Structure and clumping in the fast wind of NGC6543

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ABSTRACT
Far-UV spectroscopy from the FUSE satellite is analysed to uniquely probe spatial structure and clumping in the fast wind of the central star of the H-rich planetary nebula NGC 6543 (HD 164963). Time-series data of the unsaturated P Cygni 1128 resonance line P Cygni profiles provide a very sensitive diagnostic of variable wind conditions in the outflow. We report on the discovery of episodic and recurrent optical depth enhancements in the Pv absorption troughs, with some evidence for a ~ 0.17-day modulation time-scale. SEI line-synthesis modelling is used to derive physical properties, including the optical depth evolution of individual ‘events’. The characteristics of these features are essentially identical to the ‘discrete absorption components’ (DACs) commonly seen in the UV lines of massive OB stars. We have also employed the unified model atmosphere code CMFGEN to explore spectroscopic signatures of clumping, and report in particular on the clear sensitivity of the P lines to the clump volume filling factor. The results presented here have implications for the downward revision of mass-loss rates in PN central stars. We conclude that the temporal structures seen in the P lines of NGC 6543 likely have a physical origin that is similar to that operating in massive, luminous stars, and may be related to near-surface perturbations caused by stellar pulsation and/or magnetic fields.

Key words: stars: outflows – stars: evolution – stars: individual: NGC 6543.

1 INTRODUCTION
As the immediate precursors of white dwarfs, the central stars of planetary nebulae (CSPNs) provide fundamental tests in key areas of stellar astrophysics, including evolutionary theory, non-LTE model atmospheres and plasma hydrodynamics. An important challenge is to understand details of the mass-loss process through the planetary nebula stage. Specifically, the fast winds of CSPN provide a probe of the current mass-loss, and represent a valuable setting for the study of radiative and mechanical interactions between stars and their environments.

Shortly after the launch of the International Ultraviolet Explorer (IUE) satellite, it became clear that fast winds are a common feature of CSPN (e.g. Heap, 1979; Perinotto, Cerruti-Sola, Benvenuti, 1982). The P Cygni UV resonance line profiles have been decoded to record maximum wind velocities of up to a few 1000 km s⁻¹ and estimates of the mass-loss rate range between ~ 10⁻¹⁰ to 10⁻⁶ M⊙ yr⁻¹ (see e.g. Perinotto, 1989 and references within). Our objective in this paper is to exploit new Far-Ultraviolet Spectroscopic Explorer (FUSE) satellite time-series spectroscopy of the central star of NGC 6543 to uniquely examine the time-variable characteristics of its fast wind.

An improved understanding of variability and clumping in the fast winds of CSPN is important for several reasons: Temporally variable spatial structure implies a clumped and at least locally non-spherical fast wind, which can modify how the supersonic outflow interacts with the nebular material (e.g. Falle et al. 2002; Steffen & Lopez 2003). Substantial wind clumping can also significantly complicate determinations of the mass-loss rates from the central stars. For example, recent analyses of optical and UV lines in luminous, massive O-type stars have provided evidence for extreme wind clumping factors, with implications that the mass-loss rates of OB stars may have previously been over-estimated by factors of between 3 to 10 (e.g. Hillier, Lanz & Heap 2003; Massa et al. 2003; Markova et al. 2004; Bouret, Lanz & Hillier 2005; Fullerton, Massa & Prinja 2006).

Recent Chandra and XMM–Newton observations have established the presence of diffuse X-ray emission from within the nebular interior regions (e.g. Guerrero et al. 2001; Kastner et al. 2003; Maness & Vrtilek, 2003). The source of the X-rays from the central star vicinity remains uncer-
tect, and one possible origin would be the presence of shock-heated gas arising from instabilities in a variable fast wind (e.g. Akashi, Soker & Behar, 2006).

The present study is also motivated by a need to understand the relation between optical spectroscopic (radial velocity) and photometric changes evident in several CSPN. The frequently imaged non-spherical and bipolar morphologies of the planetary nebulae (e.g. Zuckerman & Aller, 1986) raise the possibility that the planetary nebulae may have been ejected via common envelope interaction in close binary central stars (e.g. Sandquist et al. 1998). Surveys of the PN binary population are currently frustrated by the physical interpretation of the observed radial velocity and photometric variations, which might at least in part be due to changes in the fast wind (e.g. Handler, 2003; De Marco et al. 2004).

