction $f_{\text{ratio}}$ of typically 50% of the light in the Hα line core, the following relation is used $p = -(\phi/360)(\lambda/B)(1/f_{\text{ratio}})$. We find that the astrometric shifts induced by the inhomogeneous Hα emission reach 0.5 mas (0.2$R_*$), but are lower than 0.3 mas most of the time. The event observed in 2008 is remarkable as the full line appeared to be off-center relative to the continuum. A similar event was observed on 2009/10/01 to have an opposite direction.

3.3. The Si 6347–6371Å line-formation regions

The Si 6371 line was observed simultaneously with the Hα line in the blue camera (Fig. 5) in 2008. The line profile shows a pure absorption, but is slightly asymmetric with an extended blue wing due to extended absorption in the wind regions. The VEGA/CHARA observations of Deneb obtained in 2008 indicate that the line-formation region of the Si 6371 line is more extended than the continuum forming region, with differential-visibility dips of 10%, 19%, and 15% for baselines in the range [5°:10°], [-10°:20°], and [-35°:50°]. The rms of the dispersed visibilities is 5%. The line FWHM estimated from Gaussian fitting is $55\pm3$ km s$^{-1}$ and the FWHM of the visibility dip is narrower with a FWHM decreasing from $33\pm4$ km s$^{-1}$ to $24\pm4$ km s$^{-1}$ for P.A. from [5°:10°] to [-35°:50°], respectively. One can roughly estimate the extension of the line-forming region using the minimum of the visibility and UD approximation to be 2.6 mas, 2.7 and 2.75 mas using the value of 2.34 mas from NPOI as the diameter at 630 nm. One may speculate whether this trend in the visibilities is permanent or a transient event closely related to the asymmetries inferred from the differential phases in the Hα line. Because of a spectrograph realignment carried out in 2009, the Si 6371 line was not any longer observable with the blue camera in 2009, but the Si 6347 was well-centered and could be analyzed. No such signal was observed at anytime.

Despite the large depth of the silicon lines, no differential-phase signal was detected above an rms of $\lesssim$2°. This means that the imprint of the rotation of the star on the Si 6371 line-formation region is not detected in the data, probably because of insufficient spectral resolution. Strong Si lines were also observed in Rigel’s spectrum, but neither differential visibility nor any phase signal was detected. The SNR of the data is poorer than the Deneb observations, with an rms in the dispersed visibilities and phases of 10%.

Fig. 4. Top: Hα observations of Rigel on 2009.10.01 (upper curve), and the corresponding differential visibility, scaled to the expected absolute level of the continuum (lower curve). Bottom: Differential phase curve exhibiting a clear S-shape signal, indicative of rotating circumstellar material. A vertical dotted line is shown in both panels to indicate the location of the Hα rest-wavelength determined by a Gaussian fitting of the visibility curve.

Fig. 5. Time evolution of the differential phases of Deneb. The strong phase signal observed in 2008 is indicative of a very asymmetric environment, off-centered from the continuum source. No clear S-shape signal is observed, in agreement with the low $\nu \sin i$ of Deneb of $\sim$20 km s$^{-1}$, unresolved by the instrument.
Fig. 6. Left: In the bottom panel, we show a contour plot of the quantity $P \times I(P)$ as a function of Doppler velocity and impact parameter $P$ for Hα, computed with CMFGEN using the stellar parameters of Deneb and a mass-loss rate value of $3.1 \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$, corresponding to the best-fit model. This figure illustrates the distribution of intensity with impact parameter, and in particular serves to infer the regions that contribute significant flux to the line, and hence the spatial extent of the Hα line-formation region. In the top panel, we show the corresponding normalized synthetic flux in Hα. Right: Same as left, but now for a mass-loss rate value of $6.2 \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$. Notice the sizable change in profile morphology, echoing the change in the extent of the line-formation region.

