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Coordinated ultraviolet and Hα spectroscopy of bright O-type stars*

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Abstract. As part of our search for the origin of stellar-wind variability, we have conducted simultaneous ultraviolet and Hα spectroscopy of a number of bright O stars. The observed changes in the Hα line occur at low velocity (0−0.2v∞) on timescales that are characteristic of the development and evolution of discrete absorption components (DACs) in UV resonance lines. In some cases, a direct relationship is found between the changes occurring in the Hα line and subsequent variations in the high-velocity stellar wind. On the basis of this relationship, the appearance of a DAC in the UV resonance lines can be predicted from (ground-based) Hα observations.

These observations show that the stellar wind is variable down to regions close to or at the stellar surface. Since the timescales of the variations can be related to the rotation periods of the stars in our sample, we propose that a stellar magnetic field (which remains undetected) might play an important role in affecting the base of the stellar wind. The observed variations are interpreted in terms of corotating wind structures, similar to the Corotating Interaction Region (CIR) model proposed by Mullan (1986) and recently simulated by Cranmer & Owocki (1996).

Key words: stars: early-type – stars: magnetic fields – stars: mass loss – stars: rotation – ultraviolet: stars

1. Introduction

Winds of O-type stars are strongly variable on timescales down to less than one hour. Time-resolved series of high-resolution UV spectra obtained with the International Ultraviolet Explorer (IUE) have shown that the variations in the blue-shifted absorption troughs of UV resonance lines are not chaotic, but occur in a well-defined “pattern” (e.g. Prinja et al. 1987, Henrichs et al. 1988, Massa et al. 1995, Kaper et al. 1996 [Paper I]).

Discrete absorption components (DACs) are the most prominent features of wind variability in O-type stars. DACs migrate from red to blue through (unsaturated) P Cygni lines: they appear as broad absorption features at low velocity (central velocity v_c ∼ 0.2 − 0.5 v∞) and develop into narrow absorption components during their subsequent acceleration towards the terminal velocity, v∞, of the stellar wind. In saturated resonance lines DACs cannot be observed; the steep blue edge of these profiles, however, often shows regular shifts of up to 10% in velocity, on a timescale comparable to that of the DACs. This edge variability is presumably related to the DAC behaviour; the observed differences in the asymptotic velocities of the DACs might cause the less regular behaviour of the high-velocity edges (cf. Kaper et al. 1997 [Paper II]).

Because of their specific shape, DACs are readily recognized in single “snapshot” spectra. Howarth & Prinja (1989) detected DACs in more than 80% of the spectra in a sample of 203 galactic O stars. Henrichs (1984) and Grady et al. (1987) also found DACs in many Be stars, although not in non-supergiant B stars. Thus, the occurrence of DACs is a fundamental property of hot-star winds, and knowing how DACs develop is considered essential for our understanding of stellar-wind physics.

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* Based on observations collected with the International Ultraviolet Explorer from Vilspa, Madrid, Spain, and GSFC, Greenbelt, USA and the 1.52m telescope with Aurélie at O.H.P., France
A key issue in the study of wind variability is the recurrence timescale associated with DACs. Starting with Henrichs et al. (1988) and Prinja (1988), all papers in which more than one sequence of DACs is described suggest that DAC patterns repeat on a time scale comparable to the (estimated) rotation period of the star (Kaper & Henrichs 1994, Howarth et al. 1995, Prinja et al. 1995, Paper I, Paper II). The regular appearance of DACs might therefore be related to the rotation of the star. The nature of this relationship was recently the focus of a large IUE observing campaign (the IUE MEGA Campaign; Massa et al. 1995).

Owocki et al. (1995) and, more recently, Cranmer & Owocki (1996) tried to explain the periodic modulation of UV P Cygni lines in terms of corotating wind streams, similar to those occurring in the Corotating Interaction Region (CIR) model proposed by Mullan (1984,1986). The CIR model, which was first applied to the solar wind, invokes fast and slow wind streams that originate at different locations on the stellar surface. Due to the rotation of the star, the wind streams are curved, so that fast wind material catches up with slow material in front, forming a shock at the interaction region. The shock “pattern” in the wind is determined by the boundary conditions at the base of the wind and corotates with the star.

Previous studies revealed that subordinate UV lines also show signatures of wind variability. Prinja et al. (1992) and Henrichs et al. (1994b) demonstrated that for some stars DACs appear as well in the N\textsuperscript{iV} subordinate line at 1718 Å. Since subordinate lines arise from an excited atomic level, these lines are formed in the relatively dense parts of the expanding atmosphere, i.e., close to the stellar surface. This is in accordance with the low velocity at which these variations are usually observed. Furthermore, the fact that the subordinate N\textsuperscript{iV} line varies in concert with the UV resonance lines (e.g., of Si\textsuperscript{iv} and C\textsuperscript{iv}), indicates that the early evolution of DACs is traced by the subordinate lines.

Strong subordinate lines are also found in the optical region of the spectrum (e.g., H\textalpha), and these lines are similarly formed in the base of the stellar wind. In his survey of a dozen OB supergiants, Ebbets (1982) found dramatic changes in the shape and strength of H\textalpha, but the time sampling of his observations was too irregular to permit the timescales (1–10 days) to be estimated reliably. Although it is very likely that the wind variability observed in UV P Cygni lines is related to variability in the H\textalpha line, coordinated optical and UV observations of O-type stars to demonstrate this expected relationship do not exist.

The aim of the present paper is to investigate the occurrence of wind variability in the deepest layers of the stellar wind and its relation to DACs observed in the UV resonance lines formed systematically further out in the wind. Studying lines formed in different layers of the stellar wind simultaneously provides the opportunity to search for the origin of wind variability and to test the predictions of, e.g., the CIR model.

For this purpose, we have organized several multi-wavelength, multi-site observing campaigns. Here we report on results from four such campaigns. We also included polarimetry in the campaign observations as an additional source of information about the properties of the wind material, especially its geometrical distribution. The polarimetry results will be published in a separate paper. In the next section the observations and the reduction methods are described. In Sect. 3 we focus on the variability and periodicity observed in the H\textalpha line for 8 bright O stars. The relevant UV observations, which have been thoroughly discussed in Papers I and II, are summarized here. In Sect. 4 we elaborate on the simultaneous H\textalpha and DAC behaviour and the role of rotation. Our results are discussed in the context of the CIR model; constraints on this model are inferred from our observations. The possible role of surface magnetic fields is discussed in Sect. 5, which ends with a summary of the conclusions.

2. Observations

Time series of H\textalpha spectra were obtained for the target stars listed in Table 1 during coordinated optical/UV observing campaigns in September 1987, February and October 1991, and November 1992. The optical data for the September 1987 campaign were obtained at the McDonald Observatory and the Dominion Astrophysical Observatory; all the other H\textalpha data were obtained at the Observatoire de Haute Provence (OHP). Except for α Cam, time series of IUE were collected simultaneously with the H\textalpha data. The IUE results from these campaigns have been described in detail in Papers I and II. Here, we concentrate on the optical lines formed in the stellar wind and compare their variability to the simultaneous wind variations detected in the UV P Cygni lines.