There is a clear need therefore to investigate further the detailed temporal variability of the fast winds in CSPN. To date, studies of variability in these outflows have primarily relied on (limited) multiple UV spectra obtained with the IUE satellite (e.g. Patriarchi & Perinotto, 1997). Generally however the detection of wind line variability with IUE (or HST) was extremely difficult since the only UV resonance lines accessible are strongly saturated, thus masking all changes except at the extreme violet edges of the line profiles. In addition, the exposure times of high resolution IUE spectra were rather long, i.e. ~2 to 3 hours, which is in fact comparable to the wind flushing time in these stars. We provide here new perspectives on variability in the fast winds of CSPN by exploiting FUSE (λλ 905 to 1187 Å) time-series observations. FUSE can uniquely deliver the requisite high signal-to-noise data in short integration times, while also potentially providing access to unsaturated resonance lines, including \( \text{P} \), \( \text{S} \), \( \text{N} \), \( \text{O} \), and \( \text{C} \).

### 1.1 The target, NGC 6543

We present in this paper a study of structure and variability in the fast wind of the central star of the planetary nebula NGC 6543 (HD 164963; BD +66° 1066). The nebula is well studied, with HST images in particular revealing complex structures that include phenomena such as bubbles and precessing jets (e.g. Harrington & Borkowski 1994; Balick 2004; Wesson & Liu, 2004). X-ray emission has been detected with Chandra (Chu et al. 2001; Guerrero et al. 2001), which is consistent with a point source at the central star and diffuse emission from within the elliptical central shell. Various studies have reported evidence for time-variable changes associated with the central star, including Mendez, Herrero & Manchado (1990; optical spectroscopy), Bell, Pollacco & Hilditch (1994; photometry), and Patriarchi & Perinotto (1997; UV spectroscopy). Fundamental parameters of the central star based on non-LTE model atmosphere analysis have been derived by de Koter et al. (1996; ISA-Wind code) and Georgiev et al. (2006; CMFGEN). Key adopted parameters for the central star in NGC 6543 are listed in Table 1.

We note that for a \( \beta = 1 \)-type wind velocity law (e.g. Sect. 5), the wind flushing time to travel from 0.1 to 0.9 of the terminal velocity \( v_\infty \) is only ~45 mins.

### 2 FUSE TIME-SERIES DATA

Our study of the fast wind of NGC 6543 is largely based on FUSE data from Program F034 (P.I. – D.L. Massa), secured between 2007 January 13 to 16. A summary log of observations is provided in Table 2. The observations were obtained through the MDRS (4′ × 20′) aperture, spanning a total wavelength range of 905 to 1187 Å at a spectral resolution of ~15 km s\(^{-1}\). (The instrument and performance is discussed by Moos et al. 2000 and Sahnow et al. 2000.) Typical individual integration times in HIST mode are ~

![Mean FUSE spectrum of the central star in NGC 6543 from the F034 run in January 2007.](image-url)
10 minutes. Using the MDRS aperture unfortunately meant that occasionally the target was not fully captured and there were cases of light loss. The most usable components are 59 spectra (processed through CalFUSE version 3.1.8) in the LiF2 channel (segment A; λλ1086 to 1182 Å) which covers the strategic line of Pv λλ1117.98, 1128.01. A sparser sequence of 29 spectra for the LiF1 channel (segment A; λλ987 to 1082 Å) provided some information on the behaviour of the (stronger) Ovi λλ1031.92, 1037.62 wind-formed line.

The mean FUSE spectrum is shown in Figure 1. Aside from Pv and Ovi, a strong P Cygni line is also seen in Svi λλ933.38, 944.52. There is some evidence for blue-ward absorption in the excited Niv λλ955.34 line profile and Ciii λλ977, 1031.92, 1037.62 wind-formed line. Even the low velocity (redward of ∼−600 km s\(^{-1}\)) region of this line is likely optically thick and variance analysis does not support any changes in Ovi that are significant above a 95% confidence level.

