TELESCOPES AND INSTRUMENTATION

PlanetPol: A High Sensitivity Polarimetre for the Direct Detection and Characterisation of Scattered Light from Extra-solar Planets

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After commissioning on the University of Hawaii 88-inch telescope, PlanetPol has been used successfully on the WHT in April and October 2004. The instrument, funded by PPARC, was designed and built at the University of Hertfordshire.

PlanetPol is a stellar polarimetre designed to measure fractional polarisations of 10^{-6} or less. With this sensitivity PlanetPol should be capable of detecting the polarisation signature of so-called hot-Jupiters. These are extra-solar planets (EXP) whose size is approximately that of Jupiter but with orbits that are 0.1 AU or less (orbital periods of a few days). The linear polarisation should vary with phase angle from zero at full phase to a maximum whose amplitude and position depends on the nature of the scattering particles in the planetary atmosphere. Measuring the polarisation signature not only gives a direct detection of the EXP, in contrast to the more usual indirect detections by which most EXPs are discovered, but can provide information about the planet's albedo and radius, and on the nature of the scatterers. Further, from the position angle of polarisation the inclination of the planet's orbit (i) can be determined thereby enabling the planet's mass to be determined. In contrast, techniques such as the RV method only measure $M \sin i$.

Polarimetry is a technique that is capable of very high sensitivity as it is a differential technique that in principle is not affected by the Earth's atmosphere, and hence is limited only by photon noise. However, fractional polarisations of a few parts in a million are lower than most astronomical polarimetres can achieve, although comparable sensitivities have been obtained before, albeit under somewhat idealised conditions. Kemp et al. (1987, *Nature*, **326**, 270) measured the integrated light from the sun and gave an upper limit for the fractional linear polarisation of $2{\times}10^{-7}$. However, Kemp et al. used a polarimetre that directly viewed the sun, rather than using an intermediate telescope, and hence avoided the potential problem of telescope polarisation.

PlanetPol has a classical design and takes advantage of some of the techniques pioneered by Kemp. It was designed for use on a range of telescopes, mounted at the unfolded Cassegrain so as to minimise telescope polarisation.

All high sensitivity polarisation measurements to date have made use of photoelastic modulators (PEM) in which a slab of non-birefringent material is stressed using a piezo at the resonant frequency of the slab, f_0, thereby reducing the power needed to sustain a standing wave in the PEM. Such devices are ideal as polarisation modulators as they operate at frequencies of tens of kHz, well above seeing or scintillation fluctuations produced by turbulence in the Earth's atmosphere and they do not involve any rotating parts and so do not produce any periodic motion of the image on the detector, nor any periodic light

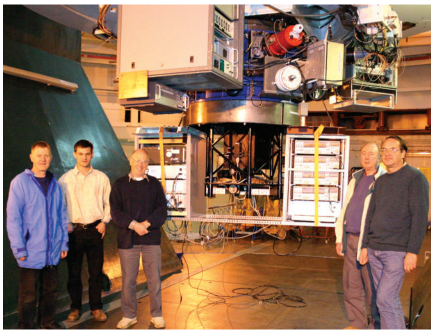


Figure 1. Top: Picture shows PlanetPol on the WHT, with left to right: Edwin Hirst, Phil Lucas, Jim Hough, Dave Harrison and Jeremy Bailey. Bottom: PlanetPol instrument.

modulation produced by dust on the modulator. The PEMs in PlanetPol are type I/FS20 made from fused silica, with a PEM90 Controller, all manufactured by Hinds Instruments.

A 3-wedge Wollaston is used as the analyser, giving better image quality than the more usual 2-wedge device. Following the analyser are wheels with colour filters and neutral density filters. Two-element Fabry lenses image the primary mirror onto single element detectors, sufficient for a stellar polarimetre, and these also eliminate any problems with flat-fielding. The very high modulation rates of the PEMs (20 kHz for PlanetPol) are, in any case, incompatible with the readout rates for CCDs, although the solar ZIMPOL Polarimetre, see `http://www.noao.edu/noao/staff/keller/` uses the charge shifting and storage capabilities of CCDs to act as a synchronous demodulator, thus largely overcoming the readout limitations.

PlanetPol uses Avalanche Photodiodes (APD), which have higher quantum efficiency than photocathodes and less noise than the external amplifier of a photodiode, providing the best signal to noise for the photon rates achieved with PlanetPol. The APDs were specially designed by Hamamatsu (type C4777-SPL-S2383-70K), operating with a gain of 100, a spectral response covering 400–1000 nm, a frequency response of 0–70 kHz (3 dB) and employ a 2-stage thermoelectric cooler (TEC), giving a detector temperature of −20°C. They have a nominal size of 1 mm with an active area of 0.70 mm. Their NEP is < 2 fWHz$^{-½}$.