4. Comparison with radiative transfer models

The BA supergiants, especially nearby ones, have been extensively studied with sophisticated radiative-transfer codes. It is not in the scope of this paper to determine more reliably the fundamental parameters of Deneb or Rigel. However, we wish to investigate several important issues related to the putative effects of the wind on the interferometric observables. Deneb has been observed by several northern-hemisphere interferometers in both the visible and the near-IR. Rigel is currently monitored with VEGA/CHARA in the northern hemisphere, as well as in the southern hemisphere with the VLTI. Hence, in this study, we used the stellar parameters obtained by Przybilla et al. (2006) and Schiller & Przybilla (2008) for Rigel and Deneb, respectively. After developing a convergent model for a reference mass-loss rate value at which Hα is predicted in absorption, we then increased the mass-loss rate (keeping the other stellar parameters fixed) until the Hα line exhibited a well-developed P-Cygni profile. In this way, we explored the following questions:

– To what extent the angular diameter inferred from optical and near-IR continua is sensitive to changes in mass-loss rates?
– Are the Hα, Paβ, and Brγ line-formation regions reproduced by radiative-transfer simulations accounting for a wind? These lines form in different parts of the wind and can thus be used simultaneously to constrain its properties.

In this paper, we focus on the Hα line because it can be observed with VEGA/CHARA. A similar study for Paβ and Brγ line-formation regions is postponed to another paper in preparation.

4.1. Numerical simulations

Our radiative-transfer calculations were carried out with the line-blanketed non-LTE model-atmosphere code CMFGEN [Hillier & Miller 1998, Dessart & Hillier 2005], which solves the radiation-transfer equation for expanding media in the co-moving frame, assuming spherical symmetry and steady-state, and under the constraints set by the radiative-equilibrium and
Fig. 7. Top: Theoretical visibility curves for Deneb, computed at selected wavelengths in the range \(\sim 6562\text{–}6571\,\text{Å}\), and thus containing the \(\text{H}\alpha\) line, and for mass-loss rate values of \(3.1\times10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) (left) and \(6.2\times10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) (right). Bottom: Same as top, but now for Rigel and using mass-loss rate values of 1 (left) and \(2\times10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) (right). The dotted and dashed lines correspond to the best UD curves fitting the visible and the near-IR continua, respectively. The range of baselines of the VEGA/CHARA is indicated by two vertical dash-dotted lines.

statistical-equilibrium equations. It treats line and continuum processes, and regions of both small and high velocities (relative to the thermal velocity of ions and electrons). Hence, it can solve the radiative-transfer problem for both O stars, in which the formation regions of the lines and continuum extend from the hydrostatic layers out to the supersonic regions of the wind, and Wolf-Rayet stars, in which lines and continuum both originate in regions of the wind that may have reached half its asymptotic velocity.

We used the stellar parameters inferred by Schiller & Przybilla (2008) for Deneb, and by Przybilla et al. (2006) and Markova et al. (2008) for Rigel. The Mn resonance lines suggest terminal wind speeds of \(\sim 240\,\text{km}\,\text{s}^{-1}\) for Deneb (Schiller & Przybilla 2008) and \(\sim 230\,\text{km}\,\text{s}^{-1}\) for Rigel (Kaufer et al. 1996b). Their projected rotational velocities are low, i.e. \(20\pm2\,\text{km}\,\text{s}^{-1}\) and \(36\pm9\,\text{km}\,\text{s}^{-1}\) respectively.

Even for sources as “close” as Deneb and Rigel, the distance estimates remain quite inaccurate. Schiller & Przybilla (2008) derived a luminosity of \(1.96\times10^5\,\text{L}_\odot\) for Deneb, using a distance of \(802\pm66\,\text{pc}\) (assuming that Deneb is a member of the Cyg OB7 association), while the one derived from Hipparcos (van Leeuwen 2007) is significantly smaller (i.e., \(432\pm61\,\text{pc}\), which infers a luminosity estimate of \(5.5\pm1\times10^4\,\text{L}_\odot\). This reassessment directly scales down by almost a factor two the linear scales of the size parameters. Furthermore, recalling that the mass-loss rate scales with the luminosity, this should imply a weaker steady-state wind mass loss for Deneb. The corresponding uncertainties are considerably lower for Rigel, which is much closer than Deneb.

