Tenth anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies
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PLANETPOL: polarimetry of hot Jupiters at the parts per million level

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Abstract. We summarize the preliminary results from 3 observing runs with PLANETPOL, a polarimeter designed to achieve sensitivities of order 10^{-6} in fractional polarization for nearby hot Jupiter systems. We also describe some of the problems associated with measuring very small fractional polarizations and the solutions we have adopted. These observations were conducted at the 4.2-m William Herschel Telescope.

1. Introduction

Polarimetry has the potential to be a very powerful method for obtaining data on hot Jupiter planets. The basic premise is that the direct light from the central star has little or no linear polarization (LP), while reflected light from the planet will in general be polarized, perhaps at the level of tens of per cent. Hence by measuring the polarized flux from a hot Jupiter system we expect to remove the stellar flux and observe only the planet, thereby circumventing the contrast problem without using a high resolution imaging system.

PLANETPOL is a polarimeter built at the University of Hertfordshire specifically to attempt this type of observation. In section 2 we outline the information that can potentially be extracted from polarimetry of hot Jupiter planets. In section 3 we describe the principles upon which the design of the instrument is based. Section 4 contains preliminary results of 3 observing campaigns and outlines the practical observing issues which arose during them. Conclusions are given in section 5.

2. Hot Jupiter science with a polarimeter

The polarization signal from an extrasolar planet is expected to vary periodically in magnitude and position angle with the orbital period of the planet. The period and timing of the target planets is usually well measured by the radial velocity method, and will also be known for planets detected by the transit method. Hence it should be straightforward to confirm the planetary nature of any polarization signal which is detected from a hot Jupiter system by testing for repeatability.

The position angle of the polarization is always centrosymmetric with respect to the star to planet radial vector. Hence measurement over a full orbit will yield the orbital inclination, i. In combination with the $M.sin(i)$ measured by radial velocities this yields the exact mass, M, so polarimetry of a large sample could in principle be used to improve measurements of the hot Jupiter mass function.

The amount of fractional polarization can also be used to estimate the radius, R_P, of the planet with precision comparable to that provided by transit surveys, since the reflected signal will always be proportional to $p\phi(\alpha)R_P^2$, where p is the geometric albedo and $\phi(\alpha)$ is the phase function at phase angle α. The latter two terms can be determined by constructing a model atmosphere and comparing the predicted polarization as a function of orbital angle with the observations. Detailed models of this kind can be found in Seager, Whitney, & Sasselov (2000) and Stam, Hovenier, & Waters (2004).

In addition, polarimetry as a function of orbital phase can be used to determine the composition of the planet's atmosphere. Reflection due to Rayleigh scattering, sub-micron dust grains or larger dust grains all vary with orbital phase in a different manner, as shown in the papers referenced above. Observation as several different wavelengths would maximize the amount of information extracted on the size distribution and refractive index of reflecting particles. It may then also be possible to infer the chemical composition of different types of dust grain (Seager et al. 2000) or identify broad absorption features due to atomic and molecular gas (Stam et al. 2004).

3. Principles of PLANETPOL design

The design of PLANETPOL is described in Hough et al.(2001). Here we list some of the key features which allows us to reach a sensitivity of 1 part per million (ppm) for bright stars. Note that Kemp et al.(1987) achieved a sensitivity of ~1 part in 10^7 in observations of the full solar disk, but these observations did not require a telescope to gather the light. Previous night time polarimetry has generally not achieved a sensitivity better than 10^{-4} in fractional polarization.

PLANETPOL uses photo-elastic modulators (PEMs) supplied by Hinds optics as the modulating element, not a conventional half-wave retarder. The light passes through the PEM, and then a Wollaston prism. The PEMs are composed of a silica glass which is piezoelectrically stressed at their natural frequency ($\sim$ 20 kHz), producing a sinusoidally varying retardance of the orthogonal planes of polarization with a tunable amplitude which is set to half of the desired wavelength. The PEM+Wollaston optical train causes the linearly polarized component of the light to oscillate in intensity at harmonic overtones of the fundamental frequency. The light from the 2 beams exiting the Wollaston is detected by single element low noise avalanche photo-diodes (APDs), which are sensitive to DC and high frequency signals. Lock-in amplifiers are then used to pick out the first harmonic at 40 kHz and filter out noise at all other frequencies.

