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Resolved polarization changes across Hα in the classical T Tauri star RY Tauri

Jorick S. Vink[1], J. E. Drew[1], T. J. Harries[2], R. D. Oudmaijer[3], and Y. C. Unruh[1]

[1] Imperial College of Science, Technology & Medicine, Blackett Laboratory, Prince Consort Road, London, SW7 2BZ, UK
[2] School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK
[3] The Department of Physics and Astronomy, E C Stoner Building, Leeds, LS2 9JT, UK

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Abstract. We present linear Hα spectropolarimetry of the classical T Tauri star RY Tau. A change in the polarization percentage and position angle across Hα is detected, which suggests that line photons are scattered in a rotating disc. We derive the position angle from the slope of the loop in the (Q, U) diagram and find it to be $146 \pm 3^{\circ}$. This is perpendicular to the position angle of the disc of $48 \pm 5^{\circ}$ as deduced from millimeter imaging by Koerner & Sargent (1995). This finding is consistent, as scattering off the imaged millimeter disc is expected to yield a polarization signature in a direction that is rotated by 90° from this disc. The observed spectropolarimetric behaviour of RY Tau is reminiscent of that seen in a large group of Herbig Ae stars, suggesting a common circumstellar origin of the polarized photons.

Key words. stars: formation – stars: pre-main sequence – stars: individual: RY Tau – stars: circumstellar matter – techniques: polarimetric

1. Introduction

Low-mass stars form through the collapse of a rotating interstellar cloud, thereby creating a circumstellar disc. During the subsequent pre-main sequence (PMS) T Tauri phase circumstellar material accretes through the disc onto the central star, most likely via magnetospheric funnels (see Johns-Krull et al. 1999 and references therein). While the basic picture of low-mass star formation is widely accepted, many issues remain. For instance, little is known about the size of the inner hole, the shape of the inflow and outflow, or in short, the geometry of material close to the star. For more massive stars the picture becomes even more unclear. For stars above 10 $M_{\odot}$ there is not even any consensus on the underlying star formation process itself (e.g. Bonnell et al. 1998 versus Behrend & Maeder 2001). It is clear that observations of the near-star environment of a range of PMS stars are needed to understand star formation as a function of mass.

Spectropolarimetry is a powerful tool for studying the near-star regions of PMS stars and determining their geometries. The technique has widely been applied to early-type stars. Here circumstellar free electrons – e.g. in a disc – are able to polarize the continuum light more than the line photons, as emission lines are formed over a much larger volume (e.g. in a disc) than the continuum. Hence, the line photons are subject to fewer scatterings leading to a drop in the polarization percentage across the emission profile (in the absence of interstellar polarization). This "line effect" is often referred to as "depolarization" (e.g. Clarke & McLean 1974). The high frequency of depolarization line effects in Herbig Be stars (Oudmaijer & Drew 1999; Vink et al. 2002) provides evidence that these stars are surrounded by flattened structures. A switch in phenomenology is likely to occur at some point working down the stellar mass range, since different physical mechanisms may play a role at different spectral types. For instance, radiation pressure forces are likely to play a role for the higher-luminosity Herbig Be stars, whereas magnetic fields may become more dynamically prominent at A and later type. If magnetic fields are present, the inner accretion disc may be truncated, and depolarizations would then be absent because the inner hole will lead to reduced intrinsic continuum polarization. One might therefore anticipate that line effects would be scarce at later spectral types. However, this is not the case, and the frequency from early B to late A spectral type does not drop at all (Vink et al. 2002). The data on Herbig Ae stars suggest that here the *line* itself is polarized (rather than the continuum), and that perhaps hot spots on the stellar surface provide the required compact source of Hα photons that can be scattered off material within a rotating disc.

