On the Instrumental Polarisation of NAOS–CONICA

Gunther Witzel[1]
Andreas Eckart[1]
Rainer Lenzen[2]
Christian Straubmeier[1]

[1] I. Physikalisches Institut, Universität Köln, Germany
[2] Max-Planck-Institut für Astronomie, Heidelberg, Germany

As expected for a Nasmyth instrument, NAOS–CONICA shows a significant instrumental polarisation that is strongly dependent on the parallactic angle of the source and can reach up to 4 % in the degree of linear polarisation. Detailed modelling of the polarimetric properties of the optical components of NAOS–CONICA using the Stokes/Mueller formalism allows the instrumental polarisation to be corrected with an accuracy of better than 1 % in linear polarisation. In addition we propose an observation strategy that is expected to allow instrumental polarisation effects to be corrected to an accuracy of about 0.1 %.

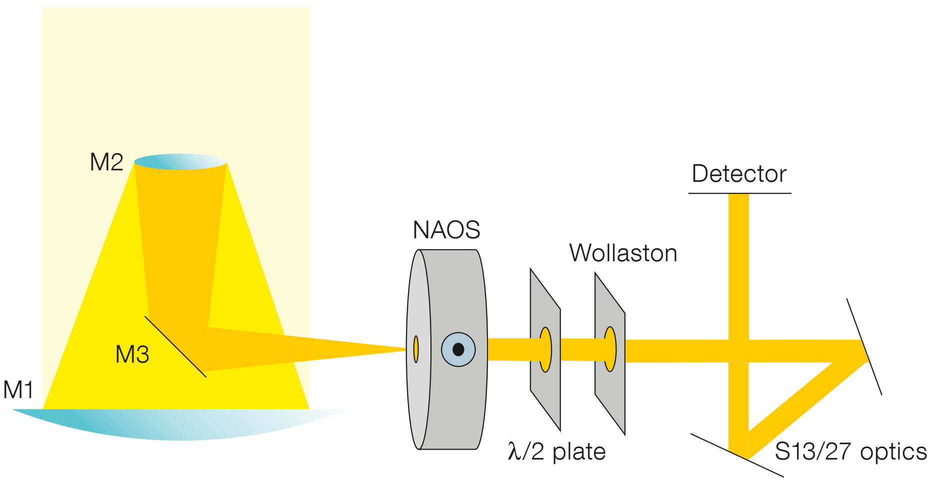
Polarimetric measurements can provide important information on the nature of radiative processes, which completes the picture obtained from total intensity observations. In particular this is the case for the supermassive black hole at the centre of the Milky Way and its associated variable near-infrared source Sagittarius A* (Sgr A*). Here, as for other targets, the interpretation of the polarimetric data depends crucially on the quality of the polarisation calibration and the knowledge of instrumental systematic errors. The majority of polarimetric observations of Sgr A* have been conducted with the near-infrared imager NAOS–CONICA (NACO) at the VLT, and we report here the results of a comprehensive analysis of the instrumental polarisation (IP) of this instrument. Full numerical details can be found in Witzel et al. (2010).

NACO and its polarimetric mode

NACO is the adaptive optics near-infrared imager at VLT Unit Telescope 4 (UT4, Yepun), consisting of the adaptive optics module NAOS and the camera CONICA. This instrument provides a mode for polarimetric differential imaging combining a Wollaston prism and a λ/2 wave plate (a half-wave plate, HWP). The Wollaston prism separates the incoming partially polarised light into two orthogonal, linearly polarised outgoing beams (the ordinary and extra-ordinary beams). The HWP enables the observer to change the angle at which the measurement is conducted without rotating the Wollaston prism with respect to the detector and thus without changing the field of view. Intensity measurements over at least four angles (0°, 45°, 90° and 135°) in two integrations (two orthogonal beams simultaneously) are necessary to obtain information about linear polarisation. Circular polarisation cannot be measured, since the polarimetric mode of NACO does not include a λ/4 wave plate.

After about eight years of successful operation of NACO and plenty of polarimetric observations of the Galactic Centre (GC), Sgr A*, and of many other targets, it now seemed plausible to analyse the polarimetric mode on the basis of public ESO archive data. Long polarimetric light curves of bright sources at the GC have been especially useful in investigating the dependency of the IP on the telescope position, and in determining the accuracy achieved to date and attainable for future observations.

Figure 1. Optical elements of VLT UT4, NAOS and CONICA and their relative orientation are sketched at the moment of the meridian transit.



A model of the instrumental polarisation

To understand the IP of NACO we have developed a model of the instrumental effects within the Stokes/Mueller formalism. The polarisation of the incoming light is mainly affected by reflections at metallic coatings of mirrors within the light path of NACO. Each reflection causes crosstalk between the four Stokes parameters that describe the polarisation state. For unpolarised incoming light this crosstalk generates, for example, linear polarisation orthogonal to the plane of incidence. The magnitude of the crosstalk depends strongly on the angle of incidence: only mirrors with an inclination of > 20° will contribute significantly to the IP. All polarimetric effects of the optical elements and their relative orientation can be described by linear operations on the Stokes vector, the so-called Mueller matrices.

