Dual-Beam Imaging Polarimetry of Circumstellar Environments

M. Rodenhuis, University of Utrecht (May 2010)

Application Note

Introduction

The direct observation of extrasolar planets and other objects orbiting nearby stars is complicated by the combination of the small separation between the star and the object under study as viewed from Earth, and the very large contrast between them. Models predict that the intensity of light reflected by extrasolar planets is 10^{-9} times that of its host star for a Jupiter–like exoplanet. For circumstellar disks this ratio is more favourable, between 10^{-4}–10^{-6}. An effect that can be used to increase the visibility of circumstellar material is the fact that light scattered of this material will become linearly polarized, as depicted in figure 1. For gaseous planets at optimal scattering angles (close to 90°), the resulting degree of linear polarisation can be up to 30% in the visible part of the spectrum.

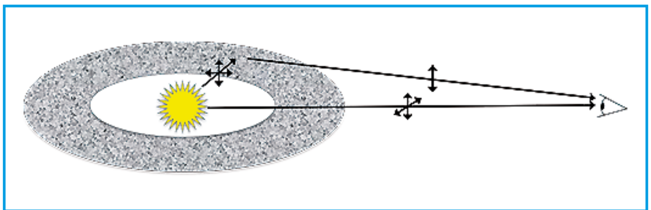

Figure 1: Scattering of starlight on circumstellar material produces linear polarisation

The Astronomical Institute of Utrecht University has developed the Extreme Polarimeter (ExPo), an imaging polarimeter that employs this effect to observe circumstellar disks. The instrument works in the visible part of the spectrum (600–900 nm) with a field of view of 20x30 arcseconds. It can achieve a contrast ratio of 10^{-5} in polarimetry, without the use of Adaptive Optics (AO) to correct for the atmospheric turbulence. Several successful observing campaigns have been conducted with ExPo at the William Herschel Telescope on La Palma, one of the Canary Islands.

Measurement Principle

To measure polarisation, the measurement will always have to be differential. In the case of linear polarisation, two measurements taken through orthogonal linear polarisers are subtracted. An unpolarised source will vanish in the difference, while any polarised signal will be stronger in one of the two measurements and will remain. It is desirable to make the two measurements simultaneously, as temporal changes in the image will otherwise appear as false polarisation signals. A polarising beamsplitter can be used to do this. However, any transmission or detector efficiency differences in the two beams will still appear as false signals.

A polarisation modulator can be used to alternately rotate the polarisation by 90°, effectively swapping the polarisation orientations between the two beams, which will cancel out any transmission differences in the two beams. This method, the dual beam–exchange method, is shown graphically in figure 2.

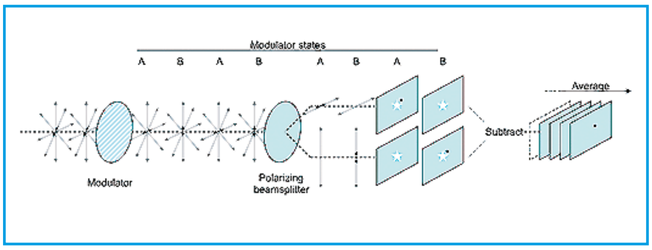

Figure 2: The dual beam--exchange principle. Incoming light consist of a strong, unpolarised (grey arrows) and a faint, polarised (black arrow) component. The modulator alternates between two states that align the polarised signals with the two orthogonal directions of the beamsplitter. The polarised signal will then alternate between the two beams of the beamsplitter. Subtracting the images from each other and averaging over a large number of images brings out the faint, polarised signal.