For the even later type (G-K) T Tauri stars only limited narrow-band linear polarimetry has been attempted in the past (Bastien & Landstreet 1979; Bastien 1982). In the compilation of Bastien (1982), the results of observations through a 5 Å wide filter, flanked by contemporary broadband 5895 Å

Send offprint requests to: J. S. Vink,
e-mail: j.vink@ic.ac.uk

and 7543 Å observations, are listed for just 6 T Tauri stars. Of these objects, RY Tau is the only example for which a change in the line with respect to the broadband continuum was detected. Partly based on what Bastien (1982) noted as a general absence of polarization changes across Hα, he advanced what is now the commonly accepted view of the origin of T Tauri polarization: namely that it is due to scattering off extended dusty envelopes.

We shall show that the wavelength averaging using even these narrow-band Hα filters can easily fail to pick up polarization changes that occur on a finer wavelength scale of an Ångstrom or less. We have already shown that just such complex changes are commonplace among Herbig Ae stars (Vink et al. 2002). Here we report the first spectropolarimetry observation of an object classified as a T Tauri star, and we find similar complexity. Again this is RY Tau. We show that if our data were averaged – as in the Hα filter observations of Bastien – they would most likely have produced a null result!

In Sects. 2 and 3 we discuss how the observations were obtained and present the linear Hα spectropolarimetry of RY Tau. We detect polarization changes and a clear rotation in the polarization angle across Hα, which translates into a loop in (Q, U) space, a behaviour often seen in Herbig Ae stars. In Sect. 4, we review other relevant information on RY Tau (Sect. 4.1), and discuss how our data add to our understanding of the complicated flows around this and other T Tauri stars (Sect. 4.2). Finally, in Sect. 5, we summarize, and discuss what the RY Tau data may teach about more massive PMS stars in turn.

2. Observations

The linear spectropolarimetry for RY Tau was obtained on the night of December 26 (2001) using the ISIS spectrograph mounted on the Cassegrain focus of the 4.2-meter William Herschel Telescope (WHT), La Palma. A slit width of 1.1″ was used. Although the sky was relatively clear, the seeing was rather poor (~2″). We used a 1024×1024 pixel TEK-CCD detector with the 1200R grating, which yielded spectral coverage from 6370–6760 Å. The spectral resolution was approximately 35 km s^{-1} around Hα (measured from arc lines).

To obtain the linearly polarized component in the starlight, ISIS was equipped with the appropriate polarization optics. This consisted of a rotating half-wave plate and a calcite block to rotate and separate the light into the ordinary (O) and extraordinary (E) light waves. Two holes in the Dekker allowed for simultaneous observations of the object and the sky. Hence, in each observation, four spectra were recorded: the O and E rays of both the target and sky. One complete observation set consisted of a series of four exposures at half-wave plate position angles of 0°, 45°, 22.5°, and 67.5°. After each of these sets of four frames was obtained, the target and the sky were interchanged by placing the star in the other Dekker hole, so as to compensate for any possible asymmetry in the detector or the instrument. The total exposure time on RY Tau was 2640 s. Polarized and zero-polarization standards were also observed during the run and an intrinsic instrumental polarization of 0.01 percent and a position angle (PA) of 31° (the PA is

