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Observing Circumstellar Neighbourhoods with the Extreme Polarimeter

M. Rodenhuis,[1] H. Canovas,[2] S. V. Jeffers,[3] M. Min,[4] and C. U. Keller [1]

[1]*Sterrewacht Leiden, Niels Bohrweg 2, NL-2333CA Leiden, The Netherlands*

[2]*Departamento de Fisica y Astronomia, Universidad de Valparaíso, Valparaíso, Chile*

[3]*Institut für Astrophysik, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany*

[4]*Sterrekundig Instituut Anton Pannekoek, University of Amsterdam, Kruislaan 403, NL-1098SJ Amsterdam, The Netherlands*

Abstract. The study of circumstellar environments at ever higher contrasts has generated considerable interest in recent years. One method to increase the contrast is to observe the linearly polarized light scattered by the circumstellar material while suppressing the unpolarized stellar flux. This paper presents some sample imaging polarimetry results obtained with the Extreme Polarimeter (ExPo). ExPo operates in the visible part of the spectrum, and currently achieves a polarimetric sensitivity of 10^{-4}. Despite the demise of the Utrecht Astronomical Institute, where this instrument was developed, the instrument is still being used and upgraded. It has now moved to the Leiden Observatory.

1. Introduction: The Extreme Polarimeter

One of the last astronomical instruments to be developed at the Utrecht Astronomical Institute was the Extreme Polarimeter, or ExPo, a high-contrast imaging polarimeter working at visible wavelengths. The ExPo project was initiated by Professor Christoph Keller, who obtained a VICI grant from the Netherlands Organization for Scientific Research, NWO, for developing and operating the instrument over a five-year period. The design and development of the actual instrument and its data-reduction pipeline was done by graduate students Michiel Rodenhuis and Hector Canovas, respectively. Dr. Sandra Jeffers was responsible for the science coordination.

ExPo saw first light in October 2008, little over a year-and-a-half from the start of the project. Since then, five successful observing runs have taken place. Science observations have been focussed on circumstellar disks around young stars and dust envelopes of evolved stars, although we have also observed solar system planets and a comet (P103/Hartley). All observations have been performed as a visiting instrument on the Nasmyth platform of the William Herschel Telescope (WHT) on La Palma.

ExPo builds on technology and methods from solar magnetic field observations to achieve high polarimetric sensitivity. ExPo employs the dual-beam exchange method (Semel et al. 1993) to perform sensitive polarimetric measurements. The two orthogo-

nal polarization states are measured simultaneously and the polarization states are modulated such that their measurement alternates between the two instrument channels. In this way, neither time delays between measurements nor differential aberrations between the channels can introduce systematic errors. By being very sensitive to linearly polarized light but very insensitive to unpolarized light, ExPo is able to suppress the unpolarized flux from the star by four orders of magnitude or more while recording the faint, linearly polarized light scattered by circumstellar material.

ExPo as installed at the WHT is shown in figure 1. The polarization modulation frequency is 35 Hz, limited by the frame rate of the detector. A high modulation rate is desirable to limit the effect of atmospheric seeing variation between the images as ExPo has so far been used without an adaptive optics system.

