Clumping in Hot Star Winds
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Structure in the fast wind of NGC6543

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We exploit time-series *FUSE* spectroscopy 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). Episodic and recurrent optical depth enhancements are discovered in the P V absorption troughs, with some evidence for a ~ 0.17-day modulation time-scale. The characteristics of these features are essentially identical to the 'discrete absorption components' (DACs) commonly seen in the UV lines of massive OB stars, suggesting the temporal structures seen in NGC 6543 likely have a physical origin that is similar to that operating in massive, luminous stars. The mechanism for forming coherent perturbations in the outflows is therefore apparently operating equally in the radiation-pressure-driven winds of widely differing momenta ($\dot{M} v_\infty R_\star^{0.5}$) and flow times, as represented by OB stars and CSPN.

1 Introduction

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. An improved understanding of variability and structure in the fast winds of CSPN is important since (i) spatial structure and clumping can modify how the supersonic outflow interacts with the nebular material, (ii) substantial clumping can impose downward revisions to estimates of the mass-loss rates from the central stars, (iii) the source of the X-rays from the central star vicinity remains uncertain, and one possible origin would be the presence of shock-heated gas arising from instabilities in a variable fast wind (e.g. Guerrero et al. 2001; Akashi, Soker & Behar, 2006).

To date, studies of variability in PN fast winds 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. We have therefore embarked on a new project to directly probe variability in the fast winds of CSPN by exploiting *FUSE* ($\lambda\lambda$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.

We present here a summary of our study of structure and variability in the fast wind of the central star of the planetary nebula NGC 6543 (HD 164963; BD +66^o 1066). The target has a complex nebula (Balick 2004), and exhibits X-ray emission which is consistent with a point source at the central star and diffuse emission from the within the hot central cavity of the nebula (Chu et al. 2001). Key adopted parameters for the central star in NGC 6543 are $R_\star$ = 0.6R$\odot$, $T_{\rm eff}$ = 63000K, mass-loss rate $\sim 1\times10^{-7}$ M$\odot$ yr^{-1} (Georgiev et al. 2006), and we estimate $v_\infty \sim 1400$ km s^{-1} (and a wind flushing time of $\sim$ 45 mins for a 'β=1'-type velocity law).

1.1 FUSE dataset

The data for this investigation were secured between 2007 January 13 to 16 (Program F034; P.I. – D.L. Massa). The observations were obtained through the MDRS (4" $\times$ 20") aperture, spanning a total wavelength range of 905 to 1187 Å at a spectral resolution of $\sim$ 15 km s^{-1}, with individual integration times in HIST mode of $\sim$ 10 minutes. The primary time-series discussed below are 59 spectra (processed through CalFUSE version 3.1.8) in the LiF2 channel (segment A; $\lambda\lambda$1086 to 1182 Å) which covers the strategic (unsaturated) P Cygni line of P V $\lambda\lambda$1117.98, 1128.01.

Unambiguous flux changes are evident in the absorption trough of P V at $\sim$ 10 to 20% of the continuum level, spanning a range of ~ -500 to -1300 km s^{-1}. The S VI $\lambda\lambda$933.38, 944.52 and O VI $\lambda\lambda$1031.92, 1037.62 P Cygni lines are saturated, and the weaker lines of excited N IV λ955.34 and C III λ1175.67 do not reveal any evidence for variability.

