Linear line spectropolarimetry of Herbig Ae/Be stars

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Abstract Accretion is the prime mode of star formation, but the exact mode has not yet been identified in the Herbig Ae/Be mass range. We provide evidence that the maximum variation in mass-accretion rate is reached on a rotational timescale, which suggests that rotational modulation is the key to understanding mass accretion. We show how spectropolarimetry is uniquely capable of resolving the innermost (within 0.1 AU) regions between the star and the disk, allowing us to map the 3D geometry of the accreting gas, and test theories of angular momentum evolution. We present Monte Carlo line-emission simulations showing how one would observe changes in the polarization properties on rotational timescales, as accretion columns come and go into our line of sight.

Keywords Herbig Ae/Be stars; T Tauri stars; pre-main sequence stars; polarization; star formation

1 Introduction

Herbig Ae/Be stars with masses in the range 2-15 $M_\odot$ lie at the interface between low-mass and high-mass star formation. One of the key goals is to unravel whether the magnetospheric accretion model that is very successfully applied in low-mass ($M < 2M_\odot$) T Tauri stars may also be of relevance for higher mass stars. Whilst circular Stokes $V$ spectropolarimetry can be used to measure magnetic fields, linear Stokes $QU$ polarimetry may be employed to probe the gas geometry within the innermost regions between the star and the disk – on the scale of just a few stellar radii.

Such work is needed to unravel the complex accretion flows onto T Tauri and Herbig stars, in order to understand issues such as the mass-accretion rate $\dot{M}_{\text{acc}}$ versus stellar mass relation (Garcia-Lopez et al. 2006; Mendigutia et al. 2012) as well as the more general questions as to whether even the highest mass stars in the Universe form by disk accretion or whether more exotic formation mechanisms, involving for instance stellar collisions, need to be invoked (e.g. Bestenlehner et al. 2011).

We will explore the alignment between disk position angles (PAs) measured from linear $QU$ spectropolarimetry and those from Herbig binaries, showing that our data are fully consistent with disk accretion and fragmentation in the intermediate mass 2-15 $M_\odot$ (Harmanec 1988) range. Note that this is independent of the polarizing mechanism in Herbig Ae/Be stars.

2 The method

Linear Stokes $QU$ polarimetry can be used to measure flattening of the circumstellar medium. In principle, continuum polarization would already be able to inform us about the presence of an asymmetric disk-like structure on the sky, but in practice this issue is complicated by the roles of intervening circumstellar (as e.g. in the UXOR phenomenon; Grinin 1994) and/or interstellar dust, as well as instrumental polarization. This is one of the reasons why spectropolarimetry, measuring the change in the degree of linear polarization across spectral lines is such a powerful tool, as intrinsic information can directly be obtained from the Stokes $QU$ plane. The second reason is the additional bonus that it may provide kinematic information of the flows around young stars.

Figures 1-3 show spectropolarimetry cartoons (both in terms of polarization “triplet” spectra and $QU$ planes) for the case that a spatially unresolved object...
Fig. 1 Cartoon indicating the simplest case of no line effect. On the left, the polarization spectrum triplot – and on the right its accompanying QU diagram. A typical emission is shown in the lower panel of the triplot, the %Pol is given in the middle panel, while the Position Angle (PA) is shown in the upper panel of the triplot. See Vink et al. (2002) for further details.

Fig. 2 Cartoon indication depolarization or dilution of the emission line. The depolarization across the line is as broad as the Stokes I emission. Depolarization translates into Stokes QU space as a linear excursion. See Vink et al. (2002).
is (i) spherically symmetric on the sky with “no line effect”, (ii) asymmetric subject to line “depolarization” where the emission line simply acts to “dilute” the polarized continuum, or (iii) where the line effect is more subtle, involving PA flips across intrinsically polarized emission lines.

In its simplest form, spectropolarimetry can be used to detect a difference between an unpolarized emission line such as H$\alpha$ and a polarized continuum that results from scattering off a circumstellar disk (Fig. 2). This tool has for instance been employed on samples of classical Be stars in the 1970s (e.g. Poockert & Marlborough 1976). These observations gave an incidence rate of order 60%, which is fully consistent with all classical Be stars being embedded in electron scattering disks. Given that the PA measured from linear spectropolarimetry was consistent with those from interferometry, the technique was considered to be a particularly efficient and accurate method for discovering disks around stars that would otherwise remain unresolved.

