Polarimetry: From the Sun to Stars and Stellar Environments
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Emission line spectropolarimetry and circumstellar structures

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Abstract. We discuss the role of linear emission-line polarimetry in a wide set of stellar environments, involving the accretion disks around young pre-main sequence stars, to the aspherical outflows from O stars, luminous blue variables and Wolf-Rayet stars, just prior to explosion as a supernova or a gamma-ray burst. We predict subtle *QU* line signatures, such as single/double *QU* loops for un/disrupted disks. Whilst there is plenty of evidence for single *QU* loops, suggesting the presence of disrupted disks around young stars, current sensitivity (with S/N of order 1000) is typically not sufficient to allow for quantitative 3D Monte Carlo modeling. However, the detection of our predicted signatures is expected to become feasible with the massive improvement in sensitivity of extremely large mirrors.

Keywords. polarization, scattering, line: profiles, stars: emission-line, Be, stars: mass loss, stars: pre–main-sequence, stars: formation, stars: winds, outflows, stars: rotation, stars: Wolf-Rayet

1. Introduction

Circumstellar (CS) structures around both (i) young pre-main sequence (PMS) stars and (ii) (evolved) massive stars can be diagnosed via their emission lines. Stokes *I* alone is not sufficient to provide geometrical constraints of this CS medium. Therefore, other techniques such as interferometry are often employed, but in order to unravel the 3D geometry of the CS material for objects far away (in principle as far as the edge of the Universe) linear *QU* emission-line spectropolarimetry needs be utilized.

2. Dilution versus intrinsic line polarization

QU polarimetry can be utilized to constrain the large-scale 2D asymmetry of stellar winds (Petrenz & Puls 2000; Müller & Vink 2014), or any other type of CS medium, such as disks, including the smallest spatial scales, involving the inner disks around PMS stars (Vink *et al.* 2005), and the driving region of massive star clumpy winds in close proximity to the stellar photosphere (Cantiello *et al.* 2009).

In principle, continuum polarimetry may inform us about the presence of a large-scale asymmetric structure on the sky such as a disk or a flattened wind (see contributions of Magalhaes, and Landstreet, this volume). However, in practice, the issue is somewhat more complicated due to the roles of intervening interstellar dust and instrumental polarization. This is one of the reasons as to why linear *spectro*polarimetry, measuring the change in the degree of polarization across emission lines, is such a powerful tool, because intrinsic information can be directly gleaned from the *QU* plane. The second reason is that it may also provide *kinematic* information of the flows around both young PMS, as well as massive stars.

Figures 1-3 show *QU* line polarization cartoons (both in terms of polarization “triplot” spectra and Stokes *QU* planes) for the case that the spatially unresolved object under

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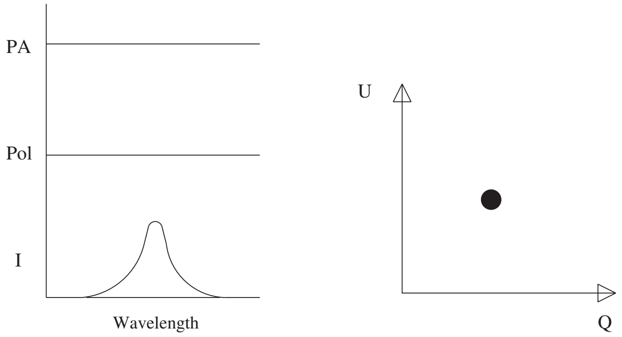

Figure 1. Cartoon indicating the simplest case of no line effect. On the left, polarization spectrum triplot and a Stokes QU diagram on the right. A typical emission line is shown in the lower panel of the triplot, the %Pol in the middle panel, while the Position Angle (PA) is sketched in the upper panel of the triplot. See Vink *et al.* (2002) for further details.

