Monte-Carlo Simulations of Linear Polarization in Clumpy OB-Star Winds

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Observations of linear polarization in OB-star winds can in principle be used to constrain the characteristics of wind clumping. However, models exploring this possibility have so far been restricted to the single-scattering or few-clump cases. We present preliminary results from a new Monte-Carlo radiative transfer code, which suffers from neither of these limitations. Application of the code to P Cygni indicates that previous models have underestimated the degree of clumping in the star's wind.

Wind Clumping

A variety of observational diagnostics indicate that the radiation-driven winds of OB stars are clumpy [1]. 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 wind. By comparing the measured (time-varying) Stokes vector against predictions from polarization models, constraints can be placed on the nature of the clumping.

In any model it is necessary to make some broad assumptions about the clumping. Here, we consider a wind of spherical clumps embedded in a vacuum, that individually conserve mass and solid angle as they advect outward in accordance with the standard velocity law $v(r) = v_\infty (1-R_*/r)^\beta$. This set-up is very similar to the recent studies by [2] and [3], although these authors assume shell-fragment clumps rather than spheres.

Two parameters establish the overall clump properties: the mean number of clumps N emitted at the stellar surface per unit wind flow time $t_{fl} \equiv R_*/v_\infty$, and the initial radius of the clumps ℓ_*. In the porosity formalism of [4], these parameters correspond to a terminal porosity length $h_\infty = 3R_*^3/N\,\ell_*^2$.

The YARG Code

Given wind and clump parameters, we calculate time-series Stokes vectors for the complete star/wind system using YARG, a Monte-Carlo code we have developed for simulating radiative transfer (RT) through a spherical-clumped, electron-scattering medium.

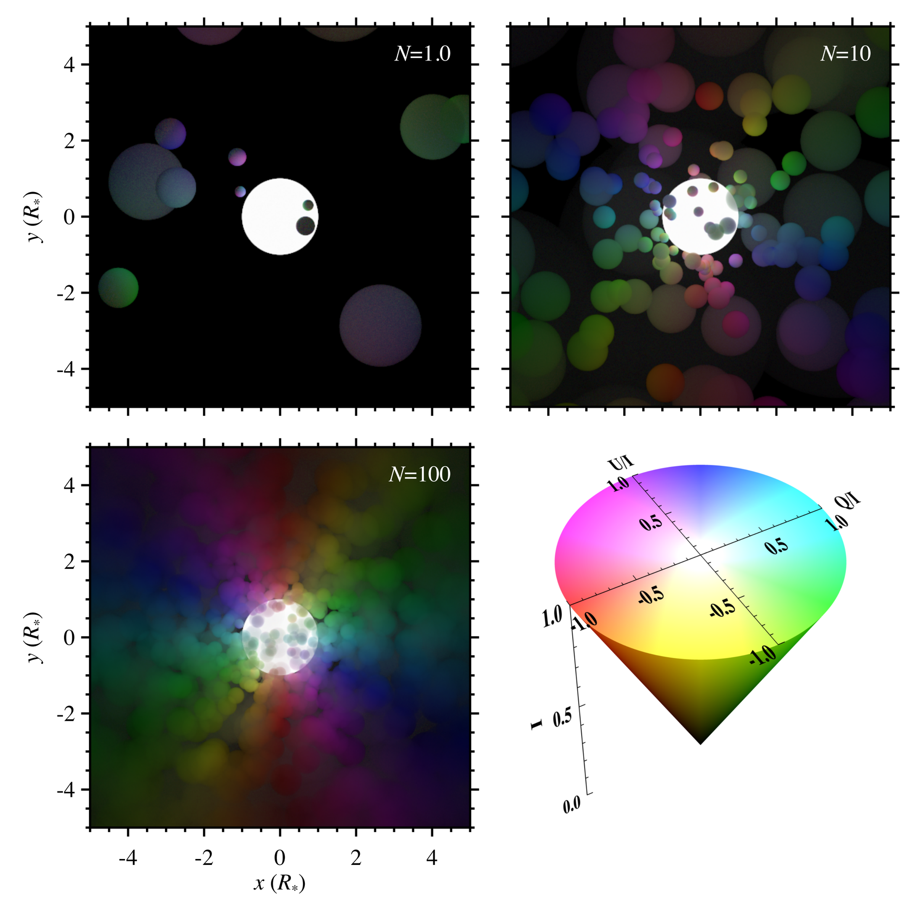

Figure 1. Stokes-vector image snapshots from the N = 1, 10 and 100 simulations of P Cygni. As indicated by the legend in the lower right, color codes for the normalized linear polarization components Q/I and U/I, while brightness codes for the intensity component I. The star at image center appears white because it emits unpolarized light: I = 1, Q = U=0.