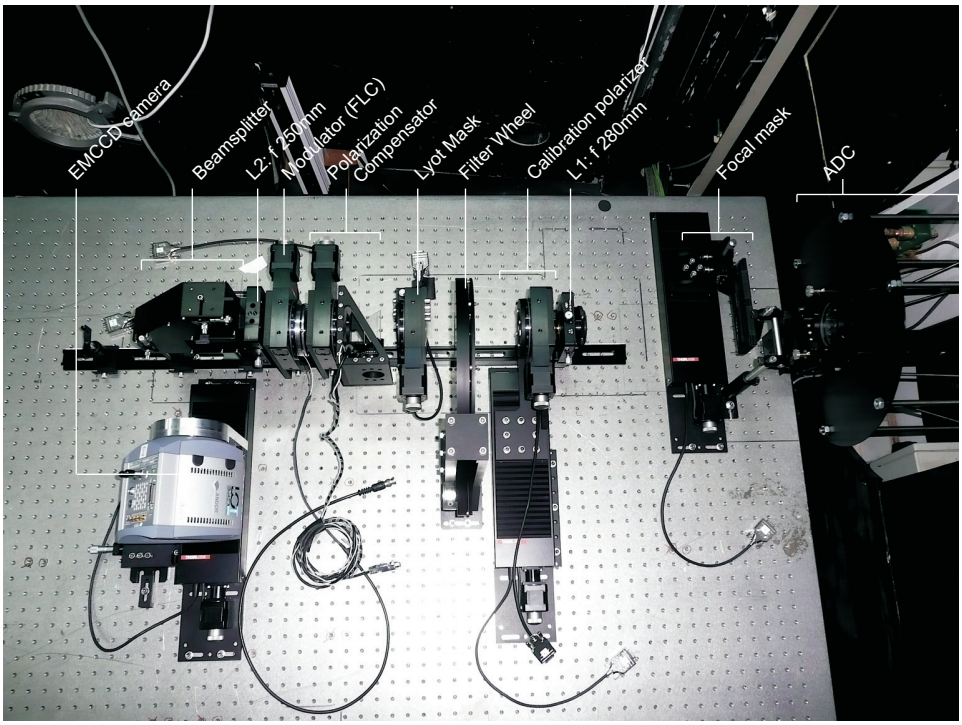

Figure 1. Image showing the instrument as installed on the WHT Nasmyth port optical table during one of the observing runs.

In order to reach sufficient S/N during the 29 ms exposures, an Electron-Multiplying CCD sensor is used. The polarization modulation done using a Ferroelectric Liquid Crystal (FLC) device and the beamsplitting with a polarizing beamsplitter. A filter wheel and a coronagraph can also be used during observations. Details on the design of ExPo can be found in (Rodenhuis et al. 2012a). Some key ExPo parameters are listed in table 1.

2. High-contrast observations with ExPo

Excellent and unique science has been obtained with ExPo, the only high-contrast imaging polarimeter currently operating in the visible part of the spectrum. typical ExPo

Table 1. ExPo key numbers.

Wavelenght range (nm):	500 - 900
Field of view (″):	20×30
Image scale (″/pix):	0.078
Modulation frequency:	35 Hz
Polarimetric sensitivity:	10^{-4}
Polarimetric contrast at 2″:	10^{-6}
Polarimetric accuracy:	1-2%

observations achieve a suppression of the unpolarized stellar flux of 10^{-4}. This means that at a distance of a few arcseconds, a contrast of 10^{-6} can be achieved. An nice example of an ExPo result is the observation of T-Tauri, presented in figure 2.

The polarimetric calibration of ExPo observations is performed by taking images of dome flats or unpolarized standard stars through a calibration polarizer at four different positions. This is used to obtain a polarization response matrix for the instrument. The inverse of this matrix can be used to calibrate ExPo observations. Typically, the calibrated polarization accuracy obtained is 1-2%.

3. Polarimetry: more than contrast alone

Observing the polarized flux from circumstellar matter offers more than increased contrast alone. As a fundamental property of light, polarization is a powerful diagnostic of the scattering medium.

In a dusty medium, the degree of polarization of the scattered light will depend on the combination of the dust grain size distribution, and the wavelength of the light. Comparison of observations at multiple wavelengths is therefore a method to determine or at least constrain the grain size distribution and the dust composition. Using multiple filters, ExPo can be used for this type of observations. This has however so far been hampered by the fact that ExPo is a seeing-limited instrument. Changes in the atmospheric conditions between observations with different filters makes it difficult to compare them.

The polarization direction is also key to interpreting polarimetry observations. Generally, the polarization direction will be perpendicular to the scattering plane. This allows us to verify that measured polarized flux actually originates from circumstellar material illuminated by the observed source. An example of this is provided by the observation of R Coronae Borealis, see figure 3. The full R CrB observation and its interpretation is presented in (Jeffers et al. 2012).