2.1. UV spectroscopy

High-dispersion ultraviolet spectra were obtained with the Short Wavelength Prime camera on board the IUE satellite. The log of these observations can be found in Paper I, which also provides a detailed description of the data reduction, which was carried out with the IUEDR software package (Giddings 1983). Interstellar lines were used to align the wavelength calibration; échelle-ripple correction was performed with the method described by Barker (1984). The spectra were mapped on a uniform wavelength grid of 0.1 Å. Reseau marks were removed by linear interpolation. The maximum signal-to-noise of the spectra is about 30 (see Henrichs et al. 1994b).

A quantitative analysis of the DAC behaviour in the UV resonance lines is given in Paper II. The migrating DACs were modelled in the way developed by Henrichs et al. (1983) and extended by Telting & Kaper (1994), by using a template spectrum for the stationary underlying P Cygni profile. In Paper II we measured the central velocity and optical depth, width, and column density for each pair of DACs in the UV resonance doublets. A period search was performed, which provided a quantitative determination of the recurrence timescale of DACs and the timescale of regular changes occurring at the blue edge of P Cygni profiles.
2.2. Optical spectroscopy

During the 1991 and 1992 campaigns, Hα time series were obtained at OHP with the Aurélie spectrograph at the coudé focus of the 1.52m telescope. The February 1991 campaign was hampered by problems with the detector cryostat, so that we could only use the spectra collected during the last two nights (February 5 and 6). The October 1991 campaign was more successful: spectra were obtained from October 21 to 28, while October 26 and 27 were clouded. We were confronted with computer hardware problems in the November 1992 campaign and could only observe on November 5, 6 and 12.

We used the Aurélie spectrograph in a variety of configurations with the 2 × 2048 Thomson CCD detector to obtain high-resolution spectra. In February 1991, grating#5 was used in second order to produce spectra covering 60 Å centered on Hα with resolution R ∼ 70,000. We started with the same configuration during the October 1991 campaign, but switched to grating#7, which produced spectra with half the resolution and twice the wavelength coverage. Grating#7 was also used during the November 1992 campaign. During all runs, calibration frames were obtained regularly in order to correct for the bias and dark current levels of the CCD. Th-Ar and tungsten flatfield exposures taken at ∼ 2 hour intervals through the night provided wavelength calibration and correction for pixel-to-pixel variations of the detector, respectively. Spectra with S/N of 200 per pixel in the continuum were obtained for the target stars with exposures of 10 to 30 minutes duration, depending on the weather conditions and the instrumental configuration.

The atmospheric water vapour lines (which vary in strength from night to night and even within one night) were removed from the Hα profiles by means of an automated procedure using a table with wavelength positions, strengths and widths of water lines, which were assumed to be gaussian. The table was empirically constructed from high-resolution spectra of rapidly rotating non-variable stars. Maintaining the relative values of the positions, strengths and widths of the standard table, the best fit for each spectrum was determined for a number of water-line profiles in a few suitable regions, after which a synthetic waterline spectrum was generated and used for the removal. During the wavelength calibration procedure we took into account the correction for the earth’s motion with respect to the heliocentric rest frame. The spectra were resampled to a uniform wavelength step of 0.1 Å and normalized by fitting a spline function through carefully selected wavelength intervals located on both sides of the line profile.

We have also included an archival time series of Hα spectra of ξ Per obtained from the McDonald Observatory and the Dominion Astrophysical Observatory during the 1987 IUE campaign in this analysis. A total of 21 spectra with R ∼ 12,000 were obtained in short exposures (typically 2.5 minutes) with the coudé spectrograph of the 2.1m Struve telescope at McDonald. The instrumental configuration consisted of a 600 l/mm grating blazed at 8.700 Å that was used in first order, an OG550 order-blocking filter, a 120 µ order, a slit, and a small, 512 RCA CCD detector with 30 µ square pixels. This setup produced spectra with reciprocal dispersion of 0.28 Å per pixel, and the wide slit projected to ∼2 pixels FWHM on the detector. Twenty-five spectra with R ∼ 22,000 were obtained with the coudé spectrograph of the 1.22m telescope at DAO. Grating 1200H, which is blazed at 6.000 Å, was used in first order together with the IS32R red image slicer and an 1872 Reticon detector (pixels 15 µ wide) to produce spectra with a linear dispersion of 0.15 Å per pixel in exposures of typically 10 minutes duration. At both sites Fe or Fe-Ar comparison sources and flatfield lamps were observed frequently through the night in order to provide reliable wavelength and photometric calibration, and spectra of broad-lined standard stars were obtained to permit the removal of telluric features. The two time series were merged after the DAO spectra had been resampled to the nominal resolution of the McDonald spectra.

A temporal variance spectrum (TVS) analysis (Fullerton et al. 1996) was applied to the Hα time series obtained in September 1987 and October 1991 to detect line-profile variations in an objective and statistically rigorous manner. For the best observed targets, Fourier analysis based on the iterative CLEAN algorithm (Roberts et al. 1987) was used to search for periodic variability. The time coverage of the February 1991 and November 1992 data was too sparse to produce useful constraints on their time-dependent behaviour. For the targets observed during these runs, only the observed profiles are presented.
Fig. 1. ξ Per October 1991: Time sequence of H_α spectra; a shift of 0.2 in the vertical direction separates successive nights. The dotted line is the average of the spectra obtained in the night of October 22. The H_α line shows a modulation in strength with a period of two days. Note the pronounced emission bump detected in only two H_α spectra (separated in time by half an hour) during the night of October 25.

3. H_α variability and DACs

Below we describe the results obtained from the H_α observations for the O stars listed in Table 1. We discuss the periodic variations encountered in this near-photospheric line that might be related to the cyclical variability (in the form of DACs) detected in UV resonance lines. Detailed background information on the individual objects can be found in Paper I.

3.1. ξ Per O7.5 III((f))

3.1.1. October 1991 campaign

A time sequence of 15 H_α spectra of ξ Per, obtained during the October 1991 campaign is shown in Fig. 1. The average of the three spectra taken in the night of October 22 is represented by a dotted line for comparison. Due to the imperfect removal of the atmospheric water vapour lines, small residuals are still present in the spectra. The absorption strength of the H_α line varies regularly on a timescale of two days. During the night of October 25, an emission bump appears in the red wing of the line at a velocity of about +75 km s\(^{-1}\) (measured in the stellar rest frame). Two spectra, taken half an hour apart, show the same feature.

