THE FUTURE OF PHOTOMETRIC, SPECTROPHOTOMETRIC AND POLARIMETRIC STANDARDIZATION
ASP Conference Series, Vol. 364, 2007
C. Sterken

Low Polarization Standards

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Abstract. There is renewed interest in high sensitivity polarimetry as a means of observing the polarization signal of extra-solar planets. We describe the measurement of low polarized standards at fractional polarizations of parts per million.

1. Introduction

In principle polarimetry is capable of very high sensitivity, even from ground-based telescopes, and solar astronomers have achieved sensitivities of $\sim 5 \times 10^{-6}$ (Stenflo 2003). Kemp et al. (1987) measured the integrated light from the sun, giving an upper limit for the fractional linear polarization of 2×10^{-7}. 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. Renewed interest in high-sensitivity polarimetry has arisen through the goal of detecting the direct light from extra-solar planets, particularly the close-in older planets such as the hot-Jupiters (for a recent review of extra-solar planets see Marcy et al. 2005). For these planets, the light at optical and near-infrared wavelengths is reflected light from the central star and hence will be polarized. For an unresolved system, direct light from the star will considerably reduce the polarization and maximum fractional polarizations of parts per million might be expected, although the amount depends on the planet size, distance from the star and the planet albedo. Instruments attempting to resolve close-in planets, using high-order adaptive optics (e.g. the planned ESO VLT instrument SPHERE), need to use differential imaging to overcome speckle noise and polarimetry, being inherently differential, is one of the techniques being employed. Even in these cases, residual light from the central star will still dilute the planet polarization resulting in fractional polarizations of order a few in 10^5. Polarization standards with very low fractional polarizations are therefore required.

2. Instrument Details

PlanetPol is a new stellar polarimeter (Hough et al. 2006) specifically designed to achieve fractional polarization sensitivities of at least 1 in 10^6. Briefly, the instrument uses photoeleastic modulators (PEM) operating at 20 kHz, triple-wedge Wollaston prisms and avalanche photodiodes, with phase sensitive detectors used to measure the modulated (polarized) signal which for linear polarization is at a frequency twice the PEM frequency. There are two optical beams on the sky, one for the star, which is on the optical axis of the telescope, and a sky beam offset set by 95mm (428 arcsec at the William Herschel Telescope (WHT) where all observations to date have been made). The instrument has to be rotated through 45 degrees in order to measure both linear Stokes parameters There are standard B, V, R and I colour filters, plus two additional filters, $OG590$ and $RG695$ allowing the use of very wide passbands with the long wavelength cut-off defined by the detector response.

3. Calibration of Polarization

Observations reported here were made with the OG590 filter, thus covering the wavelength range from 590 nm to the detector cut off at about 1000 nm. With such a wide band the exact effective passband and effective wavelength will depend on the colour of the object being observed. The polarization efficiency will also vary across the band as the PEM only gives half-wave retardance at one wavelength. Details of calculating the effective bandpass and the polarization efficiency are given in Hough et al. (2006), taking into account the spectral energy distribution (SED) appropriate to the source being observed, modified by an interstellar extinction curve, the Earth's atmospheric transmission curve, and the instrumental response.

The measured degree of polarization is usually calibrated by using an upstream calibrator, such as a Glan prism. This was difficult to accommodate with PlanetPol, as it would have to be placed in the telescope Acquisition & Guidance box as the polarimeter has to be rotated to get both Stokes parameters for linear polarization. Furthermore, the polarization signal is not a linear function of polarization for high degrees of polarization. Instead we used several highly polarized standards from the literature (see Table 1) and these same standards were used to determine the zero of polarization position angle on the sky. By combining the Serkowski wavelength dependence of polarization (Serkowski 1973) with the instrument response model described previously we can predict the polarization that we expect to observe in PlanetPol's broad red band for any polarized standard star.

Once corrected, the differences between predicted and observed polarizations for the standard stars (final column of table 1) have a standard deviation of 0.11%, and this drops to 0.04% if the one most discrepant point (HD 154445 on 2005/5/4) is omitted. In view of the quoted accuracies of the $P_{\max}$ values (typically ∼0.05%) and the fact that there are indications of variability in these standards (Bastien et al. 1988, and these proceedings), the agreement is excellent. The absolute accuracy of measuring polarization, by comparison with all

Table 1. Observations of polarized standard stars.

