

PROBING THE CIRCUMSTELLAR STRUCTURE OF PRE-MAIN SEQUENCE STARS

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Abstract We present $H\alpha$ spectropolarimetry of a large sample of pre-main sequence (PMS) stars of low and intermediate mass, and argue that the technique is a powerful tool in studying the circumstellar geometry around these objects. For the intermediate mass ($2 - 15 M_{\odot}$) Herbig Ae/Be stars we find that 16 out of 23 show a line effect, which immediately implies that flattening is common among these objects. Furthermore, we find a significant difference in $H\alpha$ spectropolarimetry behaviour between the Herbig Be and Ae groups. For the Herbig Be stars, the concept of an electron scattering disc is shown to be a useful concept to explain the depolarizations seen in this spectral range. At lower masses, more complex $H\alpha$ polarimetry behaviour starts to appear. The concept of a compact source of $H\alpha$ emission that is formed close to the stellar surface, for instance by hot spots due to magnetospheric accretion, is postulated as a working hypothesis to qualitatively explain the $H\alpha$ spectropolarimetry behaviour around Herbig Ae and lower mass ($M < 2 M_{\odot}$) T Tauri stars. The striking resemblance in spectropolarimetric behaviour between the T Tauri star RY Tau and the Herbig Ae stars suggests a common origin of the polarized line photons, and hints that low and higher mass pre-main sequence stars may have more in common than had hitherto been suspected.

1. Introduction

One of the most intriguing open issues in star formation concerns the formation of massive stars (e.g. Zinnecker; these proceedings). Although there is a well-established paradigm for the formation of low mass T Tauri stars, namely via magnetospheric accretion, it is as yet unclear whether such a scenario would also apply to the more massive stars. To be able to answer the question whether Nature allows the scaling-up of the formation mechanism of the Sun to the most massive stars, it first needs to be established whether the conditions known to prevail in the lower mass pre-main sequence (PMS) T Tauri stars, such as the

presence of circumstellar discs and stellar magnetic fields, persist up to the intermediate mass (2-15 M_{\odot}) PMS Herbig Ae/Be stars.

The question as to whether Herbig Ae/Be stars in general are embedded in circumstellar discs, is still under debate. Although there are clear indications for flattening from millimeter imaging on larger spatial scales (a few hundred AU) for at least some objects (Mannings & Sargent 1997), other studies, probing smaller spatial scales, yield results that seem contradictory. For instance, the IR interferometry of Millan-Gabet et al. (2001) probes scales of only a few AU, and in this regime the geometry is found to be rather more spherical. Nonetheless, to be able to study the circumstellar geometries around PMS stars at the closest spatial scales, one needs to resort to the tool of spectropolarimetry, as this is the only technique that may probe the geometry on scales of stellar radii (equivalent to ~ 0.05 AU) compared to the > 1 AU scales probed by other methods.

2. The Tool of Linear Spectropolarimetry

In principle, the detection of linear polarization of $\sim 2\%$, would teach us directly that a specific source is non-spherically symmetric on the sky. However, such a level of polarization may also be due to polarization by dust grains in the interstellar medium operating between the source and the observer. Unfortunately, properly correcting for this interstellar contribution has been proven to be a difficult task (e.g. McLean & Clarke 1979). This is one of the prime reasons as to why spectrally-resolved polarization changes across emission lines are so valuable, as the interstellar polarization affects the continuum and the line in exactly the same way: any observed change in the polarization across the line has to be intrinsic to the source.

Although spectropolarimetry has widely been applied to more evolved early-type stars, such as classical Be stars (e.g. Poeckert 1975), the technique has only recently been applied to pre-main sequence stars (Oudmaijer & Drew 1999, Vink et al. 2002, 2003). For classical Be stars, the dominant effect is known to be due to unpolarized line emission in the presence of intrinsic continuum polarization (e.g. Clarke & McLean 1974). This ‘depolarization’ effect across emission lines occurs because the line photons are formed over a larger volume (in the circumstellar disc) than the continuum photons and are therefore scattered to a lesser extent off free electrons in the disc than are the continuum photons. Consequently, a drop in the polarization percentage is seen (see Fig 1a for an example).

