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Monte-Carlo simulations of linear polarization in clumpy OB-star winds

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Abstract. We present results from Monte-Carlo simulations of linear polarization in clumped OB-star winds. We find that previous single-scattering models of clumped winds have overestimated the degree of polarization, even in cases where individual clumps are optically thin. An application to P Cygni suggests the star's wind is more fragmented than previously thought.

Keywords. polarization, radiative transfer, scattering, methods: numerical, techniques: polarimetric, stars: mass loss, stars: early-type, stars: winds, outflows, stars: individual (P Cygni)

1. Introduction

A wide variety of observational diagnostics indicate that the radiation-driven winds of OB stars are clumpy. However, the properties of the clumps (small or large? optically thick or thin?), and their origins (wind instabilities? photospheric perturbations?), remain unclear. One promising approach to resolving these uncertainties is analysis of the continuum linear polarization arising from electron scattering in the clumped wind. By comparing the measured (time-varying) Stokes vector against predictions from polarization models, constraints can be placed on the nature of the clumping.

2. Simulations

We model the Stokes vector for a clumpy wind outflow using YARG, a Monte-Carlo radiative transfer code that tracks polarized photon propagation through an ensemble of spherical electron-scattering clumps. As these clumps advect outward in accordance with the standard β velocity law $v(r) = v_\infty(1 - R_*/r)^\beta$, their radius ℓ grows in proportion to

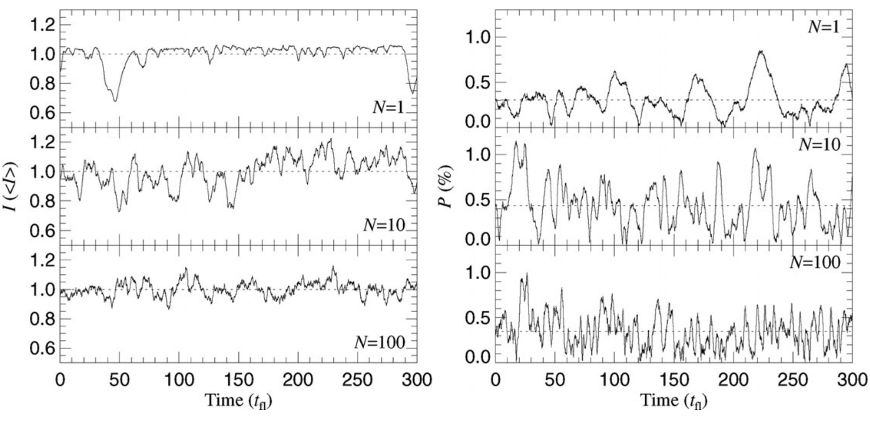

Figure 1. Time-series intensity (left) and fractional linear polarization (right) for the $N = 1, 10$ and 100 simulations. The abscissa is in units of the wind flow time $t_{\rm fl} = 3.3\,$d, and the dotted lines indicate mean levels.

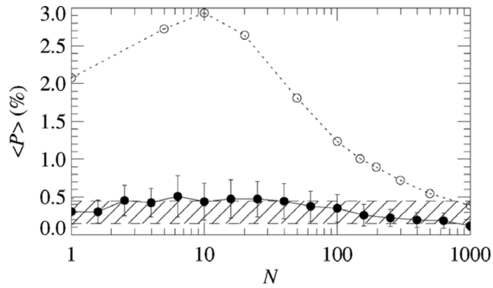

Figure 2. The simulated mean linear polarization $\langle P \rangle$ and 1-σ variability limits of P Cygni, plotted as a function of N (lower curve: Monte-Carlo, present work; upper curve: single-scattering, from D07). The hatched region shows the observed $0.3\% \pm 0.15\%$ polarization.

r. Two parameters establish the overall wind clumping properties: the mean number of clumps N emitted at the stellar surface per unit wind flow time $t_{\rm fl} \equiv R_*/v_\infty$, and the initial clump radius ℓ_*. In the porosity formalism of Cohen *et al.* (2008), these parameters correspond to a terminal porosity length $h_\infty = 3R_*^3/N\ell_*^2$.

As an initial application of YARG, we simulate time-series Stokes vectors for the LBV P Cygni. Parameters follow those of Davies *et al.* (2007; hereafter D07): $\beta = 1$, $\pi\ell_*^2 = 0.04R_*^2$, and the overall wind optical depth scale is $\tau_* \equiv \kappa\dot{M}/4\pi R_* v_\infty = 0.42$, corresponding to an optical depth from the sonic point to infinity of $\tau_{\rm s} = 1.3$. Time series spanning $300\,t_{\rm fl}$ are calculated for $\log N = 1.0, 1.2, 1.4, \ldots, 2.8, 3.0$.

3. Results

Fig. 1 presents the time-series intensity I and fractional linear polarization $P = \sqrt{Q^2+U^2}/I$, for the $N = 1, 10$ and 100 YARG simulations. Fig. 2 combines the data from all simulations to plot the mean polarization $\langle P \rangle$, and its 1-σ variability limits, as a function of N. Also shown are data from the single-scattering P Cygni models of D07, which are seen to be larger by a factor of 3–6. This difference arises due to multiple scatterings: although individual clumps are optically thin for $N \gtrsim 20$, the wind of P Cygni *as a whole* remains optically thick ($\tau_{\rm s} > 1$). Thus, multiple, different-clump scatterings are inevitable, reducing net polarization levels to below the single-scattering limit.

D07 quote a mean *observed* polarization of 0.3% for P Cygni, with variability at the $\pm 0.15\%$ level. These two values are consistent with our $N \sim 100$ simulations (Fig. 2). Percy *et al.* (2001) likewise report light variations with a typical semi-amplitude $\Delta V \sim 0.1$, again consistent with the $N \sim 100$ case (see lower-left panel of Fig. 1). Thus, we conclude that P Cygni has a moderately clumped wind ($N \sim 100$, $h_\infty \sim 2.4\,R_*$), in contrast to the smoother wind ($N \gtrsim 1{,}000$) proposed by D07.

Acknowledgements

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