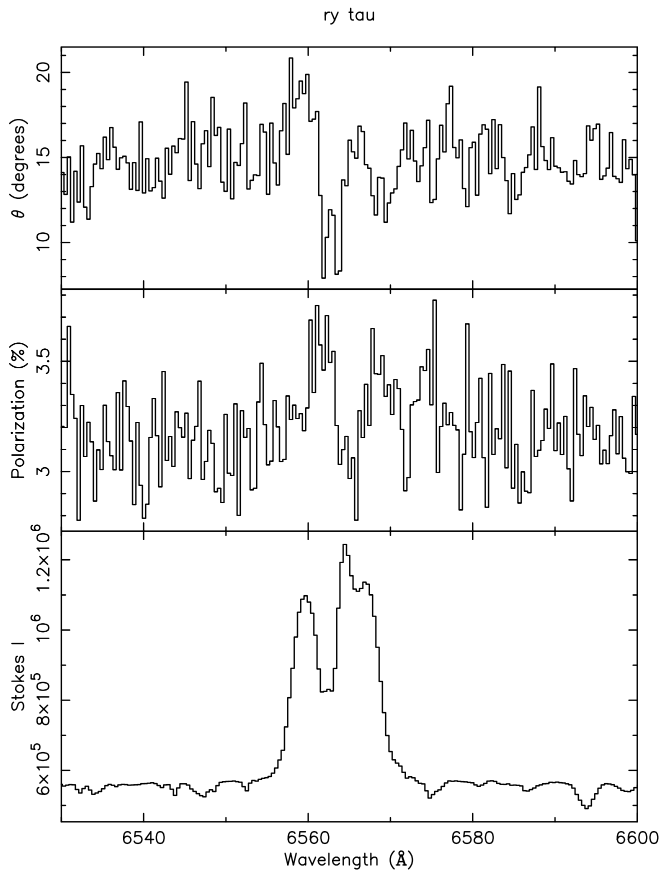

Fig. 1. Triplot of the observed polarization spectra of the classical T Tauri star RY Tau. The Stokes I "intensity" spectrum is shown in the lowest panel of the triplot, the %Pol is indicated in the middle panel, while the PA (θ; see Eq. (2)) is plotted in the upper panel. The data are not rebinned.

extremely uncertain) were revealed. As the instrumental polarization is found to be negligible, we have not corrected for it.

The data reduction steps included bias-subtraction and flat-fielding, cosmic ray removal, extraction of the spectra, and wavelength calibrations of the O and E spectra. The Stokes parameters Q and U were subsequently determined from these O and E rays, leading to the percentage linear polarization P and its PA or θ:

$$P = \sqrt{(Q^2 + U^2)} \quad (1)$$

$$\theta = \frac{1}{2} \arctan\left(\frac{U}{Q}\right). \quad (2)$$

The achieved (relative) accuracy of the polarization data is in principle only limited by photon-statistics and can be very small (typically 0.01%). However, the quality and the amount of data taken on spectropolarimetric standard stars is at present not yet sufficient to guarantee absolute accuracies to within 0.1%.

3. Results

The linear spectropolarimetry data for RY Tau are shown in the triplot of Fig. 1. The Stokes I "intensity" spectrum is

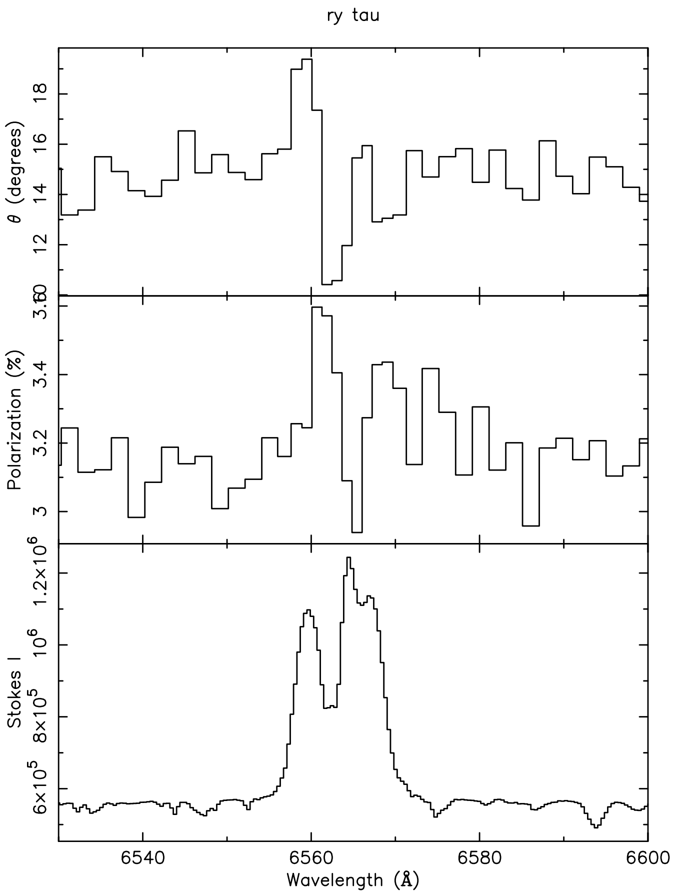

Fig. 2. Same as Fig. 1 but now rebinned such that the 1σ error in the polarization corresponds to 0.09% as calculated from photon statistics.

