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Direct Imaging of Extrasolar Planets by Means of Polarimetry with SPHERE/ZIMPOL

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Abstract. Direct imaging of extrasolar planets is one of the most exciting but also challenging topics in modern astrophysics. Up to now, more than 300 extrasolar planets have been detected by indirect methods, mostly by radial velocity measurements. A step further is the direct imaging of extrasolar planets, which is extremely demanding due to the huge contrast and the tiny separation between star and planet. There are different approaches to reach the goal. One amongst is imaging polarimetry. We will report on the polarimetric mode of SPHERE, an ESO VLT second generation instrument. We will emphasize the special technique used to reduce the noise to reach the extremely high polarimetric precision.

1. Introduction – SPHERE

In 2001 ESO made a call for VLT second generation instruments. Two competing consortia formed with the goal to build instruments capable to directly image extrasolar planets. In 2005 ESO merged the two consortia with the purpose to benefit from the advantages of both teams. The new project – SPHERE (Spectro-Polarimetric High-contrast Exoplanet REsearch) – is now, in summer 2008, close to its final design review. First light is planned early 2011.

SPHERE will be attached at the Nasmyth platform of a VLT unit. The instrument will be operated with a diffraction limited resolution (15 – 30 mas). An extreme adaptive optics (AO) will be operating, called SAXO (Sphere Adap-

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tive optics for eXoplanet Observations). SAXO is based on a Shack-Hartmann wavefront sensor and on a 41×41 actuator deformable mirror providing a Strehl ratio of 90% in the H-band. In addition, different stellar coronagraphs can be inserted to further reduce the intensity of the bright star.

Among the three focal plane instruments there is ZIMPOL (Zurich IMaging POLarimeter). ZIMPOL will search and analyze the reflected, and thus polarized, light from older planets around nearby stars. Its spectral working range is from 600 to 900 nm. The two other instruments provide differential imaging (IRDIS) and integral field spectroscopy (IFS) in the near-infrared from about 1 to 2 μm.

ZIMPOL is one of the most sensitive imaging polarimeters. Its high polarimetric precision of 10^{-5} per image element or even better can only be reached with a sophisticated, multiple-stage differential technique.

In the next section the measuring principles of ZIMPOL will be described in detail.

2. ZIMPOL

ZIMPOL is a high-precision imaging polarimeter developed at the Institute of Astronomy at the ETH Zürich (Povel et al. 1994). ZIMPOL/SPHERE is based on a fast modulation technique using ferro-electric liquid crystals (FLC) and on-chip demodulation with a special charge transfer CCD.

Reaching a high polarimetric precision requires the reduction of the noise to a sufficiently low level. This is reached by a multiple-stage differential technique. The first step is the temporal and spatial separation of the two orthogonal polarization directions. This is done faster than seeing variations. The second step aims to reduce fixed pattern noise caused by the demodulation on the CCD. In addition the instrumental polarization offset must be kept low because ZIMPOL reaches its high precision only for polarimetric signals which are well below 1%. This means that the instrumental polarization must be compensated *during* the measurements and not only when reducing the data. As a last differential step, noise signals which are not locked to the sky field (mostly instrumental effects) are reduced by a rotational differential technique.

2.1. ZIMPOL Modulation/Demodulation Principle

The key devices within ZIMPOL/SPHERE are the FLC (modulator), the polarizing beam-splitter (analyzer) and the bi-directional charge transfer CCD (demodulator). In Fig. 1 the principle of modulation/demodulation is explained graphically. The two orthogonal polarization directions (depicted with solid and dashed arrows) are flipped back and forth at the modulation frequency ($\approx$ 1 kHz), i.e. the FLC acts like a half-wave plate which can rotate its optical axis by 45° very quickly. At position 0° the vertical and horizontal polarization directions pass the FLC without change, whereas at position 45° the polarization directions are rotated by 90°. The polarizer separates the vertical and horizontal polarization directions. The originally (in front of the FLC) vertical and horizontal polarization directions fall alternatingly onto the detector. There, the two polarization directions must be separated. This is achieved by occulting every second pixel row by an opaque stripe mask and shifting the accumulated charges of the CCD back and forth (perpendicular to the stripe mask) synchronized with the modulation frequency. Cylindrical microlenses are fixed above the CCD collecting the light into the open rows for preventing stray-light and for not loosing half of the light due to the stripe mask.

