Scientific Requirements for Extremely Large Telescopes
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The polarization signature of extra-solar planets

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Abstract. Despite recent advances in the study of extra-solar planets the detection of reflected light from planetary atmospheres remains a major goal. For the so-called hot-Jupiters, which are unlikely to be spatially resolved from the central star in the foreseeable future, very high sensitivity measurements are required to detect the reflected signal from the very much larger direct starlight. We describe an optical photo-polarimeter designed to have a polarization sensitivity of at least 1 in 10^6 and some early observations made in an attempt to detect the polarization signature of τ Boo b. We discuss the role of such an instrument for the planned ELTs.

Keywords. Instrumentation: polarimeters; Planets: extrasolar planets.

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1. Introduction

Progress in the study of extrasolar planets, hereafter EXPs, has progressed rapidly since the first discovery a decade ago (Mayor & Queloz 1995). Over 160 EXPs have now been discovered, mostly by indirect means using radial velocity measurements of the central star or, far less frequently, through reductions in brightness of the star as a planet transits (for a recent review see Marcy *et al.* 2005). Detailed observations of a transit, such as those made of HD 209458 b (Charbonneau *et al.* 2000) can give information about the planetary atmosphere but this method is really only applicable to the tenuous upper atmosphere of the planet. Recently, Deming *et al.* (2005), using Spitzer observations, report the detection of mid-infrared radiation from HD 209458 b, by observing the reduction in flux during secondary eclipse, when the planet passes behind the star. Lastly, direct images of planets at large distances from a young star (Neuhauser *et al.* 2005) and from a brown dwarf (Chauvin *et al.* 2004) have been made. To date, however, there are no detections of the reflected light from planets, and for the so-called hot-Jupiters, with orbital radii less than 0.1AU, there is little prospect of being able to spatially resolve them from the very much brighter central star. Hence, to study their atmospheres, very high sensitivity observations have to be made to separate the reflected light from the direct star light.

The magnitude of the problem can be readily seen (e.g. Seager, Whitney & Sasselov 2000). Assuming a Lambert sphere, a hot-Jupiter with radius $= 1.5R_J$, where R_J is the radius of Jupiter, at a distance of 0.05AU, has a maximum ratio of reflected light to direct starlight of $\sim 1.5 \times 10^{-4}$, with a maximum orbital change in brightness of 150μmag for an inclination of 90°. Such very small changes are too small for ground-based telescopes to observe. Assuming Rayleigh scattering, the maximum fractional polarisation is 5.5×10^{-5} although more detailed models (e.g. Seager, Whitney & Sasselov 2000), give peak fractional polarizations that are a few $\times 10^{-6}$, but with significant variations in the peak polarization and orbital signature, depending on the assumptions made on the nature and size of the atmospheric particles. Thus, to measure the polarization of these unresolved systems requires a polarization sensitivity of at least 1 in 10^6.

Polarimetry is a technique that is capable of very high sensitivity even with ground-based telescopes. It is a differential technique that in principle is not affected by the Earth's atmosphere and is limited only by photon noise. However, most polarimeters used by night-time astronomers achieve fractional polarizations of only 10^{-4} although solar astronomers have achieved sensitivities of $\sim 5 \times 10^{-6}$ (Stenflo 2003), and Kemp *et al.* (1987) gave an upper limit of 2×10^{-7} for the fractional linear polarization of the integrated light from the sun. However, Kemp *et al.* used a polarimeter that directly viewed the sun, rather than using an intermediate telescope, and hence avoided the potential problem of telescope polarization (TP).

Assuming that the light from the star is unpolarized, the observed intrinsic polarized signal is a direct measure of the reflected light from the planetary atmosphere. The variation of polarization position angle with orbital phase gives the inclination of the orbit and hence the mass of the planet (removing the $M \sin i$ uncertainty from radial velocity measurements); the magnitude of peak polarization gives information on the planetary albedo and radius, and the phase of peak polarization gives information on the size and nature of the scattering particles in the atmosphere.

2. Instrument design and performance

The polarimeter, known as PlanetPol, was designed for use on a range of telescopes, mounted at the unfolded Cassegrain so as to minimize telescope polarization. Basically, the instrument uses a photoelastic modulator (PEM), a triple-wedge Wollaston prism and Avalanche Photodiode Detectors (APDs). It has two channels, an object channel on the telescope axis and a sky channel offset by 95mm (see Fig. 1). Standard B, V, R and I colour filters are available, plus two very wide pass-bands additional filters, OG590 and RG695. Further details are given in Hough *et al.* (2005) and Hough *et al.* (in preparation).

All observations reported here were made on the William Herschel Telescope, La Palma, with PlanetPol mounted at the unfolded Cassegrain. The TP was determined by observing bright nearby stars (typically within 25pc) with the telescope de-rotator enabled causing the TP to rotate while any interstellar/intrinsic polarization and instrument polarization are fixed. If TP dominates then the Q and U Stokes parameters should be sinusoidal functions of the parallactic angle, with an amplitude equal to the TP and phase shifted by 45° (see Fig. 2). For the observing runs to date the TP has ranged between $(10\text{–}20) \times 10^{-6}$, including a re-aluminization of the primary mirror, with a typical fit at one particular epoch giving $\mathrm{P} = (16.4 \pm 0.3) \times 10^{-6}$, showing that the TP can be measured to an accuracy of a few parts in 10^7. The instrument itself has a constant fractional polarisation (IP) of $\sim 2 \times 10^{-6}$, measured by observing the same low polarisation standard at instrument rotation angles of 0 and 90 degrees or 45 and –45 degrees.