The degree and direction of the scattering polarization are closely linked to the scattering angle. The degree of polarization peaks at 90°scattering while at extreme forward scattering angles (160°- 180°) the polarization may become negative (i.e. perpendicular to the standard scattering polarization orientation). Mapping the deviation of the polarization direction from that perpendicular to the scattering plane allows us to probe the structure of the scattering medium in the direction perpendicular to the image plane. We have used this diagnostic to constrain the shape of the bipolar outflow of the variable post-AGB star Mira (Rodenhuis et al. 2012b).

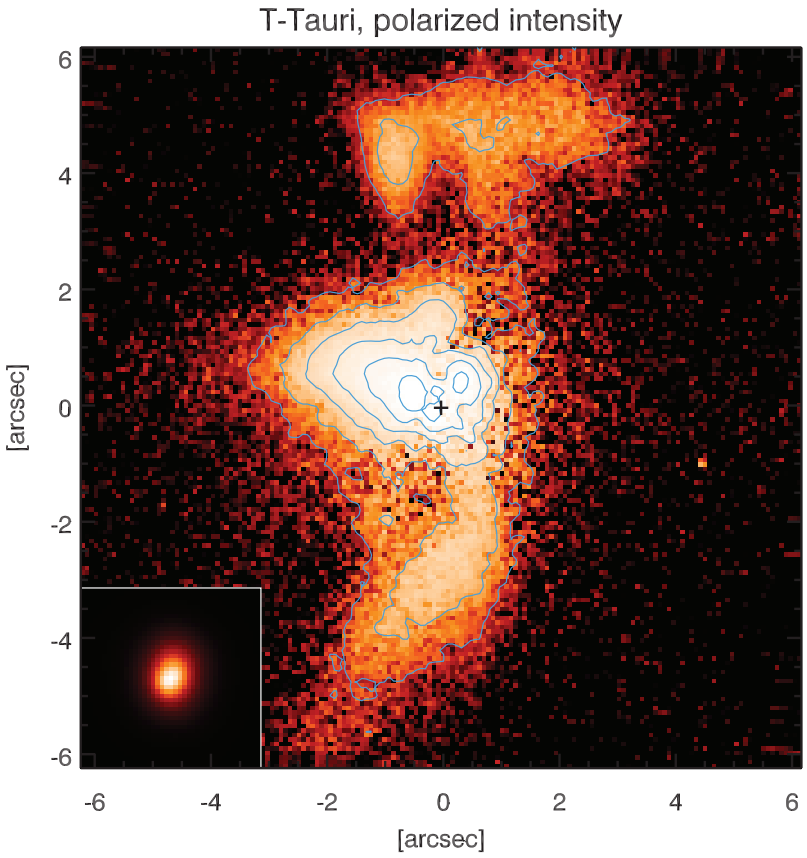

Figure 2. A beautiful ExPo imaging polarimetry target: T-Tauri. The main image presents the linearly polarized flux. The insert is the unpolarized flux image at the same spatial scale. The intensity scale of both images is linear between their respective minimum and maximum.

4. The future of ExPo

After the demise of the Utrecht Astronomical Institute, ExPo has moved to the Leiden Observatory. Here the instrument continues to be improved. A successful commissioning run of ExPo upgraded with a custom polarimetry-optimized AO system was conducted in June 2012. The AO offers numerous advantages: Apart from better resolution, the greatly improved tip-tilt stability and better concentration of the stellar flux means the ExPo coronagraph can be used to greater effect. Further improvements, such as a spectro-polarimetric integral field unit are in progress. As such, the aim is to use ExPo as a test bed for future imaging polarimeters such as the EPIC-EPOL instrument, while simultaneously producing novel and interesting science.

