Polarization of terrestrial planets and the ZIMPOL technique

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Introduction

Light reflected from planets is polarized. This basic property of planets provides the possibility for detecting and characterizing extra-solar planets using imaging polarimetry. The scattering polarization of planets depends on the scattering angle and is therefore locked to the orbital motion as illustrated in Fig. 1. Moreover, the polarization has significant diagnostic potential as it depends strongly on the surface properties.

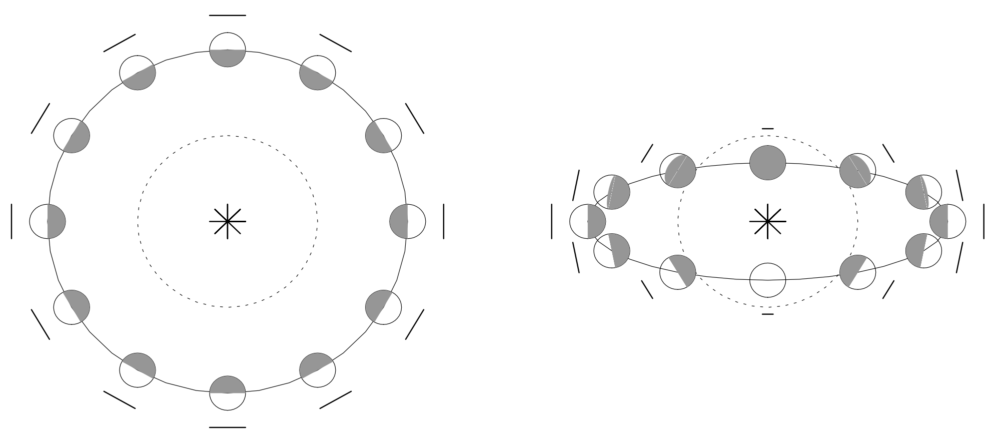

Fig.1. Schematic illustration of the irradiation and the expected scattering polarization (Rayleigh scattering) from an extra-solar planet for a low (left) and high (right) inclination system. The position of the parent star is indicated by an asterisk. For small apparent separations (dotted circle) the planet is too close to the star to be detectable. The bars indicate strength and direction of polarization which is particularly high for scattering angles of 90^o.

Polarimetry is a differential imaging technique which has reached a very high sophistication, so that polarimetric measurement may become a powerful tool for the future investigation of extra-solar planets.

The science case

The expected polarization differs strongly between different types of planets. This can be illustrated with the polarization characteristics of solar system objects. In Fig. 2 we have plotted for various solar system planets and moons the visual geometric albedo versus the integrated V-band disk polarization p(90) for a scattering angle of 90^o.