PlanetPol has 2 channels, the star channel, on the telescope axis, and a sky channel, offset by 95 mm. As only one PEM is used in each channel, the instrument has to be rotated through 45 degrees to measure the second Stokes parameter for linear polarisation. The analyser, together with the filters, and detector assemblies, can be rotated through 90 degrees so as to change the phase of the modulated signal by 180 degrees, and hence eliminate any offsets in the signal detection train.

Each of 4 signal channels uses a Stanford Research SR830DSP lock-in amplifier to extract the linear polarisation signal modulated at 40 kHz (twice the modulation frequency of the PEM). The DC signal from the detectors is fed to a 16-bit ADC. An ARCOM Industrial PC, running Agilent Vee Pro 6 is used to control all the mechanical functions of the instrument, the settings of the lock-in amplifiers and ADCs, and also acquires and displays the data. Communication with the ARCOM computer is via an Adderlink KVM Extender, using a dedicated ethernet line to a remote monitor and keyboard in the observatory's control room. Data reduction is carried out using a laptop running IDL, which shares files with the ARCOM over the LAN.

Figure 2. Schematic of PlanetPol.

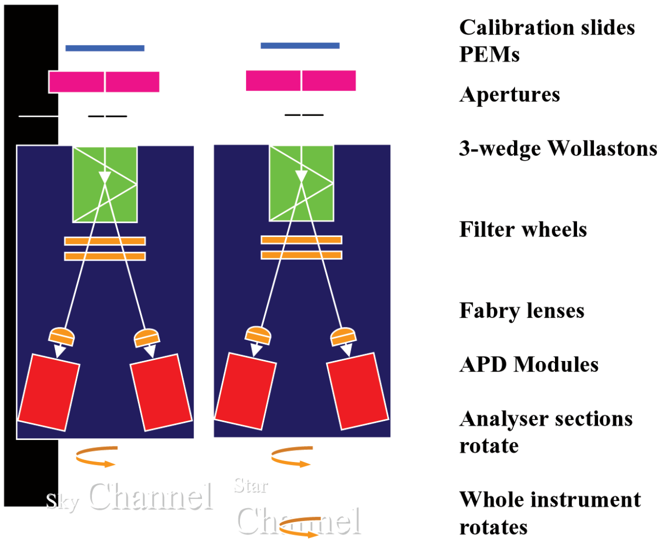
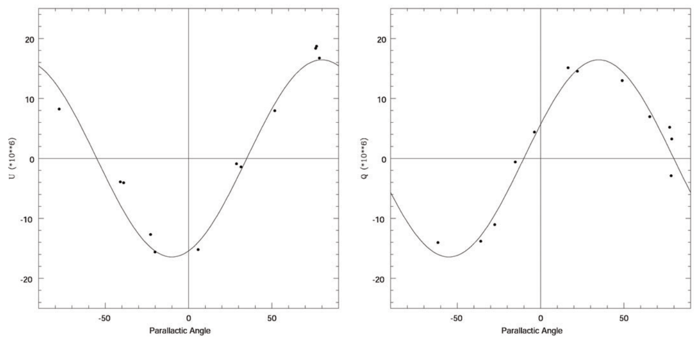


Figure 3. U and Q polarisations for nearby stars at different parallactic angles. U and Q are not shown in the equatorial coordinate system. Fractional polarisations are in units of 10^{-6}.



In order to measure fractional polarisations of 10^{-6} or less, it is essential to determine the telescope polarisation (TP) so that the absolute error in TP is much lower than 10^{-6}. This was achieved by observing nearby stars (typically within ~20 pc) with the telescope de-rotator on, causing the TP to rotate while any other contributions to the polarisation are fixed. Measuring the polarisation of these nearby stars as a function of parallactic angle should produce, in the absence of any intrinsic stellar polarisation, interstellar polarisation, and instrument polarisation, a sinusoidal curve in U and in Q with an amplitude equal to the telescope polarisation, and phase shifted by 45°. Figure 3 shows the measured U and Q polarisations as a function of parallactic angle. In practice, even for very nearby stars, there will be some interstellar polarisation and a curve was fitted to the data set taking this into account. The best fit curves give a fractional polarisation for the TP of $(16.45 \pm 0.20) \times 10^{-6}$. This very low TP makes the WHT an ideal telescope for making very high sensitivity polarisation measurements.

In the two observing runs to date observations were made of τ Boo and υ And, although poor weather has meant that we have only limited data. Nonetheless, the very good performance of PlanetPol gives us confidence that we can determine the polarisation signature of the hot-Jupiter EXPs.

There are also several other observational programmes that will be possible with PlanetPol, with its very high sensitivity. Of course, very high sensitivities require large numbers of photons with a fractional polarisation of 1×10^{-6}, requiring 2×10^{12} detected photons.

Some possible programmes are:
– the distribution of dust in the local ISM,
– oblateness of rapidly rotating stars,
– star spots on active stars,
– debris discs around young main sequence stars. ¤

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