We performed a Fourier analysis for each wavelength bin in the H_α time series. The middle panel of Fig. 2 displays a grey-scale representation of the power at a given frequency (in cycles per day) as a function of wavelength. The appearance of the emission bump on October 25 is clearly reflected by the peak in the TVS. Note that this incipient emission is slightly red-shifted. Significant H_α variability is observed over the range from about −400 to 300 km s\(^{-1}\). The periodogram exhibits maximum power at a frequency of 0.51 day\(^{-1}\), which is concentrated at the center and blue extension of the H_α line.

The power summed over the line is shown in Fig. 3. The main peak is centered at a frequency of 0.51 ± 0.03 day\(^{-1}\), which is equivalent to a period of 1.96 days. The other peaks are probably not significant: the second highest peak (0.19 ± 0.03 day\(^{-1}\) or 5.3 days) is at a period close to the length of the dataset, the third peak (1.12 ± 0.03 d\(^{-1}\) or 0.89 days) might be a harmonic
of the main peak (e.g., due to the non-sinusoidal character of the 2-day period variation).

The UV P Cygni lines show simultaneous variability on an identical timescale (cf. Paper I). In Fig. 4 we show a time series of the Si iv P Cygni profile. The Si iv doublet includes discrete absorption components that migrate from intermediate (central velocity $\sim 0.5v_{\infty}$, where $v_{\infty} = 2350$ km s$^{-1}$) to high velocities on a timescale of two days, in accordance with previous studies (Prinja et al. 1987, Henrichs et al. 1994b). The terminal velocity of the wind has been determined from the highest velocity reached by the DACs (cf. Henrichs et al. 1988, Prinja et al. 1990). Close inspection of the DAC events reveals that they consist of multiple components, a strong one followed less than a day later by a weaker one (see Paper II for DAC fit parameters). In the Si iv line two strong DACs are first detected at JD 3.4 and 5.2; the weaker components appear at JD 4.1 and 6.0. The emission part of the P Cygni profile is constant with time. The development of a DAC in the Si iv line (data taken from Paper II) is plotted in the lower panel of Fig. 5 (open circles), where the maximum EW has been normalized to unity. By definition, the DACs are in absorption and an increase in EW means an increase in the number and/or strength of the DACs. The development of a DAC in the Si iv doublet is heralded by an increase in EW; the first appearance of a relatively strong (S: $N_{\text{col}} \geq 5 \times 10^{12}$ cm$^{-2}$) or weak (W) DAC in the Si iv lines is indicated in Fig. 5. With a dotted line we plotted a sine curve:

$$EW(t) = a + b \sin \left( \frac{2\pi}{P} (t - t_0) \right)$$

with period $P$ taken from the corresponding Fourier analysis and $a$, $b$, and $t_0$ chosen such (i.e., not fitted) that the function overlays the observations reasonably well. The intention of the
dotted line is to guide the eye and to emphasize the period of variability detected by the Fourier analysis. Note that the EW is an integrated quantity; the Fourier analysis was performed for each resolution element across the line profile separately. In principle, the EW can remain constant while the line profile undergoes (periodic) variations.

The appearance of an emission bump at \(+75\, \text{km s}^{-1}\) in the H\(\alpha\) line on October 25 (corresponding to the points with EW about 1.2 in Fig. 5) suggests that the decrease in H\(\alpha\) EW is mainly due to an additional amount of incipient emission originating in the stellar wind. If the appearance of incipient H\(\alpha\) emission is related to the development of a DAC in the N\,\text{iv} and Si\,\text{iv} P Cygni profiles, it is interesting to determine whether a phase lag exists between the two. It turns out that a minimum in H\(\alpha\) EW (maximum emission, minimum absorption) approximately coincides with a minimum in Si\,\text{iv} EW (beginning of new DAC episode), although the time coverage of the H\(\alpha\) line is too sparse to make a firm statement. Evidently, the onset of the increase in incipient H\(\alpha\) emission occurs somewhat earlier than the minimum in EW is reached: how much earlier depends on the interpretation of the line variability (i.e., is the change in H\(\alpha\) EW due to incipient emission only, or does the line absorption contribution also change with time?). We will return to this point in the next section. Furthermore, the appearance of a strong DAC as derived from our model fits (indicated by S in Fig. 5) does not coincide with a minimum in Si\,\text{iv} EW, but is detected somewhat later. This time lag is important if the additional incipient H\(\alpha\) emission is only detectable for relatively strong DAC events.

H\(\alpha\) spectra with minimal EW were taken at JD 52.7, 54.6, 55.7, and 58.7. The Si\,\text{iv} spectra with smallest EW were obtained at JD 52.8, 54.8, and 56.7. If the minima in Si\,\text{iv} EW mark the beginning of a DAC event, we measure (for the first two events) a phase lag of 0.1-0.2 day between the variations characterized by a 2-day period in the H\(\alpha\) and UV wind lines. It is tempting to relate the two subsequent minima in H\(\alpha\) EW at JD 54.6 and 55.7 to the last DAC event covered by the IUE observations (appearing JD 55). This event is clearly split up into two components (much more pronounced than during the first DAC event, see Fig. 4): a strong component is first detected at JD 55.2, followed by a weaker one at JD 56.0 (see above). If this interpretation is correct, the phase lag between maximum incipient emission in the optical lines and the appearance of a DAC component in the UV wind lines would be longer than the 0.1-0.2 day derived above, most likely on the order of 0.5 day.

### 3.1.2. September 1987 campaign

The TVS and 2-d Fourier transform of the archival time series of H\(\alpha\) spectra from the 1987 campaign are illustrated in Fig. 6. These data cover \(\sim 2\) hours per night over 5 nights with higher time resolution than the data obtained in 1991. As with the data from the 1991 campaign, significant variations extend over the entire profile. These are dominated by a single Fourier component with period 2.1 \(\pm 0.1\) days, which (within the uncertainties) is the same period observed in 1991. The velocity interval over which the 2-day period is observed, is larger compared to 1991: \(-550\) to \(+50\, \text{km s}^{-1}\). Although the limited coverage precludes firm conclusions concerning the phase relation between these variations and the occurrence of DACs in the UV P Cygni profiles, the maximum EW in H\(\alpha\) seems to lag the appearance of a DAC (by \(\sim 0.2\) days). This is broadly consistent with the analogous shifts observed in 1991 (though for the 1991 dataset we measured the phase lag between the occurrence of minimum H\(\alpha\) EW and the cyclical appearance of DACs). In any case, it is significant that a 2-day period has persisted in \(\xi\) Per for at least 4.1 years, which amounts to \(\sim 750\) cycles (if they are coherent).

### 3.2. \(\alpha\) Cam O9.5 Ia

The UV resonance lines of the supergiant \(\alpha\) Cam are saturated, and this prohibits the detection of additional absorption features. The UV P Cygni profiles did not exhibit any significant variability in February 1991 (Paper I). However, we detected strong variations in simultaneous H\(\alpha\) observations (Fig. 7). Ebbets (1982) found similar variations in Reticon H\(\alpha\) spectra of \(\alpha\) Cam; he detected only very minor changes within a night, but found
large differences between Hα profiles obtained days (or months) apart.