The data for Pv are by contrast very revealing. Representations of the variability evident are displayed in Figure 3 as dynamic spectra (i.e. two-dimensional images of individual spectra ordered in time). The images reveal clear evidence for systematic and organised line profiles changes. Specifically, localised (in velocity) absorption enhancements are seen (darker shades in Fig. 3) migrating blueward from ∼−400 to ∼−1000 km s\(^{-1}\). We identify at least 4 separate episodes of recurring features. The patterns in Fig. 3 are essentially identical to the ‘discrete absorption components’ (DACs) commonly seen in UV resonance lines formed in the radiation-pressure-driven winds of massive OB stars (e.g. Kaper et al. 1996; Prinja, Massa & Fullerton, 2002). The lower left-hand panels in Fig. 3 focus on three of the more prominent DAC-like features in NGC 6543, with central velocities that increase between ∼−830 to −1010 km s\(^{-1}\) over 1.1 hours, ∼−510 to −1290 km s\(^{-1}\) over 6.0 hours, and ∼−700 to −1070 km s\(^{-1}\) over 1.3 hours.

The DAC velocities above provide (linear) accelerations of between 3 \times 10^{-2} km s\(^{-2}\) to 8 \times 10^{-2} km s\(^{-2}\). These values for NGC 6543 are up to a factor of 10 faster than typical acceleration rates measured for features in OB star wind (e.g. Prinja 1998). However the characteristic radial flow time of the wind (which scales as \(R_*/v_{\infty}\) in NGC 6543 is only ∼5 minutes (Table 1), compared to ∼hours for O stars. The time-scales associated with the DACs in NGC 6543 are therefore significantly greater than the wind flushing time.

| Obs. ID | No. of exp. | UT Date     | MJD(start) | ∆T (hours) |
|---------|-------------|-------------|------------|------------|
| F0340105 | 26          | 2007-01-13  | 54113.1260 | 9.7        |
| F0340106 | 18          | 2007-01-14  | 54114.1097 | 5.9        |
| F0340107 | 19          | 2007-01-15  | 54115.0933 | 7.3        |
| F0340108 | 9           | 2007-01-16  | 54116.0680 | 1.4        |

Figure 2. Fluctuations in the Pv resonance line profiles compared to the more stable low-velocity regions of Ovi λλ1037.6.
Figure 3. Dynamic spectrum representations of organised, hourly variability in P\textsubscript{v} λλ1118,1128. In the upper plot the ordinate is the sequential spectrum number, and the panel on its right is a temporal plot showing the relative time of each exposure. The gray scales in the lower plot show the organised, hourly variability. Starting from the bottom, data in the pair of (lower) left-hand and right-hand panels span a total of \sim 1.22 days and 1.02 days, respectively. To enhance the contrast in these images the individual spectra have been normalised by the mean profile for the time-series.
over the line formation region, which suggests that it is very unlikely the wind structures in the PN central star are due to processes entirely intrinsic to the fast wind. The DACs cannot, for example, be due to mass-conserved shells or blobs ‘riding’ with the outflow from the star. As is widely believed for OB stars, the perturbations more likely arise as a result of inhomogeneities close to the stellar surface, such as pulsations or magnetic fields. The empirical evidence provided here suggests that the physical mechanism for initiating wind structure in the fast wind of NGC 6543 may the same as that operating in massive, luminous stars (see Sect. 6).

4 MODULATED OR CYCLIC BEHAVIOUR

In a few case studies based on very extended IUE spectroscopy it has been demonstrated that the DACs in OB stars are modulated or quasi-cyclic, on variability timescales that may relate to stellar rotation periods (e.g. Massa et al. 1995, Fullerton et al. 1997, de Jong et al. 2001, Prinja et al. 2002). From the viewpoint of nebular shapes, central star binarity, and wind structure in line-driven winds, it is obviously interesting to consider whether the optical depth changes seen in the PV lines of NGC 6543 are systematically variable. The rotation period of NGC 6543 is not known, and determinations of the projected rotation velocities are sparse for PN central stars in general. Note also that the central star in our study is a member of the ZZ Lep class of variable stars (e.g. Handler 2003). Bell, Pollacco & Hilditch (1994) document differences of ∼ 0.01 mag in 5300 Å CCD photometry though with little evidence for periodic variations that are consistent over the four nights of their observations. Individual nights provided evidence for modulations over ∼2.6 hours and 3.2 hours. Analysing the same dataset, Handler (2003) cites a photometric modulation of 3.5 ± 1.5 hours. The origin of the photometric changes in NGC 6543 may relate to photospheric (pulsational) changes or indeed the inner regions of the fast wind. The strong FUV photospheric lines in our FUSE data are relatively fixed in velocity (to within ± 10 km s⁻¹) and do not support any significant role for binary motion.