In practice we reach a fractional polarization of 1×10^{-6} in 370s integration time, for a $I = 0$ mag star on a 4-m telescope, with a filter passband of $\sim$320nm.

3. Observations of τ Boo

The star τ Boo has a hot-Jupiter EXP, τ Boo b, with an orbital period of $\sim$3.3 days, an Msin$i$ of $3.87 M_J$ and an orbital radius of 0.0462AU (http://cfa-www.harvard.edu/planets-/cat1.html). Data from three different observing runs, between April 2004 and May 2005,

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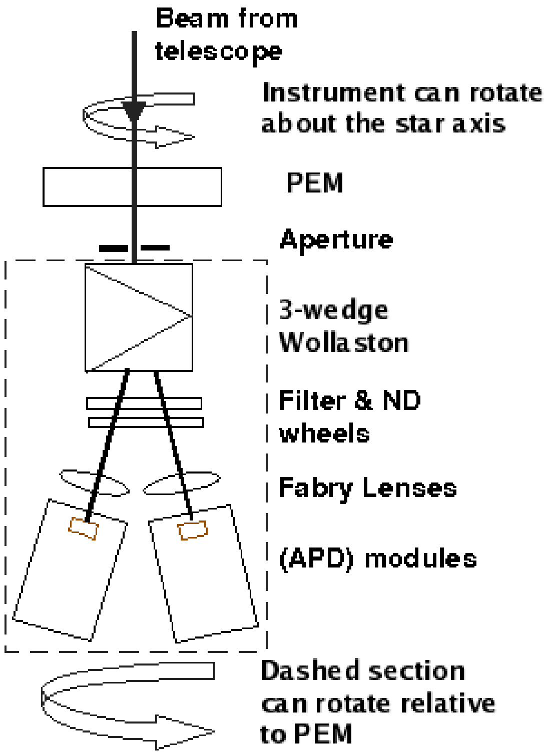

Figure 1. Schematic of PlanetPol. There are two identical channels with only one shown: the object channel is on the telescope axis and the sky channel is offset by 95mm. The instrument is rotated through 45° to measure the second linear Stokes parameter. The analyser, together with the filter and detector assemblies, is rotated by 90° (from −45° to +45° relative to the PEM axis) changing the polarity of the modulated signal thereby minimizing systematic errors.

are shown in Fig. 3, where the small data points are the individual observations and the larger data points are the averages over 3 or 4 adjacent measurements. Compared to the stars used to define the TP, and for some other programmes we have carried out, it appears that we are not getting consistent polarizations from orbit to orbit. Interestingly the MOST satellite reports that it sees variations in the brightness of τ Boo that can be as much as 2.5 millimag and attribute this to the planet 'stirring' up the stellar surface (Walker (2005)). Nonetheless, from our data to date we are able to put an upper limit on the geometric albedo of 0.20 (for a $1.2R_J$), smaller than the 0.3 previously established by searching for the Doppler shifted reflected spectrum (Leigh *et al.* 2003). The albedo limit is based on an estimate for a planetary photosphere dominated by small particles or Rayleigh scattering from molecules (Seager, Whitney & Sasselov 2000).

With hindsight, τ Boo was perhaps not the best target to have chosen as τ Boo b is unusually massive and hence more likely to have an effect on the star. However, there was no indication of high stellar activity in either the rms error of the radial velocity fit or the CaII activity index. Other targets such as υ And b, for which we have preliminary data, 51 Peg b, and the recently discovered hot Neptune 55 Cnc e, all being much less massive than τ Boo, might give a better chance to detect the polarization signature.

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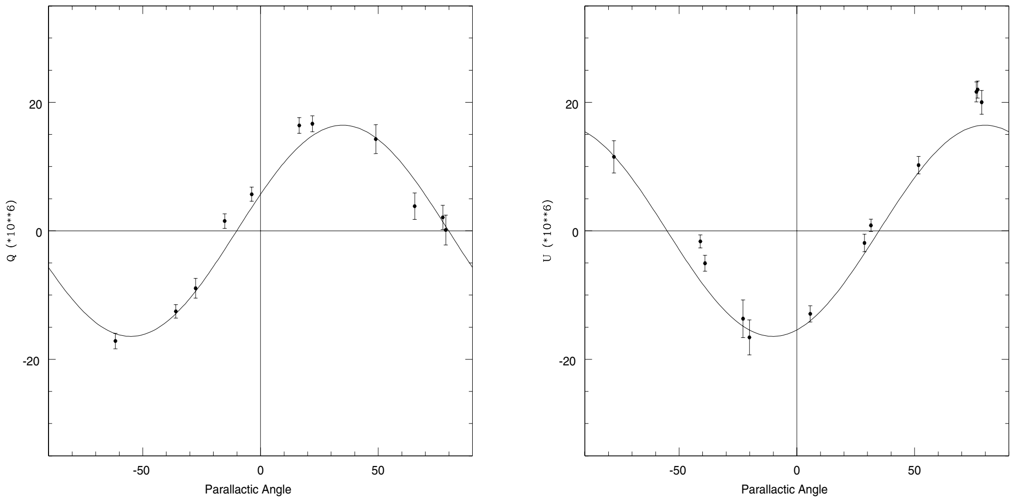

