TIME-DEPENDENT PHENOMENA IN OB STAR WINDS

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Abstract. Spectroscopic observations are discussed which indicate that the winds of luminous OB stars are highly structured in space and variable in time. Blueward migrating discrete optical depth enhancements in the absorption troughs of P Cygni profiles are the characteristic signatures of the evolving structure. Constraints on physical mechanisms are discussed, provided by the observed accelerations of the migrating features, the evidence for rotationally modulated variability, and the behaviour of the winds at very low velocities.

1. Observations of Evolving Wind Structure

I shall discuss here some of the recent developments in our understanding of the time-variable nature of winds in luminous OB stars. The view I present is mostly as witnessed by the remarkable *IUE* satellite, since UV spectroscopy still provides one of the most sensitive probes of hot, stellar outflows.

One of the important discoveries made with *IUE* data is that the UV resonance line P Cygni profiles of OB star are *systematically* variable on time scales down to less than 1 hour, and that the profile changes are primarily due to variable "Discrete Absorption Components" (DACs). Recent reviews of DAC properties in OB stars have been provided by Henrichs (1988), Prinja (1992) and Howarth (1992). The DACs are initially recognised as localised optical depth enhancements at typically ≥ 0.3 of the wind terminal velocity (v_∞), in the absorption troughs of the UV P Cygni profiles. They subsequently accelerate to the shortward wing of the profile over $\sim$ 1–2 days, and usually recur at intervals of $\geq$ 1 day. The full-width at half-maximum of the absorption enhancements may vary over $\sim 0.05v_\infty$ to $0.25v_\infty$, with some dependence on the central velocity. Typical Si^{3+} column densities due to DACs range from $\sim 1 \times 10^{13}$ cm^{-2} to $\sim 3 \times 10^{14}$ cm^{-2} (assuming locally plane-parallel geometry). Migrating DACs have now been reported in the UV wind lines of a wide range of hot stars, including early, mid and late O-type dwarfs, giants and supergiants, plus early B supergiants, and a WN7 Wolf-Rayet star. Individual case studies combine with surveys of the time-averaged wind properties (e.g. Howarth & Prinja 1989), to suggest that evolving optical depth enhancements are present all the time in the wind-formed UV lines of most O stars.

The progressive DACs provide direct evidence that the winds of OB stars are highly structured in space. The structures must be substantial and large scale since DACs can account for $\sim$ 20% to 50% of the wind line profile, with observed central optical depths which often exceed 0.5. Clues that

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the DAC line-formation region is *not* spherically symmetric come from noting that the observed profile variability is confined (in *IUE* data) to the absorption regions only, with no corresponding fluctuations evident in the emission components of the P Cygni profiles. The structured nature of hot star winds has some bearing on the determination of important parameters such as mass-loss rate, terminal velocity, ionization balance, and on theories concerned with the hydrodynamics of the outflows. An attractive physical process for generating a degree of evolving wind structure is that due to strong line-driven instabilities (see e.g. reviews by Owocki 1991, 1992). The radiation hydrodynamics simulations of Puls *et al.* (1993) show for example that the evolution of dense clumps formed in the wind due to the action of the radiative instability do indeed reproduce some of the observed DAC behaviour.

I discuss below three aspects of the observed time-dependent nature of OB star winds which are relevant to the development of physical models addressing evolving wind structure; i.e. (i) the observed DAC accelerations, (ii) evidence for rotationally modulated variability, and (iii) the behaviour of the wind at very low velocities ($\ll 0.3v_\infty$).

2. The Observed DAC Accelerations

The observations of DACs moving through line profiles provides an important, and rare, opportunity to determine directly the acceleration of material associated with hot stellar winds. The ranges of DAC accelerations for 10 hot stars are listed in Table 1, based on UV and optical spectroscopic time-series studies. Typically, the acceleration of the UV absorption enhancement is largest ($\sim$ 2–3 $\times$ 10^{-2} km s^{-2}) close to its initial observed central velocity ($\sim$ 0.3–0.5v_∞), where the feature may be more than 600 km s^{-1} broad. The acceleration decreases to $\leq 1 \times 10^{-3}$ km s^{-2} towards the 'end-point' of the DAC evolution, where a narrow absorption component ($\leq$ 100 km s^{-1} wide) becomes 'lost' in the blue edge of the line profile. The trend of acceleration as a function of velocity is variable for different DACs in an individual star. The accelerations of sequential features in a star are not always the same for example at similar velocities. Indeed, there are no clear cases where it may be argued—from the recorded trends of central velocity, width, acceleration, and strength—that a given structure has entered the line-of-sight more than once during time-series observations typically spanning $\sim$ 2–5 days.

