Disk Orientations in PMS Binary Systems Determined Through Polarimetric Imaging With UT1/FORS

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Summary

Photons are an expensive product of astronomical telescopes. The wide wavelength and instrumental techniques coverage offered by the VLT allows astronomers to dissect the incident radiation in many ways: spectroscopy and imagery are well-known observing techniques to VLT observers. A maybe less well-known technique is polarimetry. The IPOL mode of FORS on UT1 allows to measure high-quality polarimetric images on a wide field of view. We used this instrument during period 65 to determine the respective orientation of circumstellar disks in pre-Main-Sequence binaries. In this paper, we present our method and first results obtained with FORS/IPOL. Thanks to the top-quality assistance of the VLT and FORS teams, our run was remarkably successful and the instrument appears extremely well adapted to fine polarimetric measurements on large fields of view. Our first results suggest that circumstellar disks tend to be aligned in PMS binaries.

Introduction

Our current understanding of low-mass stellar formation has to take into account two very different yet complementary constraints. On one hand, when we consider individual stars, the current model put forward for embedded Young Stellar Objects (YSOs) includes a central stellar core, surrounded by an equatorial accretion disk and a remnant infalling envelope. This stage is frequently associated with energetic bipolar molecular outflows, perpendicular to the disk and tracing the symmetry axis of the whole system (Fig. 1a).

On the other hand, we also know that a large fraction of T Tauri stars (TTS) form in binary or multiple (N>2) systems. This ubiquitous property of the stellar formation process has a potentially enormous influence on the previous one because the circumstellar environment of the individual components of a multiple system can be deeply modified by the presence of a companion. The study of individual disks in PMS binary systems and in particular their relative orientations can provide strong constraints on the star-formation process (Fig. 1b).

Strictly speaking, a full 3-D orientation determination of the rotation axes of both components requires the knowledge of 2 angles: the inclination on the line of sight and the orientation in the plane of the sky. The former angle can be obtained through the combination of the projected rotational velocity, *v sin i,* the rotational period, and an estimate of the stellar radius. This determination is quite indirect and can induce large uncertainties. Polarimetry can give access to the disk orientation in the plane of the sky, provided the disk is far enough from pole-on, a condition met in more than 50% of the cases.

Method

The presence of a disk, even if spatially unresolved, can be traced in large parts by the thermal emission of its dust. This dust, and especially its small particles, also polarises the starlight in the optical and near-infrared in a fashion that depends on the scattering geometry. Numerical simulations show that unresolved aperture linear polarimetry can be used to extract information about the geometry of the scattering medium.

Models of bipolar reflection nebulae by Bastien and Ménard (1990) have shown that the position angle of the integrated linear polarisation of the scattered starlight is parallel to the equatorial plane of the disk, provided the inclination is sufficiently large (see Fig. 2). The method is thus likely to give good results when circumstellar disks are present around the two stars in the binary, i.e. when both are Classical TTS (CTTS). We have chosen our targets so that at least one of the components can be classified as an active T Tauri star. Previous observations of PMS binary stars have shown that most of the time, if one of the components of a young binary system has an active disk, so has the other.

Caveat

One of the main problems of polarimetric measurements in young systems is that such stars are often deeply