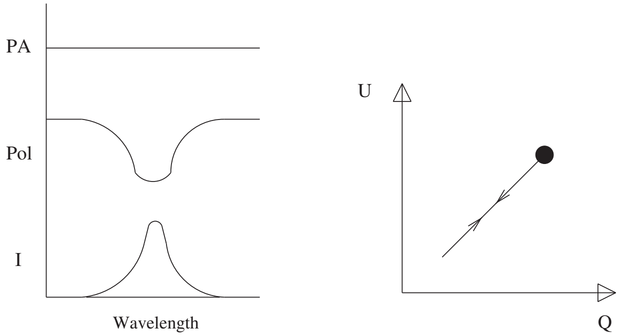

Figure 2. Cartoon indication simple dilution. Note that the dilution across the line is as broad as the Stokes I emission. Dilution translates into QU space as a linear excursion. See Vink *et al.* (2002) for further details.

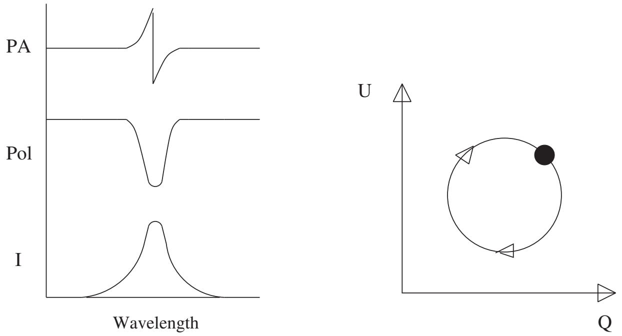

Figure 3. Cartoon of a compact source of line photons scattered off a *rotating* disk. The polarization signatures here are relatively narrow compared to the Stokes I emission. The PA flip is associated with a loop in Stokes QU space. See Vink *et al.* (2002, 2005) for further details.

consideration is (i) spherically symmetric on the sky showing "no line effect", (ii) asymmetric showing line "dilution" where the emission line simply acts to dilute the polarized continuum, or (iii) cases where the line effects are more subtle, involving position angle (PA) flips across intrinsically polarized emission lines, which translate into rounded "loops" when plotted in the QU plane (see Fig. 3).

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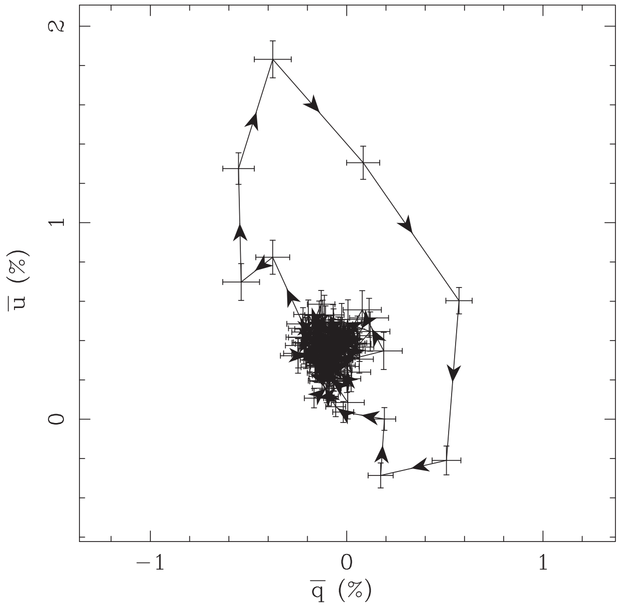

Figure 4. *QU* diagram of the Herbig Ae star MWC 480. The PA flip is associated with a loop in Stokes *QU* space. See Vink *et al.* (2002) for further details.

3. Massive star winds

3.1. *2D large-scale structures*

Stellar winds from massive O-type stars above 30 $M_\odot$ "drive" these objects from their main sequence locations into the Luminous Blue Variable (LBV) and Wolf-Rayet (WR) phases. It has often been claimed that LBVs and WR stars have disks similar to those of the lower mass ($\sim$10 $M_\odot$) classical Be stars that were found to be polarized in the 1970s (e.g. Poeckert & Marlborough 1976). Interestingly, O stars, even including the higher mass counterparts of the Be stars, the Oe stars, are largely unpolarized (Vink *et al.* 2009). However, for the more evolved phases of the more massive stars, the LBV and WR objects, the jury is still out.