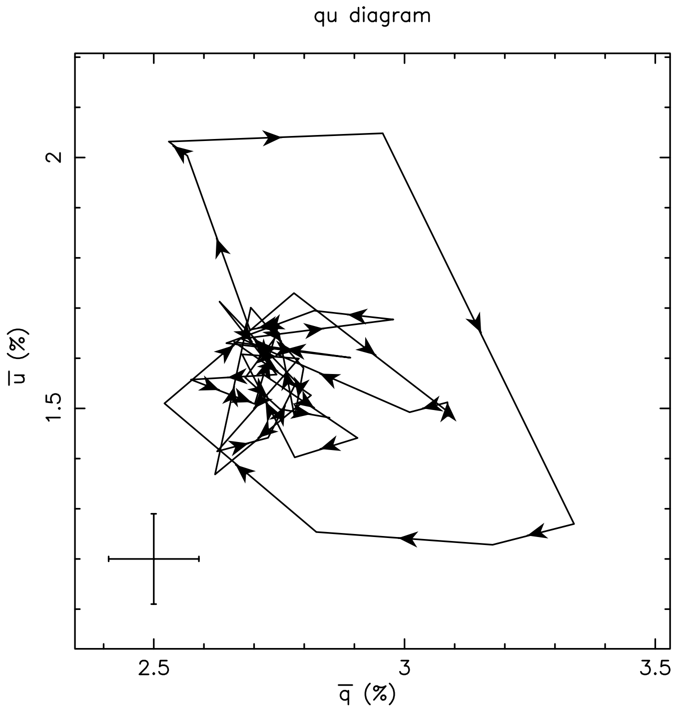

Fig. 3. (Q, U) diagram of RY Tau, also rebinned to a 1σ error in the polarization of 0.09%. Note that the direction of the arrow denotes the increase in wavelength.

depicted in the lowest panel, the %Pol is indicated in the middle panel, while the PA (θ; see Eq. (2)) is plotted in the upper panel. Note the presence of clear changes across the Hα line in both the %Pol and the PA. The Stokes I Hα profile itself is complex, as is common for T Tauri stars. One interpretation is that it consists of both a double-peaked profile, which is consistent (but no proof) of rotation in a disc, as well as a P Cygni component on top of this, indicative of a wind. As far as the spectropolarimetry is concerned, we choose to rebin the data, aiming to obtain a reduced and fixed error per bin. However, we need to ensure simultaneously that we do not lose relevant spectral resolution as a result of this. We found that a constant error of 0.09% polarization represents the best compromise between minimizing the error per bin and resolving the line profile. The resulting Hα polarization data are shown in the triplot of Fig. 2. The data are alternatively represented in a (Q, U) diagram (Fig. 3) where the direction of the arrow denotes the increase in wavelength. The dense knot of points located at $(Q_{\rm obs}, U_{\rm obs}) = (2.75, 1.56)$%, represents the observed level of continuum polarization with a mean value $P = 3.16 \pm 0.01$% and a PA of $14.2 \pm 0.1^{\circ}$. Note the clear presence of the loop, which is the equivalent of the flip in the PA across Hα in the upper panel of Fig. 2. This would not have been observed when a 5 Å narrow-band filter (as used by Bastien) had been used. Integrating the polarization over 5 Å from 6560–6565 Å yields a mean PA of 14°, which would be indistinguishable from the continuum PA of 14.2°. Yet we *do* detect structure of less than an Ångstrom across Hα by performing spectropolarimetry.

If the scattering leading to polarization occurs predominantly in a rotating disc-like configuration, the subsequent breaking of left-right reflection symmetry in the velocity field leads to a changing PA with wavelength (see e.g. McLean 1979; Wood et al. 1993), which appears as a "loop" in (Q, U) space. This is precisely what is detected here in the classical T Tauri star RY Tau and has previously been seen in a large group of Herbig Ae stars (Vink et al. 2002).