A periodogram analysis was carried out to search for evidence of repetitive or cyclic properties in the PV line profile changes. The basic Fourier method involved uses the iterative CLEAN algorithm (Roberts, Lehár & Dreher 1987) to deconvolve the features of the window function from the
discrete Fourier transform. (A gain of 0.5 with 100 iterations was used.) The power spectrum sampled over $\sim -600$ to $-1100 \text{ km s}^{-1}$ (i.e. the range of well-developed DACs) in $P_{\text{v}}$ is shown in Fig. 4. The data sampling is generally not intensive enough for a very robust period search and the power in $P_{\text{v}}$ is spread across several frequencies. Nevertheless we identify as potentially interesting the main power peak in $P_{\text{v}}$ at $\sim 5.85 \text{ days}^{-1}$, corresponding to a period of $\sim 0.17 \text{ day}$. The half-width at half-maximum of the zeroth order peak in the window function provides an approximate (and conservative) estimate of the error in the frequency of $\sim 0.1 \text{ day}^{-1}$. Independent determinations of the period sampled over $300 \text{ km s}^{-1}$ bins in the region between $-600$ to $-1100 \text{ km s}^{-1}$ suggest an error in the frequency of $\sim 0.5 \text{ day}^{-1}$.

The adjacent peaks in the power spectrum (Fig. 4) are comparatively less stable in similar velocity bin sampling. Grayscale of individual spectra normalised to the mean are shown in Fig. 5 phased on the $0.17 \text{ day}$ period. The diagnostic $P_{\text{v}}$ data do clearly show some coherency on the $0.17 \text{ day}$ time-scale. The modulation is represented by the occurrence of two sequential episodes of migrating structures in the wind. (Recall that the total length of the FUSE time-series combined here is $\sim 3 \text{ days}$, and therefore spans several ‘cycles’.)

Tentative evidence of variability on hourly time-scales can also been gleaned by examining low-resolution ($R \sim 300$) IUE spectra of the central star. We have retrieved from the ESA IUE archive a sequence of 38 spectra (SWP54865 to SWP54960), which extend over $4.2 \text{ days}$. Despite being saturated, the blue-wing of C iv is apparently highly variable (e.g. Patriarchi & Perinotto, 1997). Furthermore, studies of fluctuations in the extended blue-wings of saturated P Cygni profiles have (perhaps surprisingly) revealed evidence for modulated behaviour (see e.g. Howarth, Prinja & Massa, 1995; Prinja et al., 1998). We used high-resolution IUE spectra of NGC 6543 that were degraded (by convolution with a 5Å full-width at half-maximum Gaussian), to improve the internal consistency of the low-resolution data and to normalise the continuum fluxes near C iv. The variance characteristics of the low-resolution IUE C iv time-series is shown in Fig. 6. There is a double-peaked nature to the TVS (e.g. Fullerton, Gies & Bolton 1996) spectrum, and
we elect to sample in particular the profile changes between −1000 and −2000 km s\(^{-1}\), since these are likely to represent variability in the extreme blue-wings. However, no signal is detected in C\(\text{IV}\) at the frequency identified for P\(\text{V}\) modulations. The IUE data quality prevent us from making any firm conclusions as to whether any (quasi-)periodic signal in NGC 6543 is long-lived. We also attempted to phase-fold the original photometric data of Bell et al. (1994, obtained in 1993; Don Pollacco private communication) but did not find any convincing evidence for a modulation on \(\sim 0.17\) days.

5 LINE-SYNTHESIS AND OPTICAL DEPTHS

In order to further quantify the physical properties of the DACs in the wind of NGC 6543, the FUSE resonance lines were modelled using the SEI method (see Lamers, Cerrutti-Sola & Perinotto 1987), with the modified procedures of Massa et al. (2003). The radial optical depth, \(\tau_{\text{rad}}(v)\), is treated as 21 independent velocity bins (each \(\sim 0.05\) \(v_{\infty}\) wide) to provide greater flexibility in matching absorption optical depths in a structured wind that is affected by variable features such as DACs. We assume a standard parameterised velocity law of the form,

\[
w = w_0 + (1 - w_0)(1 - 1/x)^{\beta},
\]

