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Polarimetry of Gas Planets

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<tr>
<td>ADC</td>
<td>Atmospheric Dispersion Compensator</td>
</tr>
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<td>AO</td>
<td>Adaptive Optics</td>
</tr>
<tr>
<td>BS</td>
<td>Beamsplitter</td>
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<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
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<td>CHEOPS</td>
<td>Characterizing Extrasolar planets by Opto-infrared Polarimetry and Spectroscopy</td>
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<td>CP</td>
<td>Common Path</td>
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<tr>
<td>DM</td>
<td>Deformable Mirror</td>
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<tr>
<td>ETH</td>
<td>Eidgenössische Technische Hochschule</td>
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<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
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<tr>
<td>FLC</td>
<td>Ferro-electric Liquid Crystal</td>
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<tr>
<td>FOV</td>
<td>Field of View</td>
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<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
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<tr>
<td>HWP</td>
<td>half-wave plate</td>
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<td>HWPz</td>
<td>half-wave plate in front of ZIMPOL</td>
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<tr>
<td>IFS</td>
<td>Integral Field Spectrograph</td>
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<td>IRDIS</td>
<td>Infrared Dual-beam Imager and Spectrograph</td>
</tr>
<tr>
<td>LAOG</td>
<td>Laboratoire d’Astrophysique de Grenoble</td>
</tr>
<tr>
<td>M1, M2, M3, M4</td>
<td>Mirror one, two, three, four</td>
</tr>
<tr>
<td>mas</td>
<td>milliarcsecond</td>
</tr>
<tr>
<td>MPIA</td>
<td>Max-Plack Institute of Astronomy</td>
</tr>
<tr>
<td>NACO</td>
<td>NAOS-CONICA</td>
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<tr>
<td>NIR</td>
<td>Near Infrared</td>
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<tr>
<td>nm</td>
<td>nanometer</td>
</tr>
<tr>
<td>PF</td>
<td>Planet-Finder</td>
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<tr>
<td>PSF</td>
<td>Point Spread Function</td>
</tr>
<tr>
<td>SAXO</td>
<td>SPHERE Adaptive Optics for Exoplanet Observation</td>
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<tr>
<td>SDI</td>
<td>Simultaneous Differential Imaging</td>
</tr>
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<td>SPHERE</td>
<td>Spectro-Polarimetric High-contrast Exoplanet Research</td>
</tr>
<tr>
<td>TTM</td>
<td>Tip-Tilt Mirror</td>
</tr>
<tr>
<td>VLT</td>
<td>Very Large Telescope</td>
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<tr>
<td>WFS</td>
<td>Wave Front Sensor</td>
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<tr>
<td>XAO</td>
<td>eXtreme Adaptive Optics</td>
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<td>ZIMPOL</td>
<td>Zurich Imaging Polarimeter</td>
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Abstract

The quest for new worlds was not only an adventure at the times of Columbus. Also nowadays mankind searches for new, undiscovered territories. But today they lie no longer only on our Earth, but also well outside the solar system. There, new planets are sought and found.

One of the challenges of modern astrophysics is the direct detection of extra-solar planets. To reach this goal, the largest available telescopes and most sophisticated detection techniques are required.

A promising method to "see" and analyse extra-solar planets is based on the fact, that light reflected by a planet can be polarised. For its detection, accurate polarisation measurements are needed. This is one of the methods ESO intends to make use of to find new planets outside the solar system. The Institute of Astronomy of ETH Zürich contributes ZIMPOL to this planet-finder project. ZIMPOL is a very sensitive imaging polarimeter.

This thesis is situated within the ESO-planet-finder project. It deals with two problems that are crucial for a successful mission: (1) Instrumental polarisation can seriously hamper the performance of the instrument. It is therefore essential, to keep instrumental polarisation very low. (2) A knowledge of the polarisation properties of our targets would be very helpful. For this reason the polarisation properties of our solar system planets are investigated.

Promising candidates for a detection with ZIMPOL are large planets with atmospheres similar to those of our giant gas planets Jupiter, Saturn, Uranus and Neptune.

In the first part of the thesis the planet-finder project is presented and the role of ZIMPOL is explained. To obtain the instrumental polarisation, the polarimetric properties of mirrors and other optical components of our planet-finder instrument are analysed.

The instrumental polarisation for the wavelength range of 600 to 1000 nm and for all zenith distances is calculated with Mueller matrices. Methods for reducing the instrumental polarisation are proposed and checked by the renewed application of the Mueller calculus. The correction of the instrumental polarisation is divided into two parts. First, a combination of a rotating half-wave plate and a plane mirror compensate the polarisation introduced by the Nasmyth mirror. Secondly, a rotatable and tiltable glass plate compensates the residual polarisation introduced by oblique reflections on mirrors after the Nasmyth mirror.

Further, possible aging effects of the mirrors are considered and consequences for the polarisation are highlighted. An error budget for non perfect retardation of the half-wave plate is also regarded, and the effects for the polarisation are calculated.

In the second part spectropolarimetric measurements of the four gas planets Jupiter,
Saturn, Uranus and Neptune for the wavelength range from 530 to 930 nm are presented.

Our measurements of Uranus and Neptune are the first of their kind. For Uranus and Neptune a second-order scattering effect, leading to limb polarisation, has been measured. This effect is expected in atmospheres of Rayleigh scattering type and allows conclusions on the properties of the scatterers and the stratification inside the atmosphere. The limb polarisation reaches a maximum of more than 3% on Uranus.

Spectropolarimetric plots for selected regions on Uranus and polarimetric profiles parallel to the spectrographic slits are presented. An enhanced polarisation in the methane absorption bands is detected. For both planets the limb polarisation decreases with wavelength.

For Jupiter and Saturn profiles parallel to the slits and polarimetric spectra for some selected regions such as the poles of Jupiter or the ring system of Saturn are presented. The poles of Jupiter exhibit a large polarisation (up to 10%) perpendicular to the limb. In the methane absorption bands at the Jovian poles the polarisation is enhanced compared to the adjacent higher albedo regions. The polarisation decreases from short wavelengths towards longer wavelengths.

Disc resolved spectropolarimetry of Saturn has not yet been published in the literature. Therefore, the spectropolarimetric data of Saturn presented in this thesis are the first of their kind. The polarised profiles for Saturn show an enhanced limb polarisation at the South Pole perpendicular to the limb and a small negative polarisation for the ring system (parallel to the scattering plane). In addition, we observe, an enhanced polarisation at northern mid-latitudes.

An appendix is added that contains numerous spectropolarimetric plots and all profiles of the four planets. The main body of the text only contains a small selection of these data.
Zusammenfassung

Die Suche nach fremden Welten war nicht nur zu Zeiten des Columbus ein Abenteuer. Auch in der heutigen Zeit wird nach neuen, unerforschten Welten gesucht. Dabei beschränkt man sich nicht ausschliesslich auf Teile der Erde, sondern man ist heute daran, andere Planeten ausserhalb unseres Sonnensystems zu entdecken und zu erforschen.

Ein Ziel der modernen Astrophysik ist es deshalb, extra-solare Planeten auf direktem Wege nachzuweisen. Dazu sind die grössten verfügbaren Teleskope und ausgefeilte Messtechniken nötig.

Eine vielversprechende Methode extra-solare Planeten zu "sehen" und zu analysieren, basiert auf der Tatsache, dass Licht, welches an einem Planeten reflektiert wurde, polarisiert sein kann. Um ein derartiges Signal nachzuweisen sind aber hochpräzise Polarisationsmessungen nötig. Polarimetrie ist eine Methode, welche die ESO sich zunutze macht, um nach extra-solaren Planeten zu suchen. Das Institut für Astronomie der ETH Zürich beteiligt sich mit ZIMPOL, einem äusserst empfindlichen bildgebenden Polarimeter, am ESO "planet-finder" Projekt.

Die vorliegende Dissertation behandelt zwei Fragestellungen, welche zu einem erfolgreichen Gelingen des "planet-finder" Projektes beitragen: (1) Um genaue Polarisationsmessungen zu ermöglichen, müssen instrumentelle Polarisationseffekte auf tiefem Niveau gehalten werden. (2) Um eine Vorstellung über die Polarisationseigenschaften unserer Zielobjekte zu erhalten, werden die Polarisationseigenschaften der solaren Planeten untersucht.

Gute Kandidaten, um von ZIMPOL detektiert zu werden, sind grosse Planeten mit Gasatmosphären ähnlich unseren vier Gasplaneten Jupiter, Saturn, Uranus und Neptun.

Im ersten Teil der Dissertation wird das "planet-finder" Projekt vorgestellt und die Aufgabe von ZIMPOL erläutert. Um die instrumentelle Polarisation zu bestimmen, werden die Polarisations eigenschaften von Spiegeln und anderen optischen Komponenten analysiert, welche im "planet-finder" Instrument eingesetzt werden.


Es werden des weiteren mögliche Alterungserscheinungen der Spiegel in Betracht ge-
zogen und die Auswirkungen auf die Polarisation berechnet. Zum Schluss wird eine Fehleranalyse über eine nicht-perfekte Verzögerung der Halbwellenplatte und dessen Auswirkungen auf die Polarisation vorgestellt.

Im zweiten Teil werden spektropolarimetrische Messungen der vier Gasplaneten Jupiter, Saturn, Uranus und Neptun für einen Wellenlängenbereich von 530 bis 930 nm vorgestellt.


Im Anhang sind zahlreiche polarimetrischen Spektren und Profile der vier Planeten dargestellt. Im Textteil der Dissertation wird nur eine kleine Auswahl dieser Daten präsentiert.
Chapter 1

Introduction

Almost the only way to get information from very distant objects, what is common in astronomy, is to interpret the electromagnetic radiation coming from those targets. Thus, it is the goal of any observer to read as much as possible from the photons attending us.

Light, as it can be described by a wave, carries besides the intensity and the wavelength another very important property: the polarisation. The polarisation is described by its direction and its strength and has therefore the nature of a vector. The polarisation direction is defined by the orientation of the electric field vector of the electromagnetic wave. The strength of the polarisation is the amount of intensity with the electric field vector in one direction relative to the total intensity. Because of the \( \pi \)-periodicity of the polarisation the definitions of “direction” and “strength” need further explication and are therefore explained in Sect. 1.2.

Knowing the polarisation status of light means to have an additional information, i.e. to know more. By just “counting” photons distributed over an array of a CCD camera, like for common imaging, one loses the polarimetric part of the information, since the CCD is not (yet) sensitive to the direction of the exciting field.

Knowing the polarisation of light gives the possibility to draw conclusions from the physics of the origin of that light, because natural light sources normally don’t emit polarised light. Polarised light is generated by a violation of symmetry. This can happen at the source itself (if the geometry of the source is asymmetric or if a magnetic field is present) or on the way from the source to the detector (if light passes through an inclined glass plate or if it is reflected on an inclined mirror or by being scattered in the atmosphere of a planet, etc).

It is up to now not easy to get a good spatial resolution for polarimetric measurements because of the challenging technique required. Measuring the polarisation is mainly a differential technique, where in principle the image obtained for one polarisation direction is subtracted from the image obtained for the orthogonal orientation. Differential imaging can be done in two main ways: the first is to record primarily the image in one and later in the perpendicular direction, called temporal modulation. A second method is to split the incoming light spatially according to their polarisation directions. Both methods suffer from different disadvantages. Later in this thesis a method is presented how the advantages of both methods are combined and the disadvantages are suppressed.

First polarimetric measurements of the planets of the solar system were carried out in the beginning of the last century by B. Lyot. He mainly observed Jupiter. Later A. Dollfus repeated and completed Lyot’s observations. Polarimetric data of Saturn and the
1.1. Polarised light

other giant gas planets Uranus and Neptune are rarer and obtained later by, for example, M.G. Tomasko and L. R. Doose for Saturn around 1980 or by J. J. Michalsky, R. A. Stokes, W.V. Schempp and W.H. Smith for Uranus since 1970.

Imaging polarimetry and spectropolarimetry of high quality for those planets are only few found in the literature. Often, only aperture polarimetry or spectropolarimetry for the integrated planetary disc was achieved. Therefore, the measurements presented in this thesis contribute with new, accurate spectropolarimetry obtained with a modern ESO-polarimeter.

The topic of this thesis is divided into two main parts. In the first part the ESO planet-finder instrument SPHERE is presented as it is planned at the time of writing (autumn 2006). Special attention is paid on the polarisation properties of the instrument. Several polarisation simulations of the instrument are presented in detail, problems are highlighted and possible solutions are proposed.

The second part is the more "scientific" fraction where spectropolarimetric measurements of solar system giant gas planets are presented. The main focus is laid on Uranus. But also the data of Neptune, Jupiter and Saturn are carefully reduced and presented. Polarised spectra are shown for all four planets with different directions for the spectrographic slit on the planets as well as intensity and polarisation profiles along the slits are presented for the polarisation.

The remaining part of this chapter gives a short introduction to polarimetry.

1.1 Polarised light

To avoid confusion I shall mention here, that of course each photon is polarised, thus only polarised light exists. Speaking about polarised light always means an assembly of many photons polarised in the same direction. One distinguishes normally between linearly and circularly polarised light. The general case is elliptically polarised, which can be separated into a linear and a circular part.