4. Discussion

4.1. RY Tau

RY Tau is a classical T Tauri star of spectral type F8III (Mora et al. 2001). Photometric monitoring studies have shown that the brightness of the star varies by up to 2–3 mag over a timescale of decades (e.g. Beck & Simon 2001 and references therein). Herbst et al. (1994) classify the object as a type III variable. Although there is no consensus on the underlying mechanism of these objects, variable circumstellar obscuration most likely plays a role, as in UX Ori variables. The star has a rather low level of veiling, i.e. ≤ 0.1 in the visible (e.g. Basri et al. 1991), and a rotational velocity of $\upsilon \sin i = 55 \pm 3$ km s^{-1} (Mora et al. 2001). The mass-accretion rate is of the order of $\dot{M} = 7.5 \times 10^{-8}\ M_{\odot}\ {\rm yr}^{-1}$ (Bertout et al. 1988). Spectroscopic variability has also been noted, but whether the Hα line strength correlates with the V magnitude (Vrba et al. 1993), or not (Petrov et al. 1999) is under debate.

Most relevant for this study is the high level of linear polarization of a few percent. The variability of its polarization was discovered by Vardanyan (1964) and has been confirmed ever since (e.g. Serkowski 1969; Schulte-Ladbeck 1983; Bastien 1985; Oudmaijer et al. 2001). The linear percentage polarization %Pol has been reported to vary between 1 and 6%, and its PA between −20 and 75$^{\rm o}$, with %Pol $\simeq$ 3 and PA $\simeq 20^{\rm o}$ being typical "median" values (taken over several epochs and with values reported by authors employing different techniques).

The interpretation of the level of polarization as well as its variability is ambiguous for this, as for any other, T Tauri star. The scattering that leads to polarization could either be due to gas or dust, and although the wavelength dependence of the observed polarization surely implies a strong dust component, this dust polarization could be interstellar, as well as circumnebular, and/or circumstellar: decomposing these different contributions has since long been recognized to be a particularly difficult task (see e.g. McLean & Clarke 1979). The variability of the observed polarization may help identify its origin. It has been suggested that rotational modulation may signal cool and hot spots on the stellar surface (e.g. Stassun & Wood 1999), but also variable extinction by a dusty disc can lead to quasi-periodic behaviour of the observed level of dust polarization (e.g. Ménard & Bastien 1992).

4.2. Spectropolarimetry on RY Tau

Spectropolarimetry is unique in that it is possible to retrieve the PA from (Q, U) plane excursions without relying on uncertain values of the foreground polarization. This is because interstellar dust treats the line and the continuum in an entirely similar way. For instance, Oudmaijer et al. (1998) were able to obtain the intrinsic PA of the scattering material in the rotating disc of the B[e] star HD 87643. It has been suggested that the intrinsic PA of the scattering material can be obtained from the increased polarization across blueshifted absorption (McLean 1979). If one accepts the view that the Stokes I profile in Figs. 1 and 2 indeed consists of a double-peaked as well as a P Cyg profile, one may obtain the intrinsic PA from the increased polarization over the absorption part of the line, which occurs at a PA of 160−167$^{\rm o}$. Alternatively, we can measure the PA of the scattering material from the slope of the loop in the (Q, U) diagram, $\theta_{\rm intr} = 0.5 \times {\rm atan}(\Delta U/\Delta Q) \simeq 146 \pm 3^{\rm o}$. Note that the error on this PA is determined as follows. We have replotted the polarization data in (Q, U) space applying a range of sampling errors. At each replotting, the slope of the (Q, U) loop was measured. The error quoted above is the standard deviation of these 10 independent measurements.

