New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
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Linear line spectropolarimetry as a new window to measure 2D and 3D wind geometries

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Abstract. Various theories have been proposed to predict how mass loss depends on the stellar rotation rate, both in terms of its strength, as well as its latitudinal dependence, crucial for our understanding of angular momentum evolution. Here we discuss the tool of linear spectropolarimetry that can probe the difference between mass loss from the pole versus the equator. Our results involve several groups of O stars and Wolf-Rayet stars, involving Oe stars, Of?p stars, Onfp stars, as well as the best candidate gamma-ray burst progenitors identified to date.

Keywords. techniques: polarimetric, circumstellar matter, stars: early-type, stars: emission-line, Be, stars: mass loss, stars: rotation, stars: winds, outflows, stars: Wolf-Rayet

1. Introduction

Ultimately, we would like to understand massive stars and their progeny both locally as well as in the distant Universe. What is clear is that rotation, mass loss, and the link between them, play a pivotal role in the fate of massive stars. However, in order to test mass-loss predictions for rotating stars, we need to probe the density contrast between the stellar pole and equator. In the local Universe, this may potentially be achievable through the technique of long-baseline interferometry, as discussed during this meeting. However, in order to determine wind asymmetry in the more distant Universe we necessarily rely on the technique of *linear* spectropolarimetry. The only limiting factor is then the collecting power of the mirror of the largest telescopes.

2. 2D Wind Predictions

Until 3D radiation transfer models with 3D hydrodynamics become available, theorists have necessarily been forced to make assumptions with respect to either the radiative transfer (e.g. by assuming a power law approximation for the line force due to Castor *et al.* 1975) or the hydrodynamics, e.g. by assuming an empirically motivated wind terminal velocity in Monte Carlo predictions (Abbott & Lucy 1985; Vink *et al.* 2000). Albeit recent 1D and 2D models of Müller & Vink (2008, 2014) no longer require the assumption of an empirical terminal wind velocity.

There are 2D wind models on the market that predict the wind mass loss predominately emanating from the equator (Friend & Abbott 1986; Bjorkman & Cassinelli 1993; Lamers & Pauldrach 1991; Pelupessy *et al.* 2000), whilst other models predict higher mass-loss rates from the pole, in particular as a result of the von Zeipel (1924) theorem, resulting in a larger polar Eddington factor than the equatorial Eddington factor (Owocki *et al.* 1996; Petrenz & Puls 2000; Maeder & Meynet 2000; Müller & Vink 2014).

The key point is that mass loss from the equator results in more angular momentum loss than would 1D spherical or 2D polar mass loss, so we need 2D data to test this.

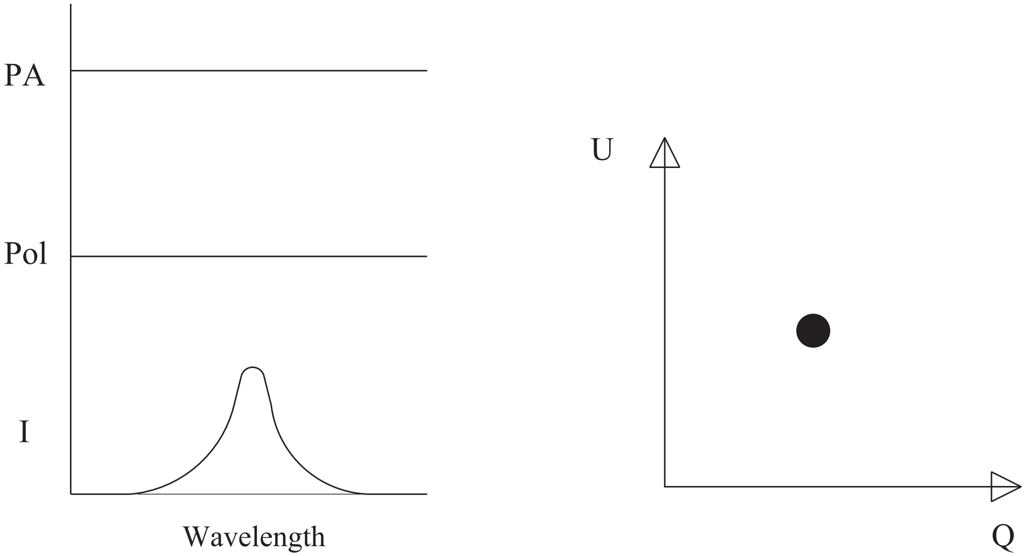

Figure 1. Cartoon indicating “no line effect’. On the left, polarization spectrum “triplot” and a Stokes QU diagram on the right. A typical Stokes I emission is shown in the lower panel of the triplot, the %Pol in the middle panel, while the Position Angle (PA) is sketched in the upper panel of the triplot.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