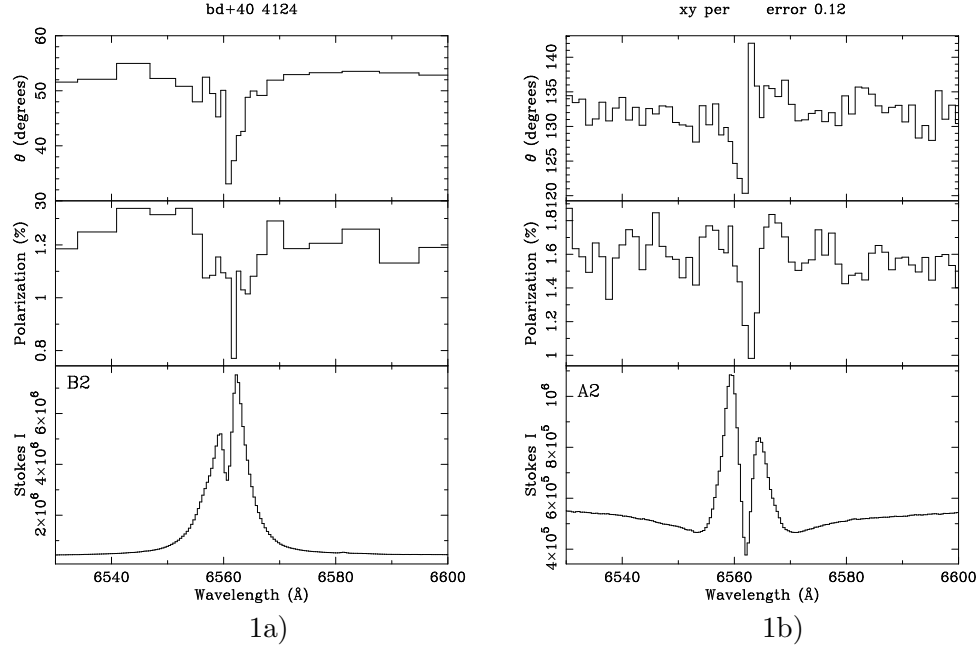


Figure 1: Triplots of the observed polarization spectra at $H\alpha$ of the Herbig Be star BD+40 4124 (LHS) and the Herbig Ae star XY Per (RHS). On both plots, the Stokes I spectrum is shown in the lowest panel, the %Pol is indicated in the middle panel, while the position angle, θ , is plotted in the upper panel. The data have been rebinned to constant errors of 0.05 % for BD+40 4124 and 0.12 % for XY Per, as calculated from photon statistics. The data are taken from Vink et al. (2002).

In certain circumstances however, it is feasible that the converse occurs: a proportion of the *line* photons originate from a compact source and are scattered and polarized themselves (McLean 1979; Wood et al. 1993). Observationally, such effects have only recently been detected in intermediate and low mass Herbig Ae and T Tauri stars (Vink et al. 2002, 2003) using medium/high resolution ($R \simeq 8000$) spectropolarimetry. Here, the $H\alpha$ line is believed to be polarized by scattering in a rotating non-spherically symmetric medium, most likely an accretion disc. Examples of both types of line effect, i.e. depolarization versus line polarization, are presented for respectively Herbig Be and Ae stars in Sects. 1.3 and 1.4 below.

3. The Herbig Be Stars

A polarization spectrum for the Herbig Be star BD+40 4124 is shown in Fig. 1(a), and the observed behaviour across the $H\alpha$ line profile in both polarization percentage (%Pol) and position angle (PA) is considered to be consistent with depolarization. The reason the PA shows a

change across the line as well is attributed to the vector addition of the interstellar polarization contribution. Note that the smooth and broad depolarization effect is represented in the QU diagram of Fig. 2(a) by a more or less linear excursion of the line points out from the dense knot representing the continuum at $(Q, U) = (-0.3, 1.25)$. The angle between this knot and the linear line excursion is directly related to the direction of the flattening of the presumed electron scattering disc around BD+40 4124.