Erasmus Bartholinus (1625-1698) discovered the birefringence of calcite in 1669 when he observed that a light beam passing through the crystal was spread into two single beams. The beams were fully polarised. He published an accurate description of the phenomenon, but since the physical nature of light was poorly understood at the time, he was unable to explain it. Only consulting the modern wave theory, based on the works of Christiaan Huygens (1629-1695) and James Clerk Maxwell (1831-1879), an explanation of the observed phenomenon was proposed.

From the wave equation in three dimensions

$$\nabla^2 \vec{u}(\vec{r}, t) = \frac{1}{c^2} \frac{\partial^2 \vec{u}(\vec{r}, t)}{\partial t^2},$$  \hspace{1cm} (1.1)

where $\vec{u}$ stands for an arbitrary vector field that is in case of electromagnetic waves the electric or the magnetic field, one gets solutions in $x$ and $y$ direction, if the Cartesian system is aligned in that way that the $z$ axis is parallel to the direction of propagation of
the electromagnetic wave:

\[ u_x(r, t) = u_{0x} \cos(k \cdot r - \omega t + \delta_x) \]  
\[ u_y(r, t) = u_{0y} \cos(k \cdot r - \omega t + \delta_y), \]  

where \( u_{0x} \) and \( u_{0y} \) are the amplitudes and \( k \) is the wave vector. \( \delta_x \) and \( \delta_y \) are arbitrary phases.

One knows from the Maxwell Equations that the electric field vector \( \vec{E} \) is perpendicular to the magnetic field vector \( \vec{B} \) and both are perpendicular to the direction of propagation.

The polarisation orientation of an electromagnetic wave is defined as the direction of the electric field vector \( \vec{E} \) in the plane perpendicular to the direction of propagation.

We can replace \( \vec{u} \) by the electric field vector \( \vec{E} \) and write (1.2) and (1.3) again:

\[ E_x(r, t) = E_{0x} \cos(k \cdot r - \omega t + \delta_x) \]  
\[ E_y(r, t) = E_{0y} \cos(k \cdot r - \omega t + \delta_y), \]  

The linear combination of two solutions (1.4, 1.5) of the wave equation (1.1) is again a solution:

\[ \vec{E}(r, t) = \vec{e}_x E_{0x} e^{ik \cdot r - i\omega t} + \vec{e}_y E_{0y} e^{ik \cdot r - i\omega t + \delta}, \]  

where \( \vec{e}_x \) and \( \vec{e}_y \) are the unit vectors for the \( x \) and \( y \) directions.

For different strengths of the electric fields \( E_{0x} \) and \( E_{0y} \) and the phase difference \( \delta \) the general case of polarisation is described. The tip of the real part of the electric field \( \vec{E}(r, t) \) draws an ellipse as shown in Fig. 1.1.

Fig. 1.1: The polarisation ellipse

Regarding the two electric field vector components \( E_{0x} \) and \( E_{0y} \) and the phase difference between the two waves \( \delta \) one can make some statements on the polarisation of the real part of the linear combination of the two waves:
1.2. Stokes formalism

- If either $E_{0x}$ or $E_{0y}$ is zero, the electric field vector $\mathbf{E}(\vec{r}, t)$ is parallel to the $y$ or the $x$ axis for all $t$ and one speaks of (vertical or horizontal) linearly polarised light.

- If $\delta = 0$ or $\delta = \pi$ the field vector $\mathbf{E}(\vec{r}, t)$ forms an angle of $\gamma = \arctan \left( \frac{E_{0y}}{E_{0x}} \right)$ with the $x$ axis. This is also linearly polarised light, but with an inclination relative to the axis of the coordinate system.

- If $\delta = \pi/2$ or $\delta = 3\pi/2$ and $E_{0x} = E_{0y}$, the tip of the electric field vector $\mathbf{E}(\vec{r}, t)$ at a fixed position $z$ circles around the $z$ axis and one speaks of right or left circularly polarised light.

The description by the electric fields or the polarisation ellipse holds for mathematical and theoretical handling but a disadvantage is that it suffices only for totally polarised light, but not for partially or even unpolarised light. In nature most light sources emit unpolarised or partially polarised light and one is interested in the polarisation state of any light sources. Therefore, one has to look for an alternative characterisation of polarised light, which deals with measurable quantities of light and also holds for all states of polarisation, such as unpolarised and partially polarised light.

In 1852, Sir George Gabriel Stokes (1819-1903) expressed the polarisation state of light in form of intensities.

More details about polarised light can be found in Collett (1993) and in Jackson (1962).

1.2 Stokes formalism

An elegant way to describe polarised light is to measure the intensity of light polarised in the envisaged polarisation direction. For this, one distinguishes between four parameters describing polarised light, called Stokes parameters: The difference of the intensity polarised in vertical direction ($i_{0\degree}$) and the intensity polarised in horizontal direction ($i_{90\degree}$) gives the amount of $Q$ polarised light ($Q = i_{0\degree} - i_{90\degree}$). Rotating the whole measurements by $45\degree$ in counter-clock direction ($i_{45\degree} - i_{135\degree}$) leads to the $U$ polarised light and the difference of right circularly minus left circularly polarised light yields Stokes $V$. As fourth Stokes parameter the total intensity $I$ is used.

It is common to represent the Stokes parameters in form of a “vector”, the Stokes vector:

$$\mathbf{S} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}.$$ (1.7)

It is not a vector in the true mathematical sense, but its use is very adapted in polarimetrical calculations. The Stokes parameters $Q$ and $U$ describe the linearly polarised light, whereas $V$ accounts for the circular polarisation. Following equation holds for all Stokes vectors:
The equals sign in equation (1.8) holds only for entirely polarised light. The degree of polarisation \( p \) can be expressed as:

\[
p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I},
\]

and the direction of the linearly polarised light is given by the angle \( \theta \):

\[
\tan(2\theta) = \frac{U}{Q},
\]

counted in counter-clock direction with \( 0^\circ \) at the direction of \( Q \).

Often, the Stokes parameters are used as normalised Stokes parameters \( Q/I, U/I \) and \( V/I \) and then expressed in percentage.

Drawing the directions of the polarisation orientations onto a piece of paper is for people who are not familiar with polarisation somewhat impinging. The polarisation of light is subject to \( \pi \)-periodicity, i.e. after the rotation of a coordinate system by \( 180^\circ \) the polarisation situation is the same again. In Fig. 1.2 the orientations of the linear polarisation directions is drawn. It is arbitrary to define the positive \( Q \) direction vertically but normally the habit, whereas the counter-clock wise orientation of the angles is usually predefined.

Fig. 1.2: Orientations of the linear polarisation directions, with obvious \( \pi \)-periodicity.

1.3 Mueller Calculus

When a light beam, described by its Stokes parameters \( \vec{S} = (I, Q, U, V) \), is interacting with an optical element, the polarisation state is generally influenced and therefore, after the interaction the Stokes vector has changed to \( \vec{S}' = (I', Q', U', V') \). From mathematics it is known that a vector can be transformed into another vector by the use of a linear
operation expressed by a matrix in an appropriate coordinate system. The interaction with the optical element in optics is the analogon to the linear transformation concerning the state of polarisation. Therefore, the interaction of light with optical elements can be described by $4\times4$ matrices, called Mueller matrices.

A Mueller matrix $\mathbf{M}$ transforms the Stokes vector $\mathbf{S}$ of the incident light beam into the new Stokes vector $\mathbf{S'}$ according to:

$$\mathbf{S'} = \mathbf{M} \mathbf{S} \quad \text{(1.11)}$$

If the light beam is affected by $n$ optical components, each described by its Mueller matrix $\mathbf{M}_i$, all interactions can be taken together to a single Mueller matrix $\mathbf{\widehat{M}}$ and the relation between the incident light beam $\mathbf{S}$ and the resulting Stokes vector $\mathbf{S'}$ can be computed easily by:

$$\mathbf{S'} = \mathbf{\widehat{M}} \mathbf{S}, \quad \text{(1.12)}$$

with

$$\mathbf{\widehat{M}} = \prod_{i=0}^{n-1} \mathbf{M}_{n-i} = \mathbf{M}_n \mathbf{M}_{n-1}...\mathbf{M}_1 \quad \text{(1.13)}$$

where $\prod$ is the operator of matrix multiplication.

This is a very convenient and simple method to calculate the polarimetric impact of a train of optical elements. Further, a lot of Mueller matrices for simple optical elements such as polarisers, retarders, mirrors, etc. are known (e.g. Collett (1993)) and can therefore be used like elements of a construction set.

Subsequently, some examples of Mueller matrices for very simple optical elements are presented. Note, that a Mueller matrix is dependent on the "coordinate system", i.e. like in linear algebra a matrix is just a representation of a linear map and therefore dependent on the basis of the vector space, i.e. a Mueller matrix is only valid for a previously defined orientation of the polarisation directions. Therefore, there doesn’t exist a Mueller matrix for a mirror, but for a mirror where the positive $Q$ direction is perpendicular to the plane of scattering, for example.

All following Mueller matrices in the entire thesis where the scattering plane can be defined (mirrors and dielectric plates) are given for the case where the positive $Q$ direction is perpendicular to the scattering plane.

**Linear polariser**

A linear polariser is an element that attenuates the amplitudes of the electric fields in $x$ and in $y$ direction of the incident light $E_x$ and $E_y$ according to $E'_x = p_x E_x$ and $E'_y = p_y E_y$, respectively, with $0 \leq p_x, p_y \leq 1$ the attenuation coefficients. The Mueller matrix of such a polariser has therefore the following form (Collett (1993)):

$$\mathbf{M}_{\text{linpol}} = \frac{1}{2} \begin{pmatrix}
    p_x^2 + p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\
    p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0 \\
    0 & 0 & 2p_x p_y & 0 \\
    0 & 0 & 0 & 2p_x p_y
\end{pmatrix}, \quad \text{(1.14)}$$
For a perfect linear polariser the attenuator coefficient in one direction is unity whereas the orthogonal attenuator coefficient is zero.

**Retarder element**

A retarder is a birefringent element that exhibits different refraction indices depending on the direction of the incident electric field vector $E_x$ and $E_y$. This yields two different light speeds for the two orthogonal polarisation directions and thus, a phase shift of $\varphi$ between one polarisation direction and the orthogonal. The phase shift depends on the optical length of the plate (thickness) and is valid for one specific wavelength. The Mueller matrix for a retarder element with retardation $\varphi$ and the optical axis in direction of $Q$ is:

\[
M_\varphi = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \cos \varphi & -\sin \varphi \\
0 & 0 & \sin \varphi & \cos \varphi
\end{pmatrix}.
\]

(1.15)

For $\varphi = 180^\circ$ the retarder is called half-wave plate and for $\varphi = 90^\circ$ it is a quarter-wave plate.

**Rotator**

As explained, the Mueller matrices are given for a certain geometry of the coordinate system. Sometimes an optical element is not in the appropriate orientation to be described by the given Mueller matrix. Then it makes sense to rotate the incoming Stokes vector into the right position, operate with the Mueller matrix and then rotate the influenced Stokes vector back into the original orientation. This can be obtained by a rotation matrix $R(\alpha)$, with the rotation angle $\alpha$. The rotation and derotation is also given by the product of Mueller matrices:

\[
M(\alpha) = R^{-1}(\alpha) M R(\alpha),
\]

(1.16)

where the representation of $R(\alpha)$ by its Mueller matrix is:

\[
R(\alpha) = \begin{pmatrix}
1 & 1 & 0 & 0 \\
0 & \cos 2\alpha & \sin 2\alpha & 0 \\
0 & -\sin 2\alpha & \cos 2\alpha & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

(1.17)

$R^{-1}(\alpha)$ is the inverse matrix of $R(\alpha)$. For a rotation matrix, the inverse matrix is simply the rotation matrix with the opposite angle, i.e. with sign inverted angle: $R^{-1}(\alpha) \rightarrow R(-\alpha)$. 


Part I

The planet-finder project
Chapter 2

History

Since 1995, when the first extra-solar planet around a solar type star, 51 Peg b, was detected indirectly using the radial velocity method by Mayor & Queloz (1995), a new field of science has continuously been developed. The hunt for extra-solar planets is now, more than 10 years later, in full swing and has become one of the most popular topics in astrophysics. More than 190 extra-solar planets have been detected up to now (autumn 2006), but none of them could be “seen” because all have been detected indirectly, mostly by radial velocity (Horne (2006); http://exoplanet.eu/catalog.php).

One has to mention that the last sentence could be considered as wrong, depending on how an extra-solar planet is defined. For example, a “small” (~5 MJ) companion around a brown dwarf has directly been imaged in 2005 with VLT/NACO (Chauvin et al. (2005)) and denominated as an extra-solar planet. But, it is still a controversial subject if this shall be considered as an extra-solar planet or not. As long as no clear definition is available, I do not denominate 2M1207b, as the companion was named, as an extra-solar planet, because its harbouring object is not a star. Therefore, the first direct imaging of an extra-solar planet is still owing and a severe competition about finding the first extra-solar planet by direct imaging is in progress from ground as well as from space.

In November 2001 ESO made a call for proposals for second generation VLT instruments. New ideas on how extra-solar planets could be imaged were in demand.