All the DAC accelerations listed in Table 1 are slow in comparison with steady-state wind model predictions. The observed accelerations of representative DACs in the UV spectra of ζ Pup, 68 Cygni, and HD 64760 are plotted as a function of central velocity in Fig. 1. The corresponding accelerations

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TABLE I
Observed DAC accelerations

Star	Sp. type	DAC velocity range (v_c/v_∞)	DAC acceleration range (10^{-2} km s^{-2})	Reference
HD 93131	WN 7	0.55–0.85	~ 1.0–0.15	Prinja & Smith (1992)
ζ Pup	O4 I(n)f	0.30–0.75	~ 3.2–0.10	Prinja *et al.* (1992)
λ Cep	O6 I(n)fp	0.26–0.75	~ 2.2–0.20	Kaper (1993)
68 Cyg	O7.5 III:n((f))	0.47–0.95	~ 3.0–0.05	Fullerton *et al.* (1991)
ξ Per	O7.5 III(n)((f))	0.70–0.90	~ 3.0–0.50	Prinja *et al.* (1987)
HD 152408	O8:Iafpe	0.05–0.45	~ 0.15–0.05	Prinja & Fullerton (1994)
HD 151804	O8 Iaf	0.12–0.48	~ 0.35–0.10	Fullerton *et al.* (1992)
19 Cep	O9.5 Ib	0.53–0.73	~ 0.10	Prinja (1992)
ζ Oph	O9.5 V	0.80–0.96	~ 0.20–0.05	Howarth *et al.* (1993)
HD 64760	B0.5 Ib	0.17–0.95	~ 2.0–0.10	Massa *et al.* (1994)

expected for a velocity law of the type $w = w_0 + (1 - w_0)(1 - R_\star/r)^\beta$ for $\beta = 1$ are also shown (e.g. steady-state wind calculations of Friend & Abbott 1986; Pauldrach, Puls & Kudritzki 1986). The observed DAC accelerations are frequently less than 50% of the acceleration expected for the ambient stellar wind. However, the successes of the steady-state wind models (see e.g. Pauldrach, Puls & Kudritzki 1986), the overall observed morphology of the P Cygni profiles (e.g. Groenewegen & Lamers 1989), and the global O star density structures based on Hα observations (e.g. Leitherer 1988), all combine to indicate persuasively that the mass-flux in the time-averaged hot star wind follows a $\beta \sim 0.8$–1 type velocity law. This apparent discrepancy is resolved by the notion that the migrating DACs are due to perturbations or structures in the outflow, through which stellar wind material flows (i.e. we are not observing the same mass-conserving feature at all times). Fullerton & Owocki (1992), for example, picture this perturbation as a plateau in the flow that varies in velocity and radial extent as a function of time. The wind material flows through the plateau, and the observed acceleration of the optical depth enhancement is then associated with the (slow) motion of the plateau, rather than the acceleration of the global mass-flux.

Ultimately, numerical hydrodynamical simulations of (intrinsic or induced) wind perturbations, yielding DAC-like structures, need to match, (i) the initial broadening (to FWHM $\sim 0.25 v_\infty$) and subsequent narrowing ($\leq 0.1 v_\infty$) of the absorption enhancement as a function of increasing velocity, (ii) the