By adopting values these parameters from previous works, we find that the synthetic spectra computed by CMFGEN agree favorably with the observations. We thus adopt these stellar parameters and vary the mass-loss rate value to assess the impact on the spectrum and in particular \(\text{H}\alpha\) and \(\text{Si}\ii\,\text{6347–6371.4}\,\text{Å}\). In practice, we explore the effect of a wind mass-loss rate of \(1.55, 3.1, 6.2, \text{and } 12.4\times10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}\) for Deneb, and values of \(1, 2, 4, \text{and } 8\times10^{-8}\,\text{M}_\odot\,\text{yr}^{-1}\) for Rigel. A typical effect that appears in theoretical models is illustrated in the bottom panels of Fig. 6: where we show the distribution of the emergent intensity \(I\) (scaled by the impact parameter \(p\)), as a function of Doppler velocity and \(p\). This type of illustration was introduced by Dessart & Hillier (2005) to study line formation in hydrogen-rich core-collapse supernova ejecta. Here, it provides a measure of the extent of the line-formation region of
Hα relative to the neighboring continuum and the sites where most of the emergent photons originate. Comparing the left and right panels suggests that a variation by a factor of two in the mass-loss rate value leads to sizable changes in the extent of the line-formation region, and correspondingly, large changes in the observed line profile. While spectroscopy is sensitive to the latter, interferometry is sensitive to the former. Below, we describe the interferometric signals associated with these intensity maps computed with CMFGEN and produced using the stellar parameters suitable for Rigel or Deneb, and various mass-loss rates tuned to match observations. This is illustrated in Fig.8 in the case of Deneb and Rigel, using two different mass-loss rates. The visibility curves for various spectral channels in the vicinity of Hα are plotted as a function of the spatial frequency. The differential visibilities observed by VEGA are generating by plotting the differential value for a given projected baseline (between 27m and 33m).

4.2. Visible and near-IR continuum forming regions

In Fig.10, we show a zoom of the 0.6μm and 2.2μm squared-visibility curves of Deneb in the second lobe with the various mass-loss rate values used in this paper. The visible continuum appears to be far more sensitive to such changes than the near-IR continuum. We note that these visibility curves are computed for a spectral resolution of 30 000, and cannot be directly compared with the broadband measurements of FLUOR/CHARA over the full K′-band (Aufdenberg et al. 2008).

Doubling the mass-loss rate from 3.1 to 6.2×10⁻⁷ M☉ yr⁻¹ does not significantly alter the optical thickness of the wind. The angular diameter of the star in the continuum near Hα determined by a UD fitting of the visibility curve does not therefore change by more than 2%. However, we note that the second lobe is significantly affected. This conclusion is also true in the near-IR. All models also show that the near-IR UD angular diameter is systematically larger than the visible one by ~2.5-3%, due to the increasing continuum opacity with wavelength (free-free and bound-free processes). The near-IR models were scaled to match the accurate CHARA/FLUOR value of 2.363 mas, and this implies that the expected UD diameter in the Hα overlapping continuum is ~2.31±0.02 mas. This expectation agrees with the NPOI measurements of 2.34±0.05 mas at 0.8μm and 2.26±0.06 mas at 0.55μm.

For Rigel, the difference between the near-IR UD angular diameter and its visible counterpart is increased slightly to reach ~3.0-3.5%. Using the FLUOR/CHARA measurement of 2.758 mas as reference, this would imply a diameter of about 2.64 mas in the visible. In the near-IR, some instruments such as FLUOR/CHARA have an accuracy often better than 1% depending on the atmospheric conditions, and the ability to observe with long baselines. The interpretation of the observations obtained with this instrument might be affected by a mass-loss rate variation in the form of localized inhomogeneities, but probably on a smaller scale than an instrument with a similar accuracy operating in the visible.

The second lobe of the visibility curve is far more sensitive to any fluctuation of the mass-loss rate in the visible than the infrared. The reasons are twofold: a higher sensitivity to limb-darkening effects in the visible, and a more extended continuum-formation region, despite the very limited amount of flux involved (the wind remains in any case opti-
4.3. Dependence of the $\text{H}\alpha$ and $\text{Si}$ lines on the mass-loss rate

We then computed the spectrum and the dispersed visibilities in the $\text{H}\alpha$ line at a spectral resolution $R=30\,000$. We were unable to perform a satisfactory fit to the $\text{H}\alpha$ profile for either Deneb or Rigel, the absorption component being systematically too deep (Fig. 8). This conclusion was reached in many studies, and these profiles could not be reproduced in terms of spherically-symmetric smooth wind models (see for instance Fig. 7 in Markova et al. (2008), Auffenberg et al. (2002), and Schiller & Przybilla (2008)). In this temperature regime, the models systematically predict profiles in absorption partly filled-in by wind emission, hence only lower limits to the mass-loss rate can be derived by fitting the $\text{H}\alpha$ line.