The few Hα spectra that we obtained in February 1991 do not permit the timescale associated with the variability to be derived accurately. In October 1991 we again collected Hα spectra of α Cam (see Fig. 7). The variations found in both datasets are consistent with Ebbets’ results; the variability timescale is probably several days. A longer sequence of observations is clearly needed to quantify this.

3.3. λ Ori O8 III((f))

Although the shape of the Hα line indicates that the photospheric profile is partly filled in by wind emission, no significant variations take place in the November 1992 Hα spectra of λ Ori (Fig. 8). Simultaneous UV spectra show evidence for a migrating DAC at high velocity in the SiIV lines and a constant, strong, displaced absorption component at $-2000$ km s$^{-1}$ in both the Nv and the SiIV resonance lines (Paper I). Thus, in the case of λ Ori (and 10 Lac, see below) the UV resonance lines do exhibit wind variability, while the Hα line does not.

3.4. ζ Ori O9.7 Ib

Both the Hα profile (Fig. 9) and the UV resonance lines (Paper I) of ζ Ori show strong and complicated variations in November 1992. Variations in the Hα profile of ζ Ori were reported by Ebbets (1982) and are similar in character to the variations shown here. The Hα variability is concentrated to the blue-shifted absorption part of the P Cygni profile. On November 11 the ultraviolet Nv line shows the development of a DAC at a velocity of $-800$ km s$^{-1}$; this night was not covered by the Hα observations. At the beginning of the IUE observations (November 8) an absorption event was already present in the Nv line at high velocity ($-1400$ km s$^{-1}$). In Paper II we derive timescales of 1.6 and 6 days for the DAC variability; the latter period corresponds to the highest peak in the power spectrum, but is longer than the time span covered by our observations. Unfortunately we cannot relate the Hα and the UV variations due to the lack of observations between November 7 and 13.

3.5. 68 Cyg O7.5 III:n((f))

Fig. 10 displays a time sequence of Hα spectra of 68 Cyg obtained in October 1991. The dotted line represents the mean of the spectra obtained in the night of October 25. The Hα profile shows red and blue emission “humps”. This profile shape can be modelled when the effects of the (differential) rotation of photosphere and wind are taken into account (Petrenz & Puls 1996, their Fig. 8). 68 Cyg is the star with the largest projected...
rotational velocity in our sample \((v \sin i = 274 \text{ km s}^{-1})\); see Table 1).

A TVS and 2d-Fourier analysis of this dataset is shown in Fig. 11. The TVS (upper panel) indicates that (small) variations occur over the full width of the line profile. The sharp peaks in the TVS at the blue and red side of the line can be attributed to residual telluric absorptions, and serve to illustrate the small amplitude of the variations in the H\(\alpha\) line. The periodogram (gray-scale panel) shows that periodic variability is present in the line core and red wing.

The highest peak in the Fourier spectrum is centered at a frequency of \(0.25 \pm 0.06 \text{ day}^{-1}\) (4.0 days), which is longer than the observing period (3.85 days) and therefore unreliable. The second highest peak (red wing) is at \(1.7 \pm 0.05 \text{ day}^{-1}\) (0.59 day). The third peak (line core) is found at \(0.76 \pm 0.06 \text{ day}^{-1}\) (1.31 day). At the same time, the Si \(\text{iv}\) resonance lines of 68 Cyg show DAC variability in a velocity range of \(-800\) to \(-2600 \text{ km s}^{-1}\). The DACs are relatively weak compared to previous years and produce a rather complicated pattern. A Fourier analysis of the Si \(\text{iv}\) time series reveals a period of 1.37 days (Paper II). This is consistent with the 1.3-day period present in the H\(\alpha\) line core. Thus, also for 68 Cyg the H\(\alpha\) line shows variability with a period that can be identified with one detected in the stellar wind. The 0.59d-period detected in the H\(\alpha\) line is not present in the UV resonance lines.

Fig. 12 shows the variability of the EW of H\(\alpha\) and the Si \(\text{iv}\) DACs as a function of time. Dotted lines indicate sine curves with periods of 1.31 days (H\(\alpha\)) and 1.37 days (Si \(\text{iv}\)) on top of the data to illustrate the periodic behaviour of the spectral lines. Here the minima of the curves do not coincide: in contrast to \(\xi\) Per, we find that the H\(\alpha\) EW reaches a minimum after the Si \(\text{iv}\) EW reaches a minimum.

How does this correspond to the appearance times of DACs? On the basis of the 1.3 day periodicity, we can identify two series of DACs in the Si \(\text{iv}\) line: series A, which appears at JD 52.8, 53.9, 55.5, and 56.5 and series B, which appears at JD 53.4, 54.7, and 56.0. The sampling time of the UV data is 0.1 day. The time lag between the two series is about half a day, series A followed by B. We discovered that the two series differ in terminal velocity of the DACs (Paper I and II): series A reaches about 2450 km s\(^{-1}\), while B gets to about 2200 km s\(^{-1}\) or less. A difference in DAC terminal velocity was also discovered for \(\xi\) Per. The H\(\alpha\) minima are reached at JD 52.4, 53.7, and 55.0. This is about half a day earlier than the appearance times of series A. Apparently, we cannot use the Si \(\text{iv}\) EW as a straightforward indicator of the DAC behaviour for this star. However, the periodicity of the variability is well reflected by the EW.

3.6. 19 Cep O9.5 I\(\text{b}\)

We find similar results for the O9.5 I\(\text{b}\) supergiant 19 Cep with the main difference being that the timescale of variability is much longer than encountered in \(\xi\) Per and 68 Cyg. Fig. 13 shows a time series of H\(\alpha\) spectra obtained in October 1991. The H\(\alpha\) profile has a central emission core that is variable in strength. This profile shape is also observed in other late-O, early-B type supergiants, like \(e\) Ori (B0 Ia) and \(\kappa\) Ori (B0.5 Ia) as demonstrated by Ebbets (1982).

The dotted line in Fig. 13 represents the H\(\alpha\) spectrum of 19 Cep on October 25, which has the largest equivalent width of the series, i.e., it is the “least-emission” spectrum. In the spectrum of Oct 21 (JD 51.45) some additional emission is present at the red side of the profile (0 to 200 km s\(^{-1}\)), while one day
later the incipient emission has reached maximum strength and extended blueswards (−175 to 125 km s\(^{-1}\)). The TVS and 2d-Fourier transform of the H\(\alpha\) time series is given in Fig. 14. The power concentrates towards the red side of the line, the most prominent peak in the Fourier spectrum is centered at 0.21 ± 0.05 day\(^{-1}\) (4.9 days). Two small peaks are at a frequency of 0.49 ± 0.07 and 0.78 ± 0.06 day\(^{-1}\), respectively (2.1 and 1.3 days).