As a Nasmyth focus instrument, NACO shows an instrumental polarisation that depends strongly on the parallactic angle of the observed source. The cause of the variable part of the IP is the folding mirror M3 that is tilted at 45° (see Figure 1). While NACO itself is de-rotated with respect to the source, the orientation of M3 and, therefore, also the orientation of its IP with respect to the polarisation of the observed source, changes with the parallactic angle. As shown in Figure 1, other mirrors within NAOS and CONICA

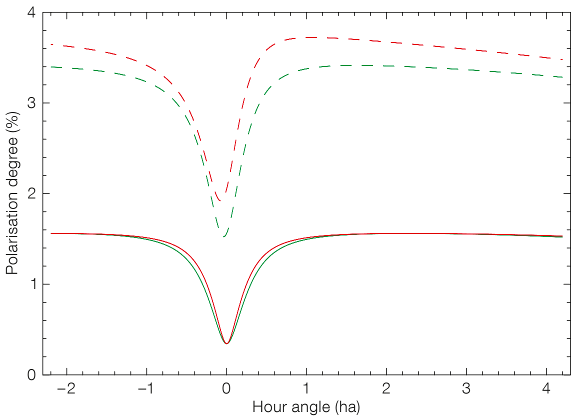


Figure 2. The polarisation degree of the instrumental polarisation as predicted by the model is shown as a function of hour angle. Linear polarisation (in green) and total polarisation (including the circular polarisation, in red) are shown for an unpolarised source with (dashed line) and without (solid line) the systematic effects of the analyser and flat-fielding.

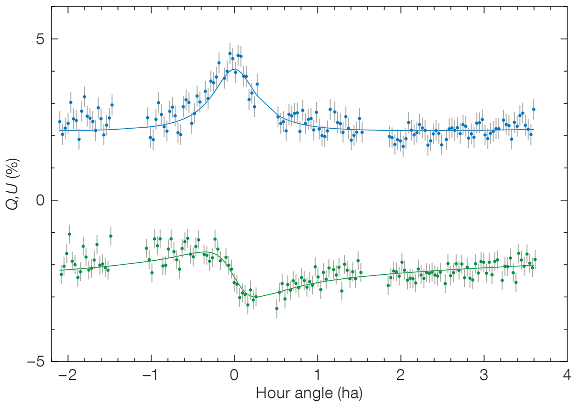


Figure 3. Stokes *Q* (in blue) and *U* (in green) parameters as a function of hour angle for IRS16C (linear polarisation 4.6 % at PA18°, m_k = 9.55). The solid line is the best χ^2-fit of the model and the points represent observations from 2009. The fitting confirms the time dependency of the instrumental polarisation as predicted by the model and additionally allows the apparent polarisation of this star to be determined.

contribute as well. Since these mirrors are part of the de-rotated instrument their contribution is, however, constant.

An important effect is caused by the HWP. A maintenance inspection revealed that the actual reference system for the HWP position angle is turned by –6.6 +/– 0.2° with respect to the reference assumed in the NACO manual. This results in an angle offset of –13.2° for measurements of the polarisation angle that has to be compensated for.

A simulation of the polarisation degree of the IP as a function of hour angle (for a source at the position of Sgr A*) is shown in Figure 2. The maximum instrumental polarisation is about 4 % (all effects, including the optical elements of CONICA) and drops significantly at the time of meridian transit. A comparison of our model with the observed time series of the Stokes parameters of bright sources at the GC and with standard star observations confirms the model (see Figure 3). The polarisation of standard stars can be calibrated with an accuracy of better than ~ 0.5 % for the *Q* and *U* Stokes parameters.

To our knowledge our results for the IRS16 stars at the GC are the first polarimetric measurements of sources within the central parsec of the GC, since Knacke & Capps (1977), that are independently calibrated using a method that goes beyond “boot-strapping” procedures. An example is shown in Figure 3. The accuracy for sources of this brightness (m_k > 9.5 mag) is better than ~ 1 % in linear polarisation and better than ~ 5° in polarisation angle for polarisation degrees higher than ~ 4 %.

A strategy for high precision polarimetry

The remaining systematic uncertainties of about 1 % in linear polarisation result from insufficient knowledge of the characteristics of the Wollaston prism (such as the relative transmission of the orthogonal channels) and the effects of the flat-field calibration (the calibration light for the flat field is potentially polarised intrinsically up to 1 %). A common calibration method to circumvent problems like this is “channel-switching”. In this method, at four additional angles — with a 90°-offset with respect to the above-mentioned four angles — intensities are measured. With this additional information Stokes parameters that are corrected for parts of the IP can be calculated. In particular, the effects of the Wollaston and the flat-fielding can be compensated for by this strategy.