The key feature of such a PEM-based system is that the polarized flux is separated from the unpolarized flux by being converted to a high frequency signal. Hence very small fractional polarizations can be measured without the need for high precision. The high frequency also removes the effects of the earth's atmosphere. Such systems are not truly differential since the two beams produce first overtone signals with identical amplitude, the only difference being a phase difference of pi radians. Each beam separately measures the same Stokes parameter.

Conventional dual beam polarimeters (half-wave plate + Wollaston) can remove the effects of the Earth's atmosphere by providing a differential measurement of orthogonal planes of polarization. However, they cannot measure fractional polarizations at the 10^{-6} level because the polarized signal is not separated from the much larger unpolarized signal, so that an unachievable absolute precision of 10^{-6} would be required in the measurements with each detector.

Other important elements of the PLANETPOL design are: as follows. (1) A Fabry lens, which images the telescope primary mirror on to the APDs. This is preferable to imaging the star, which might move about within the detector area on the atmospheric seeing timescale and cause problems due to non-uniform sensitivity. (2) A completely separate sky channel, offset by a few arcminutes on sky from the star channel (which is on the telescope axis). This is used to measure any polarized flux from the night sky within a 6 arcsecond detector aperture, which can then be subtracted from the planetary signal. (3) The APDs and the Wollaston (in both the star and sky channel) are mounted in rotatable housings which are used to change the angle between the axes of the PEM and the Wollaston from +45° to −45° every few minutes. This '2nd stage chopping procedure' removes the effect of any drifts in the electronics. (4) Absolute encoders with a step size of 0.009° are used to measure the rotation angles used in 2nd stage chopping and the rotation angle of the whole instrument. The instrument is rotated back and forth through 45° to measure the Stokes Q and U parameters. This permits high precision measurements, so that small planetary polarization signals can be detected despite the presence of other polarization signals such as telescope polarization, which can be large at some telescopes.

4. Results

Three observing campaigns were carried out at the 4.2-m William Herschel Telescope (WHT) at Roque de los Muchachos Observatory in La Palma in April 2004, October 2004 and April-May 2005. The first run aimed to detect τ Boo b, the second to detect υ And, and the third was a double run observing τ Boo b and starting an unbiased survey of nearby bright stars. All observations used a broad 590-950 nm bandpass, limited at the long end by detector response. In this section we briefly summarize the results.

The precision achieved is photon noise limited, declining with the square root of stellar flux. Sky polarization is only occasionally significant (eg. during conditions of bright moonlight illuminating thin cloud). For bright stars a precision slightly better than 1 ppm in fractional polarization has been achieved. However the noise is $\sim 2\times$ higher than expected, which is presently attributed to an additional source of photon shot noise arising in the APDs. The majority of the nearest bright stars show very little polarization. The observed signal from these stars is often dominated by the polarization of the telescope, which is typically 10-20 ppm at the WHT, with variations only on a timescale of months. This low telescope polarization (TP) can only be achieved at a Cassegrain focus or prime focus where there are no off-axis reflections. It appears to be due to spatial variations in the reflectivity of the mirror surface rather than any asymmetry in the mirror figure (which might change with zenith distance in a poor quality telescope) or any effect of the secondary mirror support spider. The WHT is an alt-azimuth telescope, so the Cassegrain focus is rotated to keep the image from rotating during observations as the telescope tracks. Hence the TP in each Stokes parameter is a function of telescope parallactic angle.