An identical second detector is used to not loose the light deflected by the polarizing beam-splitter. After thousands of modulation cycles the CCDs are read out in about one second.

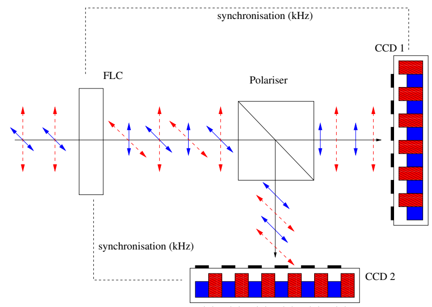

Figure 1. Measuring principle of ZIMPOL. The vertically polarized light passes the FLC where it is modulated into a time dependent polarization signal. The polarizing beam-splitter separates the two polarization directions into two time dependent intensity signals. The demodulation with the two CCDs is synchronized with the FLC.

2.2. ZIMPOL Double-phase Mode

The modulation/demodulation technique has unique advantages like the detection of both polarization directions with the same pixels and faster than seeing variations. But there is also noise connected to the special ZIMPOL CCD technique, especially stray light and charge transfer inefficiency leading to a fixed pattern noise (Gisler et al. 2004). To minimize this noise a second differential technique called double-phase mode has been applied. The sign and amplitude of the detected polarization signals depend on the freely adjustable phase between modulation and demodulation. Between two consecutive exposures, the phase is shifted by half a period (π), which means that the polarization component previously buffered in the odd rows is now stored in the even rows and vice versa. During the first phase the two sub-frames $i_\parallel^0$ and $i_\perp^0$ are recorded and during the second phase $i_\parallel^\pi$ and $i_\perp^\pi$. The following combination of the sub-frames adds up the polarization signal in a constructive way whereas the noise is cancelled.

$$
\begin{aligned}
Q^0 &= i_\parallel^0 - i_\perp^0, \qquad Q^\pi = i_\parallel^\pi - i_\perp^\pi \\
Q &= \frac{1}{2}\left(Q^0 - Q^\pi\right) = \frac{1}{2}\left(i_\parallel^0 - i_\perp^0 - i_\parallel^\pi + i_\perp^\pi\right) \qquad (1)\\
I &= \frac{1}{2}\left(i_\parallel^0 + i_\perp^0 + i_\parallel^\pi + i_\perp^\pi\right)
\end{aligned}
$$

The fixed pattern noise is not locked to the demodulation phase and therefore does not change sign, whereas the polarization signals do change sign. Thus, with Equation (1) most of the fixed pattern noise can be eliminated.

2.3. Telescope/Instrumental Polarization

SPHERE is a Nasmyth instrument equipped with adaptive optics and stellar coronagraphy. Thus, strong telescope (Nasmyth mirror M3) and instrumental (de-rotator, oblique reflections, ...) polarization is induced. The instrumental polarization is not stable in time nor in wavelength. To eliminate the telescope/instrumental polarization several steps are foreseen:

Telescope polarization Due to the 45° reflection on the Nasmyth folding mirror M3 strong polarization is induced (∼5% at 800 nm). The induced polarization changes relative to the analyzing system dependent on zenith distance. To temporally stabilize the M3 polarization a rotatable achromatic half-wave plate (HWP1) is introduced after M3. HWP1 rotates with half the angular speed of the telescope zenith distance and thus keeps the polarization induced by M3 in a zenith independent orientation parallel to the Nasmyth platform. To compensate this temporally stable but spectrally dependent polarization a folding mirror (M4) with preferably identical surface properties as M3 is introduced after HWP1, compensating the polarization due to M3.

Instrumental polarization Since SPHERE is not attached to the adapter rotator a de-rotating system is needed. A three mirror system is placed early in the beam producing several percent of polarization. This instrumental polarization but also the induced polarization due to the other (sparse) inclined mirrors are compensated by a rotatable and tiltable dielectric plate in front of ZIMPOL. The plate deflects one polarization direction more than the other one (depending on the tilt angle). By rotating the plate the desired instrumental polarization can be compensated. It is very important to keep the polarization offset well below 1% before entering ZIMPOL, since the high precision of ZIMPOL is only possible for low polarization. The solution with the dielectric plate as compensator ensures that the background polarization is well below one percent.