Fig. 15 shows a grey-scale representation of the Si \(\text{iv}\) profiles of 19 Cep, obtained with IUE in October 1991. To enhance the contrast, individual spectra were divided by the least-absorption template (see Paper II) displayed in the upper panel. The observed spectra are shown in the middle panel and the residual spectra are stacked in time in the lower panel, where the residual flux has been converted into levels of gray. The white dots represent the central velocity of the DACs, as derived from model fits (Paper II). At JD 53.3 a new DAC appears in the Si \(\text{iv}\) lines at a velocity of 450 km s\(^{-1}\); in the previous spectrum, obtained at JD 53.0, we did not detect it (we observed 19 Cep three times a day). The DAC reaches its maximum column density (2 \(\times\) 10\(^{15}\) cm\(^{-2}\)) at JD 55.7, just before the development of a new (and stronger) DAC close to the end of the campaign at JD 55.9.

Fourier analysis of the spectral time series of the Si \(\text{iv}\) and N \(\text{v}\) resonance lines results in a period of 6.3 ± 2.1 and 5.6 ± 1.9 days, respectively (see Paper II). These periods are longer than the length of the dataset (4.2 days) and therefore not reliable. Although the DAC behaviour in the Si \(\text{iv}\) doublet might suggest this (see Fig. 15), a period close to 2.5 days is not detected. From IUE observations of 19 Cep in November 1992 we derive a period of 4.6 days (0.22 ± 0.14 day\(^{-1}\)) while the observations spanned 5.6 days. A period of 4.6 days would be consistent with the H\(\alpha\) period of 4.9 days (in fact, this period is also consistent with the ∼6-day period due to the large error bars).

The EW of the H\(\alpha\) line of 19 Cep in October 1991 shows a gradual variation consistent with the period of almost 5 days encountered in the Si \(\text{iv}\) and H\(\alpha\) profiles (Fig. 16), supporting that the 4.9-day period detected by the Fourier analysis is the “real” wind period. The EW corresponding to the Si \(\text{iv}\) DACs increases monotonically with time and from this behaviour we cannot infer when a new DAC event starts. The H\(\alpha\) incipient emission reaches a maximum at JD 52.3, about one day earlier than the appearance of a new DAC in the Si \(\text{iv}\) resonance lines. The beginning of a second DAC at JD 55.9 is not apparent in the H\(\alpha\) EW data.

We have not observed the H\(\alpha\) profile of 19 Cep without a central emission reversal. In May 1993 we observed 19 Cep again in H\(\alpha\) (no simultaneous IUE observations) and
detected a very strong emission peak in the center of the profile (see Fig. 17). This emission, centered at rest wavelength, approached the continuum level on May 21 and decreased rapidly in strength. On May 23 the central emission had returned to the “normal” level, similar to the spectra of October 1991. If the strength of the incipient emission is related to the column density of the DACs, the Hα emission detected in May 1993 might be related to a strong DAC event, perhaps similar to the one observed with IUE in August 1986 (see Paper I and II) with a Si IV column density of $10^{15}$ cm$^{-2}$, i.e., five times stronger than the DACs observed in October 1991.

3.7. λ Cep O6 I(n)fp

The time evolution of the Hα profile of the Of supergiant λ Cep in October 1991 is shown in Fig. 18. Variations in the emission line profiles of λ Cep have been previously reported (e.g. Conti & Frost 1974, see also Henrichs (1991) for results on the He II λ4686 line). The Hα line has broad emission wings with a P Cygni-type profile on top. On October 21 the blue-shifted absorption core was deepest, while on October 24 the blue emission wing was stronger. The variations are concentrated towards the blue side of the line.

We performed a period search on the Hα dataset (see Fig. 19) and found a maximum in power at a frequency of $0.21 \pm 0.05$ day$^{-1}$ (4.8 days). Again this period is longer than the 3.8 days covered by our observations. A second and third peak in the power spectrum are centered at a frequency of $0.84 \pm 0.06$ and $1.25 \pm 0.06$ day$^{-1}$ (1.2 and 0.8 days, respectively).

The ultraviolet resonance lines of λ Cep are saturated, and only the Si IV lines show signatures of DACs. In October 1991 DACs appear about every 1.4 days at a velocity close to 600 km s$^{-1}$. A Fourier analysis reveals a frequency of $0.73 \pm 0.09$ day$^{-1}$ (Paper II), close to the frequency of 0.84 day$^{-1}$ measured in the Hα line. The EW of the Hα line is plotted (filled circles) as a function of time in Fig. 20, along with a sine curve of period 1.2 days (dotted line). The appearance time of the Si IV DACs is indicated by “DAC”. The minima in Hα EW approximately coincide with the first detection of a new DAC. A phase lag between the cyclical variations in the Hα line and the appearance of DACs is, however, difficult to measure. We might suspect that the Hα line of λ Cep undergoes changes in both emission and absorption, as is observed for its He II λ4686 line (Conti & Frost 1974, Henrichs 1991).
3.8. 10 Lac O9 V

In November 1992 we detected a slowly evolving DAC in the ultraviolet N\textsc{v} line, at a velocity varying from $-700$ to $-1000$ km \text{s}^{-1} (Paper I). No evidence was found for variability at lower velocities. The H\textalpha line does not show any variability (see Fig. 8). This might be related to the relatively low wind density in late-O main-sequence stars.

3.9. Summary of observational results

We have detected the characteristic timescale of UV wind variability (as diagnosed by the regular appearance of DACs in UV resonance lines) in H\textalpha line profile variations for four stars in our sample: ξ Per, 68 Cyg, 19 Cep, and λ Cep. The total equivalent width of the H\textalpha line clearly demonstrates the periodic behaviour. In the case of α Cam and ζ Ori the H\textalpha dataset did not permit us to derive an accurate H\textalpha timescale, which is probably several days. For some stars the H\textalpha line is variable, while the UV resonance lines are not (α Cam), or vice versa (λ Ori and 10 Lac), which can be understood in terms of wind density and the line-formation process.

We conclude that the (cyclical) wind variability can be traced down to the region where the H\textalpha line is formed. Consequently, the H\textalpha line can be used as a diagnostic for (cyclical) wind variability, even for stars whose saturated UV resonance lines prohibit a variability study. For stars with relatively weak stellar winds, the H\textalpha line is apparently not strong enough to detect wind variability.

For ξ Per, 68 Cyg, and 19 Cep the variations in the H\textalpha line seem to be mainly caused by a varying amount of incipient emission. The supergiants α Cam, ζ Ori, and λ Cep might also have a variable and perhaps even dominant absorption contribution. This could explain why the H\textalpha equivalent width (an integrated quantity that does not discriminate between changes in absorption or emission) still reflects the cyclical variability.