Experimental Set-up

ExPo uses a Ferro–electric Liquid Crystal (FLC) as the polarisation modulator, coupled to a polarising cube beamsplitter. Two right–angle prisms are used to project the two beams side by side onto the camera. Due to the absence of an AO system, it is desirable to take short exposures, so that the change in seeing produced by atmospheric turbulence is limited. We use an Andor iXon+ DU897 EMCCD camera capable of a full–frame rate of 35 fps. The Electron Multiplication technology of this camera allows us to observe relatively faint sources, down to 11th magnitude, at this frame rate. An adjustable tilted glass plate is used to compensate for any flat instrumental polarisation in the incoming beam. Together with the FLC and a filter wheel, this is placed in the collimated beam created between two lenses. The instrument includes a coronagraph in the telescope prime focus and a Lyot mask in the pupil image. A polariser can be inserted for calibration purposes. The instrument as installed at the telescope is shown in Figure 3.

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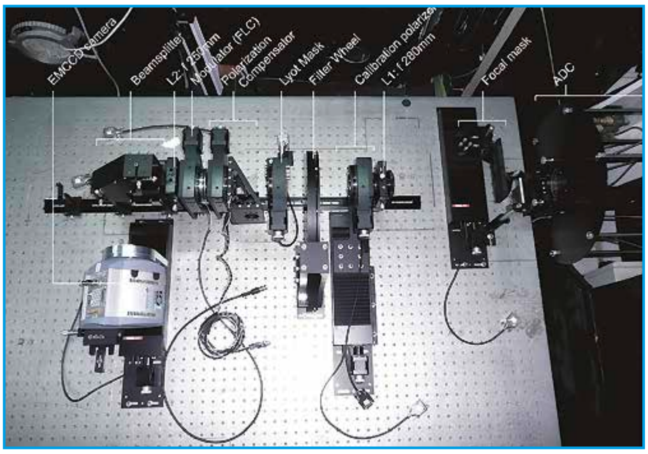


Figure 3: ExPo as installed at the William Herschel Telescope. Light from the telescope enters the instrument from the right, passing first through the Atmospheric Dispersion Compensator. A focal mask is placed in the telescope prime focus. This mask can translate to place coronagraph dots of different diameters over the star. After a collimating lens, the beam passes through the calibration polariser (which can be removed from the beam) and the filter wheel. In the pupil position, a Lyot mask removes unwanted diffraction form the telescope spiders and secondary mirror. The Polarisation Compensator uses a tilted glass plate to compensate for the flat polarisation induced by the third (Nasmyth) telescope mirror. After the Ferro--electric Liquid Crystal polarisation modulator and the focussing lens, the beamsplitter assembly includes two right--angle prisms to project the double image onto the camera.

Results

Shown below are images of the polarised light from two different stars. Both result from a subtraction of the left and right images produced in the two modulator states, averaged over about 20.000 image pairs. Figure 4a is an image of the young star AB Aurigae that is known to harbour a protoplanetary disk. The spatial polarisation structure associated with the disk shows up very clearly. For comparison, Figure 4b is an image of a diskless star.