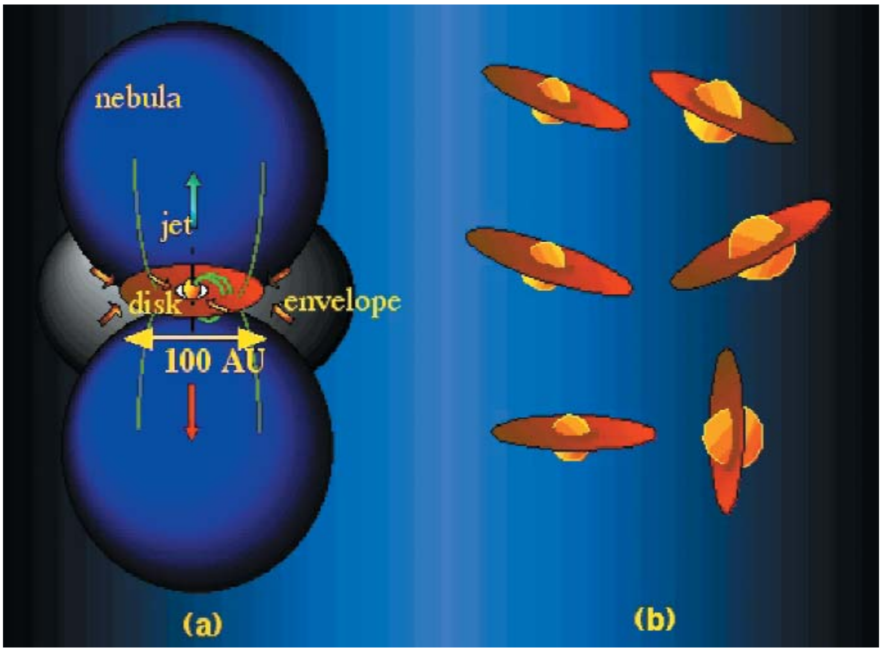

Figure 1: "Standard" TTS model including a circumstellar disk, an envelope and a nebula (a). When it comes to a binary (the most probable outcome in a young stellar object formation), the determination of the respective orientation of both disks (b) can bring new constraints on the stellar formation process.

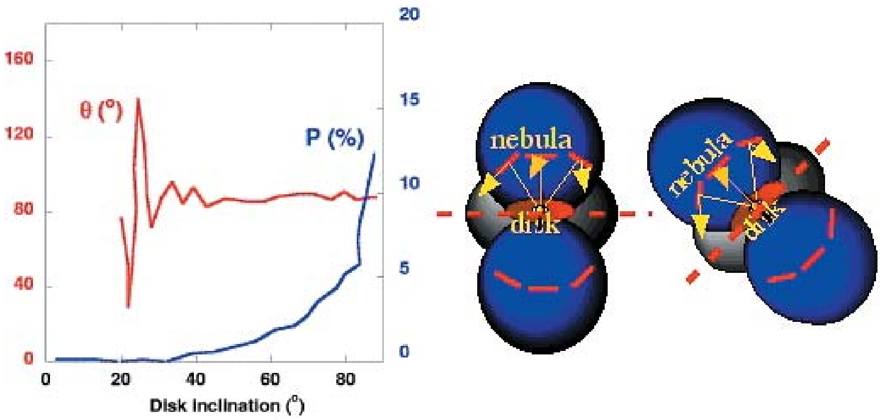

Figure 2: The circumstellar dust structure present around a TTS polarises the stellar light. Left: models by Bastien & Ménard (1990) show that if the disk is more than 45 degrees from pole-on, the polarisation direction reliably traces the disk orientation. Right: in a binary, the relative orientation of the disks can be determined from their polarisation.

embedded in molecular clouds and subject to interstellar medium polarisation. When we measure two different polarisation directions in a binary system, we can be fairly sure that they are actually different, but if they are similar, there is a chance that this identity is due to a common interstellar polarisation. This is why a large-field polarimetric imaging system like the one available with FORS/IPOL on UT1 is essential in this context. We are now able to measure *at the same time*, the polarisation on the central system and on a large number of nearby field stars (Fig. 3). These 'outsiders' measurements bring very valuable information on the large-scale interstellar polarisation pattern, providing a kind of 'calibration' of the central binary measurement.