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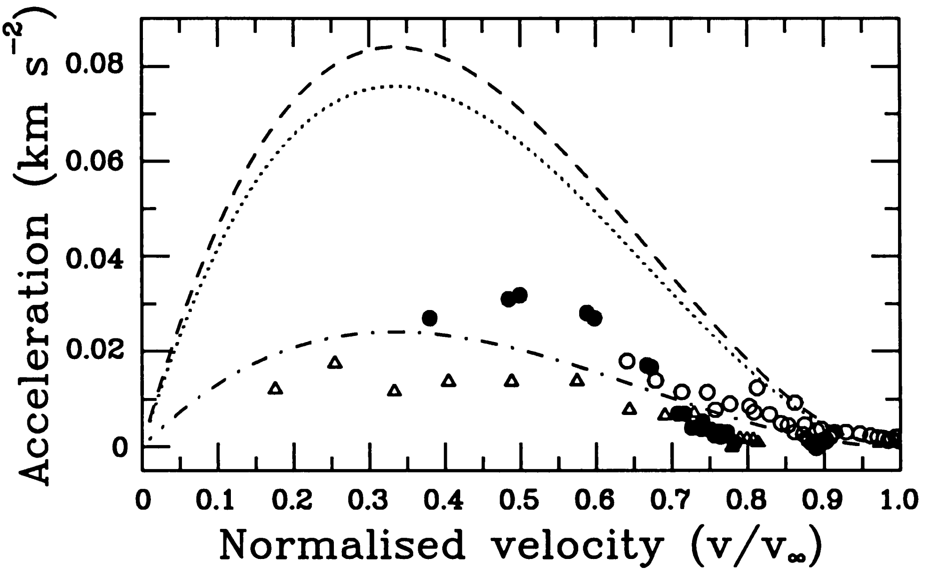

Fig. 1. The observed accelerations of representative DACs in ζ Pup (•), 68 Cyg (O) and HD 64760 (filled triangles), compared with predictions from a standard "β=1 type" velocity law (ζ Pup, dotted line; 68 Cyg, dashed line; HD 64760, dot-dashed line).

corresponding acceleration range of $\sim 2 \times 10^{-2}$ km s^{-2} to $< 1 \times 10^{-3}$ km s^{-2}, (iii) a separation time between successive episodes of ≥ 1 day, and (iv) changes in the total absorption equivalent width of the spectral line due to DACs that can exceed 50%.

3. Rotationally Modulated Wind Variability

An important finding in recent studies of stellar outflows is that the observed systematic wind variability in OB stars has some relation to the stellar projected rotation velocity ($v_e \sin i$). In particular, the time scales for the development and recurrence of discrete absorption features in O stars is dependent on stellar rotation, with a trend of faster-developing, and more frequent features, with increasing $v_e \sin i$ (see Prinja 1988; Henrichs *et al.* 1988; Prinja 1992; Kaper 1993). Some estimates for DAC recurrence times based on *IUE* spectroscopy, are given in Table 2 for 8 OB stars, together with values of $v_e \sin i$ and the maximum rotation period. Discrete absorption features typically recur every 15 – 30 hours in the fast rotators. For the low $v_e \sin i$ cases, the upper limit for the DAC recurrence time is not constrained by data sets covering ≥ 3 days.

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TABLE II
DAC recurrence times versus stellar rotation

Star	Sp. type	$v_e \sin i$ (km s^{-1})	P_{rot} (max.) (days)	DAC recurrence time (days)
ζ Oph	O9.5 V	400	1.1	~ 0.8
68 Cyg	O7.5 III:n((f))	315	2.3	~ 0.7
HD 64760	B0.5 Ib	238	4.9	~ 0.9
ζ Pup	O4 I(n)f	230	4.0	~ 0.6
ξ Per	O7.5 III(n)((f))	215	2.6	~ 1.3
HD 164402	B0 Ib	90	13.5	> 3.0
HD 162978	O7.5 II((f))	80	10.1	> 3.0
19 Cep	O9.5 Ib	40	22.8	> 2.5

This is an intriguing result that highlights the rotation period of a star as playing a key role in determining the characteristic time scale of variability in early-type stars. However, the origin and nature of this connection is not known. Since the majority of currently available *IUE* hot star time-series data sets barely cover 1–2 rotation cycles, the repeatability of the DAC behaviour (and wind structure) has yet to be established or discredited. An important unresolved issue is whether the recurrence of the DACs is *strictly* periodic. Spectroscopic monitoring of wind lines over at least 4 or 5 successive rotation periods is required for a rigorous determination of the DAC recurrence time, and to test whether it is commensurate with reasonable estimates of the stellar rotation period. Detailed DAC properties may be used to establish whether a given structure in the wind enters the line-of-sight on several occasions, in phase with the rotation of the star.

