Astronomical Polarimetry: Current Status and Future Directions
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Polarization in Optical/Infrared Interferometry

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Abstract. The combination of optical/infrared interferometry with polarimetry provides a new tool for stellar astrophysics. We review illustrative applications of this technique, point out some of the technical difficulties, and address the question whether interferometric polarimetry could be used in the future to detect and characterize extrasolar planets.

1. Introduction

Optical/infrared interferometry and polarimetry have historically been viewed widely as "exotic" techniques with limited ranges of application, practiced mostly by specialists. The intersection of both methods has been hardly explored, quite contrary to the situation in the radio regime, where interferometers routinely perform full-Stokes polarimetry. The main reason why optical interferometry and polarimetry appear so incompatible are the many oblique reflections in the beam trains, which induce very large instrumental polarization. Nevertheless there are good reasons, both astrophysical and technical, to expect this situation to change soon. The present paper elaborates on three basic conjectures:

- Interferometric polarimetry holds the promise to develop into a powerful tool that can address many interesting problems in stellar astrophysics.
- For better or worse, the builders of precise interferometric facilities and instruments need to take polarization effects into account, even if they are not interested in polarimetric data as such.
- Precise measurements of interferometric phase differences between polarization states may eventually enable high-contrast applications such as the detection and characterization of extrasolar planets.

2. Interferometric Polarimetry as a Tool for Stellar Astrophysics

Polarimetry usually becomes more interesting with improved angular resolution, because of the reduction of polarization averaging within the point spread function. Interferometric polarimetry therefore allows the observation of a number of effects that are inaccessible to polarimeters on single telescopes. A few illustrative examples are:

- *Magnetic Stars:* When rotating stars with a global magnetic field are observed in circularly polarized light, the center-of-light shifts with wavelength across spectral lines (Rousselet-Perraut et al. 2000). This leads to a phase shift in an interferometer, which is detectable even if the star is only marginally resolved. Modeling such observations gives direct information on the strength, orientation, and geometry of the magnetic field.

- *Early-Type Stars:* Thomson scattering produces linear polarization parallel to the stellar limb. This is a diagnostic tool for the structure of hot star atmospheres (Elias 2004).
- *Stellar Winds and Disks:* Mass-loss from massive stars tends to be highly asymmetric, and the resulting envelopes strongly polarized. Through a combination of interferometric and (single-telescope) polarimetric observations, Quirrenbach et al. (1997) have been able to show that the circumstellar envelopes of Be stars are strongly flattened disks. Mass-losing hot stars are thus very promising targets for detailed studies with interferometric polarimetry (Chesneau et al. 2003).
- *Starspots:* A number of long-baseline interferometers have been designed with the goal in mind to image the surfaces of spotted stars. As Sunspots (and, by inference, starspots) are polarized, interferometric polarimetry will provide additional physical information on starspots and starspot groups (Elias 2004).

3. Instrumental Requirements and Difficulties

The theory of astronomical interferometry is usually developed by treating light as a scalar wave, ignoring all effects of polarization (e.g., Quirrenbach 2001). The usual approach of designing an interferometer is making the reflections in all arms equal, thus minimizing the polarization effects, and then hoping for the best.[1] Unfortunately, "the best" is likely not good enough for the advanced applications of interferometry considered for the near future. Astrometric planet detection requires a precision of 10 micro-arcseconds, which translates into a delay measurement accuracy of 5 nm (Quirrenbach et al. 1998). Clearly, phase shifts between the two polarization states have to be understood on this level. In a nulling interferometer, destructive interference is used to reject the on-axis light from a bright star; this enables the detection of faint objects (planets!) nearby. In an otherwise perfect interferometer, the null depth $\overline{N}$ due to a phase shift $\Delta\phi_{s-p}$ between the s and p polarization states is given by (Serabyn 2000)

$$\overline{N} = \frac{1}{16}\Delta\phi_{s-p}^2 \quad . \tag{1}$$

In this case, the phase shift has not only to be *understood*, but also to be *controlled* precisely. Moreover, conversion of linear into elliptical polarization along the beam train can lead to a loss of coherence and thus damage the null depth severely.

[1] The alternative suggestion – building an interferometer with asymmetric arms and calibrating the ensuing visibility loss (Rousselet-Perraut et al. 1997a) has not been followed in practice.

At present, the detrimental effects of polarization mismatches in existing interferometers have hardly been quantified, because they are difficult to measure (requiring special equipment) and hard to predict (requiring knowledge of differential ageing of coatings, details about misalignments, etc.). The theoretical foundation for a deeper understanding has been laid, however (Elias 2001); a systematic analysis of the VLTI will be performed soon.