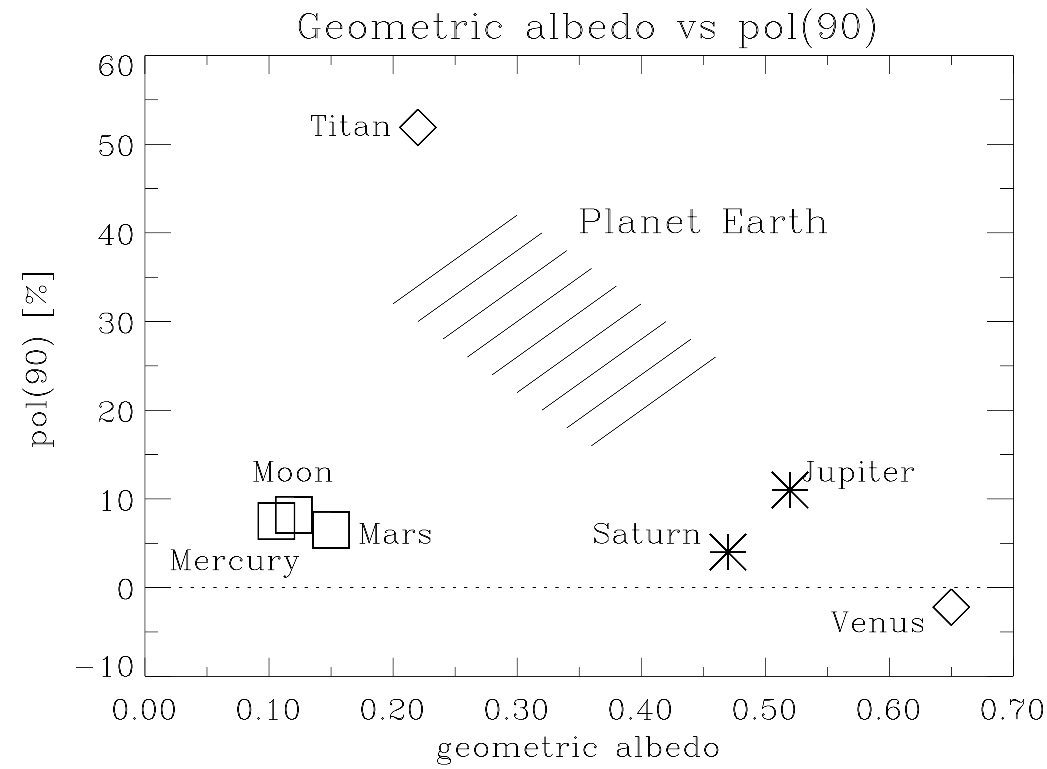

Fig. 2. Albedo and polarization p(90) for solar system objects.
Refs. albedos: Allen's Astrophysical. Quantities
Refs. p(90): Mercury (Dollfus & Auriere 1974); Venus (Dollfus & Coffeen 1970); Moon (Coyne & Pellicori 1970); Mars (Dollfus et al. 1983); Titan (Tomasko & Smith 1982); Jupiter (Smith & Tomasko 1984); Saturn (Tomasko & Doose 1984); Earth (see below)

In atmosphere-free bodies, or planets with very thin atmospheres, like Mercury, Mars, or the Moon, the light is reflected from the rocky/sandy surface. The albedo for these objects is low and the polarization is about p(90)~10%. The polarization is near zero if the light is scattered predominantly from high clouds as in Venus. Contrary to this, p(90) is very high >20% for atmospheres with optically thick Rayleigh scattering layers above the cloud tops or above the surface. Saturn's moon Titan is a good example of a high polarization object. Also planet Earth produces a high scattering polarization and lies in the above diagram in a region between Titan and the cloudy planets Venus, Saturn and Jupiter.

Planet Earth. The polarization of planet Earth depends on the cloud coverage together with the exposed areas of oceans, forests, deserts and snow fields. The contribution of each surface type is a combination of Rayleigh scattering above the surface and the reflection at the surface. The integrated effect for a pale blue dot Earth depends on the reflectance and degree of polarization of these components, which clearly depend on wavelength and scattering (or phase) angle, as well as a cloud cover. The degree of polarization, p(90), is particularly strong in the blue due to Rayleigh scattering in the clear atmosphere. For a pale blue dot Earth at 443nm and 90 degree scattering angle p(90) is 23% for average cloud cover (55%), and up to

40% for (hypothetical) 10% cloud cover. These values are calculated using polarization observations of Earth made from the Polder satellite (Wolstencroft & Breon, 2004).

Ground based observations of polarization indicate that "features" in the polarization may be seen in a pale blue dot Earth associated either with the vegetation red edge near 700nm or at the rainbow angle at 140o scattering angle (water clouds). The huge variety of potential polarimetric properties of model Earth-like planets suggests that polarimetry may play an important role in the future characterization of 'habitable' planets.

The ZIMPOL technique

A very high polarimetric precision, as required for the extra-solar planet detection, can be achieved with the ZIMPOL technique. ZIMPOL (Zurich Imaging Polarimeter) is an instrument principle based on a fast polarization modulator and a special CCD camera performing the on-chip demodulation of the modulated signal (e.g. Povel 1995).
The fast modulator, e.g. a ferroelectric liquid crystal working at a modulation frequency of 1 kHz, and a polarizer convert the polarization signal into a fractional modulation of the intensity signal. This intensity modulation is converted back into a polarization signal by a special ZIMPOL-CCD camera which measures for each active pixel the intensity difference between the modulation states. Every second row of the CCD is masked so that charge packages created in the unmasked row during one half of the modulation cycle are shifted for the second half of the cycle to the next masked row, which is used as temporary buffer storage (the CCD can be equipped with cylindrical micro-lenses which focus the light onto the open CCD rows). After many thousands of modulation periods the CCD is read out within less than 1 second. The sum of the two images is proportional to the intensity while the normalized difference is the polarization degree of one Stokes component.