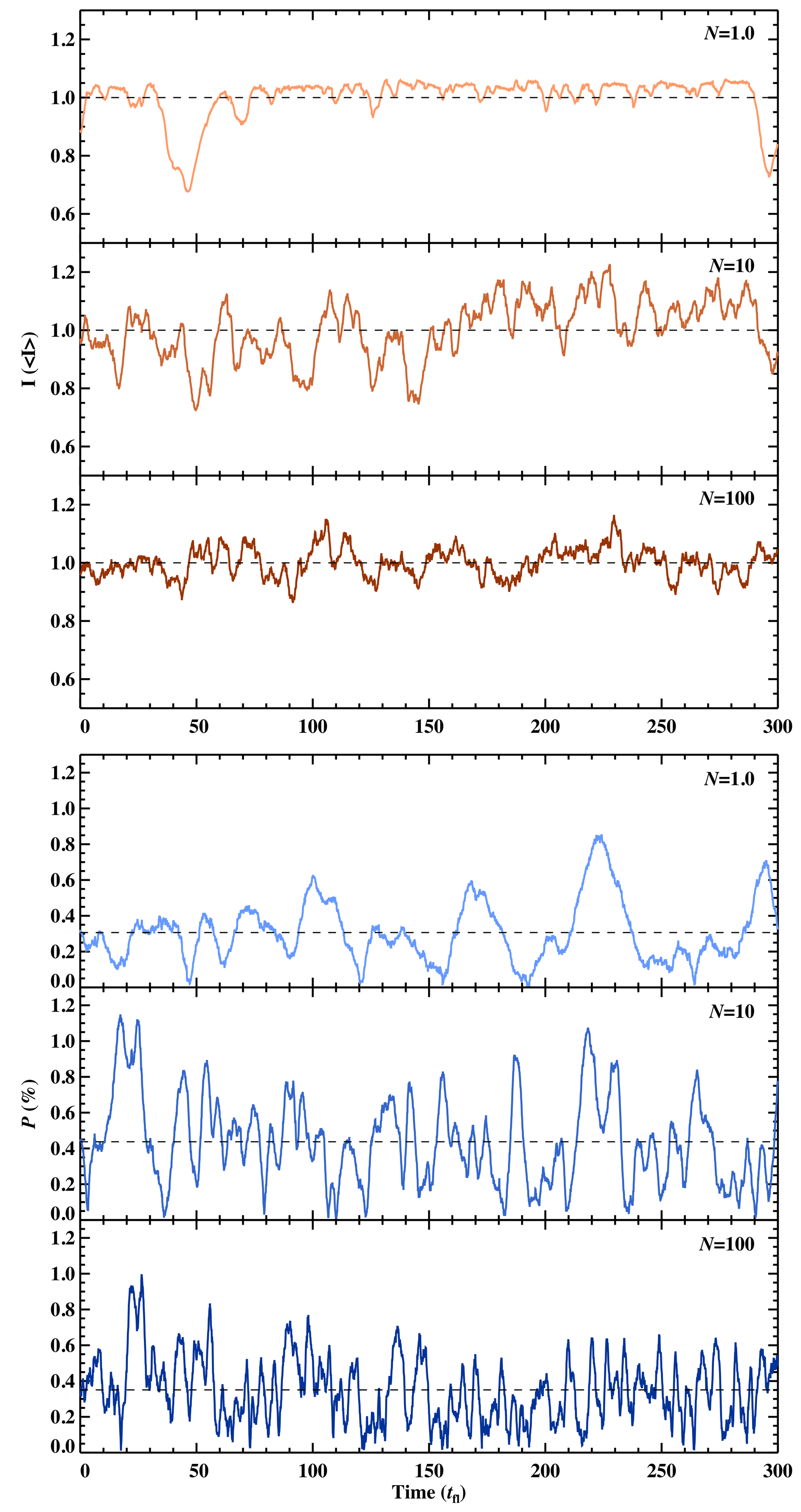

Figure 2. Time-series of the intensity I (upper panels) and linear polarization P, for the N = 1, 10 and 100 simulations. In each plot, the horizontal dashed line indicates the mean level. For the N = 1 case, the effects of single clumps can clearly be seen in the light curve.

Clumps are emitted at random locations on the stellar surface via a Poisson process consistent with N; they then advect outward in accordance with the velocity law.

At regular time intervals, the observed Stokes vector is synthesized using standard Monte-Carlo RT techniques (e.g., [5]). Optical depth integrations use the gridless exact approach discussed in [6].

The ability to handle multiple scatterings differentiates YARG from the studies by [2] and [3], which are both restricted to the single-scattering limit. Although [7] also employ Monte-Carlo RT to investigate wind clumping, their focus is almost wholly on cases involving only a single clump.