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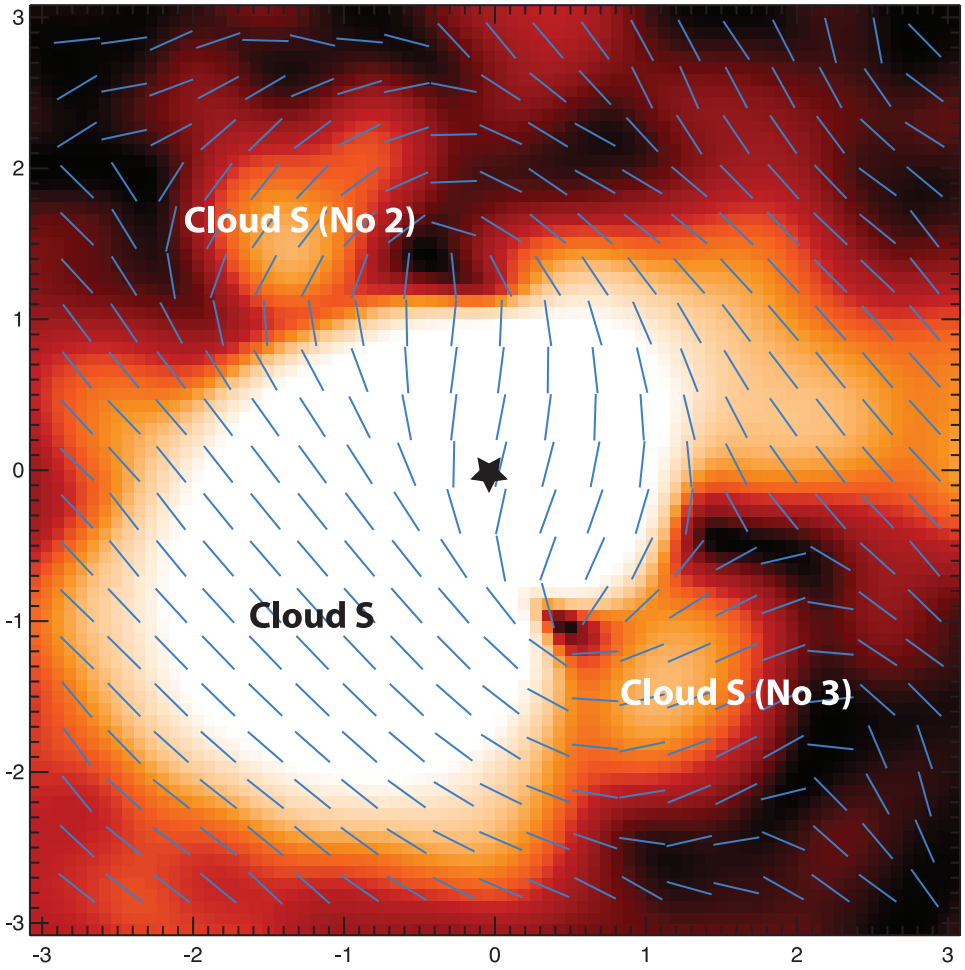

Figure 3. The variable star R Coronae Borealis emits clouds of dust at irregular intervals. One such cloud is currently positioned between us and the star, acting as a natural coronagraph and dimming the star by 9 magnitudes. Observing R CrB in linear polarization with ExPo, we discovered a second dust cloud (Cloud S in the image above). The smoothed image hints at two additional dust clouds at a contrast of 10^{-5}. The fact that the polarization direction is aligned perpendicularly to the direction to the star provides additional support for this tentative detection.

References

Jeffers, S. V., Min, M., Waters, L. B. F. M., Canovas, H., Rodenhuis, M., Ovelar, M. D. J., Chies-Santos, A. L., & Keller, C. U. 2012, Astronomy & Astrophysics, 539, 56

Rodenhuis, M., Canovas, H., Jeffers, S. V., & Keller, C. U. 2012a, Ground-based and Airborne Instrumentation for Astronomy IV. Edited by McLean, 8446

Rodenhuis, M., Min, M., Canovas, H., Jeffers, S. V., & Keller, C. U. 2012b, Imaging polarimetry of the asymmetric dust envelope around the mira binary system. In prep.

Semel, M., Donati, J.-F., & Rees, D. E. 1993, Astronomy and Astrophysics (ISSN 0004-6361), 278, 231