In the absence of such rigorous observational details, physical models attempting to connect wind activity and stellar rotation are poorly constrained, and perhaps premature. The key question of whether stellar rotation is simply a characteristic time scale for the wind variability, or whether it is directly related to the formation of DACs has a major impact on models of wind activity. In the former case the rotation related time scale may result, for example, from increased shear near the stellar surface, with observations probing the interaction between rotation and structure due to wind instabilities. Alternatively, if intensive observations demonstrate that the individual DACs are indeed periodic and tied to stellar rotation, then it is difficult to avoid a direct link to features rooted on the surface of the star. For example, Mullan (1984, 1986)—by analogy to the case of the solar wind—suggested that the entire hot star wind may be pictured in terms of 'corotating interaction regions', created at the interface of fast and slow wind streams (tied to surface magnetic fields). The interaction regions may then result in the formation of periodic DACs. The notion of surface magnetic fields playing a substantial role in hot star wind activity raises several open issues: (i) the precise physical form expected for O star winds, which are clearly dominated by radiation-pressure driving, (ii) the ubiquity of magnetic fields (and their detection) in luminous hot stars with a wide range of e.g. effective temperature, log g, luminosity (i.e. the range over which DACs are observed), (iii) the predicted morphology of the wind-formed line profiles.

4. The Stellar Wind at Low Velocities

The low-velocity, near-star, regions of the outflows deserve special attention since details on the time-dependant behaviour in this regime impact on the growth rate of perturbations, the stability of the inner wind, and the origin of wind variability. I discuss in this section new results concerning low-velocity variability, based on recent optical and UV case studies of HD 152408 (O8: Iafpe; Prinja & Fullerton 1994) and HD 64760 (B0.5 Ib; Massa, Prinja & Fullerton 1994).

4.1. Observations of structure down to $\leq 0.1v_\infty$

Prinja & Fullerton (1994) presented an optical spectroscopic analysis of wind lines in the extreme O supergiant HD 152408. Systematic variability on $\sim$ hourly time scales is particularly apparent in the well developed, recombination formed, He I λ5876 P Cygni profiles. These changes indicate the presence of evolving wind structure, which takes the form of blueward-migrating, discrete optical depth enhancements. Four distinct features may be identified in the full data set over $\sim$ 3 days, progressing slowly bluewards from a velocity of ~ -50 km s^{-1} ($\sim 0.05v_\infty$) at formation, to ~ -500 km s^{-1} at the blue edge of the He I λ5876 profile. The variations in width (FWHM between about $0.08v_\infty$ and $0.25v_\infty$) and the slow accelerations of the DACs (see Table 1) are reminiscent of the behaviour of migrating features generally seen at $\geq 0.3v_\infty$ in UV P Cygni profiles of OB stars. The stellar wind of HD 152408 is therefore structured down to very small velocities, and presumably, very small heights above the photosphere.

Although the unambiguous identification of individual, discrete absorption features in the UV spectra of OB stars is mostly limited to initial velocities $\geq 0.3v_\infty$, Massa, Prinja & Fullerton (1994) have demonstrated the presence of DACs at substantially lower velocities in HD 64760 (B0.5 Ib). A gray scale image showing the time-dependent behaviour of the Si IV $\lambda\lambda$1393.76, 1402.77 resonance line P Cygni profile is shown in Fig. 2. Up to six sequential DACs may be identified in Si IV over $\sim$ 6 days, with formation