Simulations

As an initial application of YARG, we simulate time-series Stokes vectors for the Luminous Blue Variable P Cygni. Parameters follow those adopted in [2]: β = 1, $\pi\ell_*^2 = 0.04\ R_*^2$, and the overall wind optical depth scale is $\tau_* \equiv \kappa\,\dot{M}/4\pi R_* v_\infty = 0.42$, corresponding to a sonic-point optical depth τ_s = 1.3. Time series are calculated for log N = 1.0, 1.2, 1.4, … , 2.8, 3.0; each spans 300 wind flow times with a sampling of 0.1 t_{fl}.

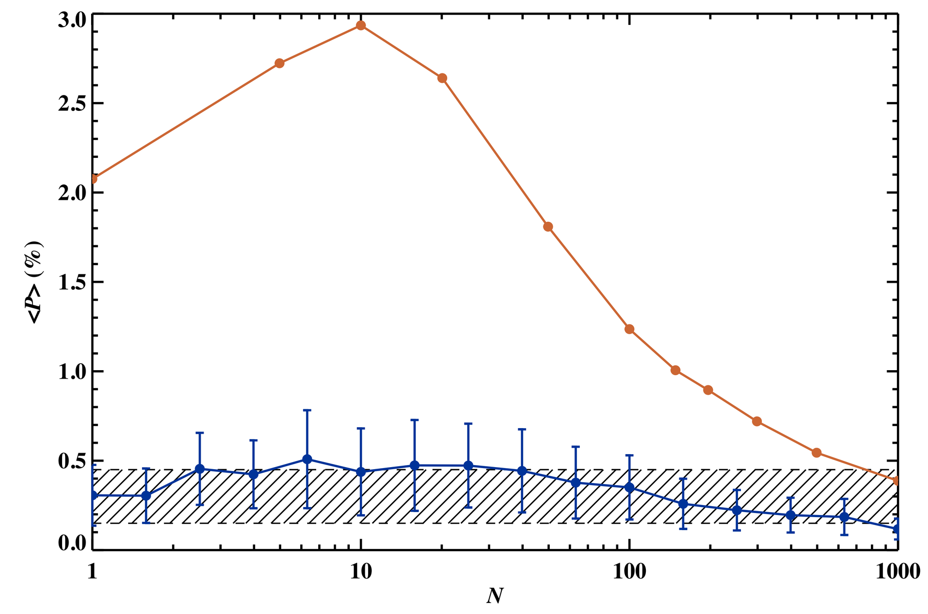

Figure 3. The predicted mean linear polarization <P> of P Cygni plotted as a function of N, from the Monte-Carlo simulations (lower curve) and from the single-scattering models of [2] (upper curve). The error bars on the former indicate the 1-σ variability limits. The hatched region shows the 0.3% ± 0.15% linear polarization observed in P Cygni (e.g., [8]).

Fig. 1 shows Stokes-vector image snapshots from the N = 1, 10 and 100 simulations. Fig. 2 presents the time-series intensity I and linear polarization $P = (Q^2 + U^2)/I$, for these same three cases. Finally, Fig. 3 combines the data from all simulations to plot the mean polarization <P>, and its 1-σ variability limits, as a function of N. Also shown in this figure are the <P> data from the P Cygni models of [2], which are based on a single-scattering formalism with a fix that limits clump optical depths to unity or less.

The Monte-Carlo RT simulations predict smaller polarizations than [2], by a factor of between 3 and 6. They furnish a good match to the observations of P Cygni, both in terms of mean polarization and level of variability, around the $N \sim 100$ point. Due to the larger polarizations seen in their models, [2] require $N \gtrsim 1000$ for consistency with the observations, corresponding to a much-smoother wind.

Discussion

The YARG simulations reveal that single-scattering models can over-predict the linear continuum polarization arising from a given clump configuration. In fact, the key determinant of whether a single-scattering approach is appropriate is *not* the optical depth of individual clumps, but the global optical depth of the wind. In the case of P Cygni, $\tau_s > 1$ indicates that multiple scatterings are unavoidable.

Because multiple scatterings reduce the overall degree of polarization, optically thick winds must be quite fragmented (smaller N) if they are to exhibit a non-negligible polarization signature. As a corollary, these winds should also display significant photometric variability. For P Cygni, [9] report aperiodic light variations with a typical semi-amplitude $\Delta V \sim 0.1$ — broadly consistent with the behavior seen in the N = 100 intensity panel of Fig. 2.

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We acknowledge support from NASA *Long Term Space Astrophysics* Grant NNG05GC36G. Thanks also to Profs. Sebastian Heinz and Ellen Zweibel for the generous loan of computational resources.