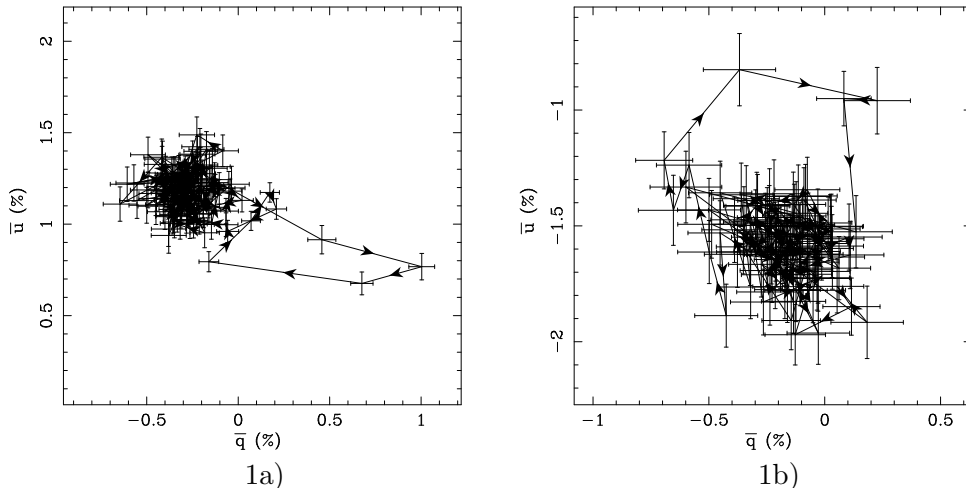


Figure 2: QU representations of the observed polarization spectra of the same data as in Fig. 1. The arrow denotes the sense of increasing wavelength. The more or less *linear* excursion of the $H\alpha$ line data for the Herbig Be star (LHS) is consistent with depolarization. The Herbig Ae data (RHS) is represented by a *loop* in the QU diagram. Note that the plot axis directions $+Q$, $+U$, $-Q$, $-U$ correspond to sky PAs of respectively 0° , 45° , 90° , and 135° (i.e. $\Delta U/\Delta Q = \tan 2\theta$).

In the event that *all* Herbig Be stars are embedded in electron scattering discs, one would not expect a 100% detection rate of $H\alpha$ depolarisations, as at least some of the sources would have their discs too “pole-on” with respect to the observer to yield a %Pol drop large enough to be detectable. To estimate the expected fraction of depolarization detections, we turn to a comparison with classical Be stars (Poeckert & Marlborough 1976), objects for which the presence of a circumstellar disc is well-established. Applying the same detection threshold to the Poeckert & Marlborough sample as in ours, we expect a detection rate of about 54%. Returning now to our Herbig Be star sample, we find that 7 out of 12 (i.e. 58%) show a detectable depolarisation (Oudmaijer & Drew 1999, Vink et al. 2002). We conclude that, given both the statistics, as well as the smooth and broad depolarization behaviour in the Herbig Be

H α data, that *all* early Herbig Be stars are likely embedded in electron scattering discs.

4. The Herbig Ae Stars

When observing the later spectral type Herbig Ae stars, one may expect to see a sharp decrease in the frequency of line effect detections, as the circumstellar ionization as well as the amount of free electrons that can scatter and polarize, are expected to drop among later type stars. Another reason to expect a decrease in the frequency of line effects going from Herbig Be to the later Ae stars is that there appears to be a general absence of H α polarization changes in the even later type PMS T Tauri stars (Bastien 1982; but see Sect. 1.6).

However, this turns out not to be the case at all. The number of line effects in Herbig Ae stars is found to be particularly high: 9 out of 11 Herbig Ae stars show a significant line effect (Vink et al. 2002). XY Per is included here as an example, as represented in Figs. 1(b) and 2(b): not only is there a line effect, it is noticeably different from the depolarization behaviour seen in the Herbig Be stars. First, the drop in the %Pol is not as broad as it is for the Herbig Be stars. Second, the behaviour in PA is not smooth. Instead, a line-center flip of the PA is clearly noticeable in the upper panel of the triplot in Fig. 1(b). This PA rotation translates into a “loop” in the equivalent QU diagram of Fig. 2(b).

The interpretation of these QU loops in Herbig Ae stars is still a matter of ongoing investigation, but in the next section (Sect. 1.5), we show that photons arising from a compact source of hot spots (a natural consequence of the magnetospheric accretion model) on the stellar surface that are subsequently scattered in a rotating circumstellar disc may explain the observed H α spectropolarimetry data of Herbig Ae (and possibly T Tauri stars; see Sect. 1.6).