A consortium consisting of German, Italian, Dutch, Portuguese and Swiss institutes, led by the Max Planck institute for astronomy (MPIA) in Heidelberg, formed with the goal to build a planet-finder instrument. The Institute of Astronomy in Zurich was a member of this consortium. The planet-finder instrument (PF) is a device that can detect light - by reflection or thermal emission - from the surface of extra-solar planets. This project, called CHEOPS (CHaracterising Extra-solar planets by Opto-infrared Polarimetry and Spectroscopy), proposed an instrument consisting of two scientific arms and an extreme adaptive optics system (XAO) to correct for the atmospheric distortion of the light. An Integral Field Spectrograph (IFS) for spectroscopy of a whole image and the Zurich IMaging POLarimeter (ZIMPOL) for differential imaging in polarimetric mode were foreseen (the latter being the contribution of the Institute of Astronomy at the ETH Zurich).

A second consortium led by the French Laboratoire d’Astrophysique de Grenoble (LAOG) followed ESO’s call too, and started at the same time as a competitive consortium to CHEOPS working out a feasibility study (phase A) for building a planet-finder. In autumn of 2004 the two phase A reports were presented to ESO for examination and
decision about which of the two groups would get the contract with ESO for building the planet-finder.

In Spring 2005 ESO decided, that a merging of the two teams would be the best solution to go on with the planet-finder project, because both teams provided some experience and knowledge in different, complementary fields but each separately would not be enough to continue alone. Therefore, a "new" consortium consisting of parts of the former competing groups was formed led by LAOG. The former CHEOPS group is contributing with two scientific instruments (ZIMPOL and IFS) and the "French" part is responsible for one scientific apparatus, named IRDIS (InfraRed Dual-beam Imaging and Spectrograph) and the common path optics, particularly containing the extreme adaptive optics system. Out of the former two competing consortia a new one has been created called SPHERE, (Spectro-Polarimetric High-contrast Exoplanet REsearch). 11 institutes in 5 European countries contribute to SPHERE.

In the next chapter a short overview of the whole SPHERE instrument will be given. At the time of writing this thesis (autumn 2006) the project is in the preliminary design phase and therefore still subject to changes. Thus, it is not guaranteed, that at the time of first light, which is scheduled for the end of 2010, the layout will still be the same.
Chapter 3

SPHERE

The main intention of SPHERE is to detect and characterise young, self luminous (warm) and old, reflecting (cold) extra-solar giant planets orbiting nearby stars by direct imaging. The challenge consists in the very large contrast and the small separation between the host star and the planet.

For warm and cold planets, very different cases arise: for warm planets the contrast is a strong function of wavelength, being most favourable in the mid and far infrared. It further depends on the luminosity of the central star where intrinsically faint stars are strongly favoured. On the other hand, the contrast is independent on the separation between star and planet.

For reflected light from extra-solar planets the luminosity contrast between star and planet is proportional to the reciprocal of the square of the separation star-planet and becomes more favourable the nearer the planet orbits its star. The contrast is not much wavelength dependent because of reflection (besides of course the spectral dependent geometric albedo of the planet). On the other hand the smaller the separation between planet and star the more the signal of the planet vanishes in the bright halo of the star. The halo is mainly caused by two effects:

- A point like source, like a star, is theoretically imaged as Airy disc on the detector due to the diffraction of the light at the exit pupil of the telescope. Therefore, the image of a point like source is characterised by the so called point spread function (PSF) which describes the radial intensity distribution of a point like source at the focal plane. Thus, a point like source is not imaged as a point.

- The atmosphere of the Earth smears our the light even more. For this, light of the central star is covering an area around the centre of the star on the CCD, depending on the seeing of the atmosphere but also on the wavelength of the source.

These two facts have crucial impact on the detectability of reflected light from extra-solar planets. Being near the central star is favoured to enhance the intrinsic contrast between planet and star, but on the other hand the intensity of the halo of the star is lower further away from the star. This is a key difficulty for the detection of reflected light from extra-solar planets.

The whole design of SPHERE is therefore optimised for reaching the highest contrast in a limited field of view around the central star. With the aid of coronagraphy (to block
the light of the inner part of the system) and an extreme adaptive optics the contrast between planet and star can be enhanced by a few orders of magnitude.

Both, evolved and young planetary systems may be detected due to their reflected light (by visible differential polarimetry → ZIMPOL) and due to the intrinsic planetary emission (using infrared differential imaging and integral field spectroscopy), respectively. Both focal plane instruments of the near-infrared arm of SPHERE will provide complementary detection capacities and characterisation potential, in terms of field of view, contrast, and spectral range.

3.1 Description of the instrument

SPHERE is divided into four major subsystems:

- Common path optics including the adaptive optics
- InfraRed Dual-beam Imager and Spectrograph (IRDIS)
- Integral Field Spectrograph (IFS)
- Zürich IMaging POLarimeter (ZIMPOL)

The conceptual design of the four subsystems shall be sketched hereafter:

**Common path with extreme adaptive optics** The correction for the instrumental polarisation due to the Nasmyth folding mirror (M3) and the stabilisation of the polarisation is the task of the first section in the common path. It consists mainly of a half-wave plate and an additional flat folding mirror (M4) with an aluminium coating (more about this later in section 4.2). The field derotator consisting of three silver coated mirrors able to correct for image and pupil rotations follows. These first optical elements in the common path form the so-called fore optics.

The SPHERE Adaptive optics for eXoplanet Observation (SAXO) is the key part of the common path. It uses a 41 x 41 actuator deformable mirror (DM) of 180 mm diameter with inter-actuator stroke > ±1 μm and maximum stroke > ±3.5 μm and a 2-axis tip-tilt mirror (TTM) with ±0.5 milli-arcseconds (mas) resolution. A Shack-Hartmann wavefront sensor with 40 x 40 lenslets, sensitive in the spectral range of 0.45 to 0.95 μm achieves a temporal sampling frequency of 1.2 kHz using a 240 x 240 pixel CCD detector (CCD 220 from EEV) (Dohlen et al. (2006)).

Other important elements of the common path are beam splitters which separate the light between different subsystems, such as the wavefront sensor or the different scientific instruments.

Efficient coronagraphy is also very important for reaching the challenging science goals of SPHERE. The task of the coronagraph is two-fold: it reduces the intensity of the stellar peak by a factor of at least 100 and it eliminates diffraction features caused by the edges of the pupil. Therefore, also coronographs or occulting masks are key components of the common path.
InfraRed Dual-beam Imager and Spectrograph  The main task of IRDIS is differ¬
ential imaging, i.e. imaging in two neighbouring spectral regions and subtracting
one image from the other. The residual is supposed to be a spectral feature only
present in either the planet or the central star. The IRDIS sub system includes a
spectral range of 950-2320 nm and an image scale per pixel of 12.25 mas. The field
of view is larger than 11" in diameter. 10 different filter couples are defined corre¬
sponding to different spectral features obtained from exo-planet models. Further,
12 narrow, medium and wide-band filters are defined for direct imaging for both
Cameras. In addition to the dual and direct imaging also long-slit spectroscopy is
provided with resolving powers of 50 and 500, respectively (Dohlen et al. (2006)).
The dual beam imaging is done simultaneously. Therefore, a beam splitter and
a folding mirror are needed to provide two parallel channels feeding two camera
systems.

Integral Field Spectrograph  One of the most limiting factors for detecting extra-solar
planets from ground is speckle noise. To minimise this noise simultaneous differential
imaging (SDI) techniques are exploit. This is subtracting an image at the wavelength
of a planetary absorption band (for example in a methane band) from one in the
adjacent continuum. But it is not suitable to use images taken one after the other,
since the speckle noise changes too fast. A promising way to realize simultaneous
differential imaging is diffraction limited, integral field spectroscopy. Integral field
spectroscopy is a method to produce “three dimensional” spectra, i.e. for each
spatial element of a two dimensional image a spectrum is obtained. Therefore, one
gets the spatial and the spectral information as well. One also speaks about “image
cubes”. This eliminates the speckle noise to a first order without destroying the
planet signal.

A micro-lens based IFS design is foreseen for SPHERE optimised for high-contrast
diffraction limited observations (Lee et al. (2001)). The SPHERE-IFS is operating
in the Y-J bands (0.95-1.35 μm) allowing parallel operation of IRDIS and IFS. The
spectral resolution will be 30 per pixel and a FOV of 1.35" square is foreseen (with
the goal of 3°).

Visible Differential Imager  The ZIMPOL subsystem is a high-precision imaging po-
larimeter working in the visual range, covering at least the spectral range from 600
to 900 nm. The instrument principle is based on fast modulation of the incom-
ing polarisation using a ferro-electric liquid crystal retarder, and demodulation of
the polarisation signal using a modified CCD array Key advantages of this tech-
nique are the simultaneous detection of two perpendicular polarisation directions
(the modulation is faster than seeing variations) and the recording of both image
elements with the same pixels. Thanks to this approach, a polarimetric precision of
10^-5 or even better will be achieved. The CCD will cover a field of 3" square and it
is foreseen that the FOV can be moved around the bright star so that a field with a
radius of 4" can be covered. In addition to polarimetric imaging, ZIMPOL provides
the possibility for high resolution imaging in the visual range using a set of broad
and narrow band filters.

The Institute of Astronomy at the ETH Zürich contributes with ZIMPOL to SPHERE. Therefore, attention will be paid on this subsystem and on issues important to ZIMPOL in the following chapters. A description of ZIMPOL is given in the next section.

![Fig. 3.1: Overall concept of the SPHERE instrument indicating the four subsystems: Common path, ZIMPOL, IRDIS and IFS.](image)

### 3.2 Zürich IMaging POLarimeter within SPHERE

The ZIMPOL branch of SPHERE aims to detect polarised light from extra-solar planets in the near infrared regime from about 600 to 900 nm (I-band). It uses the fact that light reflected by planetary atmospheres can highly be polarised for large phase angles as described for example for space missions of Pioneer and Galileo (Smith & Tomasko (1984); Tomasko & Doose (1984); Braak et al. (2002)). An exo-system consisting of a star and a planet emits light towards the observer. In the I-band we distinguish light coming directly from the star and light reflected by the planetary surface/atmosphere towards the observer. One is not interested in the light from the star but rather in the light reflected by the planet. Therefore, the sources must be disentangled.

The intrinsic polarisation of a centrosymmetric star can be considered as very low (<0.01%) (Kemp et al. (1987) and Tinbergen (1979)) and the interstellar polarisation is typically lower than 0.05% for the nearest stars (Krautter (1980)). Thus, the polarimetric signal in the PSF can be considered as polarisation zero-point on top of which a small signal from a planet has to be detected. Take the Sun-Jupiter system at 5 pc distance as example for an extra-solar planetary system model. The angular distance of the planet to the star is for a convenient star-planet configuration about 1″. The contrast in intensity between the planet and the star is at the place of the planet on the order of 10^{-8}, which is far beyond the actual precision of astronomical polarimeters. With the help of the extreme adaptive optics in combination with coronagraphy this contrast can be enhanced to about 10^{-4}, which is rather in the regime of ZIMPOL precision.
The institute of Astronomy at the ETH Zürich is responsible for the ZIMPOL instrument within SPHERE. Therefore, a general survey of ZIMPOL is the topic of the current chapter. It shall only be a rough abstract since more detailed reports and specifications of former ZIMPOL instruments can be consulted for example in Gandorfer (2001); Povel et al. (1990); Gisler et al. (2004); Gisler (2005).

ZIMPOL is an instrument for imaging polarimetry in the optical wavelength range. It has been developed at the Institute of Astronomy of the ETH Zürich by H. P. Povel and collaborators (Povel et al. (1990)). It is based on a fast polarisation modulator, e.g. a ferro-electric retarder, working in the kHz range, a polarising beam splitter and a special CCD camera performing the on-chip demodulation of the modulated signal.

Polarimetry is nothing new in the world of astrophysics. The principle of polarimetric measurements is that of a differential measurement, i.e. to subtract the images of two orthogonal polarisation directions from each other. There exist polarimeters which use a polarising beam splitter, such as a Wollaston, to produce two orthogonally polarised images of the same object simultaneously on two different areas of the CCD. Another possibility of achieving the two orthogonal polarised signals is to measure first one polarisation direction and afterwards the perpendicular direction by either rotating the polariser or by rotating an inserted retarder which rotates the incoming polarisation by 90°. This method is called temporal modulation. Both methods have advantages and disadvantages. The advantage of the first method is that the two images are detected at the same time, i.e. the seeing conditions are equal for both images, hence, there is no induced error due to different atmospheric conditions. The two images, the ordinary and the extraordinary beams, are recorded at two different areas on the CCD and this causes gain effects which leads to an artificially induced polarisation. For the temporal modulating method, the advantages and disadvantages are exchanged. Thus, a combination of the advantages of the two methods would be appreciated. This had been achieved within ZIMPOL.

The goal was to use the method of a temporal modulated observation and switch between the two measurements of the opposite polarisation directions faster than seeing variations (~ 10 ms). Rotating the polariser element would consume too much time. Also rotating an inserted half-wave plate by 45° (rotates the polarisation direction by 90°) would take too long. A retarder which can change its optical axis periodically by 45° in the kHz range was found in a Ferro-electric Liquid Crystal (FLC). The FLC is a thin layer of organic material sandwiched between two glass plates. The molecules of the organic material change their orientation under an alternating voltage, thus, change the orientation of the optical axis. Under the right conditions, such as thickness and temperature of the material an FLC acts like a half-wave plate. The voltage can be alternated at kHz frequency and thus be faster than seeing variations.