However, this discrepancy is mitigated by the quality of the visibility fit shown in the upper panel of Fig. 8, which is by far less sensitive to small absorption effects along the line-of-sight. Changing the mass-loss rate by a large factor of 2–4 has a dramatic impact on the $\text{H}\alpha$ line-formation region, changing the spectrum appearance and the dispersed visibility curve. When using a baseline in the range 26–33 m, there is a relationship between the mass-loss rate and the FWHM of the visibility dip in the line that can be approximated by a second-order polynomial in the range considered (1.55 to $12.4\times10^{-7} \text{M}_\odot \text{yr}^{-1}$). One can see in Fig. 8 that the nominal model of Deneb with a mass-loss rate of $3.1\times10^{-7} \text{M}_\odot \text{yr}^{-1}$ fits the observed visibility curves well. The model FWHM of the visibility is 89 km s$^{-1}$ and the observed FWHM is 98±3 km s$^{-1}$. Given the FWHM-mass-loss relationship, this would correspond to a mass-loss rate in the range $3.7\pm0.2\times10^{-7} \text{M}_\odot \text{yr}^{-1}$. For Rigel, a similar relationship provides a mass-loss rate in the range $1.5\pm0.4\times10^{-7} \text{M}_\odot \text{yr}^{-1}$. We have studied the variations in 2008 and 2009 of the visibility profile without detecting any significant variation in the visibility profile, which, translated in a mass-loss rate variation, suggests that the mass-loss rate has not changed by more than 5%.

By comparison, the $\text{Si}$ line is less sensitive to any variation in the mass-loss rate (Fig. 8). The FWHM of the simulated line weakly increases from 40 to 43 km s$^{-1}$, compared to the 2008 VEGA/CHARA measurement of $55\pm3$ km s$^{-1}$. The FWHM of the corresponding model visibility dip are independent of the mass-loss rate, being unchanged at the value 19.5 km s$^{-1}$ and lower than the measured mean value of $29\pm5$ km s$^{-1}$ for the 2008 observations. The depth of the visibility dip fits more accurately the curve with a mass-loss rate of $6.2\times10^{-7}$ rather than the nominal value of $3.1\times10^{-7} \text{M}_\odot \text{yr}^{-1}$ inferred from the $\text{H}\alpha$ line. It is not possible to establish whether this issue is related to a particular event occurring during the 2008 observations, or a permanent situation, or even a bias in the radiative-transfer model.

Despite the lower quality of the interferometric data on Rigel, one can see in Fig. 9 that the model provides a reasonable fit. We note that the $\text{Cr}$ lines at 6578Å and 6583Å in the spectrum of Rigel are also slightly affected by the wind. Their visibility for the VEGA baselines are about 0.5–1% lower than the nearby continuum (using our model predictions), depending on the mass-loss rate. Detecting such a weak signal would require that the accuracy on the differential visibility is about 2–3 times better than the current instrument performance.

4.4. A rough investigation of the morphology of the line-formation regions

The variability in the differential phase signal observed is a clear sign of the stochastic activity of the wind of Deneb. Even though the data secured are partial, one can note that no differential phase signal exceeds 30°, which is impressively large considering that the baseline is limited. In 2008 and in October...
2009, the differential phase signal was able to be observed throughout the full line, at a level above 30°. This signal did not appear to be due to an increased level of stochastic 'noise' expected from the signature of small, localized clumps, but exhibited a well-structured signature. At other times, the differential signal was only observed close to $±v\sin i$, and some patterns were reminiscent of the S-shape signature, originating in a rotating structure.

