Using polarization to study the winds of massive stars

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Abstract. The topic of wind-clumping has been the subject of much activity in recent years, due to the impact that it can have on derived mass-loss rates. Here we present an alternative method of investigating wind-clumping, that of polarimetry. We present simulations of the polarization produced by a clumpy wind, and argue that the observations may be reproduced just by statistical deviations from spherical symmetry when the outflow is only slightly fragmented. Here, the polarization scales with $\dot{M}$, which is consistent with observations of LBVs, WRs and O supergiants. Finally, we find clumping factors in the inner $2R_\star$ of $\sim 2 - 3$, and speculate as to the clumping stratification of hot stars.

1. Introduction

Many massive stars show evidence of variable intrinsic polarization, from OB supergiants (Lupie & Nordsieck 1987), to Luminous Blue Variables (LBVs, Davies et al. 2005, & refs therein), and Wolf-Rayet stars (WRs, e.g. St.-Louis et al. 1987). This is typically attributed to scattering off density-inhomogeneities, or ‘clumps’, at the base of the wind.

Clumping is an active research area at present due to the significant effect it has on derived mass-loss rates when incorporated into model stellar atmospheres (see e.g. Puls et al., this volume). Typically, quantitative studies of clumping involve comparison of the synthetic spectra produced by these model atmospheres with observed data. Here we present an alternative avenue of investigation into clumping, that of polarimetry. Below, the basics of the technique are described. The results of a recent spectropolarimetric survey of LBVs are reviewed, and a quantitative investigation into the data is described.

2. Studying clumping with polarization

Wind-asphericity in hot stars can produce intrinsic polarization via the following mechanism: free electrons in the stellar wind scatter continuum photons from the star, resulting in polarization of the continuum perpendicular to the plane of scattering. If the overall geometry of the scattering material is aspherical on the plane of the sky, for example in a random distribution of clumps, this results in a net continuum polarization. However, line photons which form over a much larger volume undergo less scattering, meaning that the line-emission remains essentially unpolarized. Therefore, by studying polarization as a function of
Figure 1  Polarization spectrum of the LBV HR Car. Bottom panel shows the intensity spectrum in the region of H\(\alpha\), middle panel shows the degree of polarization, and top panel shows polarization position angle. The drop in polarization across the emission line is indicative of aspherical wind geometry on the plane of the sky.

wavelength across strong emission lines, wind-asphericity can be detected as a drop in polarization across the emission line as the polarized flux is diluted. An example of this is shown in Fig. 1.

3. Spectropolarimetric survey of LBVs

The above technique was applied to all known LBVs in the Galaxy and Magellanic Clouds, originally with the aim of detecting disks / bi-polar flows. It was found that at least half of those objects studied showed evidence for wind-asphericity, and that this was more frequent in the stars with the strongest H\(\alpha\) emission. The 50% detection rate was deemed to be a lower-limit, due to the difficulty in achieving the required S/N for the faintest objects. For more details of this study, see Davies et al. (2005).

It is clear that for those objects for which multiple observations exist that the continuum polarization is variable, while the line polarization remains roughly constant. This is strong evidence that the H\(\alpha\) emission is unpolarized, and that the continuum polarization, which is variable in both strength and position-angle (PA), is caused by electron-scattering within the line-forming region. Examples of this behaviour are shown in Fig. 2.

This behaviour is strong evidence of clumping at the base of the wind, rather than wind axi-symmetry or binarity. The variability is explained as follows: the polarization at any given epoch is due to the total polarization of all clumps in the wind, and is dominated by those clumps closest to the star. As these clumps move out through the wind and new clumps are ejected, the polarization evolves. If repeat observations are spaced such that the inner-wind bears no resemblance to that at the previous observation, the polarization will have the appearance of being completely random.
4. Modelling the polarimetric variability

To make a quantitative investigation of the results the LBV survey, as well as polarimetry data of other hot stars, we have simulated the polarimetric variability of a clumpy wind with a semi-analytic model. Below is a brief outline of the model, a full description can be found in Davies et al. (in prep).

Clumps are given a constant angular size, thickness and ejection timescale. The clumps are assumed to move radially outwards according to a standard velocity-law characterized by $v_\infty$ and acceleration parameter $\beta$. By defining the parameter-space in this way, the only free parameter for a given $R_*$, $\dot{M}$ and velocity-law was the ejection-rate per wind flow-time $\mathcal{N}$, where the wind flow-time $t_\text{fl} \equiv R_*/v_\infty$.