Figure 2. Directly measured Q and U fractional polarizations in units of 10^{-6} for stars that have very small interstellar and/or intrinsic polarization. The measurements are dominated by the Telescope Polarization, shown by the sine curves (see text).

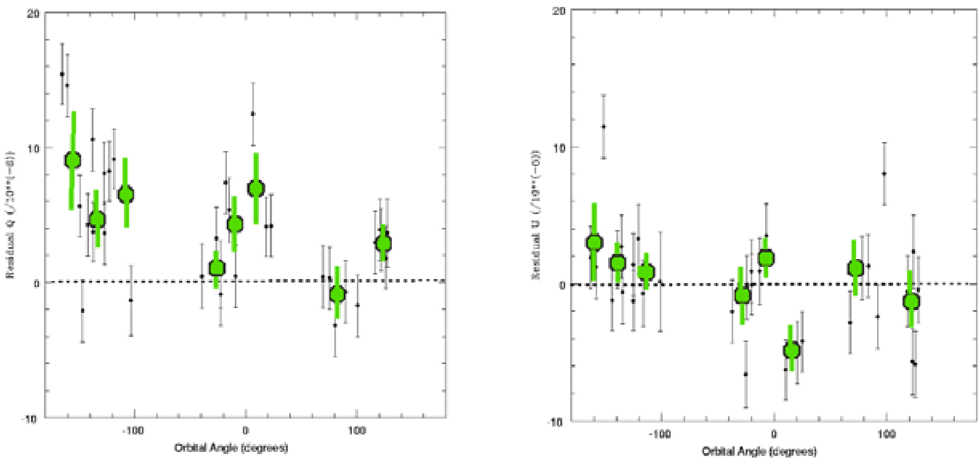

Figure 3. Q and U fractional polarizations in units of 10^{-6} for τ Boo taken over several orbital periods. Telescope polarisation has been subtracted. Larger circles are averages of the individual data points (small circles).

4. Use with ELTs

As has been often pointed out, many of the key science programmes for the ELTs require better than median conditions, particularly with regard to seeing. It is therefore

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important to have available instruments that can make use of poorer conditions. A polarimeter, such as PlanetPol, essentially requires a light bucket and is limited only by the total number of photons collected. Thus moving to a 30m or 50m class telescope gives considerable gains. For example, compared to our observations with the WHT we would be able to observe much fainter systems (9-10mag and 10-11mag), or use higher spectral resolving powers (100 and 300), or detect polarization signatures for larger orbits (0.4 and 0.63 AU), or observe smaller planets ($0.13R_J$ and $0.08R_J$), for a 30m and 50m telescope respectively. It would be important to minimize the possible telescope polarization for ELTs with symmetric optics for the telescope design. An unfolded Cassegrain focus is also important, otherwise ways of compensating for the polarization produced by oblique mirrors have to be employed.

Additionally, use of ferroelectric liquid crystal modulators, providing the same polarization sensitivities can be achieved, would provide higher modulation efficiencies than with photoelastic modulators, and with modulation frequencies of ∼1 kHz potentially allow the use of other detectors that would avoid the excess noise associated with APDs.

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Discussion

Käufl: I presume the polarization by inclined metal mirrors is 'easy' to calibrate. What is the influence of dust on such surfaces? What could happen if there were dielectric over coats (e.g. enhanced Ag)?

Hough: I don't believe it is that easy to calibrate the polarization produced by an inclined mirror to a precision of 1 part in a million. The degree of polarization depends on the nature of the reflecting surface, and on any surface contamination, but is typically a few percent in the optical for an aluminized surface. If inclined mirrors are employed then it is important that ways of reducing the polarization , e.g. by compensating mirrors, are used.

Herbst: Beyond the obvious factor of fold mirrors, what else would you tell ELT builders to do, in order to keep the polarization situation clean?

Hough: It's basically the same point, keeping all reflections perfectly symmetric with respect to the telescope axis. It would be interesting to measure the polarization of segmented mirror telescopes at sufficiently high sensitivity (about 10^{-6}).

Rouan: Once detection is done the next step is spectroscopy. How is the technique compatible with spectroscopy?

Hough: We would need to use a grism together with a detector array. A linear array of APDs would be compatible with the PEM as presently used. A CCD-type array would require a modulator operating at a lower frequency, for example a ferroelectric liquid crystal, but its not clear if they can achieve the required sensitivities.

Buckley: How achromatic are photoelastic modulators?

Hough: Not at all. It is one disadvantage compared to crystal waveplate and ferroelectric liquid crystal modulators.