Instrument

Most of the observer information can be found in the ESO FORS user manual. The basic method of linear polarisation measurements uses a transmission polariser (also called analyser in such a case) in the incident beam, so that the system measures the projected intensity going through. When using different positions of the polariser, one can reconstruct the level of polarisation and the position angle of the polarisation direction. One of the main difficulties of this method is that we want to estimate small fluctuations (typically 1%) over a large signal that remains constant when the analyser is rotated. Any transparency variation in the incident beam can be wrongly interpreted as a polarisation signal. To overcome this difficulty (as in many polarimeters), the FORS instrument is equipped with a Wollaston prism that splits the beam into two different directions with orthogonal polarisation states, the so-called *ordinary* (O) and *extraordinary* (E) beams. A stepped half-wave plate retarder is placed at the entrance of the incident beam and can be rotated at various angles multiple of 22.5º (16 positions in a complete rotation), making the incident polarisation rotate. For each position of the plate, a CCD image is recorded. The separation of the two O and E beams on the CCD is performed via the Wollaston prism, using a focal 9-slit mask, so that a given polarisation state (E or O) occupies half of the focal plane image. The total field of view of the instrument is 6.8′ × 6.8′ in the Standard Resolution (SR) mode with a focal scale of 0.2″/pixel. In this mode, the slits are 20″ wide on the CCD. One could theoretically extract the polarisation information (Stokes parameters Q & U, hence the polarisation level P and its position angle θ) with 2 positions of the half wave plate. In practice, 4 positions are often necessary. The FORS/IPOL observing blocs allow to choose 4, 8 or 16 positions, leading to 4, 8 or 16 images stored. Then a Fourier series is computed to extract P and θ from the data.

Data Reduction

We have written a dedicated data reduction pipeline using NOAO/IRAF. The first step concerns of course bias, bad pixels and flat-field corrections. Then the images go through a polarisation pipeline. Two options are available: P and θ can be estimated on a pixel per pixel basis, a useful possibility to map extended structures like reflection nebulosities, at the cost of a loss of accuracy on point sources when the image quality (FWHM) changes during a rota-

Figure 3: Resulting polarisation map on a 6.8′ × 6.8′ field of view around the SZ 60 binary. We can trace the local interstellar polarisation on a large number of surrounding field stars. These supplementary measurements are of great importance to finally determine the intrinsic polarisation on the central object.

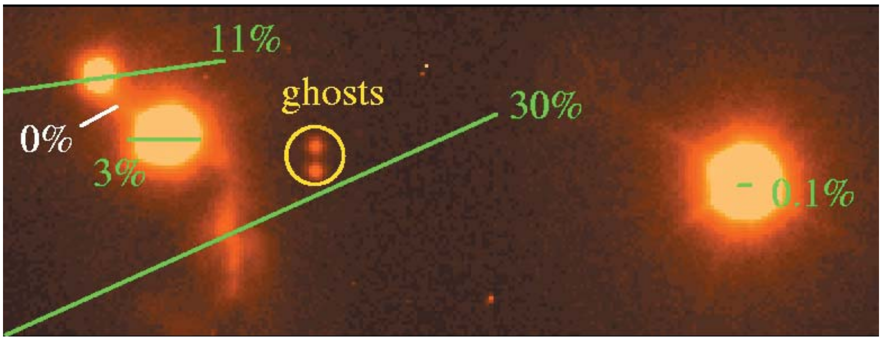

Figure 4: I band image and polarisation map of WSB 42 and its associated – strongly polarised – reflection nebula.

tion acquisition. Another possibility uses aperture photometry to estimate precise polarisation measurements on point-like objects. Indeed, the individual CTTS components and their disks in our binaries are most of the time spatially unresolved, and the disk orientation information is obtained via aperture photometry. When using aperture photometry, we can account for any FWHM change if a large enough aperture is used. Both techniques are available in our pipeline on request, to estimate the polarisation of point sources and extended features alike (see Fig. 4).

We measure the errors using two independent methods: first from the statistical photon noise on the E & O beams separately, and then propagating the errors up to U, Q, P and θ; second, measuring the standard deviation on the 4, 8 or 16 images from the half-wave plate rotation. Both estimations are consistent except in some pathological cases, and this second method is extremely useful to consistently check our results. Our conclusion on the observing strategy is that it is strongly recommended to systematically record 16 images using all the available λ/2 plate positions. The result is without question worth the time investment. Most of the time, the residual error is less than $\Delta P = 0.1\%$ (absolute value) when the binary components are well separated (≥ 1.3 arcsec). Our programme also includes tight binaries for which we have to adjust and subtract a PSF; depending on the contrast and separation, the errors can at worse reach $\Delta P = 0.25\%$, a value well within our goal.