The radiative transfer models demonstrate that at the inferred mass-loss rate of Deneb, significant emission originates in a circumstellar region of up to 2-4 stellar radii, and that the level of this extended emission depends strongly on the mass-loss rate. We tried to investigate the differential phases with ad hoc approaches using the models as a basis to generate the perturbation. Differential visibilities and phases provide contradictory and stringent constraints. On the one hand, a strong differential phase signal is observed, but on the other hand, the differential visibilities did not vary by more than 5% over the two years of sparse observations. This restricted considerably the size, flux, and location of the perturbation. The emergent flux of the best-fit model was perturbed using a 2D Gaussian as a weighting function. The parameters of the perturbation were its location, FWHM and flux ratio compared to the unperturbed model. The best parameter range was reached for a perturbation located at 2-3 stellar radii from the star, with an FWHM of 0.3-0.7 stellar radii, and a flux contrast of 10-25. One can see in Fig. 11 that the differential visibilities of the perturbed and unperturbed models are similar, whereas a significant differential phase signal is observed. The baseline is aligned in the direction of the perturbation observed in July 2008, i.e. north of the star. This model is also compatible with the differential phases observed with the two other baselines (Fig. 12). Placing the perturbation farther away leads to a phase signal that is far weaker than to the observations, since the line-forming region of the unperturbed model naturally ends at 5-6 stellar radii. This is a limitation of this ad hoc approach. Making the perturbation larger in size, even with a much lower flux contrast leads to a noticeable change in the differential visibilities. The same consequence is reached when putting the perturbation too close to the star. Finally, if the perturbation is too small (i.e. FWHM $≤$ 0.1 mas), the flux contrast required to reach the observed phases is unrealistically high, and such that a significant 'binary'-like perturbation in the visibilities should be observed. Finally, this perturbation study suggests that a large temporal variability in the visibility and phase is expected in the visible at high spatial frequencies corresponding to the second lobe of the visibility curve.

Clarke & McLean (1976) and McLean & Clarke (1979) did not detect any significant variation in the polarization of the Hβ and Hα lines in Deneb and Rigel, at a typical level of about 0.1%. Hayes (1986) performed an intensive broadband monitoring in B-band polarization of Rigel, revealing a variability at a typical level of 0.2%. The variability pattern in the $Q – U$ plane suggested that the ejection of material was not limited to a plane, and non-radial pulsation were thus proposed as the root cause of these localized ejections. This might be caused by the limited amount of intensive observations. This might also be a consequence, in the case of Deneb, of a small inclination of
the rotation axis on the sky. Any large-scale structures orbiting in the equatorial plane would generate a significant polarization variability, without any preferential direction. In addition, no direction appears to be preferred by our observations, although we emphasize that such a conclusion is very limited given the stringent limitations in the \(uv\) coverage.

5. Deneb as a fast rotator

Aufdenberg et al. (2008, 2006a) presented evidence that Deneb is a fast rotator, based on 24 high accuracy FLUOR/CHARA visibilities in the \(K'\)-band with projected baselines ranging from 106 m to 310 m, sampling the first and second lobes of the visibility curve. They detected slight departures from a purely spherical model at a level of about 2% in the near-IR, a discovery that had not been anticipated for an AB supergiant. They tentatively fitted the data with a rotating model atmosphere, and demonstrated that despite the low \(v\ \sin i\) of the star, a model at half critical speed, seen nearly pole-on may account for the interferometric observations. A by-product of this fitting process is the determination of crucial parameters in this context, namely the inclination, estimated to be \(i=30^\circ\), and the orientation on the sky of the rotation axis found to be at about P.A.=150° east from north. These findings have potentially important implications. In a general context, Deneb would be the first AB supergiant proven to be the descendant of a fast rotator. Support for this interpretation was provided by Schiller & Przybilla (2008). To more clearly interpret the pronounced mixing signature with nuclear-processed matter, these authors proposed that Deneb was probably a fast rotator initially, and is currently evolving to the red-supergiant stage.

In the context of our observations, the consequences on the \(H\alpha\) line-formation region must be evaluated. The \(H\alpha\) line may be affected by a moderate change in wind properties, such as those that occur due to a latitudinal variation in the effective temperature of the star, estimated to be \(\sim700\) K (Aufdenberg et al. 2006a). Moreover, as stated by Schiller & Przybilla (2008), hydrogen lines are mainly sensitive to variations in \(\log g\).