Star	Date	$P_{\rm obs}$ (%)	$P_{\rm ppol}$	$P_{\rm obs}/P_{\rm ppol}$	$P_{\rm obs}-P_{\rm ppol}$
HD 7927	2004/10/15	2.615±0.001	2.62	0.998	–0.03
HD 43384	2004/10/16	2.438±0.001	2.52	0.967	+0.05
HD 187929	2005/04/26	1.383±0.001	1.45	0.954	+0.05
HD 147084	2005/04/27	3.902±0.012	3.93	0.994	–0.03
HD 198478	2005/04/28	2.158±0.001	2.17	0.994	–0.02
HD 154445	2005/04/29	3.075±0.001	2.89	1.064	–0.23
HD 187929	2005/05/03	1.387±0.001	1.45	0.957	+0.04
HD 154445	2005/05/04	3.086±0.001	2.89	1.067	–0.24
HD 183143	2005/05/06	4.805±0.004	4.98	0.964	+0.10
HD 183143	2005/05/07	4.807±0.015	4.98	0.965	+0.10
HD 198478	2005/05/08	2.067±0.006	2.17	0.953	+0.07
HD 198478	2005/09/10	2.098±0.001	2.17	0.967	+0.04
HD 187929	2005/09/10	1.409±0.001	1.45	0.972	+0.02
Mean				0.986	−0.01
±stddev				±0.039	±0.11

NOTES. $P_{\rm obs}$ is the observed percentage polarization in the broad red band, and $P_{\rm ppol}$ is the predicted polarization for this band. The ratio $P_{\rm obs}/P_{\rm ppol}$ is a measure of the reduction in modulation due to detector frequency response with a mean value of 0.986. The final column gives the difference between observed and predicted polarization after dividing the observations by the 0.986 correction factor. Table taken from Hough et al. (2006) with some modifications.

the polarized standards, is 1.1%. For these highly polarizations, the telescope and instrument polarization is negligible (see below).

Table 2. Polarization of nearby bright stars.

Star	I	Spec. Type	Dist. (pc)	N	$Q/I \times 10^{-6}$	$U/I \times 10^{-6}$
HR 5854	1.54	K2IIIb	22.5	6/6	−2.16±0.98	+3.73±1.07
HR 4534	2.04	A3V	11.1	4/4	+0.64±1.16	+2.14±0.77
HR 4932	2.02	G8III	31.3	6/5	+6.31±1.14	+1.41±1.30
HR 5435	2.87	A7III	26.1	6/6	−2.39±2.15	−1.87±0.90
HR 8974	2.22	K1IV	13.8	6/6	+2.33±2.07	+4.62±2.21
HR 21	1.88	F2IV	16.7	5/5	−0.86±0.86	−0.35±2.53
HR 937	3.40	G0V	10.5	5/5	−0.68±1.68	+10.84±1.41
HR 617	0.88	K2III	20.0	4/4	−0.37±4.00	−5.48±3.53

NOTES. Q/I & U/I are in equatorial coordinates. N is the number of observations of Q/I and U/I respectively. The first 4 stars were observed between 2005 April 25–30 and the last four stars between 2004 October 15–16 and October 20. Table from Hough et al. (2006).

4. Telescope and Instrument Polarization

A major problem in measuring very low fractional polarizations is the polarization produced by the telescope and instrument. The telescope polarization (TP)

was measured by observing a number of nearby stars (typically within 25 pc) as a function of parallactic angle with the telescope de-rotator enabled. In the absence of any interstellar or intrinsic polarization the measured polarization should produce a sinusoidal curve in Stokes Q/I and in U/I with an amplitude equal to the TP, phase shifted by 45 degrees (see Fig. 1). Where there is significant interstellar or intrinsic stellar polarization we use a least squares fit, following a Gauss-Newton minimization approach, to efficiently search the parameter space in an iterative manner to determine the TP and the polarization associated with each star (see Hough et al. 2006). The instrument polarization (IP) is measured by observing the same low polarization stars at instrument rotation angles of 0 and 90 degrees or 45 and -45 degrees. This measures Stokes Q and $-Q$ or U and $-U$, respectively, so the results should change sign. The sum of such a pair of readings (after correcting for any slight change in TP between the readings) is equal to $2IP$.