For evolved WR stars, it has been shown that the vast majority (of 80%) is unpolarized (Harries *et al.* 1998, Vink 2007), but there is a polarized sub-group of presumably young rotating WR stars that may have shed an ejecta nebula during a prior red-supergiant (RSG) or LBV phase (Vink *et al.* 2011; Gräfener *et al.* 2012). This polarized sub-group of WR stars are undoubtedly the best gamma-ray burst (GRB) progenitors identified to date, though there are many puzzles remaining.

The evolutionary state of LBVs is also still under debate, as LBVs have been proposed to be direct SN progenitors (see Vink 2012; see also Hoffman this volume). Some 20 years ago, LBVs were suggested to have CS disks through polarization measurements (e.g. Schulte-Ladbeck *et al.* 1994), but when Davies *et al.* (2005) re-observed some of these well-known LBVs, it turned out that the PA had changed from previous measurements. Davies *et al.* (2005) were therefore forced to conclude that it was 3D clumpy structures that were responsible for the polarization of LBVs, rather than large-scale 2D structures.

3.2. *3D clumpy structures*

Polarization variability noted in the winds of massive stars requires an interpretation of 3D small-scale structures (clumps) in the innermost parts of their winds. In case clumps

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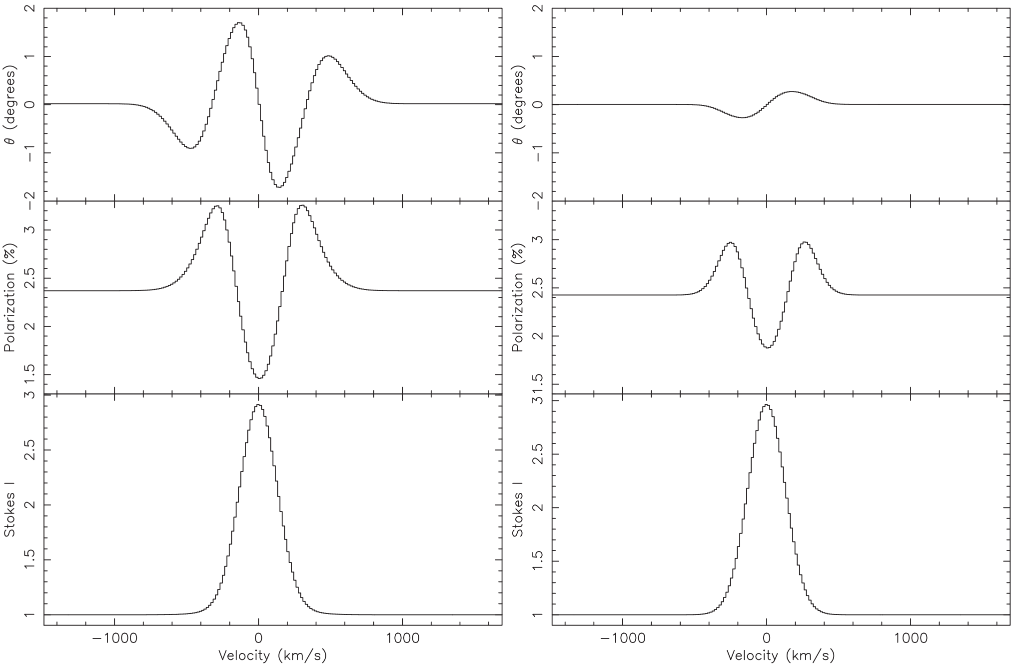

Figure 5. Monte Carlo *QU* line polarimetry predictions for a disk with an inner hole (on the left) and a disk without an inner hole (on the right). The difference is due to the finite-size of the star in the case of no inner hole. From Vink *et al.* (2005).

would only be formed far out in the wind (above some 1.5 stellar radii), for instance as a result of the well-known line-deshadowing instability (LDI), the linear polarization of a certain clump formed in one place of the wind would be cancelled by the *anti* polarization of the void-region that is simultaneously left behind. The sheer presence of polarization variability can thus be considered evidence that wind clumping must already take place in the stellar photosphere. Sub-photospheric convection or other physics associated with the iron-opacity bump may thus be key in causing wind clumping.