5. Polarimetric Line Profiles from a Spotty Star

We employ a 3D Monte Carlo scattering model TORUS (Harries 2000) to simulate a compact source of photons arising from two diametrically opposed accretion hot spots onto a circumstellar disc. The disc has an inner hole of 3 stellar radii, and is assumed to be flat. As the H α emission is compact in this model, we may expect intrinsic *line* polarization to occur. Figures 3(a) and 3(b) represent the two extreme cases for an almost edge-on (LHS) and an almost pole-on (RHS) disc respectively. As expected for an edge-on disc, there is a significant level of continuum polarization of a few percent. Due to the asymmetry in the velocity field,

one hot spot – positioned at an angle of 65° from the equator – illuminates the redshifted part of the disc that is rotating away from us, while the other (diametrically opposed) hot spot illuminates the blueshifted part of the disc moving towards us. Both spots illuminate the disc at similar angles, so that no significant PA changes occur across the line.

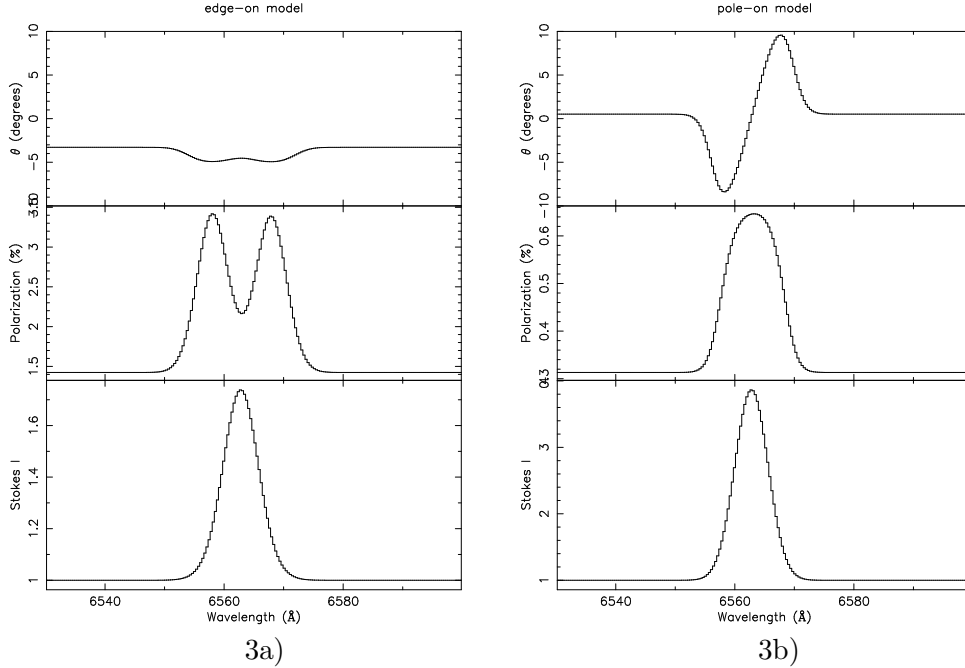


Figure 3: Monte Carlo models for an edge-on (LHS) and a pole-on (RHS) disc. The photon source is asymmetric applying two diametrically opposed hot spots.

For the more pole-on case, the first difference is the lower level of continuum %Pol, as the scattering is now more spherically symmetric (positive and negative Q and U cancel, resulting into a drop in the net polarization). As far as the line polarization is concerned, the asymmetry in the velocity field is now diminished, and this results in an effective merging of the double-peaked %Pol profile into one single peak. Finally, because the illumination of the pole-on disc no longer occurs under similar angles, there is a rotation in the PA in the upper panel of Fig. 3(b), which is indeed the same type of behaviour that is commonly observed in $H\alpha$ spectropolarimetry of Herbig Ae stars (see Fig. 1b).

6. The T Tauri Star RY Tau

Partly because of a general absence of polarization changes across $H\alpha$ using narrow band filters in T Tauri stars (e.g. Bastien 1982), the commonly accepted view of the origin of T Tauri polarization is that it is due to scattering off extended dusty envelopes.