Very few attempts have been made so far to perform polarimetric observations with optical interferometers (e.g. the GI2T, Rousselet-Perraut et al. 1997b). Once the instrumental polarization of the VLTI is better understood, polarimetry could be implemented there (Vakili et al. 2002). If future interferometers are built with the possibility of precise polarization measurements in mind (e.g., Tinbergen 2003a, 2003b), one might obtain a further substantial gain in polarimetric precision. If in a future large facility the multi-mirror beam trains used today are replaced by fiber beam transport (e.g., Quirrenbach 2004), the present difficulties with polarization could be largely overcome.

4. Extrasolar Planets

One might thus assume that mastering the polarization issues in nulling and astrometric interferometers will also yield benefits for interferometric polarimetry. Measuring differences between two polarization states with high precision would enable high-contrast observations, perhaps reaching down to the level where extrasolar planets become detectable.

The polarization of the starlight reflected by a planet varies strongly with phase angle, and reaches a maximum near 90°, i.e., when the angular separation from the star is largest. In this favorable case it can reach tens of per cent; measuring the polarization as a function of wavelength has a considerable diagnostic value for the properties of the planetary atmosphere (e.g. Stam et al. 2003). A polarimetric instrument supported by adaptive optics is currently being studied for ESO's Very Large Telescope (CHEOPS, Feldt et al. 2003, see also the contribution by Joos et al. in these proceedings), but it won't be able to resolve the brightest planets, namely the "Hot Jupiters", from their parent stars.

To illustrate the effects that occur in an interferometer, we have used a simple toy model consisting of a "Hot Jupiter" orbiting a Sun-like star in a 0.04 AU orbit at a distance from the Earth of 10 pc. At maximum elongation (90° phase angle), and for an observing wavelength of 0.8 μm, a planet albedo of 0.4 and polarization of 40% are assumed. For simplicity, the declination of the star and the geographical latitude of the interferometer are both taken to be 90°, and a baseline length of 100 m is used. In Figure 1 and 2, we plot the two most important observables, namely the square of the visibility and the phase, for both polarization states during the course of one day.

It is easy to show that at the minima of V^2 the difference in V^2 between the two polarization states is given by

$$V_{\parallel}^2 - V_{\perp}^2 = 4p\beta \quad , \tag{2}$$

where p is the degree of polarization of the light reflected by the planet, and β the contrast (in unpolarized light) between the planet and its host star. Similarly, the maximum phase difference is given by

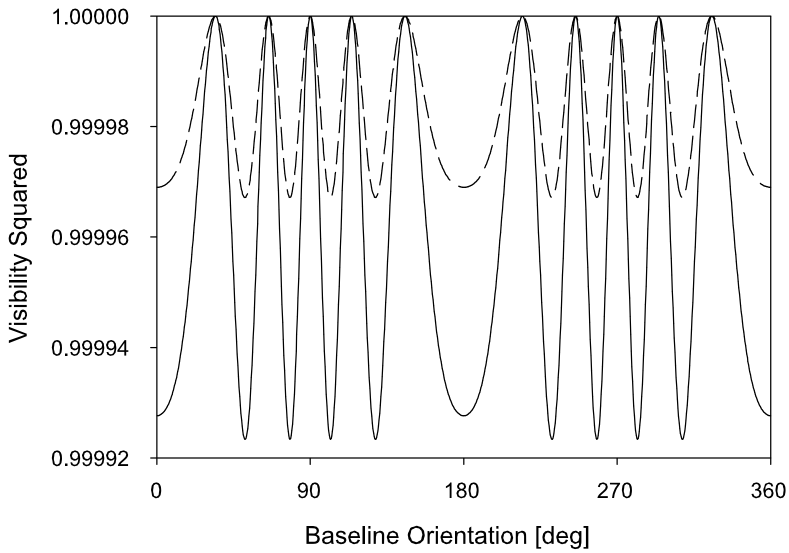

Figure 1. Square of the visibility for the two polarization states (parallel, continuous line; perpendicular, dashed line) on a 100 m baseline for a hypothetical star – planet system. The system consists of a "Hot Jupiter" with an albedo of 0.4 and 40% polarization orbiting a Sun-like star at 0.04 AU. The assumed distance to the system is 10 pc, and the observing wavelength is 0.8 μm. See text for more details.

$$\phi_{\|} - \phi_{\perp} = \pm 2p\beta \quad . \tag{3}$$

These effects are of order 10^{-5}, and can therefore in principle be measured with 10^{10} photons. The main challenge is therefore keeping instrumental effects sufficiently low to enable measurements of the signal. The variations due to Earth rotation (see Figure 1 and 2) have a characteristic signature which facilitates the measurements, but the instrumental polarization must be stable on a time scale of hours. Perhaps one could benefit from measuring closure phases on baseline triangles instead of single-baseline phases. Another idea would be the combination of polarimetry with nulling interferometry: if the star light could be rejected by a factor of 100, the signal in Figure 2 would increase by the same factor. Moving off the null through a slight change of the delay would allow a precise calibration of the instrumental polarization. In any case, the technical challenges are formidable, but our simple example demonstrates that the detection of polarization in the starlight scattered by the atmospheres of "Hot Jupiters" may be possible in the not-too-distant future.