For high $\mathcal{N}$, the clumps become less and less dense such that the wind begins to approximate to a smooth outflow. For low $\mathcal{N}$, the clumps have to become more dense in order to conserve the mass-loss rate, and at some point become optically-thick. At this point, the polarization-per-clump is assumed to reach an asymptotic value, following the Monte-Carlo results of Rodrigues & Magalhães (2000).

Figure 3 shows the time-averaged polarization $\langle P \rangle$ as a function of $\mathcal{N}$ when the model is applied to P Cyg, using the stellar/wind parameters derived by Najarro et al. (1997). The predicted behaviour can be understood as follows: at high ejection-rates, the wind consists of many low-density clumps which tend to cancel each other out, producing low levels of polarization. As the ejection-rate is decreased, the clumps must become more and more dense, and the polarization-per-clump rises, leading to higher overall levels of polarization. However, at some point the clumps become optically-thick, and the maximum polarization-
per-clump is reached. Here, $\langle P \rangle$ begins to fall again as the wind now consists of a fewer number of dense clumps.

It can be seen from Fig. 3 that P Cyg’s observed level of polarization is consistent with two ejection-rate regimes: $N \lesssim 0.1$ and $N \gtrsim 1000$. As the wind flow-time of P Cyg is about 3 days, $N = 0.1$ implies that ejections occur only once per year. If ejections were really so infrequent they would be evident in polarimetric monitoring (such as Hayes 1985), and would be spectroscopically conspicuous. Therefore, the high-$N$ regime is preferred.

At ejection-rates of $N \sim 1000$, the inner wind consists of $\sim 7000$ low-density clumps. One may expect that this situation would result in no polarization, as the clumps cancel each other out. However, only a slight imbalance is required to produce residual polarization: the maximum polarization per clump here is 0.006%, so a Poissonian $1\sigma$ deviation from spherical symmetry of around 80 clumps is enough to produce $\langle P \rangle \sim 0.5\%$. Therefore, the polarization results from the statistical deviations from spherical symmetry of a ‘fragmented’ wind.

If intrinsic polarization arises naturally from a spherically symmetric wind, then why don’t all hot stars have it? The reason may be due to the star’s mass-loss rate – for a given simulation with a fixed ejection-rate, the time-averaged polarization is directly proportional to the clump density, and hence the overall mass-loss rate. If we were to reduce the input mass-loss rate of P Cyg from $10^{-4.52} M_\odot\text{yr}^{-1}$ (derived for P Cyg by Najarro et al. 1997) to $10^{-6} M_\odot\text{yr}^{-1}$ (typical of O stars, Puls et al. 2006), $\langle P \rangle$ would fall by a factor of 30 to $\sim 0.01\%$. At this level the polarization would be completely undetectable by current instruments.

The results of the modelling suggest two things:

- if the polarization is indeed produced by a wind that deviates only slightly from spherical symmetry and homogeneity, intrinsic polarization may be ubiquitous among hot stars with mass-loss rates greater than $\sim 10^{-4.5} M_\odot\text{yr}^{-1}$.

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**Figure 3.** Time-averaged polarization of a clumpy wind as a function of clump ejection-rate per wind flow-time, using P Cyg stellar parameters. The dash-dotted line marks P Cyg’s observed level of polarization. Taken from Davies et al. (in prep).
This is supported by the results of Davies et al. (2005), which showed that intrinsic polarization was more likely to be found among the LBVs with the strongest Hα emission. It is also consistent with the results of Harries et al. (1998, 2002) who found a lower incidence of intrinsic polarization among O supergiants and WRs, which have $M \sim 10^{-6} \rightarrow 10^{-5} \, M_\odot \, \text{yr}^{-1}$.

- the polarization must be variable on very short timescales.

In order to test this second conclusion, we have begun polarimetric monitoring of the LBVs studied in Davies et al. (2005). By switching to broad-band polarimetry, the throughput can be improved such that many objects can be studied per night, while the precision of $\sigma P \approx 0.03\%$ can be reached.

Figure 4 shows the broad-band polarimetric variability of AG Car over three nights. It can be seen that the polarization jumps by $\sim 0.2\%$ between the first and second night, particularly in the $U$ and $V$ bands. As these observations were part of a short pilot study, it is not clear if nightly variations of 0.2% are typical, as one would expect from the thousands of clumps in a ‘fragmented’ wind, or are rare events associated with the ejection of dense clumps. We are presently obtaining polarimetric monitoring data over longer time baselines to investigate this.