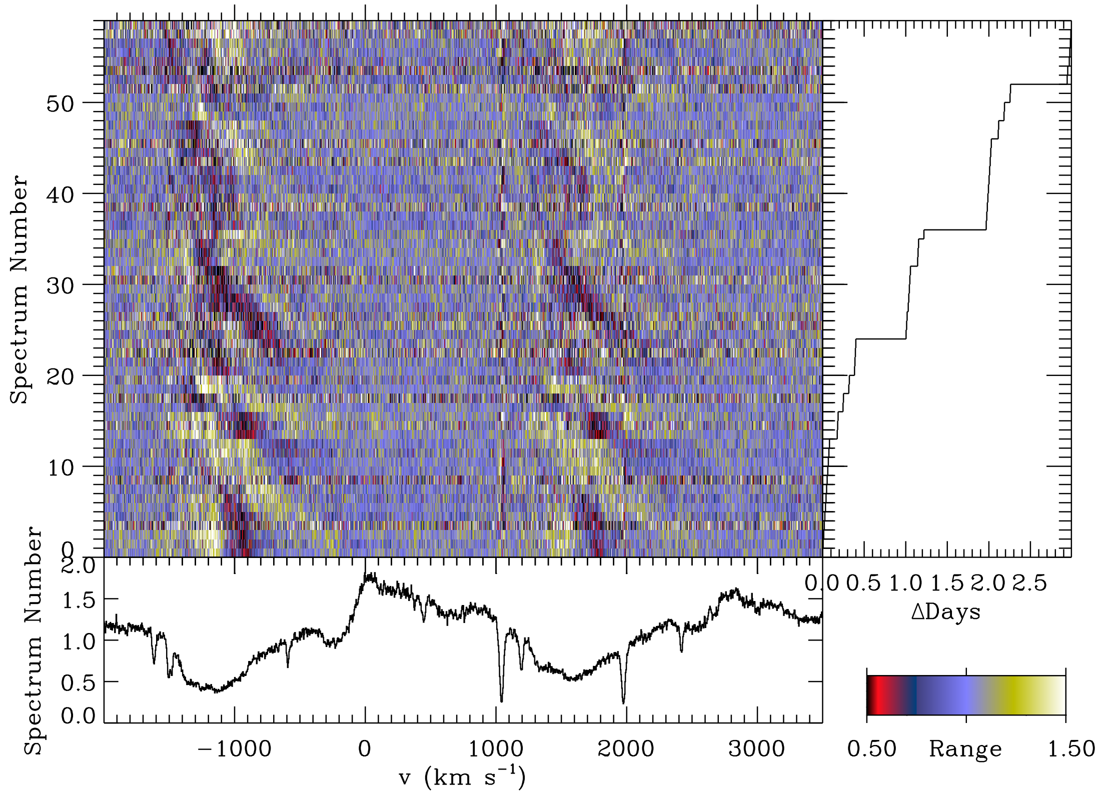

Figure 1: Dynamic spectrum representations of *organised*, hourly variability in Pv λλ1118,1128. The ordinate is the sequential spectrum number, and the panel on its right is a temporal plot showing the relative time of each exposure.

2 Discrete Absorption Components

Greyscale representations of the variability evident in the Pv doublet are displayed in Figure 1. The images reveal clear evidence for systematic and organised line profiles changes. Specifically, localised (in velocity) absorption enhancements are seen migrating blueward from ~ -400 to ~ -1000 km s^{-1}. We identify at least 4 separate episodes of recurring features. The characteristics in Fig. 1 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). We measure (linear) accelerations for the DACs of between 3×10^{-2} km s^{-2} to 8×10^{-2} km s^{-2}. The values for NGC 6543 are up to a factor of 10 faster than typical acceleration rates measured for migrating features in OB star winds. Note, however, that the characteristic radial flow time of the wind (which scales as $\sim \mathrm{R}_\star/v_\infty$) in NGC 6543 is only $\sim$ 5 minutes, compared to $\sim$ hours for O stars. The time-scales associated with the DACs in NGC 6543 are therefore significantly greater than the wind flushing time 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. The empirical evidence provided here suggests that the physical mechanism for initiating wind structure in the fast wind of NGC 6543 may be the same as that operating in massive, luminous stars.

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 employed uses the iterative CLEAN algorithm (Roberts, Lehár & Dreher 1987) to deconvolve the features of the window function from the discrete Fourier transform. We identify as potentially interesting the main power peak in Pv at $\sim$

$5.85 \pm 0.5 \mathrm{days}^{-1}$, corresponding to a period of $\sim$ 0.17 day. The individual spectra normalised to the mean are shown in Fig. 2 phased on the 0.17 day period. The diagnostic PV data do clearly show some coherency on this modulation 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 days, and therefore spans several 'cycles'.)

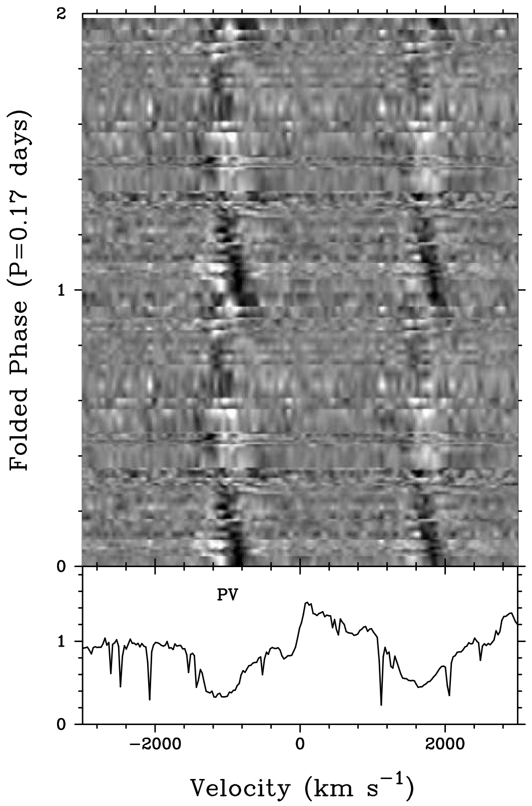

Figure 2: Individual PV spectra are shown phased over two cycles on a period of 0.17 days; a clearly coherent behaviour is evident.

3 Concluding remarks

The suggestion of quasi-periodic wind variability in NGC 6543 may be evidence that the DACs are spectroscopic signatures of spatial structures in the fast wind that are causally connected to stellar surface irregularities, such as pulsation or magnetic fields. (Unfortunately the rotation rate of the central star in NGC 6543 is not well constrained.) For example, according to the scenario for the formation of co-rotating interaction regions (CIRs; e.g. Cranmer & Owocki 1996), the 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.

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 ($\dot{M} v_\infty R_\star^{0.5}$) and flow times, as represented by OB stars and CSPN. UV (and optical) evidence for spatial structure and clumping in the fast winds of CSPN may ultimately imply downward revisions in the central star mass-loss rates, and alter 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.

(A more complete version of this paper, including results on spectral signatures of clumping based on CMFGEN models, has been submitted to MNRAS.)

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