Unfortunately this calibration is not suitable to correct all instrumental effects. In particular, the effects of reflections at metallic surfaces cannot be eliminated completely and reference offsets as caused by the HWP remain uncompensated. But we can show that this method is very useful if: 1) the HWP offset is already compensated for during observation; 2) the HWP is used to switch between the 0°/90° and 45°/135° angle pairs (respectively between their corresponding orthogonal pairs); and 3) NACO as a whole is rotated to switch by 90° for the measurement of the additional four angles. With this strategy the number of parameters of our model can be reduced to three, mainly describing the variable part of the IP that is known with an accuracy of about 0.1 % (see Figure 3). A disadvantage is the alteration of the field of view that results from a rotation of NACO as a whole as compared to the full field.

Polarised emission of Sgr A*

Figure 4 shows the derived total and polarised flux, linear polarisation and polarisation position angle for Sgr A* measured with NACO in June 2006. As a result of our analysis we can show that the common boot-strapping calibration of time series of Sgr A* on the basis of the average foreground polarisation as determined by Knacke & Capps (1977) is in good agreement with our new calibration. The main reason is that the statistical errors of the photometry dominate the described instrumental effects for short integrations of faint sources like Sgr A*. Only at the lowest states of polarisation do both methods deviate significantly in polarisation angle, an effect that can

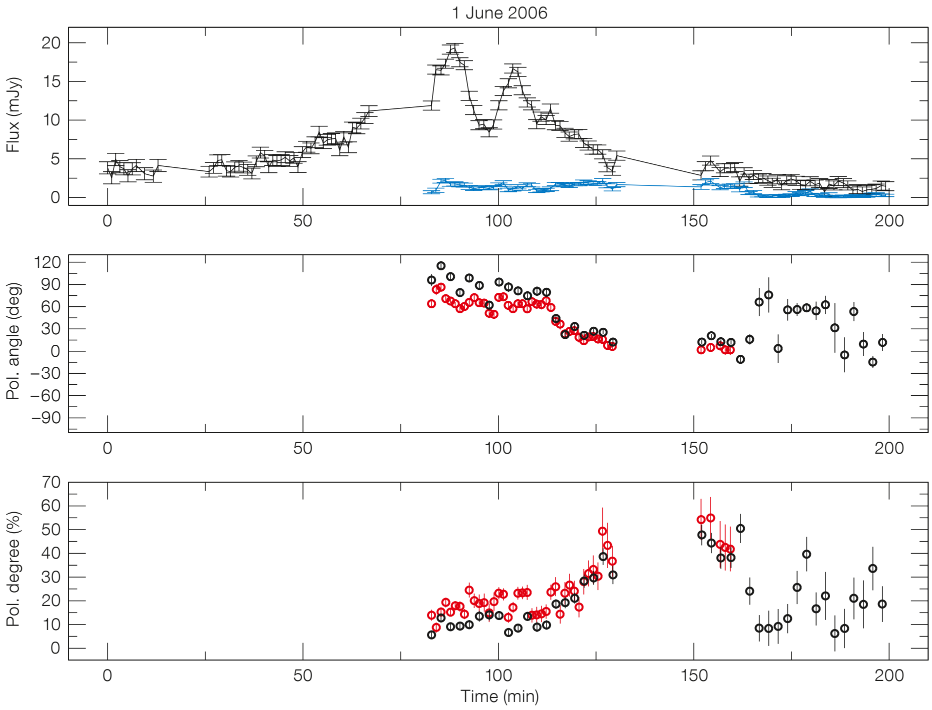


Figure 4. Light curve of Sgr A* observed with NACO in June 2006. Upper panel: total flux (black) and polarised flux (blue); middle panel: polarisation position angle; lower panel: linear polarisation. For the polarimetric parameters, the results of both calibration methods are shown: boot-strapping (red points) and the model described here (black points).

be explained by the interplay of the HWP offset and the boot-strapping method that cannot correct for it. In these polarisation states a reliable estimation of the polarisation angle is impossible anyway, and we can conclude that for Sgr A* in its bright flare phases the boot-strapping calibration yields the same results within the statistical uncertainties as a calibration with our more elaborate polarisation model. Only these bright phases have been interpreted in the framework of the relativistic modelling (Zamaninasab et al., 2010; Eckart et al., 2006; Meyer et al., 2006) that highlights the influence of strong gravity in the vicinity of the $4 \times 10^6 M_\odot$ supermassive black hole at the centre of the Milky Way.

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Image of NACO at the Nasmyth focus of VLT UT4 (Yepun). NACO consists of the adaptive optics module NAOS mated with the near-infrared imager and spectrograph CONICA.