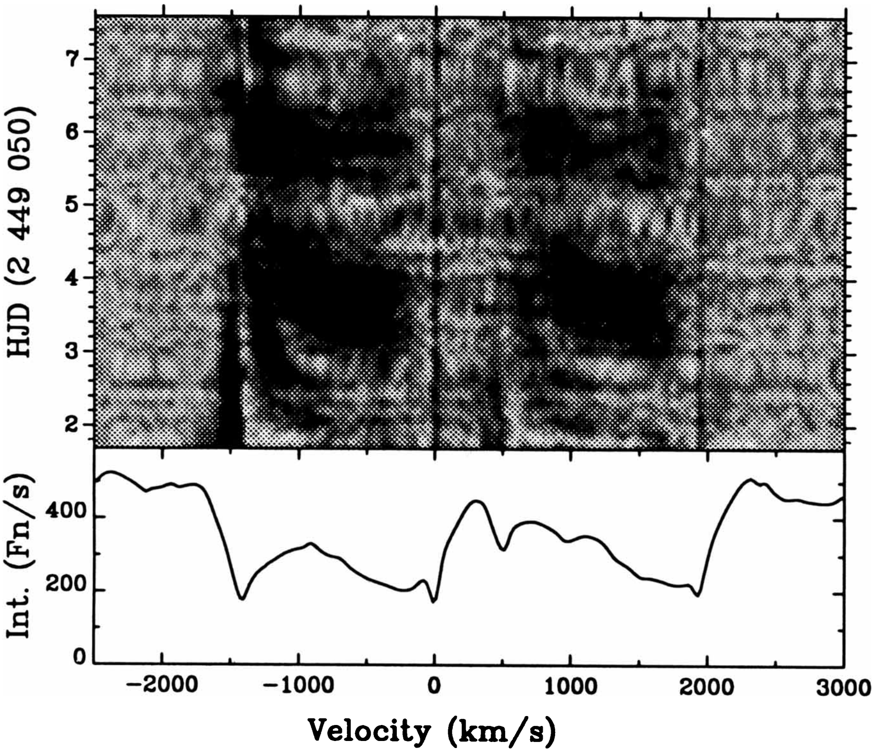

Fig. 2. Gray scale representation of the variable behaviour of the Si IV λλ1393.76, 1402.77 P Cygni profile in HD 64760 over ∼ 6 days. Individual spectra are normalised by a minimum absorption (maximum flux) template (bottom panel). Blueward migrating DACs are evident from very low velocities (dark shades).

velocities spanning $\sim 0.03v_\infty$ to $\sim 0.24v_\infty$. (Similar results are obtained from the Si III λ1206.51 wind-formed line). HD 64760 is thus another example of a hot star exhibiting extensive stellar wind structure deep in the outflow (see also the optical study of HD 151804 by Fullerton, Gies & Bolton 1992). In the context of the "line-driven instability model" (*e.g.* Owocki 1991, 1992), these results indicate that the growth rate of perturbations must remain large deep in the wind, despite the effect of line drag. Since UV observations show that, in general, the high-velocity portion of OB star wind is also variable, it seems likely that systematic structure occurs at some level throughout the hot stellar outflow.

4.2. A DEEP-SEATED CONNECTION?

Another similarity between the HD 152408 and HD 64760 is that in both cases the recorded appearance of a low-velocity DAC was preceded by velocity disturbances near the photosphere of the stars. Prinja & Fullerton (1994) detected one instance of a blueward shift of ∼ 7 km/s in the weak metallic

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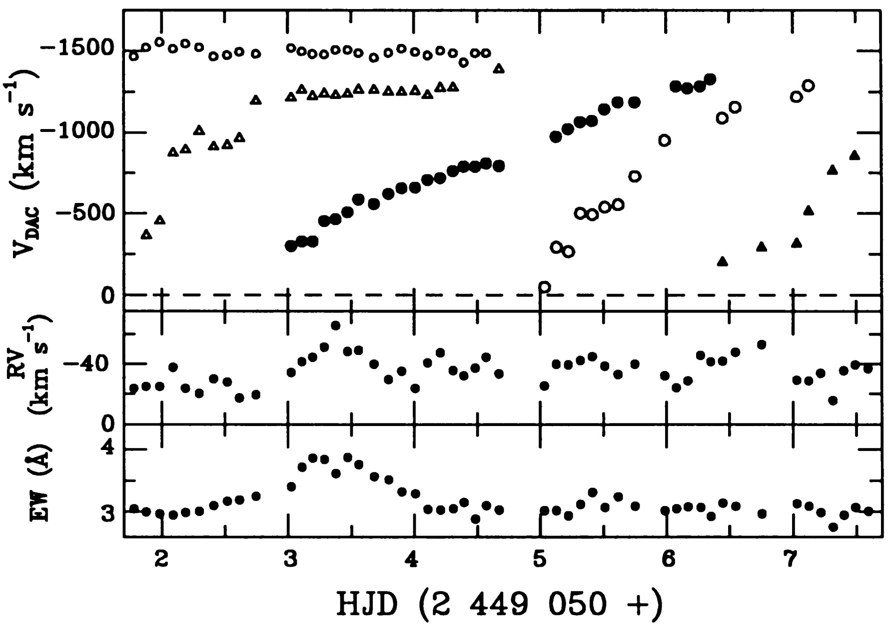