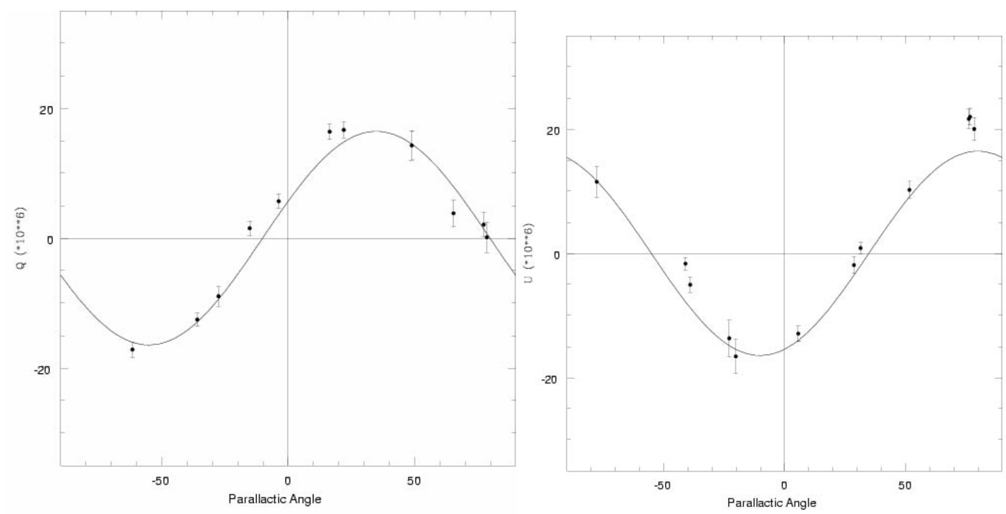

Figure 1. The measured Q and U polarizations as a function of parallactic angle for stars with very small interstellar and/or intrinsic polarization. Note the 45 degree phase shift. Source: Hough et al. (2006).

A typical fit to the measured polarization of nearby stars, as a function of parallactic angle, gives a TP of $P = (16.4 \pm 0.3) \times 10^{-6}$ and this appears to be constant during an observing run but can vary between runs, especially after the telescope mirrors have been re-aluminized. The instrument itself has a polarization that is typically between 2–6$\times10^{-6}$, with the changes between observing runs most likely caused by the slightly different mounting of the instrument on the telescope.

5. Polarization of Nearby Stars

Results for a number of nearby stars are given in Table 2 (a later paper will present polarimetry of a much larger number of stars, out to distances of 100 pc). The fractional polarizations are very low, typically a few $\times10^{-6}$. Of course these observations cover only a relatively short period of time (2004 October to 2005 April) and hence longer term variability cannot be ruled out. This could arise from intrinsic polarization or from changes in the interstellar polarization produced by changes in the column density of dust along the line of sight to the star.

6. Conclusions

PlanetPol, a new high-sensitivity polarimeter, has been used to measure the polarization of a number of nearby stars. The very low on-axis polarization of the WHT of $\sim 2 \times 10^{-5}$, and an instrument polarization an order of magnitude smaller, has made it possible to measure fractional polarizations of a few parts in a million. The low polarization of these nearby stars makes them well suited to detecting the polarization signature of unresolved extra-solar planets.

References

Bastien, P., Drissen, L., Menard, F., et al. 1988, AJ, 95, 900
Hough, J. H., Lucas, P. W., Bailey, J. A., et al. 2006, PASP, in press
Kemp J. C., Henson G. D., Steiner C. T., & Powell, E. R. 1987, Nature 326, 270
Marcy, G., Butler, R. P., Fischer, D., et al. 2005,Progress of Theoretical Physics, Supplement, 158,24
Serkowski, K. 1973, Interstellar Polarization, in Greenberg, J.M. & Christoffel, H. (eds) Interstellar Dust and related Topics, IAU Symp, 52, (Reidel, Dordrecht), p. 145
Stenflo, J. O. 2003, in Proceedings of SPIE Vol.4843 Polarimetry in Astronomy, ed. S. Fineschi, (SPIE, Bellingham, WA, 2003), p. 76

Discussion

Kidger: I think that we have some – quite a lot possibly – empirical evidence that you are right saying that the dust layer is very thin. Measuring the extincion regularly in Teide, it is striking how often nights have started with thick dust but, by the end of the night, it is totally clear, although below the observatory level the cloud remains thickly present. This tends to happen on stable nights with no wind to stir the dust up.

Hough: This is extremely useful to us. Thank you for the information.

Bastien: What is the level of polarization that you measured from Saharan dust?

Hough: We got a fractional polarization of 40×10^{-6} at a zenith distance of $\sim 40^\circ$ when the dust reduces transmission at the zenith by $\sim 25\%$ in the red.