The FLC acts as a modulator with two different modes: in mode 1 the FLC has the optical axis in a vertical or horizontal direction and has therefore no effect on light polarised parallel or perpendicular to the optical axis. Mode 2 acts as half-wave plate with optical axis at 45° and switches therefore vertically and horizontally polarised light into their orthogonal polarisation directions. Thus, in alternating sequences, it transmits the originally vertical and horizontal polarisation directions unchanged and then it flips the originally horizontal into vertical polarisation direction and vice versa. This means, that
when analysing the vertically polarised light after the FLC, one measures in alternating order the originally vertically and horizontally polarised light (see also Fig. 3.2).

The analysing is managed by a polarising beam splitter, which transmits only, say, vertically and deflects only horizontally polarised light.

With this technique one problem is not solved yet. The orthogonal polarisation information, now encoded in an intensity information, arrives at the detector (CCD) at the same frequency as the FLC modulates, i.e. on the order of 1000 times per second. This is too fast for the CCD to read out the accumulated capacities belonging to each polarisation direction. The two orthogonal polarisation informations would fall onto the same pixels and could not be distinguished anymore. This was avoided by “sticking” opaque stripe masks on every second row of the CCD and shifting the accumulated charges of the exposed pixel rows, at the exact modulation frequency, to the covered rows and back again. The covered rows act for this as temporary buffer storages. For not loosing half of the light and minimising stray light the rows of the CCD are equipped with cylindrical micro lenses of the width of two pixels focusing the light onto the open pixel rows. After many thousand of modulation periods the image is read out in less than one second and a new exposure can begin.

The next exposure begins with a phase shift of \( \pi \), i.e. if the modulator has started the first exposure with mode 1 it starts now with mode 2. The consequence of this phase shift is, that the vertically polarised photons of the first exposure are stored by pixels which are used in the second exposure as pixel storage.

The image of the first exposure (A) contains two sub-images given by the alternating rows \( i(A)_{\parallel} \) and \( i(A)_{\perp} \) according to the parallel and the perpendicular polarisation directions. The second image (B) also contains two sub-images but with exchanged polarisation directions: \( i(B)_{\perp} \) and \( i(B)_{\parallel} \). From both exposures the polarisation degree (\( p_{A/B} = Q/I \)) is computed:

\[
p_A = \frac{i(A)_{\parallel} - i(A)_{\perp}}{i(A)_{\parallel} + i(A)_{\perp}} \quad p_B = \frac{i(B)_{\perp} - i(B)_{\parallel}}{i(B)_{\perp} + i(B)_{\parallel}}.
\]  

(3.1)

The composed signal is obtained by subtracting \( p_B \) from \( p_A \):

\[
p = \frac{p_A - p_B}{2}.
\]  

(3.2)

Always two phase shifted exposures are needed to create one measurement of one Stokes parameter. Thus, this principle of modulation described in Gisler et al. (2004) is called two-phase modulation. This method of modulating the polarisation signals has a high impact on the image quality, since the subtraction of the two images causes an addition of the polarisation signals (because they have changed sign due to the phase shift) but subtracts the pixel's own fixed pattern noise (the noise is not sensitive on a phase shift). The fixed pattern noise is mostly generated by stray light and a pixel individual charge transfer efficiency. The effect with the two-phase mode is a reduction of the fixed pattern noise by at least a factor of 10 (Gisler (2005)).

With this technology of modulating the polarisation signal and demodulating it by shifting charges on the CCD, the measurement of the two opposite polarisation directions
is faster than seeing variations and the signals are detected with the same pixels which means, that the gain effects for $i_\parallel$ and $i_\perp$ are the same.

![Diagram of ZIMPOL system](image)

**Fig. 3.2:** Basic principle of the ZIMPOL technique for measuring linear polarisation. The modulator and the CCD camera are synchronised for the modulation and demodulation of the polarisation signal. Explanations are given in the text.

Figure 3.2 shows a schematic layout of a ZIMPOL system. Because the measurement is fully differential, systematic error sources are reduced to a very low level. Key advantages of this technique are:

- Images of the two opposite polarisation modes are recorded nearly simultaneously (the modulation is faster than the seeing variations).

- Both images are recorded with the same pixels.

- The two images corresponding to opposite polarisation directions are affected by exactly the same aberrations introduced by the atmosphere and the telescope/instrument, which means fully differentially.

- Integration over many modulation cycles without readout of the frame.

In Fig. 3.3 a schematic view of a ZIMPOL CCD is presented. Every second row is occulted by an opaque mask. The pixels below the mask act as temporary buffer storages for accumulated charges, whereas the open rows harbour the active pixels exposed to the light. For reasons of not losing half of the light, cylindrical microlenses are mounted above the CCD to focus the light onto the open rows.

ZIMPOL has proved to be an extremely precise technique for polarimetric imaging. It is probably the most sensitive imaging polarimeter available today. In solar applications ZIMPOL has routinely achieved an accuracy of better than $10^{-5}$ in (long-slit) spectropolarimetric mode, described in Stenflo & Keller (1996). This is more than an order of
3.3 Optical layout of the SPHERE-ZIMPOL instrument

In this section the optical layout of the SPHERE-ZIMPOL system at one of the VLT units is described in a schematic way. The scope of this section is to explain roughly the whole optical path a light beam passes from the sky to the camera. In the following chapter more details on some components are discussed.

- SPHERE will be attached on the Nasmyth platform of one of the VLT units, therefore three mirrors are already given by the telescope: the 8 m primary mirror (M1), the secondary 1.2 m mirror (M2) and the Nasmyth folding mirror M3, all with an aluminium coating.

- A super achromatic half-wave plate (HWP1) and a flat folding mirror with an aluminium coating follow M3. The half-wave plate stabilises the instrumental polarisation introduced by M3. The surface normal of the folding mirror (M4) lies in a plane parallel to the Nasmyth platform and is inclined by 45° with respect to the incident direction. This combination of the half-wave plate and the mirror M4 compensates the instrumental polarisation introduced by M3 (see Sect. 4.2 and Fig. 4.9).
3.3. Optical layout of the SPHERE-ZIMPOL instrument

- Another super achromatic half-wave plate (HWP2) is inserted after M4. The position angle of HWP2 defines the polarisation direction on the sky to be measured. A rotation of the HWP2 by 22.5° allows to change from sky Q direction to sky $U$ polarisation direction. This half-wave plate has also multiple applications regarding the calibration of SPHERE-ZIMPOL.

- A silver coated 3-mirror derotator after HWP2 corrects for field and pupil rotation. For the highest precision ZIMPOL measuring mode the derotator is fixed in a stable horizontal or vertical position.

- The whole AO related common path optics containing several curved and flat mirrors, the atmospheric dispersion compensator, the dichroic beam splitter for selecting between NIR- and visual science, a further beam splitter to separate the light for the wave-front sensor and ZIMPOL, coronagraphic and pupil masks form the main part of the common path.

- The polarisation compensator plate is the first component belonging to the ZIMPOL system, followed by calibration optics. The polarisation compensator plate will compensate the residual instrumental polarisation. A further half-wave plate (HWPz), the FLC modulator for fast switching between two orthogonal polarisation directions, the polarisation beam splitter as analysing system, several filters mounted on a wheel and the special ZIMPOL CCD camera for decoding the polarisation signal build up ZIMPOL.

The next table lists all optical elements foreseen from the primary mirror to the ZIMPOL CCD. It describes the elements which are encountered by photons reaching the ZIMPOL CCD, i.e. optical elements of the other subsystems (IRDIS and IFS) are not regarded.
3.3. Optical layout of the SPHERE-ZIMPOL instrument

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>primary, concave mirror of VLT unit, aluminium coating</td>
</tr>
<tr>
<td>M2</td>
<td>secondary, convex hyperbolic mirror of VLT unit, aluminium coating</td>
</tr>
<tr>
<td>M3</td>
<td>tertiary (Nasmyth) plane mirror of VLT, aluminium coating</td>
</tr>
<tr>
<td>HWPI</td>
<td>super achromatic half-wave plate, rotatable</td>
</tr>
<tr>
<td>M4</td>
<td>folding mirror (&quot;crossed mirror&quot;), flat, aluminium coated</td>
</tr>
<tr>
<td>HWP2</td>
<td>super achromatic half-wave plate, rotatable</td>
</tr>
<tr>
<td>Derotator</td>
<td>field and pupil derotator, rotatable, three mirror system, silver coated</td>
</tr>
<tr>
<td>Toric M1</td>
<td>pupil re-imaging, silver coated</td>
</tr>
<tr>
<td>TT</td>
<td>tip-tilt mirror, for x-y pupil stabilisation, silver coated</td>
</tr>
<tr>
<td>Toric M2</td>
<td>pupil re-imaging, silver coated</td>
</tr>
<tr>
<td>DM</td>
<td>deformable mirror, 1600 actuators, silver coated</td>
</tr>
<tr>
<td>Toric M3</td>
<td>pupil re-imaging, silver coated</td>
</tr>
<tr>
<td>F1</td>
<td>folding mirror 1, silver coated</td>
</tr>
<tr>
<td>Dichro</td>
<td>dichroic beam splitter between visual and NIR</td>
</tr>
<tr>
<td>Lens1</td>
<td>to produce parallel beam</td>
</tr>
<tr>
<td>ADC1</td>
<td>atmospheric dispersion compensator 1</td>
</tr>
<tr>
<td>ADC2</td>
<td>atmospheric dispersion compensator 2</td>
</tr>
<tr>
<td>BS</td>
<td>beam splitter between ZIMPOL and wavefront sensor</td>
</tr>
<tr>
<td>Lens2</td>
<td>to produce converging beam</td>
</tr>
<tr>
<td>F2</td>
<td>folding mirror 2, silver coated</td>
</tr>
<tr>
<td>F3</td>
<td>folding mirror 3, silver coated</td>
</tr>
<tr>
<td>Focal mask</td>
<td>coronagraphic mask</td>
</tr>
<tr>
<td>Lens3</td>
<td>to produce parallel beam</td>
</tr>
<tr>
<td>Lyot pupil stop</td>
<td>pupil mask</td>
</tr>
<tr>
<td>Pol. comp.</td>
<td>polarisation compensator glass plate</td>
</tr>
<tr>
<td>Calib. optics</td>
<td>calibration optics for ZIMPOL</td>
</tr>
<tr>
<td>HWPz</td>
<td>half-wave plate for ZIMPOL</td>
</tr>
<tr>
<td>FLC</td>
<td>ferro electric liquid crystal (modulator)</td>
</tr>
<tr>
<td>Polaris</td>
<td>polarising beam splitter (analyser)</td>
</tr>
<tr>
<td>Filter</td>
<td>filter wheel with up to 12 filters</td>
</tr>
<tr>
<td>Camera lens</td>
<td>camera lens to produce image on CCD</td>
</tr>
<tr>
<td>CCD</td>
<td>ZIMPOL special CCD with masked rows</td>
</tr>
</tbody>
</table>

Table 3.1: Elements of the optical layout of SPHERE-ZIMPOL divided into three main parts: the telescope, the common path and ZIMPOL.
Chapter 4

Instrument polarisation at the Nasmyth platform of the VLT

Since the planet-finder instrument is foreseen to be attached on a Nasmyth platform of one of the four VLT units, a simple drawing of the optical path at the VLT is shown in Fig. 4.1. The layout is shown for two different altitude positions of the telescope, one pointing at zenith and another at an arbitrary zenith angle $z$.

![Diagram of the 3 VLT mirrors for a zenith position and a zenith angle $z$.](image)

**Fig. 4.1:** Schema of the 3 VLT mirrors for a zenith position and a zenith angle $z$.

Light from a distant object is reflected on the concave primary mirror (M1) towards the convex hyperbolic mirror M2 and back towards M1 where it is deflected outwards under an angle of 90° by the planar Nasmyth mirror M3. For polarisation related purposes, the three mirrors M1, M2 and M3 can be considered as fixed relative to each other.

During an observation the telescope changes altitude and azimuth. This has, among the common field and pupil effects also an impact on the polarisation. The derotation
of the field (or the pupil) are shortly explained and afterwards the effects about the polarisation are treated in more detail.

In the present chapter many angles are used in the text. To better disentangle the variables a short list with their meanings is presented in Tabl. 4.1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>right ascension</td>
</tr>
<tr>
<td>(\delta)</td>
<td>declination</td>
</tr>
<tr>
<td>(a)</td>
<td>azimuth</td>
</tr>
<tr>
<td>(z)</td>
<td>zenith distance</td>
</tr>
<tr>
<td>(h)</td>
<td>altitude ((90^\circ - z))</td>
</tr>
<tr>
<td>(\phi)</td>
<td>geographic latitude</td>
</tr>
<tr>
<td>(q)</td>
<td>parallactic angle</td>
</tr>
<tr>
<td>(s)</td>
<td>hour angle</td>
</tr>
<tr>
<td>(\tau)</td>
<td>sidereal time</td>
</tr>
<tr>
<td>(F)</td>
<td>field angle</td>
</tr>
</tbody>
</table>

Table 4.1: Used angles and their abbreviations.

4.1 Field and pupil derotation

In this section the need for a field derotator (or pupil derotator) is justified by the fact of rotation of the celestial coordinate system during an observation at the VLT. For this, a short introduction to the celestial coordinate systems and to spherical astronomy is given.