3. Line polarization versus depolarization

Whilst *circular* Stokes V spectropolarimetry is oftentimes employed to measure stellar magnetic fields, *linear* Stokes QU polarimetry can be utilized to measure large-scale 2D asymmetry in a stellar wind or any other type of circumstellar medium, such as a disk. In this sense, the Stokes QU plane plays an analogous role to the interferometric UV plane, with the additional advantage that it can measure the smallest spatial scales, such as the inner disk holes of order just a few stellar radii in pre-main sequence (PMS) stars (Vink *et al.* 2005), which would otherwise remain “hidden”, or the driving region of stellar winds in massive stars, that we explore in the following.

In principle, linear continuum polarimetry would already be able to inform us about the presence of an asymmetric (e.g. a disk or flattened wind) structure on the sky, but in practice, this issue is complicated by the roles of intervening circumstellar and/or interstellar dust, as well as instrumental polarization. The is one of the reasons linear *spectro*polarimetry, measuring the change in the degree of linear polarization across emission lines is such a powerful tool, as “clean” or “intrinsic” information can be directly obtained from the QU plane. The second reason is the additional bonus that it may provide kinematic information of the flows around PMS as well as massive stars.

Figures 1–3 show linear line polarization cartoons (both in terms of polarization “triplot” spectra and Stokes QU planes) for the case that the spatially unresolved object under consideration is (i) spherically symmetric on the sky showing “no line effect”, (ii) asymmetric showing line “depolarization” 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 lines.

Whilst the third situation of intrinsic line polarization in a rotating disk has been encountered in PMS (see Vink *et al.* 2005), it is the second case of “depolarization” that is most familiar to the massive-star community through its application to classical Be stars, starting as early as the 1970s (see the various works by Poeckert, Marlborough,

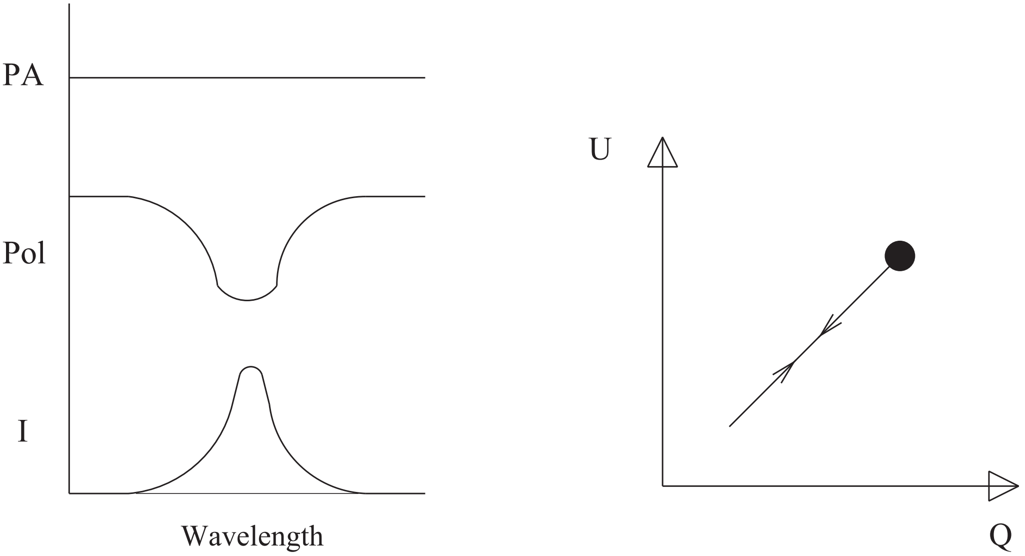

Figure 2. Cartoon indication "depolarization" or "dilution". Note that the depolarisation across the line is as broad as the Stokes I emission. Depolarisation translates into Stokes QU space as a linear excursion. See Vink *et al.* (2002) for further details.