where \(w = v/v_{\infty}\) and \(x = r/R_*\). The effect of a photospheric spectrum in the SEI profile fitting is approximated by a Gaussian of full-width at half-maximum = 250 km s\(^{-1}\); its effect is only to improve the match at low velocities (\(\lesssim 0.2\) \(v_{\infty}\)) and does not impact seriously on the overall wind parameters derived in this section. Model fits to the mean P\(\text{V}\) profile in our time-series is shown in Fig. 7, where a very good overall match is achieved for \(v_{\infty} = 1400\) km s\(^{-1}\), \(\beta = 1\), and \(v_{\text{turb}}\) (the small-scale velocity dispersion parameter) = 0.05. Note that the redward component of P\(\text{V}\) may be affected by the (neglected) contribution due to Si\(\text{IV}\) \(\lambda\lambda 1122.5, 1128.3\). These values are also consistent for reproducing the blue-wing of a much stronger (saturated) profile such as S\(\text{V}\)\(\lambda\) (Fig. 7).

The central star is H-rich, with normal solar abundance ratios though Carbon may be overabundant (e.g. Georgiev et al. 2006). The SEI model of P\(\text{V}\) in Fig. 7 therefore gives a (mean) value for the product of mass-loss rate and ionization fraction, \(\dot{M} g(P^{4+})\), integrated over 0.2 to 0.9 \(v_{\infty}\), of \(\sim 5.0 \times 10^{-9} \text{M}_\odot \text{yr}^{-1}\) (for parameters in Table 1). Over the velocity range where the peak variance occurs in P\(\text{V}\) (i.e. \(\sim 0.5\) to 0.9 \(v_{\infty}\)), SEI fits to the cases of minimum and maximum observed absorption yield \(\dot{M} g(P^{4+})\) values of \(\sim 1.9 \times 10^{-9} \text{M}_\odot \text{yr}^{-1}\) and \(3.5 \times 10^{-9} \text{M}_\odot \text{yr}^{-1}\).

The fact that the SEI model can match well the overall morphology of the observed absorption in P\(\text{V}\) permits us to model individual line profiles in the FUSE time-series. Specifically we focus on the data covering the two most prominent DAC-like features in lower left-hand panels of Fig. 3 (in both cases the features start from the normalised time of 0.0 hours; the corresponding FUSE exposures are F03401050012 to F03401050082 and F03401060042 to F03401060012). The fits to these spectra, which are varying due to the occurrence of DACs, can then be compared with a ‘no-DAC’ case i.e. a spectrum representative of maximum flux over most velocities (i.e. F03401080072).

The SEI models fits to the P\(\text{V}\) (time-series) line profiles are shown in Figure 8. The flexible optical depth bins are designed to allow matches to a wind profile that is obviously not ‘smooth’, but is instead distorted due to density, ionization or velocity features (see e.g. Massa et al. 2003). The good overall reproduction in Fig. 8 permits us to extract optical depths at the specific velocity of the migrating DACs, and normalise them to the no-DAC case. Ratios of \(\tau(\text{DAC})/\tau(\text{min})\) (obtained from fits to the individual pro-
files) are plotted as function of normalised velocity $v/v_{\infty}$ in Fig. 9. The plot therefore shows the optical depth evolution of two independent DAC episodes as a function of their central velocities. In both cases the optical depth ratio due to DACs rises to a maximum of $\sim 5$ at $\sim 0.62 v_{\infty}$, and drops to $\sim 2$ toward $0.75 v_{\infty}$. The indication that the maximum contrast of the DACs is reached at intermediate velocities is somewhat unexpected. The increase in Sobolev optical depth at these positions may be due to a plateau in the wind velocity law, i.e. a radially extended region of near-constant velocity. Wind material flows through the plateau, and the observed accelerations of DACs are then associated with the evolution (in velocity and radial extent) of the plateau as a function of time. The origin of such a plateau could, for example, relate to the formation of co-rotating interactions regions in the outflow (see e.g. Cranmer & Owocki, 1996, and discussion in Sect. 6).

To gain some insights into the ionization balance and wind clumping in NGC 6543, we also employed the unified model atmosphere code CMFGEN (Hiller & Miller, 1998), which calculates non-LTE models of spherically symmetric winds with multi-level atoms. The fundamental parameters listed in Table 1 were adopted, together with $\log g = 4.2$ and a He/H abundance ratio (by number) of 0.1 (e.g. Georgiev et al. 2006). A parametric treatment of wind clumping is implemented in CMFGEN, in terms of the volume filling factor, $f$, defined as

$$f = f_{\infty} + (1 - f_{\infty}) \exp(-v/v_{cl}),$$

where $v_{cl}$ is the velocity at which clumping starts, and which we adopt as $35 \text{ km s}^{-1}$ (i.e. above the sonic point). Our objective here is primarily to investigate the spectral signatures of clumping in CMFGEN models applied to the fast wind of NGC6543; we do not attempt a detailed exercise in fitting several lines.