We were able to measure a phase lag between the H\textalpha and DAC variability in the case of ξ Per, 68 Cyg, and 19 Cep. For ξ Per and 68 Cyg the H\textalpha EW reaches a minimum about half a day before the appearance of a DAC in the UV P Cygni lines. For 19 Cep this phase lag seems to be significantly longer, about one day.
4. Modelling the Hα and DAC variability

Hα variability in O-type stars is well known (see, e.g., Ebbets 1982), but the precise nature of these variations has remained unclear. DAC-related variability in strong optical lines like Hα has recently been proposed by Prinja & Fullerton (1994) for the O8: Iafpe star HD152408 and by Prinja et al. (1996) for HD151804 (O8 Iaf). In the He I λ5876 and/or the Hα profiles they find blueward migrating optical depth enhancements at low velocities (≤ 0.5 v∞) that are reminiscent of the DACs, which are commonly seen only at larger velocities in UV P Cygni profiles. Simultaneous UV data were, however, not available for these two extreme Of stars, so that the supposed further evolution towards higher velocities could not be studied; in any case, the UV resonance lines of these stars are saturated. On the basis of the phenomenological correspondence between the systematic variability observed in these deep-seated optical lines and the known behaviour of DACs in UV resonance lines, the authors conclude that both phenomena are caused by the same physical mechanism.

The observational evidence that the winds of O-type stars are rotationally modulated is becoming increasingly convincing. Time series of UV P Cygni lines obtained in different years reveal the same periodicity for a given star, and the period is in accordance with the estimated stellar rotation period (Kaper & Henrichs 1994, Paper I and II). Extended (> 10 days) continuous IUE campaigns carried out recently, support this conclusion (Massa et al. 1995 (MEGA campaign), Henrichs et al. 1996). Howarth et al. (1995) derive periods of 19.2 hr and 5.2 days from the IUE (MEGA) observations of the O4 I(n)f star ζ Pup. The 19.2 hr period is identified with the mean recurrence time scale of DACs, while the 5.2 day period would be the photospheric rotation period. The latter period is close to the 5.075 day period detected by Moffat & Michaud (1981) in Hα spectra. The 16.7 hr period detected in Hα (and X-ray) data by Berghöfer et al. (1996) does not seem to be present in the IUE data. Reid & Howarth (1996) find a 19.6 hr period in Hα data, plus a 8.54 hr period (in a velocity range extending to −700 km s−1) that is also detected in photospheric lines and attributed to non-radial pulsations. The comparison of the different datasets is in this case based on the periodicity only, in the absence of simultaneous observations.

The simultaneous optical and ultraviolet observations presented in this paper provided for the first time the possibility to study Hα variations in direct relation to the evolution of DACs in UV P Cygni lines. In the following we will argue that our observations support the Corotating Interacting Regions model (Mullan 1986, Cranmer & Owocki 1996).

4.1. Hα variability due to rotational modulation

Optical wind lines like Hα are predominantly formed by recombination; since this is a collisional process, the wind contribution to the line mainly arises in the high-density, near-star regions of the outflow. Therefore, it is plausible to assume that the vari-
able amount of incipient emission we observe in the \( H\alpha \) line of \( \xi \) Per, 68 Cyg, and 19 Cep is caused by structure in the inner-wind region. A precise quantification of the radial extent of the \( H\alpha \) line-forming region has to follow from detailed model calculations undertaken on a star-by-star basis (cf. Petrenz & Puls 1996).

The \( H\alpha \) time series for which we could successfully perform a Fourier analysis always included a periodic signal that can be identified with a period detected in the UV P Cygni lines. The length of this period is shorter for stars with larger projected rotation velocity and is consistent with (an integer fraction of) the estimated rotation period (see also Paper II). Consequently, we propose that the \( H\alpha \) line variability is also due to rotational modulation.

The phase lag measured between the minima in \( H\alpha \) EW and the appearance of DACs in the \( Si\ IV \) doublet is different for different stars. For \( \xi \) Per and 68 Cyg (\( v\sin i = 200 \) and 274 \( \text{km} \text{s}^{-1} \), respectively) the phase lag is about half a day. For 19 Cep (\( v\sin i = 75 \) \( \text{km} \text{s}^{-1} \)) it is longer, about one day. Although we have a few measurements only, it is tempting to attribute the difference in phase lag to a difference in rotation period.

4.2. Corotating Interacting Region model

The above arguments point to an interpretation in terms of the Corotating Interacting Region model (Mullan 1984,1986). In this model, structure in the stellar wind is caused by the interaction of fast and slow wind streams that originate at neighbouring locations on the stellar surface. Due to the rotation of the star the streams are curved, causing fast wind material to collide with slow wind material in front of it. As a result, the interaction region also has a curved shape and corotates with the star. The wind material itself flows in a (nearly) radial direction under conservation of its angular momentum, but does not corotate with the star. It meets the interaction region at a distance from the star that depends on a variety of things, including its original location on the stellar surface.

Recently, Cranmer & Owocki (1996) presented two-dimensional hydrodynamical simulations of corotating stream structure in the wind of a rotating O star. They induced an azimuthal variation in the outflow by a local increase or decrease in the radiative driving force, as would arise from a bright or dark “star spot” in the equatorial plane. Above a bright spot the mass-loss rate is enhanced and the corresponding wind stream will reach a lower terminal velocity. The faster, undisturbed wind catches up with the slow stream and interacts at its trailing border (see Fig. 21, which is adapted from Cranmer & Owocki 1996). Region I indicates the enhanced density of the slow stream coming from the bright spot in the equatorial plane. The corotating weak shock compression region (III) has the highest density.
with respect to the undisturbed wind. In absolute terms, however, the highest density is reached in region I, close to the star spot near the stellar surface and not in the CIR compression (S. R. Cranmer, private comm.); this will be of importance for the location of the formation region of incipient Hα emission. Cranmer & Owocki further argue that the largest relative contribution to the Sobolev optical depth comes from region V, the so-called radiative-acoustic kink. The resulting synthetic UV resonance line profiles show signatures reminiscent of DACs which, in this example, have a recurrence timescale of half the rotation period (if the two CIRs are identical).

The large-scale wind structure described above should be distinguished from small-scale wind structure that arises from the intrinsic instability of a radiation-driven wind (Owocki et al. 1988, Owocki 1992). It should be noted that this small-scale instability was not included in the models by Cranmer and Owocki (1996). The small-scale “clumpy” structure may explain the black troughs in saturated UV resonance lines (Lucy 1982, Puls et al. 1993) and the generation of shock-heated X-ray emission (Lucy 1982, MacFarlane & Cassinelli 1989, Cooper & Owocki 1994) observed for many OB stars.

We can check the consistency of our Hα and UV observations with the CIR model. A DAC is present in a UV resonance line when (part of) area V is located in the line of sight, which we situate in Fig. 21 as the column parallel to the line $x/R_\star = 0$ ($y/R_\star < 0$) covering the star. We assume that region I contributes most of the additional Hα emission related to the CIR structure, since this region has the highest density. For simplicity we consider only the CIR region located in the upper-left quadrant of Fig. 21 (and neglect the other one). In the situation sketched in Fig. 21, we would only see some additional Hα emission from region I. This emission should be slightly blue-shifted (in the stellar rest frame), since the wind material close to the star has a velocity component in the direction of the stellar rotation. The wind material is, however, not in corotation with the star (contrary to the CIR pattern). There is no CIR-related material in the line of sight, so that additional absorption, e.g., in the form of a DAC, is not observed.