In Fig. 4.2 a sketch of the celestial sphere is shown. The centre of the sphere is the place where the observer rests at a geographic latitude \(\phi\). On the top, above the observer's head, there is the zenith and a star is indicated as a target. The position of the star can be described by its constant (at least over a period of several years) equatorial coordinates right ascension \(\alpha\) and declination \(\delta\), or by the time dependent (during a day) and geographic position dependent horizontal coordinates azimuth \(a\) and zenith distance \(z\), respectively. Instead of the zenith distance \(z\) one can also use the altitude \(h\) \((h = 90^\circ - z)\). The azimuth here is counted from South, to West, North and East according to Waldmeier (1946).

The VLT is an altitude-azimuth mounted (alt-az) telescope and one needs therefore first to transform the equatorial coordinates of the object into the horizontal system. Zenith distance \(z\) and azimuth \(a\) depend on the geographic latitude \(\phi\) and the hour angle \(s\) of the object. The hour angle of an object is defined as the elapsed time since the transit of the object through the meridian. The sidereal time \(\tau\) is the time after the transit of the vernal equinox through the meridian, and the right ascension is the elapsed time of the vernal equinox through the meridian of the star. Thus, the following relation can be written: \(\tau = \alpha + s\), thus \(s = \tau - \alpha\).
4.1. Field and pupil derotation

Fig. 4.2: Drawing of the celestial sphere with two different coordinate systems. The horizontal system with zenith, nadir, altitude $h$, zenith distance $z$, and azimuth $a$. The equatorial system with north and south celestial poles, declination $\delta$ and right ascension $\alpha$. The geographic latitude of the telescope is $\phi$, the hour angle of the star is $s$, the sidereal time is $\tau$ and the parallactic angle is $q$. $\gamma$ denotes the vernal equinox. The azimuth is counted from South to West, North and East.

With this information one can calculate for each object of given coordinates $\alpha$ and $\delta$ the horizontal coordinates $a$ and $z$ according to Waldmeier (1946):

$$\cos z = \sin \phi \cdot \sin \delta + \cos \phi \cdot \cos \delta \cdot \cos s,$$

$$\sin a = \frac{\cos \delta \cdot \sin s}{\sin z}.$$  \hfill (4.1) \hfill (4.2)

The observations with SPHERE will take long time so that effects like field- and pupil rotation and in our special case also the rotation of the polarisation reference system must be taken into account.

Field rotation is an effect that occurs in all alt-az mounted telescopes. For Nasmyth instruments it is made up of two contributions: first the rotation of the reference system on the sky (the field) relative to the telescope system due to the non parallel azimuth axis and the rotation axis of the Earth and second, the rotation of the “telescope tube” relative to the platform, i.e. the Nasmyth platform. First depends on the azimuth $a$ and second on the altitude $h$. The field rotation is always zero for an equatorial mounted telescope or for an alt-az telescope at the geographic poles.
The speed of rotation is not constant but depends on the geographic latitude of the telescope and on the observed direction on the sky. For a telescope pointed at the direction \( a \) and \( h \) (azimuth and altitude) the field is rotated by the field angle \( F \) compared to a default direction. The field angle is dependent on the parallactic angle and the altitude. The parallactic angle can be computed as follows:

\[
q = \arcsin \left( \frac{\cos \phi \cdot \sin s}{\sin z} \right).
\]  

(4.3)

\( \sin z \) can be expressed with the aid of 4.1, thus:

\[
q = \arcsin \left( \frac{\cos \phi \cdot \sin s}{\sqrt{1 - (\sin \phi \cdot \sin \delta + \cos \phi \cdot \cos \delta \cdot \cos s)^2}} \right).
\]  

(4.4)

The north celestial pole, the zenith and the star form the so called nautical triangle (Fig. 4.2), where the parallactic angle is that angle at the position of the star.

The field angle at the Nasmyth platform for the reference system given above is then:

\[
F = q \pm h + C,
\]  

(4.5)

where the “+” sign stands for the Nasmyth platform B. The platform B is, if standing behind the telescope and watching in direction of M2, at the right side. \( C \) is a constant, that establishes the zero point of the field angle.

To obtain the rotation speed of the field, i.e. the changing of the angle with time one has to calculate the derivative of \( F \) with respect to time:

\[
\dot{F} = \dot{q} \pm \dot{h},
\]  

(4.6)

with

\[
\dot{q} = \frac{\cos \phi \cdot \cos a}{\cos h} \cdot \omega_0 \quad \text{and} \quad \dot{h} = -\sin a \cdot \cos \phi \cdot \omega_0,
\]  

(4.7)

where \( \omega_0 \) is the sidereal rate: \( 2\pi/(24 \times 3600 \text{s}) \) (1990, ESO manual).

Equations (4.6) and (4.7) affect in a rotation of the field with the angular velocity of \( \dot{F} \). This rotation must be corrected. This is normally achieved with the VLT-Nasmyth Adapter-Rotator. The instrument is therefore attached at the Adapter-Rotator and rotates at the same velocity as the field. This is not possible for the VLT Planet finder instrument because of its large size and the tight mechanical requirements on the instrument stability. Therefore, the field derotation must be procured in the instrument itself. This can be achieved by a three mirror system like in Fig. 4.3 which rotates at an angular velocity \( \dot{F} \) around an axis parallel to the incoming beam.

At the VLT the entrance pupil is produced by the mirror M1 and the exit pupil by M2. By tracking a star, the altitude changes and therefore the pupil rotates with the same speed as the altitude \( h \) of the telescope changes. A stable pupil is required for several applications such as the use of the adaptive optics. Therefore, the pupil rotation must be corrected too, which can be achieved by the derotator element.
The position of a derotator in the optical path of the instrument is critical. Because of the two large incident angles at the entrance and at the exit of the derotator strong polarisation is induced artificially. If the derotator is in front of the polarisation analysis, i.e. before the polarisation beam splitter, the induced polarisation must be corrected.

A preferable solution would be to introduce the derotator mirrors after the polarisation analyser, because there the derotator would have no polarisation impact. But this optimal solution for ZIMPOL is not feasible if one of the other two instruments needs field rotation in the common path or if the AO system, which is located in the common path, must be fed by a stable field/pupil.

Building such a high precision polarimetry instrument poses many challenges for the optical layout because every not needed or misplaced mirror in the light path can produce substantial polarisation.

We will see in the next section how sensitive inclined mirrors affect the instrumental polarisation and how this can be avoided or corrected.

4.2 Polarisation studies for VLT-SPHERE

For the ZIMPOL polarisation measurements all instrumental polarisation effects, such as the introduction of polarisation but also cross-talks, have to be taken into account. All optical components in front of the polarisation analysing system, i.e. from mirror M1 to the polarising beam splitter, can affect the measurement by changing the original polarisation and therefore falsify the result. It is therefore desired to know each optical component well enough to describe it by its Mueller matrix. By the use of Mueller calculus the instrumental polarisation effects can be modelled before having built the instrument and the best solution of correcting or avoiding the instrumental polarisation effects can be found.

ZIMPOL reaches only a very high precision \((10^{-5})\) if the instrumental polarisation in front of ZIMPOL (in front of the modulator) is lower than about 1 %. This low instrument polarisation is required for high-precision measurements because non-linearity effects in the CCD pixel efficiencies will introduce spurious signals if the intensity levels for the
4.2. Polarisation studies for VLT-SPHERE

two orthogonal polarisation directions ($I_{||}$ and $I_{\perp}$) differ substantially (Gisler (2005)). Therefore, the instrument polarisation must be held lower than or corrected to a level below 1%.

In the actual SPHERE-ZIMPOL design the light is reflected on several mirrors until it is analysed by ZIMPOL (the polarisation direction to be analysed by ZIMPOL is defined by the polarising beam splitter). Some components are fixed with respect to the analysing system of ZIMPOL others are rotating with time (M3, derotator, ADC). Therefore, two polarising effects due to the instrument are expected. The first is the induced polarisation by inclined mirrors and the second is the time dependent variation of the polarisation by temporal changing of the arrangements of optical elements.

In this section the VLT-SPHERE optical path for the ZIMPOL subsystem is divided into three parts:

- the telescope (M1, M2 & M3) plus HWP1 and M4
- a part of the common path (HWP2, derotator, AO, ADC, dichroic beam splitter, coronagraph)
- ZIMPOL (polarisation correction plate, HWPz, modulator, polarising beam splitter, filters & camera)

Polarisation studies are presented in detail for the first two parts individually and then for both, telescope and common path together. For each part, first the induced instrument polarisation is determined in terms of Mueller matrices and then solutions for the compensation are presented.

Mueller matrices in this thesis are always calculated for the spectral range of 600 nm to 1000 nm at steps of 50 nm and normally the Mueller matrix for $\lambda = 800$ nm is presented as example. Multiplying all 9 Mueller matrices for each wavelength with an unpolarised Stokes vector, gives the resulting Stokes vector for instrumental polarisation for all wavelengths from 600 nm to 1000 nm.

Optical elements in the beam like mirrors or glass plates can be characterised by a Mueller matrix. Through matrix multiplication the entire telescope/instrument matrix is obtained, which can be written as

$$
T = \begin{pmatrix}
    t_{11} & t_{12} & t_{13} & t_{14} \\
    t_{21} & t_{22} & t_{23} & t_{24} \\
    t_{31} & t_{32} & t_{33} & t_{34} \\
    t_{41} & t_{42} & t_{43} & t_{44}
\end{pmatrix}
$$

From the telescope/instrument matrix the input signal for ZIMPOL, the Stokes vector $\vec{S_T}$, can be deduced according to:

$$
\vec{S_T} = T \vec{S}
$$
or

$$
\begin{pmatrix}
    I_T \\
    Q_T \\
    U_T \\
    V_T
\end{pmatrix} =
\begin{pmatrix}
    t_{11} & t_{12} & t_{13} & t_{14} \\
    t_{21} & t_{22} & t_{23} & t_{24} \\
    t_{31} & t_{32} & t_{33} & t_{34} \\
    t_{41} & t_{42} & t_{43} & t_{44}
\end{pmatrix}
\begin{pmatrix}
    I \\
    Q \\
    U \\
    V
\end{pmatrix},
$$

(4.9)
4.2. Polarisation studies for VLT-SPHERE

where $S$ is the Stokes vector at the entrance to the telescope.

Most important for the analysis of the instrumental polarisation effects are the following matrix components:

- $t_{21}, t_{31}$ quantify the induced linear polarisation $I \rightarrow Q$, $I \rightarrow U$,
- $t_{42}, t_{43}$ quantify the cross-talk from a linearly polarised signal to a circularly polarised signal $Q \rightarrow V$, $U \rightarrow V$.

The induced linear polarisation is important because it has to be kept low (< 1\%) for a high precision ZIMPOL measurement. For the investigation of scattered polarisation from planetary systems we are measuring with ZIMPOL the linear polarisation (however circular polarisation is in principle also possible) and any cross-talk to circular polarisation reduces the measurable linear polarisation. Hence, the cross-talk from linear to circular polarisation must be low too.

Cross-talk from circular to linear polarisation $V \rightarrow Q$, $V \rightarrow U$ ($t_{24}, t_{34}$) can be neglected for most applications, because essentially all targets are expected to show a much larger linear polarisation than circular polarisation (Stam et al. (2006)). Nevertheless, a cross-talk from circularly to linearly polarised light can occur inside the instrument for special configurations and this must be avoided.

Cross-talk $Q \rightarrow U$ ($t_{32}$) or $U \rightarrow Q$ ($t_{23}$) are more harmless because they essentially just rotate the position angle of linear polarisation. The true orientation of the polarisation position angle can be reconstructed in the data reduction (calibration) procedure.

But first, let's have a look at the general polarisation properties of mirrors.

4.2.1 Polarisation due to reflection on a mirror

Light reflected by an oblique mirror is affected by being polarised. The strength of the polarisation depends mainly on two conditions, which are the incident angle of the light beam and the material of the reflector, in particular the surface. The incident angle is defined as the angle between the light beam and the surface-normal at the reflection point. The material dependency of the polarisation is determined by the complex refraction index

$$n_c = n - i \cdot k$$

of the surface material. $i$ denotes the complex number $i = \sqrt{-1}$, $n$ and $k$ are real numbers. $k$ is the extinction coefficient. Since the refraction index is wavelength dependent, the induced polarisation after reflection is also wavelength dependent.

The Mueller matrix of the reflection on a flat mirror at an incident angle $\Theta$ is given by the expressions 4.11 to 4.13 (Stenflo (1994)).

$$M_{\text{mirror}} = \frac{1}{2} \begin{pmatrix}
1 + \rho^2 & 1 - \rho^2 & 0 & 0 \\
1 - \rho^2 & 1 + \rho^2 & 0 & 0 \\
0 & 0 & -2\rho \cos \delta & -2\rho \sin \delta \\
0 & 0 & 2\rho \sin \delta & -2\rho \cos \delta
\end{pmatrix}, \quad (4.11)$$
where \( \rho \) and \( \delta \) are dependent on the surface material expressed by the refraction index \( n_c \) and the incident angle \( \Theta \). The expressions \( \rho \) and \( \delta \) are given by the following terms:

\[
\begin{align*}
\rho^2 &= \frac{\sqrt{p^2 + q^2 + s^2} - 2sr_+}{\sqrt{p^2 + q^2 + s^2 + 2sr_+}}, \\
\tan\delta &= \frac{2sr_-}{\sqrt{p^2 + q^2 - s^2}},
\end{align*}
\]

(4.12)

where

\[
\begin{align*}
p &= n^2 - k^2 - \sin^2\Theta, \\
q &= 2nk, \\
r_{\pm} &= \frac{1}{\sqrt{2}} \left( \pm p + \sqrt{p^2 + q^2} \right)^{1/2}, \\
s &= \sin\Theta \tan\Theta.
\end{align*}
\]

(4.13)

The coordinate system for matrix (4.11) is chosen in such a way, that the positive \( Q \)-direction is perpendicular to the scattering plane (see Fig. 4.4). If one compares the Mueller matrix of a reflection on a mirror (4.11) with the matrices of a linear polariser (1.14) and a retarder (1.15) one recognises that the Mueller matrix of the mirror is a combination of a linear polariser and a retarder. Matrix (4.11) is normalised, thus, is not considering intensity loss given by the common reflectivity factor.