Fig. 3. The central velocities of progressive DACs in the Si III λ1206.51 profiles of HD 64760 (top panel). The corresponding changes in the total absorption equivalent width of the Si III λ1300 (photospheric) triplet and the central velocity of the Si III λ1299 line are also shown (bottom and middle panels, respectively). Note the substantial change in the Si III λ1300 strength and velocities during the formation on the strong DAC at ~ HJD 2 449 053.0.

emission lines of N III λλ5320, 5327 and C III λ5696, ~ 5 hours prior to the initial detection of a DAC at ~ −40 km/s. The metal emission lines are likely formed very close to the stellar surface.

The central velocities of DACs in the Si III λ1206.51 line of HD 64760 are shown in Fig. 3 as a function of time. Also plotted here are the total absorption equivalent width of the Si III λ1300 (photospheric) triplet and the observed central velocity of the Si III λ1299 component. A substantial increase in Si III λ1300 strength, plus a velocity shift of ~ 40 km/s, is noted in clear association with the formation of the strongest observed DAC at ~ HJD 2 449 053.0. The Si III λ1300 UV photospheric lines are sensitive temperature and surface gravity diagnostics in early B stars, and may also show wind effects (*e.g.* Massa 1989, Massa *et al.* 1992). Therefore these lines likely sample both the photosphere and the densest regions of the stellar wind. It is an interesting possibility then that the observed disturbances in these lines are perhaps a precursor to the appearance of DACs at low velocities. These changes may for example diagnose the initial evolution and growth of the line-driven instability.

Further observations are needed to establish whether the perturbations near the photosphere in HD 152408 and HD 64760 are *causally* connected with the development of the DACs, and therefore provide the trigger for the subsequent formation of extended stellar wind structures.

References

Friend, D.B. and Abbott, D.C.: 1986, *Astrophys. J.* **311**, 701.

Fullerton, A.W., Bolton, C.T., Garmany, C.D., Gies, D.R., Henrichs, H.F., Howarth, I.D., Kaper, L., McDavid, D., Prinja, R.K. and Zwarthoed, G.A.A.: 1991, in Baade, D., ed., *ESO Workshop on Rapid Variability of OB-Stars: Nature and Diagnostic Value, ESO Conf. proc. 36*, ESO: Garching, 213.

Fullerton, A.W., Gies, D.R. and Bolton, C.T.: 1992, *Astrophys. J.* **390**, 650.

Fullerton, A.W. and Owocki, S.P.: 1992, in Drissen, L., Leitherer, C. and Nota, A., eds., *Nonisotropic and Variable Outflows from Stars*, Astr. Soc. Pacific Conf. Series 22, 177.

Groenewegen, M.A.T. and Lamers, H.J.G.L.M.: 1989, *Astron. Astrophys. Suppl.* **79**, 539.

Henrichs, H.F.: 1988, in Conti, P.S. and Underhill, A.B., eds., *O Stars and Wolf-Rayet Stars*, NASA SP–497, 199.

Henrichs, H.F., Kaper, L. and Zwarthoed, G.A.A.: 1988, in *A Decade of UV Astronomy with the IUE satellite.* ESA SP–281 **2**, 145.

Howarth, I.D.: 1992, in Drissen L., Leitherer C. and Nota A., eds., *Nonisotropic and Variable Outflows from Stars*, Astr. Soc. Pacific Conf. Series 22, 155.