Figure 1 shows the data from April 2004. Three Tinbergen unpolarized standards were observed several times (the points without error bars) and the close fit to the curve indicates that any interstellar or intrinsic stellar polarization is at a level of 0-3 ppm in both Stokes parameters. By contrast the Tau Boo data in Stokes Q (data with error

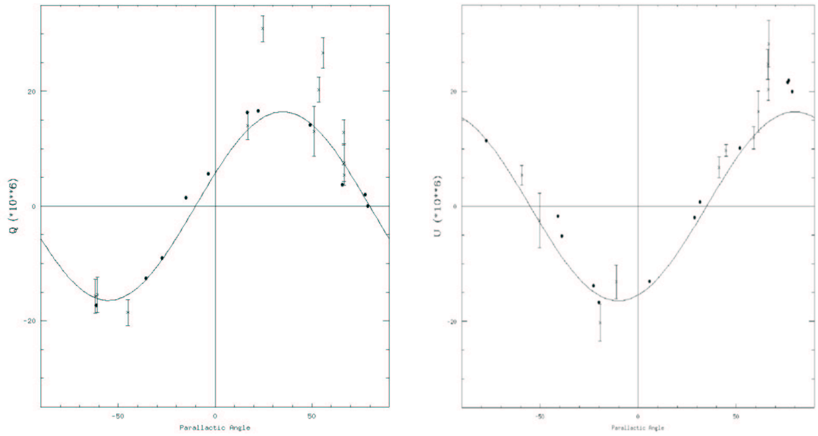

Figure 1. *Measurements from the April 2004 run plotted against telescope parallactic angle. (left) Stokes Q; (right) Stokes U. The curve in each plot shows the best fit telescope polarization. Points without error bars are for bright nearby stars with near zero polarization. Points with error bars are data for* τ *Boo.*

bars) agrees with the curve at some points and disagrees at other points. This indicates a variable polarization at the 10 ppm level due to either the planet or the star itself. There was insufficient good weather in April 2004 to make clear statements about this apparent signal.

Figure 2 shows the Tau Boo residual polarization from the longer run in April-May 2005, after the TP has been fitted and subtracted from each Q and U point and these have been combined in fractional polarization P. We plot P=$\sqrt{Q^2 + U^2 - \sigma_P^2}$ against orbital angle for the planet (orbital data courtesy Geoff Marcy, private comm.) There appears to be a great deal of scatter at a level of up to 10 ppm or more at all orbital angles for which several data points were obtained. The inconsistencies became apparent when data from 7 and 8 May were added to data from 25-30 April, after an interval of other observing programs and bad weather. This scatter is not seen for any of the several Tinbergen unpolarized standards which we have observed.

This scatter suggests that either we are observing a planet with a signal which varied strongly over an interval of 3 orbits, eg. due to weather, or that the star τ Boo itself has a significant variable polarization. Recent results from the MOST micro-satellite (Walker et al. 2005) show strong semi-regular photometric variability in this rapidly rotating star, apparently with the same period as the planetary orbit (3.3 days). (The star is believed to have been spun up by this unusually

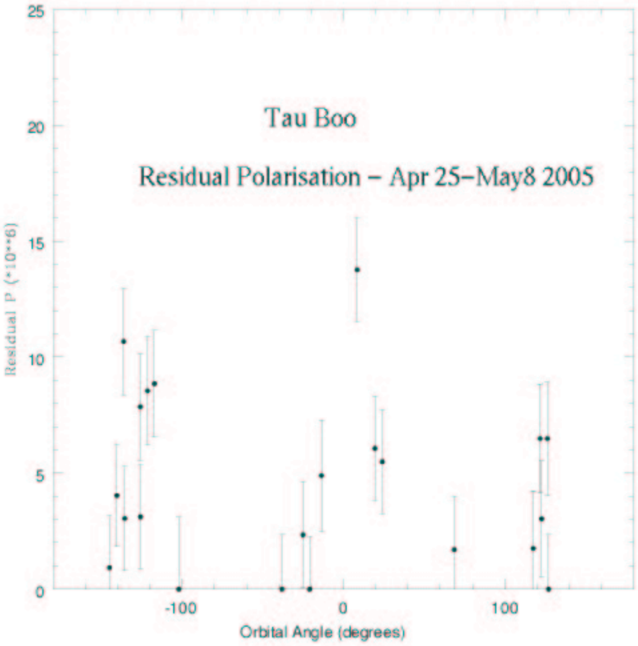

Figure 2. *Residual fractional polarization of Tau Boo in 2005. Scatter in the points at each orbital angle is attributed to the effect of the massive planet on the rapidly rotating star. Polarization variability is not seen in unpolarized standards at similar distances* ∼ 15 *pc*

massive planet). Hence it appears likely that the observed polarization variation is caused by the star (eg. a very large star spot), rather than the planet.