However, in Figure 4(a) we show the first spectropolarimetric measurements of an object classified as a T Tauri star, and we notice similar complexity across $H\alpha$ for RY Tau as seen in Herbig Ae stars. Most notable is the rotation in the PA, which translates into a loop when plotted in QU space (Fig. 4b). This change in the polarization percentage and the PA across $H\alpha$ suggests that line photons are scattered in a rotating disc. We are able to derive the value of the PA from the slope of the loop in the (Q, U) diagram and find it to be $146 \pm 3^\circ$. This is close to perpendicular with respect to the PA of the disc of $48 \pm 5^\circ$ as deduced from submillimeter imaging by Koerner & Sargent (1995). These findings are consistent, as the PA of the imaged millimeter disc is expected to lie at 90° to the scattering PA deduced from the polarization data.

We finally note that if these medium/high resolution ($R \sim 8000$) data were averaged – as in the narrow $H\alpha$ filter observations of Bastien (1982) – they would most likely have produced a null result.

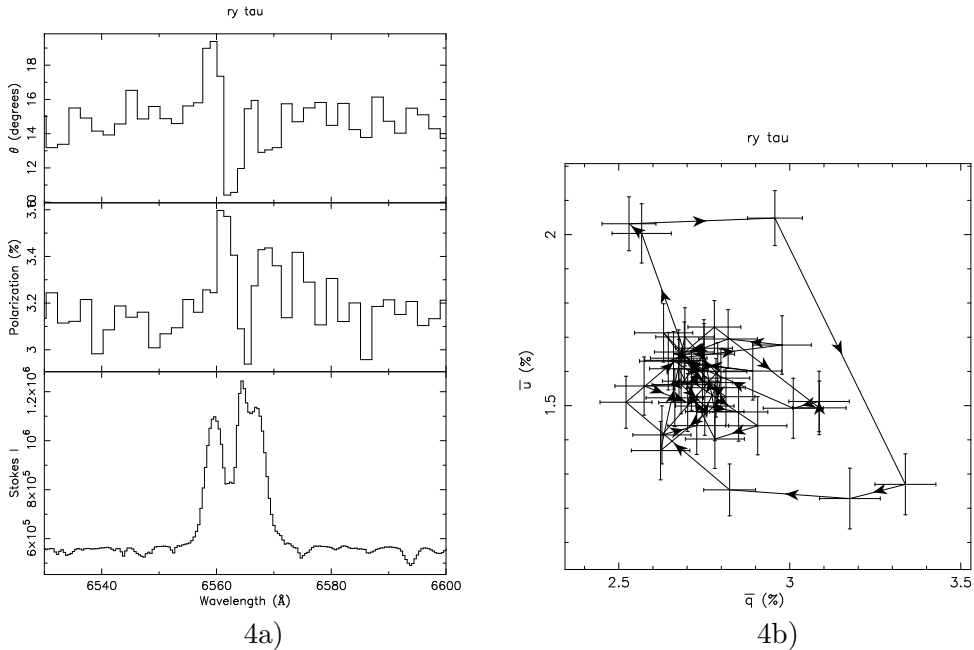


Figure 4: Triplot (LHS) and QU diagram (RHS) of the observed polarization spectrum of the classical T Tauri star RY Tau. The data are binned to a constant

error of 0.09 %. The RY Tau data are presented in Vink et al. (2003). Note the flip in PA and the corresponding loop in QU space.

7. Summary

$H\alpha$ spectropolarimetry has been shown to be a powerful tool in studying the circumstellar geometry around low and intermediate mass PMS stars. For the Herbig Ae/Be stars we found that 16 out of 23 show a line effect, which immediately implies that flattening is common among intermediate mass PMS stars. Furthermore, we noticed a clear difference in $H\alpha$ spectropolarimetry behaviour between the Herbig Be and Ae groups. For the Herbig Be stars, the concept of an electron scattering disc has been shown to be able to explain the depolarizations. At lower masses, more complex $H\alpha$ polarimetry behaviour starts to appear. The concept of a compact source of near-stellar $H\alpha$ emission, for instance associated with magnetospheric accretion, has been proposed to qualitatively explain the linear polarization changes across $H\alpha$ seen in Herbig Ae and RY Tau. The striking resemblance in spectropolarimetric behaviour between these PMS stars may suggest a common origin for the polarized line photons, and hint that low and higher mass pre-main sequence stars may have rather more in common than had hitherto been suspected.

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