Instrumental Polarisation

Of crucial importance is the determination of the instrumental polarisation. We have carefully measured it against nearby unpolarised targets. We have observed GJ 781 and GJ 781.1, two high proper-motion stars (so quickly moving indeed since the time our finding chart was made, that the VLT image pointing recognition system could not lock at first sight!). As the close solar neighbourhood is remarkably devoid of dust, the interstellar polarisation of near-Earth objects can be considered null. The average of our 4 measurements on both GJ objects gives $P_{inst} = 0.02\% \pm 0.03\%$. Even if bad luck could have made the instrumental polarisation just cancel the possible intrinsic polarisation of these test stars, we independently found some of our low-polarisation scientific targets to present linear measurements very close to previously published measurements. We believe that FORS/IPOL (+ incident optics) instrumental polarisation is actually very low, well below 0.1%, so we considered it as negligible for practical purposes and we did not remove it from other measurements.

Preliminary Results

Figure 3 shows that the interstellar polarisation can dominate over the central object intrinsic polarisation: on this image, all the polarisation vectors are aligned, with a possible fluctuation on the central objects. One of the great advantages of FORS/IPOL in this matter is that our wide-field polaro-imaging data allow us to carefully measure the local interstellar polarisation. We are currently working on a method to remove this "ambient" polarisation in order to study the intrinsic target polarisation. Another valuable result is that we have obtained images at different wavelengths (V, R and I bands) so that we will be able to check whether the expected λ dependence of the polarisation is recovered. For most of our sources, the result will remain unchanged, with both polarisations remaining parallel, but in a few cases, the changes can be clear, in magnitude and/or orientation.

The fact that in most binaries the disks appear to be mostly parallel (see Fig. 5) suggests that this is a result of the binary formation process. As these systems are young (1–3 Myr), it is unlikely that tidal interactions have had the time to realign the disks. If disks around the components in young binaries are coplanar, then they may provide stable favourable environments to build large planetary bodies.

Acknowledgement

None of our measurements would have been possible without the constant and extremely efficient support of the VLT and FORS/IPOL teams. We also acknowledge the help of the telescope operators, and they may recognise themselves when we say that there has been "no cause for alarm" during the run.

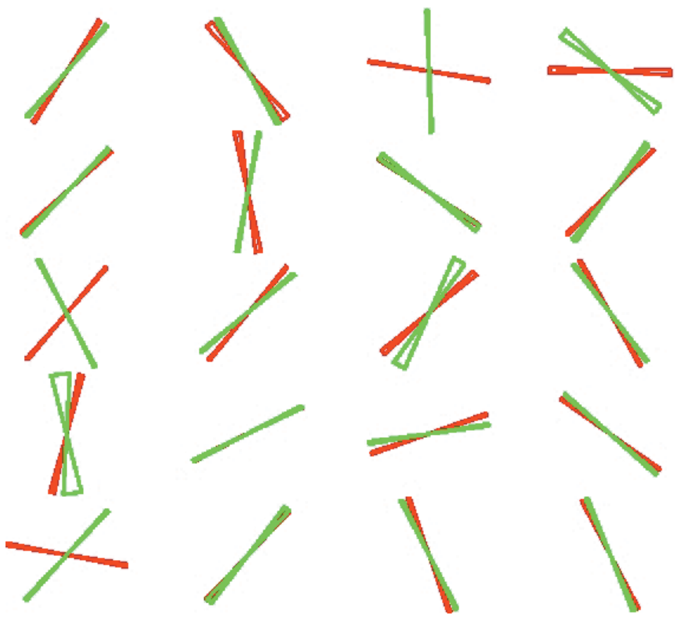

Figure 5: Orientation sketch of twenty binaries observed during our first FORS/ IPOL run. The disks are figured as bow ties of constant length and a width proportional to the residual error (primary in red, secondary in green) In more than 16 objects upon 20, both disk polarisation orientations are similar, indicating that disks tend to be physically aligned.