5. Clump ‘filling-factor’

In order to quantify wind-clumping in model atmospheres, the filling-factor is defined as $f = \langle \rho^2 \rangle / \langle \rho \rangle^2$. Under this formalism, the density of a clumped wind, and therefore the mass-loss rate, is overestimated by a factor $\sqrt{f}$. Traditionally, the behaviour of $f$ with distance from the star $r$ is assumed to be that of

![Figure 4. Broad-band polarimetry of AG Car over three consecutive nights. A jump in polarization between the first and second nights (unpublished).](image)
increasing from unity at $r = R_\star$ to some asymptotic value $f_\infty$ (e.g. Dessart et al. 2000). It was found by Hillier et al. (2003) and Bouret et al. (2005) that the clumping must reach $f_\infty$ very close to the sonic point of the wind; and Puls et al. (2006, these proceedings) have shown recently from combined Hα, IR and radio data that clumping may be strongest in the inner $\sim 15R_\star$, tending towards a smoother outflow at larger radii.

From our models, we have attempted to make an independent measurement of the clumping of the inner wind by calculating the quantity $\langle \rho^2 \rangle / \langle \rho \rangle^2$ for a given simulation. It is assumed that there is no inter-clump medium, and the clumps have mass and angular size which are constant with distance. This is unrealistic, as hydrodynamical models of radiatively-driven winds predict a wind structure which evolves with distance from the star (Runacres & Owocki 2002). However, these assumptions are valid in terms of this model as the polarization is insensitive to material greater than $\sim 5R_\star$. We therefore restrict our analysis to the clumping in the inner wind region $r_\in = 1.05 \rightarrow 2$ (as defined in Puls et al. 2006).

Figure 5 shows $f_\in$ as a function of ejection rate per wind flow-time $N$ for typical LBV wind velocities and a $\beta = 1$ velocity law. It can be seen that $f_\in$ is increased for lower ejection rates and higher terminal velocities, due to the material in the wind becoming more spread-out.

If extrapolated to higher $v_\infty$ and lower $R_\star$ the results of $f_\in$ from this model (2-3) are comparable to those derived by Puls et al. (2006) for O stars (3-6, under the assumption that the outer wind is unclumped). As the model presented here predicts a small dependence on $v_\infty$, an extension of the study by Puls et al. to cooler supergiants would be a strong test of the model’s validity.

5.1. Clumping stratification

Brown et al. (1995) showed that the radial redistribution of material above the photosphere (by e.g. radiative instabilities) could not produce polarization.
This can be understood as follows: if we take a spherically-symmetric shell and compress it in the radial direction, the optical depth along the thickness of the shell is unchanged. Hence, if a region of a smooth outflow is radially compressed, it will scatter no more light than the rest of the outflow. Therefore, the polarimetric variability of not just LBVs, but also WRs and O stars, is strong evidence that clumping begins at or below the photosphere, and is not due to radiative instability-induced clumping.

We find that, for typical LBV parameters, the clumping in the inner wind \((R_\star \lesssim 2)\) is in the region of \(~2\). Our model makes no attempt to calculate the dynamical evolution of the clumps, and hence the evolution of \(f\) with distance to the star. However, at larger radii where the Sobolev length is large, radiative instabilities could further coagulate an already clumped wind, leading to an increase in \(f\) with radius. This is consistent with the results of Puls et al. (2006), who find an increase in \(f\) beyond \(R_\star=2\), at least for stars with dense winds.

6. Summary & conclusions

We show that, through observational monitoring and quantitative modelling, polarimetry can be used to independently investigate the phenomenon of wind-clumping in hot stars. From modelling the polarimetric variability, it is found that the observations are reproduced when the wind consists of a large number of low-density clumps. Here the polarization can arise from statistical deviations from spherical symmetry in only a slightly ‘fragmented’ wind.

It is predicted that polarization scales linearly with mass-loss rate, and so is consistent with result of higher polarization in LBVs than WRs and O supergiants. Short-timescale variability is also predicted, and this has been detected in a polarimetric-monitoring pilot-study. Further observations are planned.

In an investigation of the wind clumping-factor \(f_{cl}\), we find that the wind is already significantly clumped in the inner \(2R_\star\), in agreement with recent combined \(Ha/IR/radio\) observations. The model could be further tested by extending these observations to B/A supergiants.

Acknowledgments. We would like to thank Qingkang Li, Rico Ignace and John Brown for many extremely useful discussions throughout the course of this work.

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