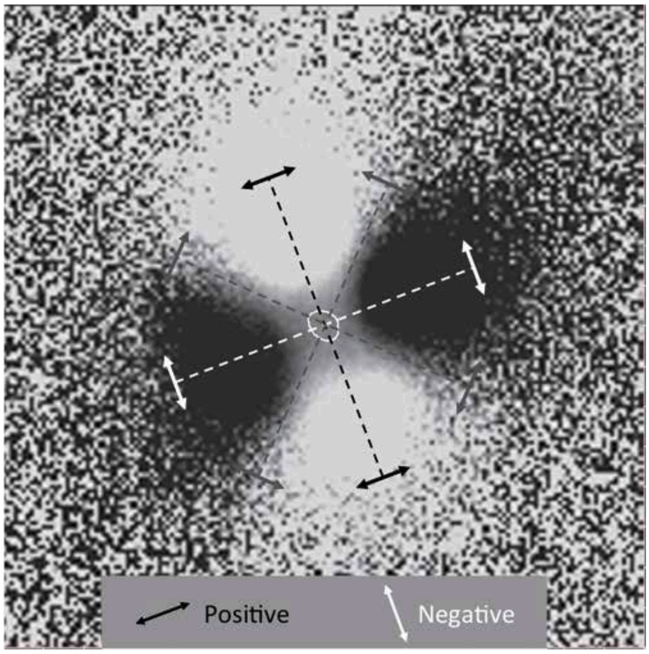
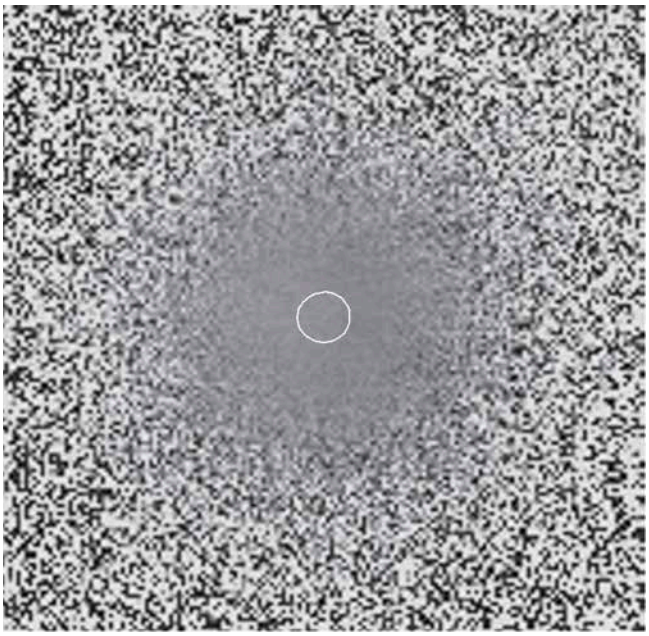


Figure 4a: Circumstellar disk around AB Aurigae in polarised light. The polarised intensity is shown with respect to an orthogonal polarisation reference system. The double--lobed "butterfly" pattern occurs because the orientation of the linear polarisation is tangential to the star, as indicated by the arrows. At the centre, a contour is drawn at the full--width half--maximum of the average intensity point spread function.



Figure

4b: Image of the diskless star HD221356. The image has been processed in exactly the same way as that of the circumstellar disk. It has the same platescale and is shown with the same greyscale range of --1% to 1% polarisation. Again, the intensity contour is shown at the centre, indicating slightly worse atmospheric seeing conditions at the time of this observation.

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Observations like these of disks around stars of different ages can be used to study the way in which circumstellar disks evolve. As planets are formed in the disks around young stars, such observations can also be used to test different planet–formation hypotheses. More efficient use of the coronagraph –and as a result higher contrast– can be achieved by including an Adaptive–Optics system. This can to a large extent remove the image blurring caused by atmospheric turbulence, producing much sharper images. This type of imaging polarimeter, combined with an AO system and installed on a larger telescope, will reach the contrast required to directly image extrasolar planets.

References

[1] M.Rodenhuis, H.Canovas, S.V. Jeffers, C.U. Keller: "The Extreme Polarimeter (ExPo): Design of a sensitive imaging polarimeter". Ground–based and Airborne Instrumentation for Astronomy II. Edited by McLean, Ian S.; Casali, Mark M. Proceedings of the SPIE, Volume 7014, pp. 70146T–70146T–9 (2008).

[2] H.Canovas, M.Rodenhuis, S.V. Jeffers, C.U. Keller: "Polarimetric Measurements of Protoplanetary Disks with ExPo". EXOPLANETS AND DISKS: THEIR FORMATION AND DIVERSITY: Proceedings of the International Conference. AIP Conference Proceedings, Volume 1158, pp. 381–382 (2009).

Contact

Michiel Rodenhuis
Astronomical Institute Utrecht
P.O. Box 80000
3508 TA Utrecht
The Netherlands

Email: m.rodenhuis@uu.nl
http://www.uu.nl/EN/faculties/science/research/researchinstitutes/aiu/Pages/default.aspx