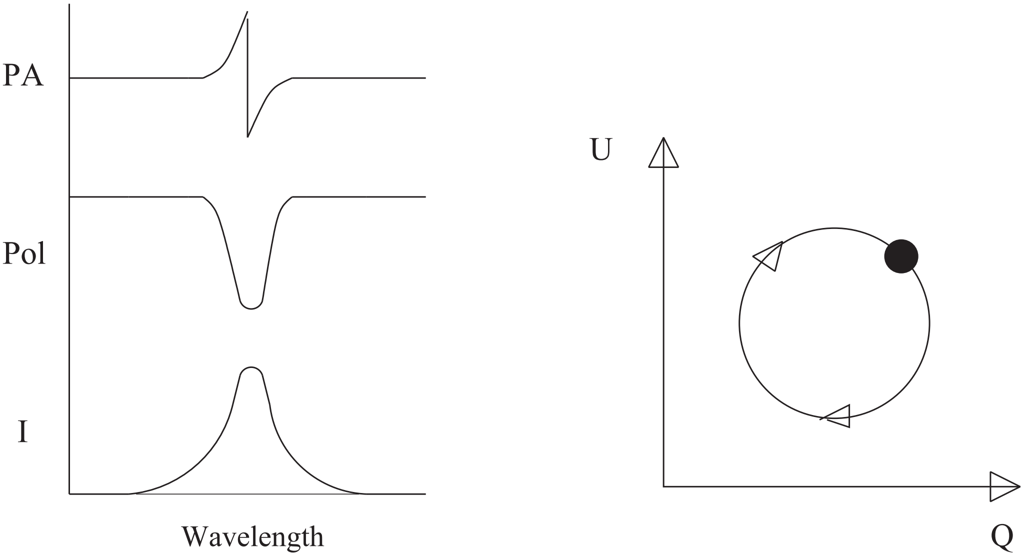

Figure 3. Cartoon indicating a compact source of line photons scattered off a *rotating* disk. Note that the polarisation signatures are relatively narrow compared to the Stokes I emission. The PA flip is associated with a loop in Stokes QU space. See Vink *et al.* (2002, 2005) for further details.

Brown, Clarke, and McLean). Interestingly, the same method has in more recent years also been applied to Oe stars, the alleged more massive counterparts of Be stars, see Fig. 4. Note that although the Oe star HD 120678 (on the right hand side of Fig. 4) has a significant observed level of linear polarization, the lack of a line effect implies that the object is not intrinsically polarized (Vink *et al.* 2009). This could either mean the object is spherically symmetric or that it has a disk that is too "pole on" to provide intrinsic

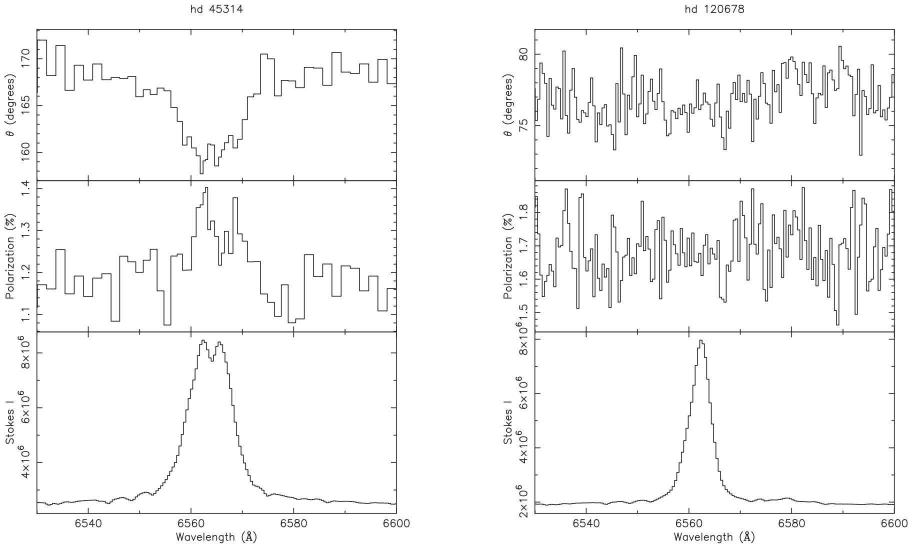

Figure 4. Hα line polarization "triplots" of the Oe stars HD 45314 and HD 120678. HD 45314 shows a line effect indicating that it is intrinsically polarized, but HD 120678 is not intrinsically polarized. See Vink *et al.* (2009) for further details.

polarization. It is for these reasons vital to consider a *sample* of objects. For Oe stars Vink *et al.* (2009) found that the incidence of line effects (1/6) was much lower than for Be stars. This implies that the chance the Oe and the Be stars are drawn from the same parent distribution is small, providing relevant constraints on the formation of Be stars.