Is there any other information available than just the PA of the (Q, U) excursions? Yes. From the observed level of continuum polarization in these new data with $(Q_{\rm obs}, U_{\rm obs}) = (2.75, 1.56)$% (see Sect. 3), we may be able to retrieve the level of intrinsic continuum polarization from the vector addition in (Q, U) space, *if* we are able to find a reliable value for the ISP. Both Efimov (1980) and Petrov et al. (1999) derive the ISP toward RY Tau obtaining values of $P = 2.69$%, $\theta = 27^{\rm o}$, and $P = 2.84$%, $\theta = 26^{\rm o}$ respectively. Although Efimov used field stars, while Petrov et al. used the variability of a huge body of 140 datapoints of the star itself, these values are strikingly alike, and may give some confidence as being close to the true value. Adopting the Petrov et al. (1999) value for the ISP (at 5500 Å), or alternatively $(Q_{\rm ISP}, U_{\rm ISP}) =$ (1.75, 2.24)%, we can estimate the intrinsic continuum polarization degree of RY Tau. Employing the vector relationship $(Q_{\rm intr}, U_{\rm intr}) = (Q_{\rm obs}, U_{\rm obs}) - (Q_{\rm ISP}, U_{\rm ISP})$, we find: (2.75, 1.56) − (1.75, 2.24) = (1.00, −0.68), This corresponds to an *intrinsic* level of polarization of 1.21% at a PA of 163$^{\rm o}$. The statistical error in this PA is insignificantly small, but the error in subtracting the ISP is subject to systematic error. Nonetheless, assuming that the estimate for the ISP toward RY Tau is correct, the PA of 163$^{\rm o}$ derived this way agrees very well with the PA from the blueshifted absorption, and is only 18$^{\rm o}$ off from the intrinsic $\theta_{\rm intr}$ of $146 \pm 3^{\rm o}$ as found from the the slope of the (Q, U) loop.

How does all this compare to other evidence for discs around RY Tau? Koerner & Sargent (1995) detected gaseous emission around RY Tau at millimeter (CO 2-1) wavelengths along a direction of elongation with a PA of $\simeq 48 \pm 5^{\rm o}$ (where the formal error is based on the goodness of fit only). In addition velocity gradients parallel to this elongation suggest that the material is rotating in a Keplerian disc. If our detected change in PA across Hα is due to scattering in a rotating circumstellar disc, as the loop in (Q, U) suggests, one would expect the PA derived from the polarimetry to be perpendicular to the CO disc, i.e. at a PA of $\simeq 48 + 90 = 138^{\rm o}$ (assuming multiple scattering effects are not important). To within the errors this agrees with the slope of the loop we found in (Q, U) space. It is important to note that the deconvolved size at mm wavelengths for RY Tau is less than the full-width at half-maximum beam size, and hence that the error on $\theta_{\rm CO}$ is likely to be greater than the quoted value of 5$^{\rm o}$ (Koerner & Sargent 1995).

5. Final remarks

To summarize, both the Hα spectropolarimetry with a PA of $\simeq 146^{\rm o}$, as well as the ISP corrected continuum measured PA of $\simeq 163^{\rm o}$, are considered to be consistent with the mm detection of the rotating disc around RY Tau with a PA of $\simeq 48^{\rm o}$. Because the scattering off a disc is expected to yield a polarization signature in a direction that is rotated by 90$^{\rm o}$ from the disc, a rather consistent picture of the RY Tau disc system emerges.

Traditionally, the switch between early and late type stars in the Hertzsprung-Russell Diagram is believed to occur between spectral type A and F, as this is where the cooler stars have convective, while hotter stars possess radiative outer envelopes. Similarly, the switch between low and high-mass star formation may be thought to occur at the T Tauri/Herbig Ae boundary (at $\simeq 2\ M_{\odot}$), where magnetic fields may be of dynamical importance in the T Tauri stars, but not in the Herbig Ae objects. The striking resemblance in spectropolarimetric behaviour between the T Tauri star RY Tau and a large group of Herbig Ae stars, as signaled by the detected change in PA and the (Q, U) loop, suggest a common origin of the polarized line photons, and hint that low and high mass pre-main sequence stars may have more in common than had hitherto been suspected.

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