In more recent years, we have found incidences of intrinsic line polarization, implying that it is the line itself that is polarized, e.g. by a rotating accretion disk around a T Tauri star that scatters line photons from the interior regions close to the star (Fig. 3), that may arise from the magnetospheric accretion model (Vink et al. 2003).

3 Results

Over the last decade, we have been active in obtaining medium resolution ($R \sim 8000$) linear spectropolarimetry on samples of several tens of T Tauri and Herbig (single and binary) stars on 4m class telescopes at high signal-to-noise ratios $>1000$ using instruments such as the ISIS spectrograph on the William Herschel Telescope (WHT).

3.1 A transition in mode of mass accretion between Herbig Ae and Be stars

Figures 4 to 7 show the difference in linear H$\alpha$ spectropolarimetry discovered by Vink et al. (2002). Herbig Ae stars show PA flips in the upper panel of the triplot, which is caused by intrinsic line emission scattered off a rotating disk. These PA flip (QU loop) data are the same in T Tauri stars, where the magnetospheric accretion model has been successfully applied. The Herbig Be stars show spectropolarimetric behaviour that is notably different: here the data are consistent with disk accretion. Note that this difference between the Ae and the Be stars is not confined to H$\alpha$, as H$\beta$ and H$\gamma$ show exactly the same differences between the Herbig Ae and the Herbig Be stars (Mottram et al. 2007).
Fig. 4  The Herbig Be star BD+40 4124 showing line "depolarization" or "dilution". The triplot shows Stokes I emission in the lowest panel, the %Pol is given in the middle panel, while the Position Angle (PA) is given in the upper panel. The data are re-binned such that the 1σ error in the polarization corresponds to 0.05% as calculated from photon statistics. See Vink et al. (2002) for further details.

Fig. 5  QU diagram of the Herbig Be star BD+40 4124 showing depolarization/dilution. See Vink et al. (2002) for further details.

Fig. 6  The Herbig Ae star XY Per shows intrinsic line polarization. Note the flip in the PA, which would translate into a loop when the data were plotted in a QU diagram. See Vink et al. (2002) for further details.

Fig. 7  QU diagram of the Herbig Ae star XY Per showing a loop representative of intrinsic line polarization. See Vink et al. (2002) for further details.
3.2 Constraining the disk inner radius

Vink et al. (2005a) performed 3D Monte Carlo scattering experiments using TORUS (Harries 2000) to constrain the disk inner radius in T Tauri and Herbig Ae stars. The results were obtained for both a flat disk and a constant opening angle “theta” disk and the model objects were found to show loops in the QU diagram data (corresponding to PA flips as shown in the upper panel of the triplot in Fig. 6). There is a notable difference between a disk with no inner hole showing double QU loops, as shown in Fig. 8, versus a disk with a small inner hole, subject to single QU loops, such as shown in Fig. 9.

Using this qualitatively different behaviour, it was shown how this methodology can be used to derive quantitative constraints on the sizes of disk inner holes around T Tauri and Herbig stars. Figure 10 summarizes our methodology. For instance, data on the bright T Tauri star GW Ori show the presence of a gradual PA change across Hα, which may be indicating the presence of a relatively small inner hole of less than two stellar radii for an inclined disk ($i \approx 75$ degrees), or a more pole-on disk, but with a larger inner hole (Vink et al. 2005a; Vink et al. 2005b).

3.3 Disk alignment in Herbig Ae/Be binaries

Vink et al. (2005b) and Wheelwright et al. (2011) compared their spectropolarimetric disk PAs to the disk PAs derived from alternative imaging techniques, such as interferometry. The excellent agreement proved that linear spectropolarimetry is an efficient tool to determine disk PAs, and that this is independent of the polarizing mechanism, whether that involves scattering (Vink et al. 2005; Milic & Faurobert 2014) or optical pumping (Kuhn et al. 2007).

The disk PAs were compared to binary PAs by Wheelwright et al. (2011) from Herbig Ae/Be binaries. Our PA data were found to be inconsistent with a random distribution, which might perhaps have been expected in case primary stars capture their companions in a cluster-like competitive accretion scenario. Instead, the PA data were found to be consistent with a disk accretion scenario, in which both the primary and secondary object fragment from the same accretion disk.