An additional rotatable half-wave plate (HWP2) after M4 is used to apply a third differential technique (among other functions). Rotating HWP2 by 45° between two series of observations changes the sign of the incoming linear polarization but leaves the instrumentally induced polarization after HWP2 constant. Computing the difference in polarization between the two series cancels out the remaining instrumental (also field dependent) polarization and adds up the polarization signal on the sky. In Fig. 2 (left) an example is schematically shown with a sky polarization of 3% and an instrumental polarization of 1%.

The compensation of instrumental polarization by using the HWP2 flip has no additional disadvantages, since HWP2 is needed anyway, e.g. to select the polarization direction on the sky.

Differential angular averaging Polarized noise connected to the instrument but not locked to the sky field can be suppressed by an additional differential technique. This last differential technique benefits from different rotational behavior of localized noise fixed to the sky field on the one hand and fixed to the "instrument field" on the other hand. Applying a field de-rotation with the three mirror system ensures the sky signals to be fixed at the detector plane whereas the instrumental effects introduced after the de-rotator will be smeared out when adding up many exposures. This can also be handled vice-versa by not

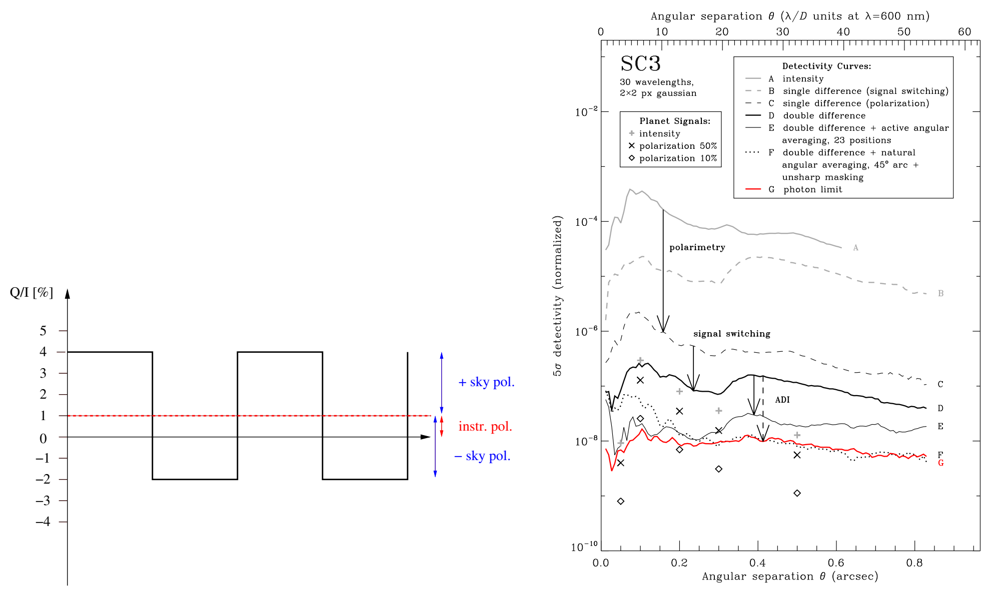

Figure 2. **Left:** HWP2 flip method: the sky polarization of 3% changes sign when HWP2 is rotated by 45° whereas the instrumental polarization of 1% remains stable. The amplitude is the sky polarization and the mean value is the instrumental polarization. **Right:** A simulated overview of the effects of different differential techniques. The 5-σ detectivity is plotted versus the separation of star and planet for several differential techniques. More on this can be found in Thalmann et al. (2008).

de-rotating the sky field with the three mirror system. This will lead to always different positions at the detector plane of the signals on the sky and stable positions of the instrumental effects. The single images are then de-rotated by means of software and added up. The effect is even better since a kind of dithering is applied.

Fig. 2 (right) shows the 5-σ detectivity as a function of separation between planet and star for the different differential techniques (Thalmann et al. 2008). One can see that applying all proposed differential techniques brings the system sensitivity close to the noise level, i.e. higher sensitivity can only be reached by increasing the number of captured photons.

References

Gisler, D., et al. 2004, SPIE, 5492, 463G
Povel, H. P., Keller, C. U. & Yadigaroglu, I. A. 1994, Appl. Opt. 33, 4254
Thalmann, C., et al. 2008, SPIE, 7014, 70143F