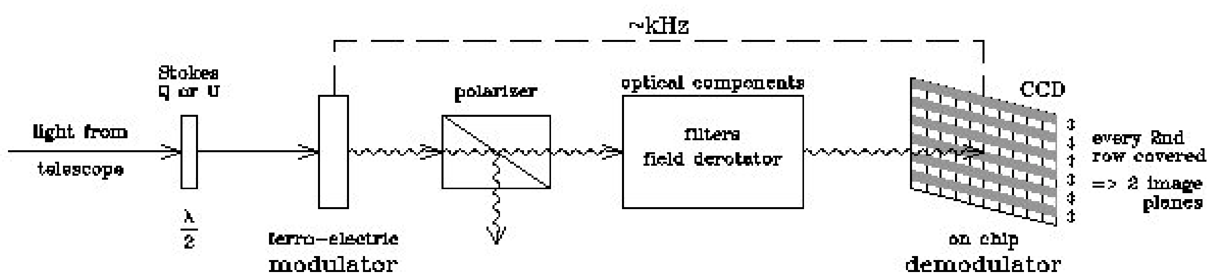

Fig.3. *Basic principle of the ZIMPOL technique. From left to right: half wave plate for choosing between Stokes Q and U, polarization modulator, polarizer, and ZIMPOL CCD. The modulator is synchronized with the CCD demodulator. In CHEOPS/ZIMPOL the second beam from the polarizer (beam splitter) goes to a second camera system.*

Because the measurement is fully differential, systematic error sources are reduced to a very low level. Key advantages of this technique are:

- images for the two opposite polarization modes are recorded practically **simultaneously** (the modulation is faster than e.g. the seeing variations or the telescope jitter),
- both images are recorded with the **same pixel**, so that the two images which are subject to exactly the **same aberrations** introduced by the atmosphere and the telescope/instrument.

ZIMPOL has achieved an accuracy of better than about 10-5 in solar applications (e.g. Stenflo & Keller 1996).

A polarimetric mode similar to ZIMPOL could be included in the coronograph concept of the TPF mission. An off-axis design produces instrument polarization which would, however, not affect the detection of a localized polarization signal. Achromatic polarization modulators may allow observations for a wide bandwidth. ZIMPOL is currently investigated in combination with an extreme adaptive optics system for the CHEOPS project which aims to detect polarimetrically extra-solar (giant) planets with the VLT (e.g. Feldt et al. 2003; Gisler et al. 2004).

References

Coyne G.V., Pellicori S.F., 1970, AJ 75, 54
Dollfus A., Auriere M., 1974, Icarus 23, 465
Dollfus A., Coffeen D.L., 1979, A&A 8, 251
Dollfus A., Deschamps M., Ksanfomaliti L.V., 1983, A&A 123, 225
Feldt M., Turatto M., Schmid H.M. et al., 2003, ESA SP-539 (TPF/Darwin), p. 99
Gisler D., Schmid H.M., Thalmann C., et al., 2004, SPIE 5492 (in press)
Povel H.P., 1995, Optical Eng. 34, 1870
Tomasko M.G., Doose L.R., 1984, Icarus 58, 1
Tomasko M.G., Smith P.H., 1982, Icarus 51, 65
Smith P.H., Tomasko M.G., 1984, Icarus 58, 35
Stenflo J.O., Keller C.U., 1996, Nature 382, 588
Wolstencroft R.D., Breon F.M., 2004, in `Astronomical Polarimetry 2004', Kona, Hawaii, ASP Conf. Proc. (in press)