In other words, our data suggest that stars up to $15 M_\odot$ may indeed form by disk accretion, as modeled by e.g. Kratter & Matzner (2006), Krumholz et al. (2009), and Kuiper et al. (2010).
4 Current applications and limitations

We have shown polarimetric line profiles for scattering off rotating disks, but we have not yet given any preference to a particular type of scattering particle. Moreover, there is usually the issue of interstellar polarization, implying that the observed continuum PA is generally not equal to zero and that the level of continuum polarization is affected by a foreground contribution due to interstellar grains. Nonetheless, the differential effect between line and continuum is not affected by foreground polarization, and the shapes of the loops in the QU plane remain exactly the same (they are just shifted). Furthermore, there is the complication of unpolarized line emission. For classical Be stars, Halpha is believed to form in the circumstellar environment, rather than at the stellar surface, as assumed in our Monte Carlo models. So, there are two potential polarization effects (dilution and intrinsic line polarization), which could sometimes be at work simultaneously, but the PA rotations due to intrinsic line polarization should be distinguishable from dilution effects because of their contrasting characteristics in the QU plane.

So far, we have assumed idealized disk geometries. One may for instance also wish to consider more sophisticated flaring disk geometries, as infrared spectral energy distribution modeling has indicated a preference for this (Kenyon & Hartmann 1987; Chiang & Goldreich 1997). These flaring disks may even possess puffed-up inner rims (e.g. Dullemond et al. 2001). A flaring disk may be able to intercept light at larger distances from the stars, which may contribute to the continuum polarization percentage. However, the differences between a flared and constant opening angle disk are expected to be minor as far as the predicted polarization changes across spectral line profiles are concerned.

The issue of the polarizing agent has not yet been settled. For hot stars, such as classical Be stars, the polarizing agent is usually attributed to electron scattering (although hydrogen continuum opacity is thought to have an effect on broad-band spectropolarimetry at ionization edges). Electrons are known to be able to smear out line polarimetric profiles because of their large thermal motions compared to the bulk motions of the stellar envelope (Wood & Brown 1994). Therefore, some of the Stokes Q and U structure across lines would be diminished for hot stars by this thermal broadening effect. This would especially be true for lower sensitivity measurements. To date, line polarimetry with 4m-class telescopes is usually performed at the S/N level of 1000, and the accuracies are therefore of the order of about 0.1%. Demands on “differential” measurements across spectral lines are less severe than absolute ones. Already some of the published data from the WHT and the Anglo Australian Telescope (AAT) has performed better than at the 0.1% level (see the data on Zeta Pup by Harries & Howarth 1996). Nonetheless, in the current era of 8m-class, and in the upcoming era of 40m-class telescopes, larger photon collecting areas will make routine high precision spectropolarimetry feasible, such that even in the presence of thermal broadening, subtle changes in the polarization and PA may become measurable.

For cooler stars, dust may be the principal polarizing agent. Although the matrices for Mie and Rayleigh scattering (as used in our Monte Carlo modeling) are different, both favour forward and backward scattering, such that the differences between our predictions and those for Mie scattering are expected to be only qualitative. Furthermore, dust grains are not expected to have large thermal velocities that would result in significant line broadening. Another potential opacity source for which smearing is not expected to be significant is that of neutral hydrogen.

Added to the high demand on sensitivity, another key aspect is that of spectral resolution. Currently, the resolution that can be achieved on common-user optical instruments is limited to R ≲ 10 000. Vink et al. (2005a) checked whether their predicted PA changes would be resolvable when they degraded their model spectra to R = 10 000. They found that the instrumental resolution would not wipe out the predicted QU profiles. The greater limitation is therefore sensitivity. This is because in the handling of spectropolarimetric data there is usually degeneracy between sensitivity and spectral resolution. Currently, one generally re-bins pixels across a spectral line, to gain the signal needed to achieve the required polarimetric accuracy.