What is the expected time evolution if the CIR model applies to our observations? The star and CIR pattern illustrated in Fig. 21 rotate counter-clockwise; rotating the line of sight in the opposite direction (clockwise) has the same effect. A quarter of a rotation period later (i.e., $90^\circ$ rotation), region I is inside the line of sight and the border of region V (which produces a DAC at low velocity in e.g. the NⅣ and SiⅣ line) enters it. This would mark the appearance of a DAC. The wind material in Region I has a velocity component towards the observer and would cause blue-shifted emission (or absorption) in the Hα profile. Rotating further, Region I leaves the line of sight while the DAC produced by Region V will move towards higher velocity. The Hα emission will be observed close to rest wavelength again. In principle, after half a rotation period one should observe slightly
red-shifted Hα emission until Region I is eclipsed by the star. By then, the DAC from Region V would probably have reached its asymptotic velocity.

We conclude that a time lag between the occurrence of incipient Hα emission and the first appearance of a DAC is predicted by the CIR model. Obviously, this time lag should be longer for more slowly rotating stars. In Table 2 we list the measured time lag $\Delta t$ between Hα and the subsequent appearance of a DAC in the Si iv emission lines, assuming that a minimum in Hα EW (maximum incipient emission) corresponds to the situation that Region I is in front of the star. To estimate the angular distance between Region I and the region where DACs are formed, we define the relative time lag $f$ as $\Delta t/P_{\text{wind}}$. The average value of $f$ for the 10 estimates we could make (see Table 2) is $0.21 \pm 0.08$. In our interpretation $P_{\text{wind}}$ equals an integral fraction $1/n$ of the stellar rotation period. Then, the relative time lag $f$ corresponds to an angular distance of $1/n$ (76° ± 29°).

If the inclination of the rotation axis $i$ and the stellar radius are known, the rotation period of the star can be derived from the projected rotational velocity $v \sin i$. In practice, $i$ is not known; however, the break-up velocity on the one hand and the case $\sin i = 1$ on the other result in, respectively, a lower and an upper limit to the stellar rotation period, provided that an estimate is available for the stellar radius (see Paper I). For some stars (e.g., ξ Per, 68 Cyg), the DAC behaviour clearly indicates that $n$ is bigger than one (cf. Paper II), most probably $n = 2$ in these cases. Since for most of our targets $P_{\text{wind}}$ is already close to the maximum rotation period (when $\sin i = 1$), $n$ cannot be much bigger than 2. Therefore, our observations suggest that the number of CIRs in the stellar wind is not large: $n = 2$ would be a good estimate.

Another prediction following from the application of the CIR model is that the development of a DAC in the UV wind lines should be preceded by blue-shifted Hα emission when region I appears at the approaching limb of the star. From Fig. 1 it is clear that such episodes indeed happen before a DAC starts to develop, but often prominent red-shifted emission is also found, in particular for ξ Per and 19 Cep. It might well be that this red-shifted emission is related to a region I at the receding limb of the star. Especially when more than one CIR is present in the wind of the star, which seems to be likely in several cases (cf. Paper II), it will be hard to disentangle the contributions from different CIRs to the line profile. Obviously, the time sampling of our Hα data is too sparse to check this prediction. A detailed modelling of the complex Hα profile behaviour would be required anyhow.

The calculations of Cramer & Owocki show that a larger bright spot amplitude (i.e. a higher mass-loss rate from the spot) will result in a higher column density of the DAC. Thus, one expects that stronger incipient Hα emission, when formed in Region I, would subsequently correspond to a stronger DAC. Although our data do not provide a definite answer, for ξ Per we can relate the appearance of the emission bump (i.e. strong incipient emission) in Hα to a strong DAC, while the subsequent event (a day later) seems to be less strong, in accordance with the weaker incipient Hα emission. We expect that the strong incipient Hα emission observed for 19 Cep in May 1993 (Fig. 17) would have been followed by a strong DAC such as e.g. detected in August 1986 (see Paper I and II), but unfortunately coordinated UV data do not exist to check this.

5. Discussion

In the previous section we argued that the observed cyclical variability in both Hα and the UV P Cygni lines can be interpreted in terms of the CIR model. A key ingredient of this model is the existence of interacting fast and slow wind streams that originate at different locations on the stellar surface. Cramer & Owocki (1996) postulated bright (or dark) spots on the stellar surface above which the emerging flow has different kinematical properties. If the CIR model is correct, an explanation has to be found for the presence of these regions on the stellar surface. The ubiquity of DACs in O-star P Cygni lines and the recurrence of similar DAC patterns over a timescale of years (Paper II) indicate that the physical process responsible for the formation of slow (or fast) streams has to be rather stable. In practice, only two processes are serious candidates for the occurrence of stellar-surface structure: non-radial pulsations or a surface magnetic field.

5.1. Non-radial pulsations

Line-profile variability is a ubiquitous phenomenon among the O-type stars. Fullerton et al. (1996) conducted a spectroscopic survey of a magnitude-limited sample of O stars (30 in total) and detected significant line-profile variations in 77% of them. The amplitude of these variations seems to be a function of luminosity class: all supergiants in their sample show variability in the optical line spectrum, while the non-variable stars are mostly dwarfs. Since the distribution of the line-profile variables in the HR-diagram agrees approximately with the predicted domain.
of strange-mode oscillations (Kiriakidis et al. 1993), Fullerton et al. propose that the prominent stellar-wind variability exhibited by most O stars might be understood as a reflection of the underlying distribution of pulsational instability.

Alternatively, the observed variability might reflect “pure” wind variability, since the density of the stellar wind is much higher for supergiants than for main-sequence stars. Consequently, variability in the wind of main-sequence stars is much more difficult to detect in the optical spectrum.

Optical observations with high time- and spectral resolution of a few O stars has revealed line-profile variability that can be attributed to non-radial pulsations (NRP). Henrichs (1991) detected NRP-like variability in the O6 I(n)f star λ Cep. Reid et al. (1993) found periodic variability in the form of “moving bumps” in absorption lines in the optical spectrum of the rapidly rotating O9.5 V star ζ Oph, which is the object Vogt & Penrod (1983) used to demonstrate the impact of a velocity field due to NRP on a rotationally broadened line profile. However, Howarth et al. (1993) did not find any evidence to suggest that the NRP of ζ Oph have a direct relationship to its DACs on long (years) or short (hours) timescales.