Cantiello *et al.* (2009) showed that the typical density scale-heights in their convective regions are of the right order of magnitude to explain the polarization variability of hot-star winds that were modeled by Davies *et al.* (2007).

Further observational work is needed to translate the insights from LBV winds into the O-star domain, which is observationally more challenging due to the faster O-star winds with shorter dwell-times, but high S/N time-resolved polarimetric monitoring is already feasible with current instrumentation.

4. PMS disks

There is a well-established magnetospheric-accretion paradigm for the accumulation of CS material onto the surfaces of low-mass T Tauri PMS stars via field lines. Whether such a mechanism may also be extended to higher mass PMS stars, such as the intermediate mass Herbig Ae/Be stars up to 20 $M_{\odot}$, remains to be seen.

Linear *QU* spectropolarimetry is able to provide some key geometric information about these types of processes though. Whilst emission line polarimetry on the highest mass Herbig Be stars has indicated the presence of accretion disks via the simple dilution effect, the lower mass Herbig Ae stars exhibit intrinsic line polarization and similar PA

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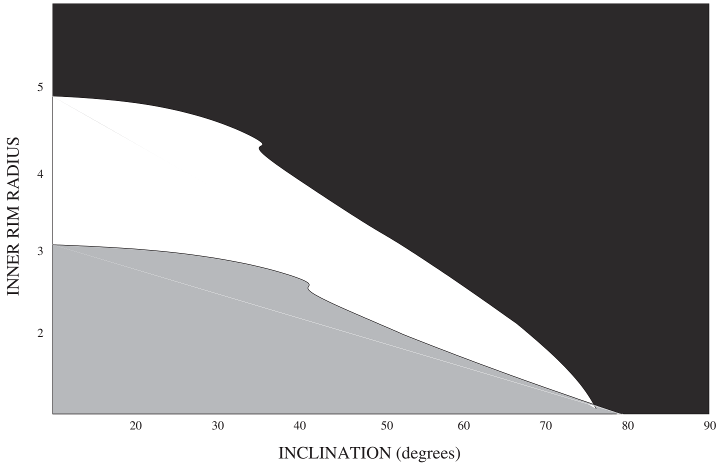

Figure 6. Constraining the disk inner hole using the inner radius versus disk inclination. Single QU loops are indicated by the dark shaded area. Double QU loops are shown by the light shaded areas. Transitional behaviour is represented by the white shaded area of the plane. See Vink *et al.* (2005).

flips as those around T Tauri stars. These PA flips show up as "loops" in the QU diagram (see Fig. 4 for the Herbig Ae star MWC 480).

Vink *et al.* (2005) performed Monte Carlo simulations of scattering disks with variable inner hole sizes (see Fig. 5), relevant for a range of physical processes from direct disk accretion (e.g. via a boundary layer) to magnetospheric accretion. First results showed that the QU loops in both the T Tauri stars and the Herbig Ae stars are consistent with magnetospheric accretion, and that the character of these loops in the QU plane may be utilized to constrain the size of their inner disk holes (see Fig. 6).

Future directions We have shown evidence for single QU loops, suggesting the presence of disrupted disks around PMS stars, which provide constraints on (magnetospheric) accretion models. However, current sensitivity is not sufficient to allow for *quantitative* 3D Monte Carlo modelling. The detection of the predicted signatures will become feasible with the massive improvement of future extremely large (30-40 meter) mirrors.

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