We conclude that while there is already plenty of evidence of single PA rotations in T Tauri and Herbig Ae stars that are entirely consistent with disrupted disks, the sensitivity is typically too poor to allow for quantitative comparisons between models and data. In any case, no instance of a double PA flip has yet been positively identified. However, this must be seen as absence of evidence rather than evidence of absence until appreciably greater sensitivity (with S/N >> 1000) becomes routine.

Note that many of the PA rotation amplitudes we have predicted correspond to changes of only 0.05-0.1% in Stokes U throughout the spectral line. Upon occasion, this is measurable with today’s instrumentation provided the integration times are long enough. This is well worth the effort, since line polarimetry can uniquely obtain combined constraints on disk inclination and inner hole radius, as shown in Fig. 10.
5 Future applications

The future of linear line polarimetry seems may become even brighter, as there are many exciting future applications to be considered. To name just a few:

1. Infrared spectropolarimetry (Oudmaijer et al. 2005)
2. Larger samples & Surveys
3. Monitoring data
4. Extra-galactic stars

With respect to (i) the (near) infrared, it might become possible not only to detect the innermost regions of the accretion disks around the obscured most massive young massive (O-type) stars, but also the earliest phases of low- and intermediate mass star formation in pre-T Tauri and pre-Herbig systems.

With respect to the (ii) larger samples, it is noteworthy to realize that with large surveys, such as IPHAS (Drew et al. 2005) and VPHAS+ (Drew et al. 2014), thousands of young Hα emitting stars are being discovered, allowing us to probe the mass-accretion physics as a function of mass, age, and environment (Barentsen et al. 2011; 2013; Kalari et al. in prep.).

With respect to (iii) the monitoring, it has recently become clear that it is the rotational timescale that is dominant in the mass-accretion physics in both T Tauri and Herbig Ae stars (Costigan et al. 2014; see Fig.11). This means that linear spectropolarimetry modeling involving monitoring data such as predicted through Monte Carlo simulations shown in Fig.12 can be employed to map the stellar-disk mass-accretion system in 3D. This might become feasible with the space-based ultraviolet and optical spectropolarimeter Arago/UVMag (PI Neiner).

Finally, with current 8m telescopes such as VLT, Herbig stars can already be discovered in the low metallicity environment of the Large Magellanic Cloud (LMC). The mass-accretion rate ($\dot{M}_{\text{acc}}$) for the Herbig B[e] candidate VFTS 822 (Kalari et al. 2014) seems particularly high, and in order to find out whether such rates are realistic we need the appropriate 3D data that will only be possible with linear spectropolarimetry.

Currently, the main limitation is still sensitivity, but we are living in exciting times where the possibility of extremely large 40m telescopes (ELTs) is about to become reality. If the ELTs materialize with the badly needed polarization optics, we might 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.

Fig. 10 Constraining the disk inner hole. Single QU loops are given by the dark shaded area, whilst double QU loops are indicated by the light shaded areas of the disk inner radius vs. disks inclination plane. Transitional behaviour is represented by the white shaded area of the plane. See Vink et al. (2005).

Fig. 11 The amplitude in mass-accretion rate $\dot{M}_{\text{acc}}$ variations for different timescales. Note that the maximum amplitude is reached on the (rotational) timescale (of days) and not on shorter timescales. On the other hand, sampling on significantly longer timescales does not seem to be required. See Costigan et al. (2014).
Fig. 12  3D Monte Carlo simulation using TORUS (Harries 2000) of a rotational modulation of 2 diametrically opposed spots on the stellar surface. The sequence consists of a full 360 degrees cycle. I.e. the eight snapshots from 0 to 315 degrees are taken every 45 degrees, i.e. at 0, 45, 90, 135, 180, 225, 270, and 315 degrees. Note that the upper spot is initially (at 0 degrees) directed towards the observer.
It is really important to note that 3D Monte Carlo radiative transfer is well able to perform the required modeling, but the main limitation is still the lack of accurate 3D data!

6 Conclusions

- Herbig Ae/Be stars have accretion disks on the smallest spatial scales.
- Linear spectropolarimetry data are entirely consistent with disk accretion and fragmentation.
- There is a transition in mass-accretion physics between Herbig Ae and Herbig Be stars.
- The rotational timescale is key to changes in $\dot{M}_{\text{acc}}$.
- We require linear Stokes $QU$ monitoring to map the 3D geometry.

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