Models were run for cases of the clump volume filling factor, $f_{\infty} = 0.06, 0.08$ and $0.1$, and the synthesised spectra are compared in Fig. 10 to key wind lines in the FUSE and high-resolution IUE data of the central star. For a mass-loss rate of $6 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1}$ the models provide good overall fits to the observed resonance and excited state line profiles. It is interesting to note that the P lines are particularly sensitive to the clumping factor, more so than O and N lines. Our data favour the case of $f_{\infty} = 0.08$, though of course we neglect here the consequences of these parameters for reproducing diagnostic optical lines in the central star of NGC 6543, such as He\textsc{ii} $\lambda 4686$ and C\textsc{iv} $\lambda 5801$. Figure 11 displays the predicted ionization fractions of $\text{P}^{3+}$, $\text{P}^{4+}$, and $\text{P}^{5+}$ as a function of velocity, and for the three different clumping factors. The dominance of $\text{P}^{5+}$ at low velocities re-
sults in the mis-match with the observed profile seen in this region (Fig. 10). The ion fractions of P\textsuperscript{3+} and P\textsuperscript{4+} increase over all velocities for lower values of $f_\infty$, with an increased recombination from P\textsuperscript{5+} to P\textsuperscript{4+} particularly evident at the highest velocities. The CMFGEN models run here generally predict C\textsuperscript{4+} and P\textsuperscript{5+} as dominant (i.e. $q_i > 0.97$ over $\sim 0.2$ to 0.9 $v_\infty$), and S\textsuperscript{2+} and O\textsuperscript{4+} close to dominant (i.e. $q_i \sim 0.6$ and 0.2, respectively).

Our results indicate that P\textsubscript{v} is a sensitive spectral diagnostic of small-scale clumping in the fast wind, together with the large-scale structures represented by the DACs discussed in Sect. 3. We highlight the need to adopt fairly small volume filling factors in order to match the P\textsubscript{v} resonance line doublet. P\textsuperscript{4+} is a trace ion, just below dominant (Fig. 11), and is therefore extremely sensitive to changes as parameterised here, since its abundance depends strongly on density. This is in contrast to the results for O stars presented by Bouret et al. (2005), where P\textsuperscript{4+} is dominant and not as sensitive to small fluctuations in density.

6 DISCUSSION

The empirical evidence presented here suggests that (i) the fast wind of NGC 6543 is highly variable on time-scales of hours, (ii) the wind changes are systematic in terms of recurrent absorptive optical depth structures that migrate blueward, and (iii) the temporal behaviour of the P\textsubscript{v} resonance line P Cygni profiles is very similar to that due to the presence of ‘discrete absorption components’ (DACs) in luminous OB stars. A comparison between the DAC properties of NGC 6543 and a ‘representative’ mid-O giant is presented in Table 3, where the latter is summarised from various studies (see e.g. those cited in Sect. 3). We note that the fundamental characteristics such as initial detection at low Doppler velocities, recurrence, modulation, and optical depth contrast are broadly similar for both cases; the same is also true for the (linear) acceleration scaled by the flow time-scale ($R_*/v_\infty$). There is some indication that the line-of-sight velocity dispersion of the DACs in NGC 6543 is somewhat smaller than for a typical O-type giant (such as ξ Per or 68 Cygni).