Neither the VEGA/CHARA data nor the theoretical study presented in this paper can provide definitive support for, or exclude, this interpretation. The \(H\alpha\) variability observed by VEGA/CHARA is related to localized inhomogeneities in the wind of this star. Is not impossible that those inhomogeneities may affect the continuum forming region in the \(K\) band, although it has been shown in Sect. 4.2 that large variations in mass-loss rate are required to significantly affect the second lobe of the visibility curves. Yet, this conclusion is based on the ideal case of a spherical model, although given that the wind is very optically thin in the continuum, those inhomogeneities should not significantly alter the properties of the continuum-formation regions.

The 2008 data arguably provide some support for the fast rotator model. We note that the S1S2 projected baselines were
roughly aligned (range of -45°/+15 degrees) within the direction of the asymmetry found with CHARA/FLUOR at 150°, i.e. the direction of the pole in the fast rotator model [Aufdenberg et al. 2006a]. On the other hand, the Hα differential phases are observed to increase from a baseline roughly aligned to the pole direction at PA=150°. This may imply that the asymmetry is greater in a direction perpendicular to the pole. On the other hand, the Si line dispersed visibilities seem deeper in the direction of the pole, suggesting a more extended line-formation region. Moreover, the high mass-loss rate inferred from the fit to the visibilities through the SiII line may also be an indication of a co-latitude dependence of the mass-loss rate. That no evidence of rotation was detected in the differential phases is an additional argument for a low $v\sin i$, and therefore a nearly pole-on configuration for Deneb. These limited observations cannot provide definite conclusions, and the fast-rotator interpretation still needs to be investigated, both theoretically and observationally. This could be done, for instance, by repeating the FLUOR/CHARA observations to check whether the near-IR interferometric signal has changed or not, or by devoting a full VEGA/CHARA run with more extensive coverage, preferably by using the 3T mode. It would also be of interest to investigate the impact of the fast rotation of Deneb on the Hα and Si 6371Å line-forming regions, using a radiative transfer model of a rotating star with a wind.

6. Conclusion

We have presented the first high spatial and spectral observations of two nearby supergiant stars Deneb and Rigel. The Hα line-formation regions were resolved and their angular size was found to be in agreement with an up-to-date radiative transfer model of these stars. The Hα line-forming region appears to be asymmetric and time variable, as expected from the numerous intensive spectral monitoring of AB supergiants reported in the literature. However, the time-monitoring of the dispersed visibilities inferred from the Hα line of Deneb did not provide evidence of mass-loss rate changes above 5% of the mean rate, and the activity observed can be considered most of the time as a second-order perturbation of the wind characteristics. The increased coverage obtained in 2008 provides some evidence of a latitudinal dependence of both the Hα differential phases and the Si 6371Å line differential visibilities. This line was not significantly resolved subsequently. Only two observations of Rigel were secured. An S-shape signal was detected in the Hα differential phase of Rigel, suggesting that the rotation signal is detected. We note that the Hα line profile was almost photospheric at the time of our observations. Observations with a large $uv$ coverage may provide, in the case of Rigel, the direction of the rotational axis on the sky and its inclination.

Given the large angular size of Rigel and Deneb, the Hα line-forming region is fully resolved by the interferometer with baselines longer than 50m, and only the S1S2 baseline of the CHARA array is short enough to permit such an investigation. Therefore, it is not easy to significantly increase the observational effort performed on these stars with such stringent observing restrictions. An extension of this work is possible for sources with an apparent angular diameter between 0.5 and 1.5 mas, that are large enough, but also bright enough to make use of the highest spectral dispersion of the VEGA instrument (limiting magnitude of about 3). This concerns the AB supergiants closer than 1.5 kpc, and the supergiants in the Orion complex ($d \sim 500$ pc) are in this context of particular interest. Simultaneous 3 telescope recombination would provide much better $uv$ coverage than the one presented in this paper. Another interesting possibility is to add to this study several diagnostic lines such as the Ca infrared triplet (849.8nm, 854.2nm, 866.2nm). These resonance lines are highly sensitive to non-LTE effects arising close to the photosphere and may shed some light on the regions were the material is launched.

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