Some of the Tinbergen "unpolarized standards" do show measurable polarization. Figure 3 shows the Stokes Q data as a function of parallactic angle from the October 2004 run. 4 Tinbergen unpolarized standards are included (large points). The left hand plot shows that they all display obvious scatter away from the best fit TP curve, at a level of 5-12 ppm. The right hand plot shows the same data after subtracting a different best fit constant Stokes Q from each star. (The TP amplitude and phase and a constant Q and U for each star are derived simultaneously by fitting all the data for unpolarized standards). The points then all lie close to the curve. It thus appears that interstellar polarization can be observed even toward these nearby stars (all within

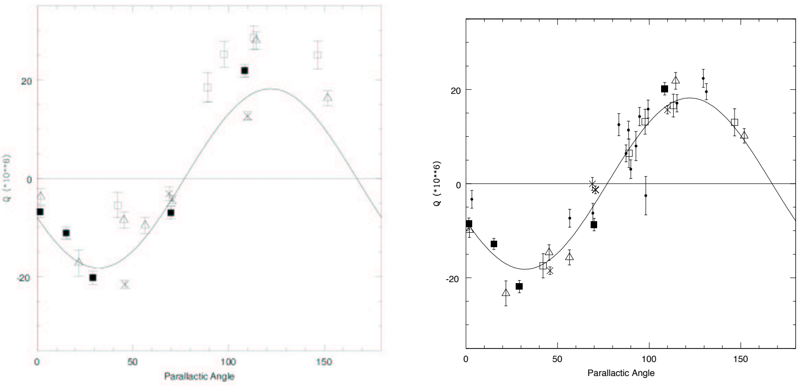

Figure 3. *A low interstellar polarization is seen toward some "unpolarized (standards". These lie off the TP curve in the raw Stokes Q data (left) but lie on the curve after fitting and subtracting a constant interstellar polarization for each standard (right). υ And data were taken near phase of minimum illumination (right plot, small filled circles).*

$\sim$ 25 pc). The amount appears to be a strong function of direction on the sky. The right hand plot in Figure 3 includes the data for υ And (small filled points). These show little departure from the curve, which is unsurprising since weather constraints allowed data collection only near the phase of minimum illumination.

5. Note on Saharan Dust

Part of the period of bad weather in early May 2005 was due to large grey particles of Saharan dust, a not uncommon occurrence in La Palma in the summer months. This introduced a polarization signal at the level of up to 40 ppm, which seriously interfered with our observations. The dust reduces throughput by $\approx$25% when the polarization effect is 40 ppm. The dust polarization, P_D, is attributed to dichroic extinction, and appears to be a strong function of zenith distance, ζ, declining to near zero at $\zeta < 20°$. If the effect is due to dichroic extinction we would expect that (i) $P_D = C(1 - cos(\zeta))$ (C being a function mainly of dust column density) and (ii) an orientation in the azimuthal plane or the altitudinal plane. The data appear to bear this out, though analysis is presently at an early stage. Hence it should be possible to minimize this effect when it occurs by observing science targets only near the zenith (reducing the effect to 1-4 ppm) and subtracting the calculated P_D. The difficulty is that the parameter C is likely to have some temporal and directional variability even within each night, so the error bars on any science data of bright science targets will be noticeably increased. This analysis will be attempted for the affected data, which was not included above.

6. Conclusions

We have shown that it is possible to observe nearby bright stars with a precision of parts per million in fractional polarization. Data for τ Boo appear to be affected by stellar variability, which may be a consequence of magnetic disturbance of the stellar photosphere by the massive planet, or simply the rapid rotation of the star (apparently spun up by the planet).

Nevertheless the low level of the observed polarization variation indicates that τ Boo b has a low geometric albedo ($p < 0.2$ perhaps, yet to be modeled). We can hope that the other bright hot Jupiter systems (υ And, 51 Peg) do not suffer from this stellar polarization variability problem since they rotate more slowly and the planets are 10× less massive than *tau* Boo b. Observation of the newly discovered class of hot Neptune planets (eg. 55 Cnc e) may also be possible with PLANETPOL.

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