The O4 I(n)f star ζ Pup appears to be a better candidate to demonstrate a relation between photospheric and wind variability (the “photospheric connection”). Reid & Howarth (1996) showed that the temporal behaviour of the Hα profile indicates the presence of both an 8.54 hr (interpreted in other absorption lines as NRP) and a 19.6 hr period (corresponding to the recurrence time of DACs). Although the authors state that this provides the first evidence for a dynamical response of a radiation-driven wind to basal velocity fields, the Hα profile is probably formed in a region that includes both the photosphere and the base of the stellar wind and might therefore reflect a combination of two “independent” types of variability (the 8.54 hr period is not detected in the UV resonance lines, see Howarth et al. 1995).

It might well be that all O stars are non-radial pulsators and, in principle, associated photospheric velocity and density variations can have a perturbing effect on a radiation-driven wind (Owocki et al. 1988). Owocki et al. (1995) explained the periodic variations in the UV lines of the B0.5 Ib star HD 64760 with a CIR model, in which the fast and slow wind streams are possibly related to a density variation over the stellar surface due to NRP (see also Fullerton et al. 1997).

However, if NRP are the surface structures that trigger the cyclic stellar-wind variability, then it is not clear why the periods obtained from stellar wind features should be so closely related to the rotational period of the underlying star. Such a relation is probably valid over short time intervals for stars that rotate sufficiently rapidly, since in these cases the rotational velocity will dominate the observed azimuthal motion of the pulsational distortions. Consequently, the wind variations would have periods that are submultiples of the rotational period, where the number of repetitions of the wind structure per rotational cycle depends on the surface distribution of amplitude associated with the dominant pulsational mode. This relationship is unlikely to hold for more slowly rotating stars, when the azimuthal velocity of the pulsations is comparable to or greater than the rotational velocity of the star. Even in the case of rapidly rotating stars, the azimuthal velocity of the pulsations will cause the pattern of wind perturbations to evolve slowly, so that the wind variability will not maintain coherence over long intervals of time. Although these considerations do not eliminate NRP from contention as a source of photospheric perturbations, they suggest that pulsations are unlikely to be the source of the cyclical stellar-wind variability in all cases.

5.2. Magnetic fields

As put forward by Henrichs et al. (1994a) and (1994b), in our opinion the strongest candidate for causing fast and slow streams in the stellar wind is a (weak) magnetic field acting at the base of the wind. Unfortunately, there are no confirmed magnetic field detections for our program stars. The detection limit is of the order of 100 G. However, present techniques allow detection of only the component of the field strength in the line of sight (see Landstreet 1992 for a review), and in the model described above, this component will be modulated with the stellar rotation period, which means that most of the time only a very small field component would be detectable.

The first results of an attempt to measure with this technique the magnetic field of ξ Per, simultaneously with wind variations, have been summarized by Henrichs et al. (1995, 1996, and in preparation), who obtained values between +135 and −80 G, with 1 sigma error bars of 70 G. These values are not inconsistent with what is expected, and set a firm upper limit. Future techniques, based on the Hanle effect as discussed by Ignace et al. (1997), might significantly improve the detection limit.

It is important to note that the magnetic field configuration is totally unknown. In the simulation of corotating stream structures in the wind by Cranmer & Owocki (1996) the best agreement with the observed P Cygni variability is obtained with the model containing a ‘bright’ spot with enhanced mass flux. The only role of the presumably small magnetic field is to provide locally a lower boundary condition for the wind that is different from elsewhere at the stellar surface. A simple estimate shows that for ξ Per a field strength of less than 100 G will already be competing with the atmospheric pressure, consistent with the upper limit mentioned above.

Indirect observational evidence for surface magnetic fields in O-type stars has been presented in a few cases. Moffat & Michaud (1981) suggested that the period of 5.075d observed in the Hα line of ζ Pup corresponds to the rotation period of the star, while the line variations are caused by a multipole magnetic field anchored in the star. Recent observations of the “Trapezium” O7 V star θ Ori C (Stahl et al. 1996) indicate phase-locked photospheric and stellar-wind variations which strongly suggest that this star is an oblique magnetic rotator. This suggestion is supported by the reminiscence of the variability to that observed in σ Ori E (a He-strong variable, cf. Bolton et al. 1987, Shore & Brown 1990). Also X-ray observations of θ Ori C (Gagné et al. 1997) seem to be consistent with this interpretation. It remains to be seen whether θ Ori C
is a member of a separate class of magnetic O stars, or just an extreme case with a stronger magnetic field.

From the theoretical side one expects weak magnetic fields to be present in O stars under certain conditions (Maheswaran & Cassinelli 1988, 1992). Models of magnetically coupled winds in early-type stars have been considered by Friend & MacGregor (1984). MacGregor et al. (1992) derive an upper limit for magnetic field strengths (< 100 G) by considering the consequences of such winds for the rotational evolution of O and B stars. If the magnetic origin of the DACs is confirmed, an estimate of the timescale during which the magnetic field(s) keeps the same configuration can be obtained by comparing the DAC behaviour over many rotation periods. Since the DAC patterns in ξ Per over five years are similar but not identical (Fig. 4 in Paper II) a lifetime of several months (tens of stellar rotation periods) can be inferred for this star. Similar timescales would apply to 68 Cyg, 19 Cep, and λ Cep (i.e., the targets observed during several campaigns).

Based on these arguments we predict that weak surface magnetic fields (about 100 G or less) are present in ξ Per, 19 Cep, 68 Cyg, and λ Cep; the detection of these fields will be a significant test for the Corotating Interaction Region model. The surface magnetic field might have a fossile origin; in this case one would predict that main sequence stars have stronger magnetic fields compared to supergiants. A consequence would, however, be that the supergiants evolving from these “magnetic” main sequence stars are not rotating very rapidly because of magnetic braking and expansion. This does not seem to be supported by the observations. Alternatively, massive stars might generate weak magnetic fields in their convective layers appearing just below the surface (Glatzel & Kiriakidis 1993, Alberts 1994). However, a quantitative estimate of the field evolution does not exist.

In the picture as described here, DACs should occur shortly after e.g, a magnetic patch or pole appears at the approaching limb. The symmetry axis of a dipole field should have a considerable tilt with respect to the stellar rotation axis in order to explain the regular recurrence of DACs in the line of sight towards the observer. Higher order fields, or more patches, will give rise to more DACs in a given rotation period. In this interpretation, the strength of the DACs depends on the field strength, since this would enhance the “kinematical” contrast between the different regions in the stellar wind.

5.3. Summary

We have presented observational evidence that the variability of the winds in O-type stars, as observed in the form of DACs in UV P Cygni lines, can be traced down to the region where Hα is formed, which is close to the stellar surface. The variations are interpreted in terms of the Corotating Interacting Regions model. We argue that the most likely explanation for the occurrence of these variations is the presence of a surface magnetic field. Detection of such a field would be the key test for such a model.

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References

Giddings, J.R. 1981, ESA IUE Newsletter, No. 12, p. 22
Glatzel, W., Kiriakidis, M. 1993, MN 262, 85
Landstreet, J.D., 1992, A&AR, 4, 35
Heber & Jeffery, Springer Berlin, p. 393

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