References

Chesneau, O., Wolf, S., & Domiciano de Souza, A. 2003, A&A, 410, 375

Elias, N.M. 2001, ApJ, 549, 647

Elias, N.M. 2004, in SPIE Vol 5432, Polarization: measurement, analysis, and remote sensing VI., ed. D.H. Goldstein & D.B. Chenault, in press

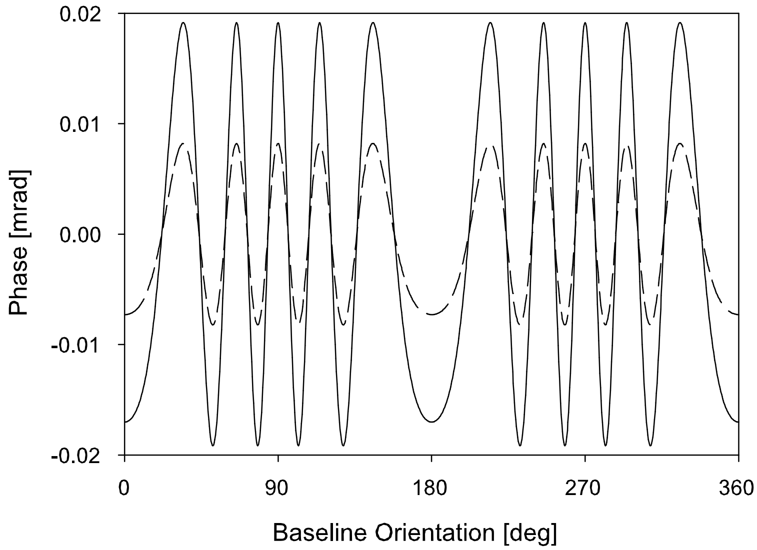

Figure 2. Interferometer phase in milliradians for the same hypothetical star – planet system and observing parameters as in Figure 1.

Feldt, M., Hippler, S., Henning, Th., Gratton, R., Turatto, M., Waters, R., & Quirrenbach, A. 2003, in ASP Conf. Ser. Vol. 294, Scientific frontiers in research on extrasolar planets, ed. D. Deming & S. Seager (San Francisco: ASP), 569

Quirrenbach, A. 2001, ARA&A, 39, 353

Quirrenbach, A. 2004, in SPIE Vol 5382, Second Bäckaskog workshop on extremely large telescopes, ed. A.L. Ardeberg & T. Andersen, 214

Quirrenbach, A., et al. 1997, ApJ, 479, 477

Quirrenbach, A., et al. 1998, in SPIE Vol. 3350, Astronomical interferometry, ed. R.D. Reasenberg, 807

Rousselet-Perraut, K., Chesneau, O., Berio, P., & Vakili, F. 2000, A&A, 354, 595

Rousselet-Perraut, K., Mourard, D., & Vakili, F. 1997a, Opt. Eng., 36, 980

Rousselet-Perraut, K., Vakili, F., Mourard, D., Morand, F., Bonneau, D., & Stee, Ph. 1997b, A&AS, 123, 173

Serabyn, E. 2000, in SPIE Vol. 4006, Interferometry in optical astronomy, ed. P.J. Léna & A. Quirrenbach, 328

Stam, D.M., Hovenier, J., & Waters, R. 2003, In ASP Conf. Ser. Vol. 294, Scientific frontiers in research on extrasolar planets, ed. D. Deming & S. Seager (San Francisco: ASP), 535

Tinbergen, J. 2003a, in SPIE Vol. 4838, Inteferometry for optical astronomy II, ed. W.A. Traub, 523

Tinbergen, J. 2003b, in SPIE Vol. 4843, Polarimetry in astronomy, ed. S. Fineschi, 122

Vakili, F., Chesneau, O., Delplancke, F., Jankov, S., Perraut, K., Stehle, C., & Stenflo, J. 2002, in Proc. of the ESO Workshop, Scientific Drivers for ESO Future VLT/VLTI Instrumentation (European Southern Observatory: Garching), 331