**Fig. 4.4:** Schematic illustration of the reflection on a flat mirror. The incoming beam from the top is reflected on the mirror and encloses the incident angle \( \Theta \) with the surface-normal. The scattering plane is defined by the points ABC. There are also the direction of Stokes \( +Q \) and \( -Q \) indicated for the incoming beam and for the analysing system, also the coordinate system how the measurement will be achieved are defined.

In the next sections the instrumental polarisation for the ZIMPOL arm of VLT-SPHERE is investigated in detail step by step and solutions to reduce the instrumental polarisation
4.2. Polarisation studies for VLT-SPHERE

4.2.2 Instrument polarisation due to the telescope

The optics belonging to the telescope are in principle only M1, M2 and M3. But from the polarimetric point of view, it makes sense to add the first half-wave plate (HWP1) and the mirror M4 to the "package" telescope. Therefore, in this section "Instrument polarisation due to the telescope" HWP1 and M4 are included. It is also understandable because HWP1 and M4 are added because of the telescope.

At the VLT M3 is a folding mirror, which reflects the light coming from mirror M2 onto the Nasmyth platform towards the instruments. M3 has an incident angle of 45° and has an aluminium coating. Thus, M3 is responsible for strong polarisation of the incoming light in the envisaged spectral range. In addition, it rotates with time and changes therefore the induced polarisation orientation. But also M1 and M2 are at some parts of the mirrors inclined surfaces and must therefore also be taken into account, which will be discussed later on.

Induced polarisation

We consider a mirror with an aluminium coating and an angle of incidence of 45° (M3) for the incident light. The telescope shall be pointed towards zenith.1 The Mueller matrix for a reflection at \( \lambda = 800 \text{nm} \) is:

\[
\begin{pmatrix}
0.9531 & 0.0469 & 0 & 0 \\
0.0469 & 0.9531 & 0 & 0 \\
0 & 0 & -0.9412 & -0.1426 \\
0 & 0 & 0.1426 & -0.9412
\end{pmatrix}
\]

The instrument polarisation \(( t_{21}/t_{11} )\) at 800 nm introduced by the aluminium coating amounts to 4.9%.

The coordinate system on the Nasmyth platform is defined that way, that the induced polarisation is \( +Q \) if the telescope is pointed at zenith \(( +Q \) is horizontal on the Nasmyth platform). But, with moving the telescope the polarisation will be transformed into components of \( U \) and \(-Q \) since the coordinate system given by the analysing system on the platform is not co-rotating.

With unpolarised incident light the reflection on mirror M3 introduces polarisation, as can be seen from the matrix element \( t_{21} \) in (4.14). As example, the Stokes vector after M3 for unpolarised incident light and the telescope pointing towards zenith is given in Fig. 4.5. This is achieved by multiplying the Mueller matrices for all wavelengths with an unpolarised incident Stokes vector \( \vec{S}_0 = (1, 0, 0, 0) \).

The upper panel in Fig. 4.5 shows the first Stokes parameter, the intensity, versus the wavelength. The lower three panels describe the normalised Stokes parameters \( Q/I \),

---

1 In principle, it doesn't matter in which direction the telescope is pointed, because a 45° inclined aluminium mirror always produces the same polarisation. But for the analysing system, the orientation of M3 relative to the Nasmyth platform defines the measured polarisation.
4.2. Polarisation studies for VLT-SPHERE

Fig. 4.5: Stokes vector for near infrared, unpolarised incident light after reflection on Mirror M3 at the VLT pointed at zenith.

$U/I$ and $V/I$, respectively. For the chosen geometry only the $Q$ polarisation direction is affected, what means, that out of an unpolarised beam an amount of about 5% linear polarisation in $Q/I$ is induced (at 800 nm). From Fig. 4.5 one can see, that the maximum of polarisation occurs around 800 nm. This is the reason, why 800 nm is chosen as representing example for the Mueller matrices.

As it is clear, that during an observation night the zenith angle of the telescope changes with time (see Fig. 4.7), also the induced polarisation due to reflection by M3 changes. For example, the Mueller matrix of M3 at 800 nm for a zenith angle of 45° is given by:

$$\mathbf{M}[M3]_{45°} = \begin{pmatrix} 0.9531 & 0.0469 & 0 & 0 \\ 0 & 0 & 0.9411 & -0.1426 \\ -0.0469 & -0.9531 & 0 & 0 \\ 0 & 0 & 0.1426 & -0.9412 \end{pmatrix}$$ (4.15)

and in Fig. 4.6 (left) the Stokes vector after M3 for the zenith angle of 45° is plotted for the whole envisaged spectral range. There, the mirror affects the unpolarised incident light exactly the same way as it was for a zenith pointing, because the relative position of the mirror seen from the incident light has remained the same, but for the observer (analysing system) on the Nasmyth platform M3 is rotated by 45° and this ends up in a rotation of the Stokes vector by 45° too. In this case, the former induced $+Q$ polarisation is now transformed into Stokes $-U$.

When we point the telescope even further away from zenith position the Stokes $-U$ component is transformed into $-Q$. In our example we point the telescope towards the

---

2 Whether it is $-U$ or $+U$ is just a question of the rotation direction of M3.
4.2. Polarisation studies for VLT-SPHERE

Fig. 4.6: Same as in Fig. 4.5 but for a zenith angle of 45° (left) and 90° (right).

horizon (which is of course just a hypothetic position). For this horizontal case the Stokes vector is also shown in Fig. 4.6 (right). In Fig. 4.7 the scattering geometry for the horizontal pointing is shown. The incident Stokes coordinate system is in a fixed position relative to M3 for all zenith angles. Only for the analysing system the geometry is dependent on the zenith angle.

Fig. 4.7: Scheme for the VLT platform. Same as in Fig. 4.4 but now the telescope is pointed horizontally, zenith angle = 90°. This is achieved by rotating mirror M3.

This is a very unpleasant side-effect of Nasmyth telescopes, which normally doesn’t bother observers not interested in polarimetry. But to achieve a sufficient accurate polarisation measurement, as it is necessary for the planet-finder, this effect must be corrected.

Compensation

There are two main disturbing effects due to the telescope. One is the polarisation direction dependency on the zenith angle and the other is the wavelength dependent induced
polarisation.

The stabilisation of the polarisation direction is achieved by introducing a half-wave plate after M3. The half-wave plate is oriented in such a way, that its optical axis is at a position angle of half the zenith angle measured from vertical position (for \( z = 0 \) the optical axis is vertical, for \( z = 90 \) the axis is rotated by 45°). The half-wave plate "flips" the vertical component of the polarisation introduced by M3 to a horizontal component (with respect to the Nasmyth platform).

Regarding the instrument polarisation, the combination of mirror M3 and rotatable half-wave plate is equivalent to a mirror M3 being always in the same position (pointed towards zenith). The normalised Mueller matrix for the aluminium coated M3 at arbitrary zenith angle \( z \) and the rotatable half-wave plate at half the zenith angle is given subsequently:

\[
M[M3 + HWP]_{z0} = \begin{pmatrix}
0.9531 & 0.0469 & 0 & 0 \\
0.0469 & 0.9531 & 0 & 0 \\
0 & 0 & 0.9412 & 0.1426 \\
0 & 0 & -0.1426 & 0.9412
\end{pmatrix}.
\] (4.16)

This is the same matrix as (4.14) except that the elements \( t_{33}, t_{34}, t_{43} \) and \( t_{44} \) are sign inverted.

In Fig. 4.8 the Stokes parameters for unpolarised incoming light after a reflection by M3 at two different zenith positions and after passing the correctly oriented half-wave plate is shown. This holds for all zenith positions.

![Stokes parameters for the reflection on mirror M3 followed by a half-wave plate.](image)

**Fig. 4.8:** Stokes parameters for the reflection on mirror M3 followed by a half-wave plate. Left, the zenith angle of M3 is 45° and right 90°. The two plots are identical, as they are also identical to Fig. 4.5 where the zenith angle is 0°.

For the compensation of the wavelength dependent instrument polarisation we consider two options which are investigated in the following paragraphs with Mueller matrix calculus:
4.2. Polarisation studies for VLT-SPHERE

**Option I: M3 (Al) with crossed mirror M4 (Al)** As we have seen, a mirror inclined by 45° induces some polarisation say in +Q direction (Fig. 4.5). By rotating the same mirror by 90° the mirror again produces polarised light but now in −Q direction. Thus, combining two mirrors of the same material (with the same optical properties) in such a way, that the incident, unpolarised light is reflected on the first mirror under an angle of 90° (incident angle 45°) in a vertical scattering plane E₁ and then led to the second mirror where it is reflected again by 90° but in a horizontal scattering plane E₂ (Fig. 4.9), the two perpendicular polarisation components, +Q and −Q cancel each other. Since both mirrors are made of the same material they both introduce the same wavelength dependent polarisation and hence, compensate for the whole spectrum.

![Fig. 4.9: Two mirrors oriented in a way to compensate their induced polarisation.](image)

The cancellation effect of two crossed mirrors (M3 and M4) at the appropriate position one relative to each other (Fig. 4.9) can also be seen in the Mueller matrix (4.17) of mirror M3 pointing at zenith and the crossed mirror M4, both aluminium coated.

\[
\mathbf{M}_{[\mathbf{M3} + \mathbf{M4}]}^{0c} = \begin{pmatrix}
0.9061 & 0 & 0 & 0 \\
0 & 0.9061 & 0 & 0 \\
0 & 0 & 0.9061 & 0 \\
0 & 0 & 0 & 0.9061
\end{pmatrix}.
\] (4.17)

This seems to be a good solution because the wavelength dependent polarisation induced by the first mirror is cancelled by the second, see Fig. 4.10. On the Nasmyth platform of the VLT M3 is present but a further, crossed mirror (M4) is not provided by the telescope standard equipment and should therefore be part of the SPHERE instrument. This is not a big disadvantage for the instrument design because it can be used as a folding mirror. M4 should be fixed on the Nasmyth platform and not be rotatable because the following optics are also mounted fix on the platform.

In combination with the mentioned HWP1 this cancellation is not dependent on zenith distance.

The Mueller matrix of the set of M3 plus appropriate positioned half-wave plate and
4.2. Polarisation studies for VLT-SPHERE

M4 (both mirrors with aluminium coating) for an arbitrary zenith angle $z$ is:

$$M[M3 + HWP + M4]_{z} = \begin{pmatrix}
0.9061 & 0 & 0 & 0 \\
0 & 0.9061 & 0 & 0 \\
0 & 0 & -0.9061 & 0 \\
0 & 0 & 0 & -0.9061
\end{pmatrix} \quad (4.18)$$

and the Stokes vector for all investigated wavelengths is shown in Fig. 4.10 where no polarisation induced by the telescope is present.

![Stokes vector of an unpolarised incoming beam after M3 (at arbitrary zenith distance), appropriately oriented half-wave plate and the crossed M4.](image)

**Fig. 4.10:** Stokes vector of an unpolarised incoming beam after M3 (at arbitrary zenith distance), appropriately oriented half-wave plate and the crossed M4.

In Fig. 4.11 a schematic design of the rotatable half-wave plate and the compensating mirror M4 is shown.

It has been shown for solar telescopes that the M3 - rotatable half-wave plate - M4 combination reduces the mirror M3 polarisation significantly (Pillet & Almeida (1991); Almeida et al. (1995)).
4.2. Polarisation studies for VLT-SPHERE

Fig. 4.11: Schematic design of the rotatable half wave plate, which will stabilise the position angle of the instrument polarisation from telescope mirror M3 and the "crossed mirror" M4, which compensates the polarisation from M3.

**Option II: M3 with gold coating** The other possible solution to compensate for the (stable) polarisation introduced by M3 is to coat the whole mirror M3 with gold, which causes a much smaller polarisation in the near infrared than aluminium does.

The normalised Mueller matrix of a reflection on a 45° inclined gold mirror at 800nm is given by:

\[
\mathbf{M}[M3(Au)]_{45°} = \begin{pmatrix}
0.9908 & 0.0092 & 0 & 0 \\
0.0092 & 0.9908 & 0 & 0 \\
0 & 0 & -0.9544 & -0.2658 \\
0 & 0 & 0.2658 & -0.9544
\end{pmatrix}
\]  

The instrument polarisation \((t_{21}/t_{11})\) at 800 nm introduced by the gold mirror is 0.9%. On the other hand the cross-talk \(U \rightarrow V\) for the gold coating given by the matrix component \((t_{43})\) is 0.2658 which is nearly twice as much as for aluminium.