4. Survey results of O and Wolf-Rayet winds

We now turn to more massive stars with stronger winds than Oe/Be stars. Linear spectropolarimetry results have been performed on relatively large samples (of order 40-100) for both O (Harries *et al.* 2002; Vink *et al.* 2009) and Wolf-Rayet (WR) stars (Harries *et al.* 1998; Vink 2007), and the key result from these surveys is that the vast majority of 80% of them is to first order spherically symmetric. This is of key importance for the accuracy of mass-loss predictions from 1D models for rotating stars.

However, the above studies also found a number of interesting *exceptions*. With respect to O stars, Vink *et al.* (2009) found that certain O-type subgroups involving Of?p and Onfp class are more likely polarized than the garden-variety of spherical O-stars. For instance, Vink *et al.* (2009) highlighted that HD 108 is linearly polarized, which may be related to its probably magnetic properties. Indeed, it was later found that HD 108 and several other Of?p stars form a magnetic sub-class. The line effects in the Onfp stars (involving famous objects like λ Cep and ζ Pup) may may involve intrinsic line polarization effects due to the rapid rotation of this O-type subgroup in addition to (or instead of) depolarization.

Turning to WR stars, Vink *et al.* (2011) and Gräfener *et al.* (2012) uncovered that the small 20% minority of WR stars that display a depolarization line effect indicating stellar rotation are highly significantly correlated with the subset of WR stars that have ejecta nebulae. These objects have most likely only recently transitioned from a red sugergiant (RSG) or luminous blue variable (LBV) phase. As these presumably youthful WR stars have yet to spin-down, they are the best candidate gamma-ray burst (GRB) progenitors identified to date. However, in our own Milky Way these WR stars are still expected to spin down before explosion (due to WR winds). However, in lower metallicity (Z) environments WR stars are thought to be weaker and WR stars in low Z environments, such as those studied in the Magellanic Clouds may offer the best way to directly pinpoint GRB progenitors (Vink 2007).

5. Future

In addition to the quest for WR GRB progenitors, there is a whole range of interesting wind physics to be constrained from linear spectropolarimetry. The main limitation at this point is still sensitivity. We are currently living in an exciting time as we are at a point where the possibility of extremely large telescopes (ELTs) may become reality. If these telescopes materialize with the required polarization optics, we might – for the first time in history – be able to obtain spectropolarimetric data at a level of precision that has been feasible with 1D Stokes I data for more than a century. It is really important to note that current 3D Monte Carlo radiative transfer is well able to do the required modelling, but the main limitation is the necessary 3D data!

Another interesting future application will involve polarimetric monitoring. Whilst we now know that on large scales the 1D approximation is appropriate for stellar winds, we have also become aware of the intrinsic 3D clumpy nature of stellar winds on smaller scales (but with macroscopic implications!). In particular the existence of wind clumps on small spatial scales near the stellar photosphere (Cantiello *et al.* 2009) has been confirmed by linear polarization variability studies (Davies *et al.* 2007), but to probe further – mapping wind clumps in detail – we need good monitoring data.

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Discussion

HENRICHS: In your very nice talk, you showed polarisation data of the HeII 4686 line of λ Cep. Since this profile is known to change in less than one hour (see our poster), it would be very interesting to see how the polarisation would change, in the hope to model the geometry. What would be a typical exposure time for this bright star? Would it be feasible?

VINK: It is a bright object, so exposure time will be short. So yes, it is possible!

NAZÉ: A comment: Linear polarisation is important, but must be detected with high sensitivity. In your 2009 paper, you detected no signal for θ' Ori C while ud Doula models and all other observations (UV, X-rays, spectropolarimetry) agree on a very axisymmetric structure of the wind down to photosphere.

VINK: Current linear polarization sensitivity is sufficient to probe density contrasts between the stellar equator and pole of as little as 1.25. Why the θ' Ori C model you refer to seems capable to reproduce 1D data, but does not seem to reproduce 3D data, is an issue that needs to be clarified.

MEYNET: You said that O/WR winds are spherical and that this is compatible with your theory. This would also be compatible with the formula we obtained with Maeder since most, if not all, these stars are rotating very far from the critical velocity. Would you agree?

VINK: Yes, I said the 80% majority is spherical because of $V_{\rm rot} < 300\,{\rm km\,s^{-1}}$. We need to test (by comparison with the data) if your formula also agrees with this. It might well be possible.

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