Our interpretation of these results therefore is that the physical mechanism responsible for the DAC structures in the fast wind of NGC 6543 is likely the same as that acting in massive OB stars. There remain several uncertainties in our understanding of this phenomena in massive stars, but in the particular case where quasi-periodic wind variability is detected, several authors have promoted a scenario in terms of co-rotating interaction regions (CIRs; e.g. Cranmer & Owocki 1996; Fullerton et al. 1997; de Jong et al. 2001). The notion is that the DACs are spectroscopic signatures of spatial structures in the wind that are causally connected to stellar surface irregularities. These photospheric inhomogeneities cause the wind from different longitudinal sectors on the stellar surface to emerge with different densities and/or velocities. The consequence is to form different adjacent streams that meet to create spiral-shaped CIRs. Key observational properties of the DACs can be matched with this model, with variable optical depth enhancements arising from the combination of a plateau in the radial velocity as well as a density perturbation. In this model, the variations in absorption which occurs over significantly larger time-scales than the wind flow speed are due to gas flowing through a semi-permanent, co-rotating structure. The rotation rate of the central star in NGC 6543 is unfortunately not known, and we are unable to comment further in this context on the significance of the $\sim 0.17$-day period identified in Sect. 4. In the case of OB stars the recurrence of DACs is mostly only quasi-cyclic, and has only rarely been demonstrated to be an integer relation to the stellar rotation rate. Nevertheless, our results provide the constraint that the mechanism for forming coherent perturbations in the outflows is apparently operating equally in the radiation-pressure-driven winds of widely differing momenta ($M v_\infty R_*/^5$) and flow times, as represented by OB stars and CSPN.
As regards the ‘trigger’ provided by photospheric irregularities for the growth of wind structure, the action of surface velocity fields due to pulsation and/or ordered magnetic fields may be just as applicable to CSPN as it is to OB stars. Multi-period pulsation modes are thought to be the cause of short-period (∼ hourly) variability seen in the photometric measurements of several central stars, including both H-rich and H-deficient cases (e.g. Handler et al. 1997; Ciardullo & Bond 1996). Kilogauss strength magnetic fields have also been detected (using spectropolarimetry) that are associated with the PN central stars (e.g. Jordan, Werner & O’Toole 2005), where they may be located mostly in the envelope, as opposed to the degenerate core, and can be affected by mass-loss. One caveat here is that the link between pulsation or magnetic fields and repetitive wind structures in OB stars has thus far proved observationally very challenging and generally unconstrained; establishing such a connection in CSPN is going to be even more difficult!

The ab inito CMFGEN calculations presented in Sect. 5 favour a small clump volume filling factor, \( f_\infty \sim 0.08 \). Whether or not the parameterisation of clumping incorporated in CMFGEN is physically meaningful, we note that the high sensitivity of the PV lines to the clumping factor is again similar to that apparent for the same line in O-type stars. Following the clumping studies of e.g. Markova et al. (2004), Bouret et al. (2005), Fullerton et al. (2006), our results for NGC 6543 would imply a reduction by a factor \( \sim 4 \) (i.e. \( \sqrt{f_\infty} \)) in the mass-loss rate due to the clumped fast wind compared to smooth-wind models. The analysis of optical lines with the non-LTE code FASTWIND by Kudritzki, Urbanova & Puls (2006) also points to substantially clumped CSPN fast winds. Downward revisions in the central star mass-loss rate would affect the dynamics of the hot central cavity excavated by the fast wind, thus modifying its interaction with the surrounding nebula, including contributions to the X-ray emission. Naturally our far-UV analyses needs to be extended to cover a large sample of central stars to permit firm assessments of any revisions to CSPN mass-loss rates, and most importantly, tested for consistency between UV and optical diagnostics of clumping. Finally, looking ahead, the vastly increased sensitivity soon to be offered at radio wave-bands by the upgraded e-MERLIN and EVLA facilities raises new possibilities for measuring the free-free emission from the fast wind itself and thus provide a powerful new constraint on the central star mass-loss.