Figure 4.12 shows the wavelength dependence of the induced polarisation and reflectance for a mirror with an angle of incidence of 45° with an aluminium and a gold coating. Aluminium shows a significant wavelength dependence for the polarisation and the reflectance around 800 nm which has to be considered in our calculations. The gold coating would provide a much lower polarisation. An additional advantage of the gold solution is of course the higher reflectivity compared to aluminium. Further, the crossed mirror M4 would not be necessary anymore which again would enhance the overall throughput of light.

Although the polarisation of a gold coated mirror is much smaller than the aluminium version, it does not vanish totally, and the residual polarisation is for the "blue" part of the spectrum on the order of 1% or even higher and must be corrected somewhere in the
4.2. Polarisation studies for VLT-SPHERE

Fig. 4.12: Intensity (top) and polarisation (bottom) as function of wavelength for an aluminium (solid line) coated and gold (dashed line) coated mirror for an angle of incidence of 45°.

optical path anyway. To stabilise the instrumental polarisation due to a gold coated M3 the half-wave plate would still be necessary.

An additional concern against a gold covered M3 is that the reflectivity of gold drops rapidly for wavelengths lower than about 600 nm and can therefore not be used for other visual VLT instruments.

For these reasons, a solution with the crossed aluminium coated mirrors is favoured and followed up for the rest of the thesis.
4.2.3 Instrument polarisation due to the common path

The common path system of SPHERE begins in principle with the first half-wave plate (HWP1) and the crossed mirror M4. But, from the polarimetric point of view it makes more sense to treat them together with the telescope, which was therefore done in the previous section. Hence, the common path as it is described in the actual section begins with the second half-wave plate (HWP2) and ends at the Lyot pupil stop. 11 mirrors with protected silver coatings build up this common path. The optical train is shown in Fig. 4.13 where it is obvious that all reflections on the mirrors occur under small angles of incidence (5.5° or less). Except the derotator causes three reflections under large angles, see Table 4.2. These large reflection angles are therefore the most critical points in the common path concerning the instrumental polarisation.

In this section the polarisation and the cross-talk of the 11 reflections are investigated and described by Mueller matrices for a selected wavelength of 800nm and plots of the
Table 4.2: The 11 silver coated mirrors in the common path with their angles of incidence in horizontal direction. The derotator consists of three surfaces (S1 – S3).

<table>
<thead>
<tr>
<th>mirror</th>
<th>horizontal angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Derotator S1</td>
<td>55°</td>
</tr>
<tr>
<td>2 Derotator S2</td>
<td>-20°</td>
</tr>
<tr>
<td>3 Derotator S3</td>
<td>55°</td>
</tr>
<tr>
<td>4 Toric 1</td>
<td>4.353°</td>
</tr>
<tr>
<td>5 Tip Tilt</td>
<td>-5.31°</td>
</tr>
<tr>
<td>6 Toric 2</td>
<td>5.5°</td>
</tr>
<tr>
<td>7 Deformable mirror</td>
<td>-4.5°</td>
</tr>
<tr>
<td>8 Toric 3</td>
<td>3.7°</td>
</tr>
<tr>
<td>9 Folding</td>
<td>-4.026°</td>
</tr>
<tr>
<td>10 Folding</td>
<td>5°</td>
</tr>
<tr>
<td>11 Folding</td>
<td>-5°</td>
</tr>
</tbody>
</table>

Stokes vector for the whole spectral range are shown.

All the studies are only executed for the highest precision polarimetric mode $P1$ where the derotator is in a fixed parallel or perpendicular position relative to the ZIMPOL analysing system, i.e. to the polarising beam splitter. For the subsequent polarisation calculations the derotator is in horizontal position, this means that it deflects the light only horizontally (as can be seen in Fig. 4.13 and Table 4.2). The high precision polarimetric mode $P2$ is equal to $P1$ in most system configurations, except for example that the derotator is actively correcting for field rotation. Further, mainly the mirrors are considered and less the other glass components like lenses and beam splitters. As at the time of writing this thesis (autumn 2006) not a lot was known or decided about the coatings of the surfaces of the mirrors (protected silver) and the glass components (atmospheric dispersion compensator, beam splitters, polarisation compensator plate), all calculations are made for optical elements on pure material without special coatings. It is self-evident that coatings will have a large influence on the polarisation but since the work on SPHERE is not evolved that far, it must be sufficient at the moment to work without specific coatings.
### 4.2. Polarisation studies for VLT-SPHERE

**Introduced polarisation**

The polarisation introduced by the common path is divided into three parts: the 11 silver coated mirrors, the atmospheric dispersion compensator and the dichroic beam splitter.

**11 silver mirrors** The polarisation introduced by one silver mirror of 5.5° incident angle is very low ($|Q/I| < 0.01\%$) and the whole train (without the derotator) induces a polarisation of $Q/I \approx -0.06\%$. Adding the derotator to the calculations the induced polarisation is $-2.398\%$ for the wavelength of 800 nm. The Mueller matrix for the common path at 800 nm is:

$$
M[CP] = \begin{pmatrix}
0.9766 & -0.0234 & 0 & 0 \\
-0.0234 & 0.9766 & 0 & 0 \\
0 & 0 & -0.5858 & 0.7810 \\
0 & 0 & -0.7810 & -0.5858
\end{pmatrix}
$$

(4.20)

The plot for the Stokes vector of the common path optics for the whole spectral range from 600 nm to 1000 nm is shown in Fig. 4.14 (left).

![Plot](image-url)

**Fig. 4.14**: Stokes parameters for the whole wavelength for unpolarised incident light after the common path optics alone (left) and after the whole optical train including telescope mirror M3 to the entrance of ZIMPOL (right).

Multiplication of matrix (4.18) by matrix (4.20) yields then the Mueller matrix for a full system of all 11 mirrors with the rotatable half-wave plate (HWP1) and the crossed mirror at 800 nm:

$$
M[M3 + HWP + M4 + CP] = 
\begin{pmatrix}
0.8849 & -0.0212 & 0 & 0 \\
-0.0212 & 0.8849 & 0 & 0 \\
0 & 0 & 0.5308 & -0.7077 \\
0 & 0 & 0.7077 & 0.5308
\end{pmatrix}
$$

(4.21)
4.2. Polarisation studies for VLT-SPHERE

In Fig. 4.14 (right) the plot for the Stokes vector for the whole train including the telescope and the common path is shown for an unpolarised entrance light beam.

Dichroic beam splitter The dichroic beam splitter will split the light between the near-IR (950 > \( \lambda > 2320\) nm) instruments (IFS and IRDIS) and the visual regime (450 < \( \lambda < 900\) nm) of ZIMPOL and wave front sensor. Reflection is foreseen for the visual and transmission for the near infra-red regime, i.e. a long pass filter. Important is that the dichroic beam splitter has a high efficiency and introduces no disturbing polarisation effects. Typical transmission and reflection efficiencies are according to “Mikroschichtoptik Jena” on the order of 98% or higher for the envisaged spectral range. In order to avoid polarisation effects a small inclination angle for the beam splitter plate is important (in the actual optical layout the incident angle is 8°).

The properties for the SPHERE dichroic beam splitter are at the moment (autumn 2006) almost unknown. Therefore, some key points of the dichroic beam splitter foreseen for the former CHEOPS instrument are discussed. For CHEOPS typical transmission and reflection curves, as well as the introduced polarisation were provided by the company “Mikroschichtoptik Jena”, who would also have provided dichroic beam splitters.

For the reflected light a very low polarisation < 0.1% from about 720 nm to 910 nm can be achieved. Below 720 nm there are one or two (in the range 650 nm to 720 nm) unavoidable narrow polarisation features of about 20 nm width, where the polarisation of the reflected beam \( R_p - R_s \) goes from zero to +1.5%, to -1.5% and back to zero, due to narrow reflection minima (\( R = 98\% \) instead of \( R = 99.7\% \)) which are not exactly at the same wavelength for the \( R_s \) and \( R_p \) components (\( R_s \) stands for perpendicular reflected intensity whereas \( R_p \) stands for parallel intensity). For broad band observations the positive and negative polarisation will compensate each other and only a very low residual polarisation is expected. These numbers were provided by “Mikroschichtoptik Jena” for an incident angle of 15° (design in CHEOPS), but the actual design in SPHERE foresees an incident angle of only 8°, which means that the polarisation would be even less critical.

In the following discussion the mentioned polarisation effects of the dichroic beam splitter are disregarded, since the introduced polarisation is very low. It will be shown, that such small and more or less temporary stable polarisations can easily be compensated.

Atmospheric dispersion compensator The essentially horizontal layers of the Earth atmosphere act like a prism and disperse the light of a source dependent on zenith distance (chromatic aberration of the atmosphere). For high spatial imaging resolution this effect must be corrected with an atmospheric dispersion compensator.

The atmospheric dispersion compensator for SPHERE-ZIMPOL is composed of two prisms (ADC1 and ADC2), one after the other. Each of them consists of two glass plates cemented together (glassA and glassB), thus defining three surfaces each (air – glassA, glassA – glassB, glassB – air, and in reverse direction for ADC2). The two prisms can rotate in opposite directions to compensate for the “strength” of the dispersion and the whole set of the two glass prisms rotates too, following the rotation of the pupil. At each surface polarisation can be introduced, depending on the inclination of the surfaces and
4.2. Polarisation studies for VLT-SPHERE

on the material. Surface 1 and 3 are nearly perpendicular to the incident light beam (0.04°, 0° for ADC1 and 0°, 0.04° for ADC2), and therefore not introducing polarisation. But surface 2 between glass A and glass B has an inclination angle of 11.14° which is supposed to produce some polarisation.

To know precisely the polarisation introduced at the surface between glass A and glass B the Mueller matrix of this surface should be known and for this the refraction indices of the two materials must be defined first, which is not the case up to now. Since the two glass prisms are both rotating and each in addition is rotating individually, this is a very important part of the common path concerning polarimetry because it changes its induced polarisation with time.

For the moment it is not possible to model the induced, time dependent polarisation of the ADC and it will be neglected in the following considerations of instrumental polarisation. But in a later modelling of the instrumental polarisation of SPHERE-ZIMPOL special attention must be paid on it.

Beam splitter An additional beam splitter after the atmospheric dispersion compensator will split the visual light into two separate channels. One feeding the visual wavefront sensor and the other leading into the ZIMPOL arm. The light for the wavefront is reflected by the beam splitter whereas for ZIMPOL the light in transmission is used. It must be admitted that here again little is specified about the beam splitter up to now and therefore, similar to the dichroic beam splitter, some assumptions must be adopted for the introduced polarisation. I therefore assume, that the induced polarisation is lower than 1% and temporary stable in such a way that the polarisation can be compensated afterwards by appropriate means (next section).

Because of the mentioned assumptions the introduced polarisation due to the beam splitter is neglected for the subsequent calculations of instrumental polarisation. It is thought that it contributes only to an offset in instrumental polarisation or to well defined temporary stable spectral features.

Compensation

The instrumental polarisation due to the common path optics is more or less constant over a long time (more than a night) and has no intrinsic zenith dependence, except the contribution of the ADC. Therefore, the polarisation can be corrected by a glass plate at the end of the common path, in front of ZIMPOL.

A glass plate or, more general, a dielectric plate, is made of two parallel surfaces with some dielectric material in between. For a light beam penetrating from outside (air) into the glass, traversing the glass according to Snellius’ law and exiting at the other surface into the air again, only the two surfaces are important concerning the polarisation.

The polarisation compensator plate produces some polarisation by deflecting more light from the s-polarisation component than from the p-component of the incident light (s for perpendicular and p for parallel part of the electric field vector). The angle of inclination (φ) determines how large the difference between the reflection of the s- and p-component is. The inclination angle φ is the angle between the surface normal of the
4.2. Polarisation studies for VLT-SPHERE

Plate and the incident light beam, i.e. the Nasmyth platform (see Fig. 4.15). Rotating
the plate around an axis parallel to the Nasmyth platform by the rotation angle \( \theta \), allows
to chose the direction of the induced polarisation. For this, the inclined compensator
plate must be oriented to the appropriate position angle of the instrument polarisation
to obtain a maximum cancellation of the residual instrumental polarisation. Fig. 4.15
clarifies the geometry of the glass plate and the inclination and rotation angles.

![Diagram of polarisation compensator plate on the Nasmyth platform](image)

**Fig. 4.15:** Polarisation compensator plate on the Nasmyth platform, with the two axis
it can be rotated around: the inclination axis (\( \phi \)) and the rotation axis (\( \theta \)).

The compensator plate should be retractable because it is not needed for differential
imaging. The inclination angle \( \phi \) and the rotation angle \( \theta \) may be determined from time
to time and for different observing setups by a loop of measurements, for example of a
zero polarisation standard star, or by internal calibration procedures.

The inclination of the compensator plate causes a displacement of the parallel beam.
Therefore the compensator plate is located after the coronagraphic pupil stop, in order
to avoid a re-centring of the pupil stop. The zero point for the rotation angle is defined
in such a way, that the surface normal lies in the same vertical plane for all inclinations
\( \phi \) (like in Fig. 4.15).

The Mueller matrix for a dielectric plate surrounded by air is given by:

\[
M[\text{Pol.Comp.}] = \sin 2\phi \sin 2t \begin{pmatrix}
\cos^4 \alpha_- + 1 & \cos^4 \alpha_- - 1 & 0 & 0 \\
\cos^4 \alpha_- - 1 & \cos^4 \alpha_- + 1 & 0 & 0 \\
0 & 0 & 2\cos^2 \alpha_- & 0 \\
0 & 0 & 0 & 2\cos^2 \alpha_- 
\end{pmatrix}
\]

where \( \phi \) is the incident angle on the first glass surface, \( t \) the transmission angle according
to Snellius' law and \( \alpha_\pm = \phi \pm t \) (Collett (1993)).