Howarth, I.D., Bolton, C.T., Crowe, R.A., Ebbets, D.C., Fieldus, M.S., Fullerton, A.W., Gies, D.R., McDavid, D., Prinja, R.K., Reid, A.H.N., Shore, S.N. and Smith, K.C.: 1993, *Astrophys. J.* in press.

Howarth, I.D. and Prinja, R.K.: 1989, *Astrophys. J. Suppl.* **69**, 283.

Kaper, L.: 1993, *Ph.D. Thesis*, Univ. Amsterdam: The Netherlands.

Leitherer, C.: 1988, *Astrophys. J.* **326**, 356.

Massa, D.: 1989, *Astron. Astrophys.* **224**, 131.

Massa, D., Shore, S.N. and Wynne, D.: 1992, *Astron. Astrophys.* **264**, 169.

Massa, D., Prinja, R.K. and Fullerton, A.W.: 1994, in preparation.

Mullan, D.J.: 1984, *Astrophys. J.* **283**, 303.

Mullan, D.J.: 1986, *Astron. Astrophys.* **165**, 157.

Owocki, S.P.: 1991, in Crivellari L., Hubeny I. and Hummer D.G., eds., *Stellar Atmospheres: Beyond Classical Models*, Kluwer: Dordrecht, 235.

Owocki, S.P.: 1992, in Heber U. and Jeffery C.S., eds., *The Atmospheres of Early-Type Stars*, Springer: Berlin, 393.

Pauldrach, A., Puls, J. and Kudritzki, R.P.: 1986, *Astron. Astrophys.* **164**, 86.

Puls, J., Owocki, S.P. and Fullerton, A.W.: 1993, *Astron. Astrophys.* in press.

Prinja, R.K.: 1988, *Mon. Not. Roy. Astr. Soc.* **231**, 21P.

Prinja, R.K.: 1992, in Drissen L., Leitherer C. and Nota A., eds., *Nonisotropic and Variable Outflows from Stars*, Astr. Soc. Pacific Conf. Series 22, 167.

Prinja, R.K. and Fullerton, A.W.: 1994, *Astrophys. J.* in press.

Prinja, R.K., Balona, L.A., Bolton, C.T., Crowe, R.A., Fieldus, M.S., Fullerton, A.W., Gies, D.R., Howarth, I.D., McDavid, D. and Reid, A.H.N.: 1992, *Astrophys. J.* **390**, 266.

Prinja, R.K., Howarth, I.D. and Henrichs, H.F.: 1987, *Astrophys. J.* **317**, 389.

Prinja, R.K. and Smith, L.J.: 1992, *Astron. Astrophys.* **266**, 377.

Discussion

Owocki: You mention that DACs can involve up to a factor of 10 increase in absorption equivalent width. It is very difficult for a theoretical model to do this without producing a comparable increase in emission equivalent width. The IUE spectra (even with their low S/N) don't show clear emission variability. Is this a real puzzle?

Prinja: Matching the observed variable UV P Cygni profiles with a line-synthesis code, for example, would imply changes in the product of mass-loss rate and ionization of up to a factor of 10 (over $\sim$ 1 day!). The fact that the emission components of P Cygni profiles are fairly constant even during large changes in the absorption trough, most likely indicates that the DAC line-formation geometry is not spherically symmetric. Small scale fluctuations are apparent in the emission part of the He I λ5876 P Cygni profile of HD 152408 (in S/N $\sim$ 200 optical data). However they are substantially less than corresponding absorption changes due to DACs.

Heap: High S/N spectra of ξ Per with HST *do* show variations in the emission component of the Si IV resonance doublet.

Have you looked at changes in the ionization state of the wind at low velocities?

Prinja: A big advantage of studying a B supergiant like HD 64760 is that the evolution of DACs can be monitored in several unsaturated lines, including Si III λ1206, Si IV λ1400, and N V λ1240. Our analysis is still at a preliminary stage, and we are currently addressing the ionization balance issues. There is evidence for a trend of increased ionization with velocity, though in the strongest DAC event a much larger increase of Si III to Si IV is noted at low velocities (with a decrease in N V).