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REFERENCES

Akashi, M., Soker, N., Behar, E. 2006, MNRAS, 368, 1706
Balick, B., 2004, AJ, 127, 2262
Bell, S.A., Pollacco, D.L., Hilditch, R.W. 1994, MNRAS, 267, 1053
Bouret, J.-C., Lanz, T., Hillier, D.J. 2005, A&A, 438, 301
Chu, Y.-H., Guerrero, M.A., Gruendl, R.A., Williams, R.M., Kaler, J.B. 2001, ApJ, 553, 55
Ciardullo, R., Bond, H.E. 1996, AJ, 111, 2332
Cranmer, S.R., Owocki, S.P. 1996, ApJ, 462, 469
de Jong, J.A. et al. 2001, A&A, 368, 601
de Koter, A., Hubeny, I., Heap, S.R., Lanz, T. 1996, ASP Conf. Series, 96, eds. C.S. Jeffery & U. Heber, p.141
De Marco, O., Bond, H.E., Harmer, D., Fleming, A.J. 2004, ApJ, 602, 93
Falle, S.A.E.G., Coker, R.F., Pittard, J.M., Dyson, J.E., Hartquist, T.W. 2002, MNRAS, 329, 670
Fullerton, A.W., Gies, D.R., Bolton, C.T. 1996, ApJS, 103, 475
Fullerton, A.W., Massa, D.L., Prinja, R.K., Owocki, S.P., Cranmer, S.R. 1997, A&A, 327, 699
Fullerton, A.W., Massa, D.L., Prinja, R.K., 2006, ApJ, 637, 1025
Georgiev, L.N., Hillier, D.J., Richer, M.G., Arrieta, A. 2006, IAU Symp. 234, 'Planetary Nebulae in our Galaxy and Beyond', eds. M.J. Barlow & R.H. Mendez., CUP, 91,119
Guerrero, M.A., Chu, Y.-H., Gruendl, R.A., Williams, R.M., Kaler, J.B. 2001, ApJ, 553, L55
Handler, G. 2003, ASP Conf. Ser., 292, p. 183
Handler, G. et al. 1997, A&A, 320, 125
Harrington, J.P., Borkowski, J. 1994, BAAS, 26, 1469
Heap, S.R., 1979, IAU Symp. 82, 'Mass loss and evolution of O-type stars', eds. P.S. Conti & C.W.H. de Loore, D. Reidel, 99
Hillier, D.J., Miller, D., 1998, ApJ, 496, 407
Hillier, D.J., Lanz, T., Heap, S.R. 2003, ApJ, 588, 1039
Howarth, I.D., Prinja, R.K., Massa, D.L. 1995, ApJ, 452, L65
Jordan, S., Werner, K., O’Toole, S.J. 2005, 432, 273
Kaper, L. et al. 1996, A&AS, 116, 257
Kastner, J. H., Balick, B., Blackman, E.G., Frank, A. Soker, N., Vrtilek, D., Li, J. 2003, ApJ, 591, 37
Kudritzki, R.P., Urbanova, M.A., Puls, J. 2006, IAU Symp. 234, 'Planetary Nebulae in our Galaxy and Beyond', eds. M.J. Barlow & R.H. Mendez, CUP, 119
Lamers, H.J.G.L.M., Cerrutti-Sola, M., Perinotto, M. 1987, ApJ, 314, 726
Maness, H., Vrtilek, S.D. 2003, PASP, 115, 1002
Markova, D., Puls, J., Repolust, T., Markov, H. 2004, A&A, 413, 693
Massa, D., et al. 1995, ApJL, 452, 53
Massa, D., Fullerton, A.W., Sonneborn, G., Hutchings, J.B. 2003, ApJ, 586, 996
Mendez, R.H., Herrero, A., Manchado, A. 1990, A&A, 229, 152
Moos, H.W., et al. 2000, ApJ, 538, L1
Patriarchi, P., Perinotto, M. 1997, A&AS, 126, 385
Perinotto, M., Cerrutti-Sola, M., Benvenuti, P. 1982, A&A, 108, 314
Perinotto, M. 1989, IAU Symp. 131, 'Planetary Nebulae', ed. S. Torres-Peimbert, Kluwer, 292
Prinja, R.K. 1998 in Cyclical variability in Stellar Winds, ESA Astrophysics Symposia, eds. L. Kaper & A.W. Fullerton, Springer-Verlag, p.92
Prinja, R.K., Massa, D., Fullerton, A.W. 2002, A&A, 388,
Prinja, R.K., Massa, D., Howarth, I.D., Fullerton, A.W. 1998, MNRAS, 301, 926
Reed, D.S., et al. 1999, AJ, 118, 2430
Roberts, D.H., Lehár, J., Dreher, J.W. 1987, AJ, 93, 968
Sahnow, D.J., et al. 2000, ApJ, 538, L7
Sandquist, E.L., Taam, R.E., Chen, X., Bodenheimer, P., Burkert, A. 1998, ApJ, 500, 909
Schneider, S.E., Terzian, Y., Purgathofer, A., Perinotto, M. 1983, ApJS, 52, 399
Steffen, W., Lopez, J.A. 2003, RMxAC, 15, 50
Wesson, R., Liu, X.-W. 2004, MNRAS, 351, 935
Zuckerman, B., Aller, L.H. 1986, ApJ, 301, 772
Zweigle, J., et al. 1997, A&A, 321, 891

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