For a 45° inclined SiO₂ glass plate at a rotation angle \( \theta = 0^\circ \), the Mueller matrix at
800 nm has the following value:
4.2. Polarisation studies for VLT-SPHERE

\[
M[\text{Pol. Comp.}]_{\phi=45^\circ, \rho=0^\circ} = \begin{pmatrix}
0.9156 & -0.0713 & 0 & 0 \\
-0.0713 & 0.9156 & 0 & 0 \\
0 & 0 & 0.9128 & 0 \\
0 & 0 & 0 & 0.9128
\end{pmatrix}.
\] (4.23)

For the whole spectral range the Stokes parameters for the mentioned orientation of the compensator plate are shown in Fig. 4.16.

![Stokes parameters for a 45° inclined but not rotated glass plate with unpolarised incident light.](image)

**Fig. 4.16:** Stokes parameters for a 45° inclined but not rotated glass plate with unpolarised incident light.

It is also important to mention, that a SiC plate has roughly no wavelength dependence in the envisaged spectral regime, i.e. the introduced polarisation is nearly a constant value versus wavelength. For this, it is not possible to correct an instrumental polarisation which is affected by strong wavelength features with a SiO$_2$ plate for the whole spectrum. In the case of SPHERE the spectral dependence of the instrument polarisation, mainly due to the derotator, has a nearly linear wavelength dependence. The polarisation offset between 600 and 1000 nm accounts for less than 2%. Thus, it is possible to compensate the instrumental polarisation for the whole spectral range to a maximum polarisation of about ±1%. Nevertheless, in a later stage of the instrumental design it is desirable to search for a dielectric material with appropriate material to correct also for the spectral dependence introduced by the silver mirrors of the common path.

The Mueller matrix for the common path and the compensating glass plate at 800 nm
4.2. Polarisation studies for VLT-SPHERE

is:

\[ M[CP + Pol.\text{Comp.}]_{\phi=30^\circ, \theta=90^\circ} = \begin{pmatrix} 0.9078 & 0.0054 & 0 & 0 \\ 0.0054 & 0.9078 & 0 & 0 \\ 0 & 0 & -0.5447 & 0.7261 \\ 0 & 0 & -0.7261 & -0.5447 \end{pmatrix} \quad (4.24) \]

In Fig. 4.17 the Stokes parameters for the combination of the common path (with derotator in horizontal position) and the compensator glass plate in appropriate position is shown. The glass plate is in a position where it corrects for the induced polarisation in such a way that the maximum residual polarisation reaches not more than ±1% along the whole spectral range. For this case the inclination of the plate is \( \phi = 30^\circ \) and the rotation angle is \( \theta = 90^\circ \). It was not the goal to reach a minimal residual polarisation at 800 nm, as can be seen in matrix (4.24).

The selected position angles \( \phi = 30^\circ \) and \( \theta = 90^\circ \) result in a perfect polarisation correction (residual polarisation \( Q/I \approx 0\% \)) for the wavelength at about 720 nm. By changing the inclination \( \phi \) of the glass plate this "zero point" can be shifted towards different wavelengths. With this, an optimal cancellation of the instrumental polarisation for the envisaged spectral range can be achieved (remember that observations with ZIMPOL are not done for the whole spectral range of 600 to 900 nm at once but with filters of a specific spectral width. With this method time-non-dependent residual polarisations can be corrected to a reasonably low level.

Fig. 4.17: Stokes parameters for the corrected polarisation of the common path with the aid of the inclined glass plate (inclined by 30° rotated by 90°).
4.2. Polarisation studies for VLT-SPHERE

4.2.4 Telescope and common path

Now, the whole optical train from mirror M3 to the last folding mirror of the common path is simulated with Mueller calculus. Only the version with crossed mirrors (M3 & M4, both aluminium coated) is followed. A discrimination between two cases is made: first, only perfect materials are considered. This means, only aluminium and silver with theoretical refraction indices and only a retardation of exactly half a wave for HWP1 are assumed. In a second step, some aging of the materials and a non-perfect retardation of HWP1 are also considered.

Perfect materials

First, perfect coatings and perfect retardation of the half-wave plate are considered. The corresponding Mueller matrix at 800 nm for the entire system for arbitrary zenith position $z$ without correction for instrumental polarisation by the compensator glass plate is:

$$
\mathbf{M}[M3 + HWP + M4 + CP]_{z0} =
\begin{pmatrix}
0.8845 & -0.0212 & 0 & 0 \\
-0.0212 & 0.8845 & 0 & 0 \\
0 & 0 & 0.5308 & -0.7077 \\
0 & 0 & 0.7077 & 0.5308
\end{pmatrix}.
$$

In Fig. 4.18 the Stokes parameters for the whole path, i.e. from mirror M3 to the last

![Fig. 4.18: Stokes parameters for the whole instrument from mirror M3 to the last folding mirror of the common path.](image-url)
4.2. Polarisation studies for VLT-SPHERE

Folding mirror of the common path are plotted for the whole spectral range. The strong negative polarisation in $Q/I$ is mainly due to the derotator in horizontal position.

With correction for the instrumental polarisation by placing the polarisation compensator glass plate in an appropriate position the strong negative linear polarisation $Q/I$ can be reduced to a more reasonable level. The Mueller matrix of the compensator plate at 800 nm for an inclination angle $\phi = 30^\circ$ and a rotation angle $\theta = 90^\circ$ is:

$$
M[M3 + HW + M4 + CP + Pol. Comp.]_{z^2, \phi = 30^\circ, \theta = 90^\circ} =
\begin{pmatrix}
0.8225 & 0.0049 & 0 & 0 \\
0.0049 & 0.8225 & 0 & 0 \\
0 & 0 & 0.4936 & -0.6580 \\
0 & 0 & 0.6580 & 0.4936
\end{pmatrix}
$$

The aim was not to bring the polarisation to the lowest possible level at 800 nm but to ensure that the instrumental polarisation does not exceed the 1% level for the whole spectral range. Therefore, the residual polarisation at 800 nm is still quite high, $Q/I = (t_{21}/t_{11} = 0.6 \%)$. Being interested in the spectral range around 800 nm the inclination $\phi$ can be changed to obtain the minimum polarisation of less than 0.008 % at 800 nm. For this, $\phi = 27.1^\circ$ and $\theta = 90^\circ$.

Figure 4.19 shows the resulting (compensated) instrumental polarisation for the whole spectral range. The overall level of polarisation is reduced to $|Q/I| < 1 \%$.

**Fig. 4.19:** Stokes parameters for the whole instrument from mirror M3 and the common path including the polarisation compensator plate. The plate is inclined by $\phi = 30^\circ$ and rotated by $\theta = 90^\circ$. 
4.2. Polarisation studies for VLT-SPHERE

Non-perfect materials and other error sources

Due to material aging and/or manufacturing tolerances of some optical components the above discussed theoretical compensation of instrumental polarisation will be affected by deviations. Some error budgets must therefore be taken into account.

There are two main error sources for the SPHERE optical design. First, there is an uncertainty about the surfaces of the chosen materials (aluminium, silver and glass) and second there is a possible non-perfect retardation of the super achromatic half-wave plate (HWP1). Therefore, the impact of non-ideal components is investigated in more detail.

In the following paragraphs some examples of possible errors for the crossed mirrors (M3-HWP1-M4) and for the common path are discussed.

Non perfect materials for M3, HWP1 and M4  The compensation of the polarisation from mirror M3 with a “crossed mirror” M4 will only work in a satisfactory way if the surface properties (the refraction indices) of both mirrors are similar. Therefore, mirror M4 must have the same coating as mirror M3.

However, different surface properties of the evaporated aluminium coatings will not be avoidable and hence, may cause deviations in the refraction indices. Such differences arise from surface oxide layers, coating morphology, or contaminations from finger prints (acts like a dielectric layer!). Theoretical values and various measurements of the optical constants are described in detail in Smith et al. (1985).

Further, also the quality of the half-wave plate which stabilises the introduced polarisation of M3 for all zenith distances must be taken into account. Super achromatic half-wave plates available from Halle$^3$ for the spectral region 600 nm - 2500 nm have (according to Halle) exceptional good polarisation characteristics. The mean retardation of the half-wave plate is accurate to about 3\%, thus $0.500 \pm 0.015$ wave. The wavelength dependence from 600 nm to 2500 nm of the retardation is constant within $\pm 0.04$\% over the entire wavelength range. Also the wavelength dependence of the position angle of the optical axis is with $\pm 0.2$\° very small.

A retardation error of 3\% ($\lambda/2 \pm 3\%$) affects the Mueller matrix of a perfect half-wave plate mainly in the $t_{34}$, $t_{43}$ components (4.27), describing the cross-talks between circular and linear polarisation.

$$
M[HWP(\pm3\%)] = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1 (+0.0044) & 0 (\pm 0.0941) \\
0 & 0 & 0 (\pm 0.0941) & -1 (+0.0044)
\end{pmatrix} \quad (4.27)
$$

Here, we evaluate the compensation of the polarisation by two crossed mirrors if mirror M4 has optical constants as measured for a very clean, perfectly coated aluminium mirror, while mirror M3 has optical constants $n$ and $k$ which are 10\% lower, as measured for “aged” telescope mirrors and vice-versa. This is already a large difference in surface properties and a better agreement in a real instrument may be expected. In addition a non-perfect retardation of the half-wave plate is included. The presented Mueller matrices

$^3$ B. Halle Nachfl. GmbH, Berlin
4.2. Polarisation studies for VLT-SPHERE

are all evaluated for 800nm. To obtain an effect caused by the non perfect retardation of the half-wave plate a zenith angle unequal zero must be chosen. For the following cases the zenith angle \( z \) was always 45°.

Subsequently, Mueller matrices for different “error-scenarios” are presented. The errors are added to M3, M4 and/or the half-wave plate. The common path is considered to be without “error”.

- Mirror M3 with 10% lower refracting indices, half-wave plate with effective retardation of \( \lambda/2 - 3\% \), mirror M4 at theoretical refracting indices as well as a perfect common path:

\[
M[M3(-10\%) + HWP(-3\%) + M4 + CP]_{z=45°} = \\
\begin{pmatrix}
0.8801 & -0.0163 & 0.0009 & -0.0042 \\
-0.0165 & 0.8782 & -0.0117 & 0.0576 \\
0.0028 & 0.0507 & 0.5844 & -0.6559 \\
-0.0016 & -0.0295 & 0.6578 & 0.5838
\end{pmatrix}
\]  
(4.28)

- Mirror M3 with 10% lower refracting indices, half-wave plate with effective retardation of \( \lambda/2 + 3\% \), mirror M4 at theoretical refracting indices as well as a perfect common path:

\[
M[M3(-10\%) + HWP(+3\%) + M4 + CP]_{z=45°} = \\
\begin{pmatrix}
0.8801 & -0.0163 & -0.0006 & 0.0043 \\
-0.0165 & 0.8781 & 0.0078 & -0.0582 \\
-0.0029 & -0.0526 & 0.4919 & -0.7277 \\
0.0014 & 0.0260 & 0.7296 & 0.4913
\end{pmatrix}
\]  
(4.29)

- Mirror M3 with 10% lower refracting indices, half-wave plate with effective retardation of \( \lambda/2 \), mirror M4 at theoretical refracting indices as well as a perfect common path:

\[
M[M3(-10\%) + HWP + M4 + CP]_{z=45°} = \\
\begin{pmatrix}
0.8801 & -0.0164 & 0 & 0 \\
-0.0164 & 0.8801 & 0 & 0 \\
0 & 0 & 0.5396 & -0.6951 \\
0 & 0 & 0.6951 & 0.5396
\end{pmatrix}
\]  
(4.30)

- Mirror M3 with theoretical refracting indices, half-wave plate with effective retardation of \( \lambda/2 - 3\% \), mirror M4 with 10% lower refracting indices as well as a perfect common path:

\[
M[M3 + HWP(-3\%) + M4(-10\%) + CP]_{z=45°} = \\
\begin{pmatrix}
0.8803 & -0.0256 & 0.0008 & -0.0045 \\
-0.0259 & 0.8784 & -0.0107 & 0.0578 \\
0.0025 & 0.0512 & 0.5623 & -0.6749 \\
-0.0014 & -0.0286 & 0.6768 & 0.5617
\end{pmatrix}
\]  
(4.31)
4.2. Polarisation studies for VLT-SPHERE

- Mirror M3 with theoretical refracting indices, half-wave plate with effective retardation of $\lambda/2 + 3\%$, mirror M4 with 10\% lower refracting indices as well as a perfect common path:

$$
M[M3 + HW P(+3\%) + M4(-10\%) + CP]_{z=45^\circ} =
\begin{pmatrix}
0.8803 & -0.0256 & -0.0005 & 0.0046 \\
-0.0259 & 0.8784 & 0.0069 & -0.0584 \\
-0.0026 & -0.0530 & 0.4675 & -0.7436 \\
0.0012 & 0.0252 & 0.7455 & 0.4668
\end{pmatrix},
$$  \hspace{1cm} (4.32)

- Mirror M3 with theoretical refracting indices, half-wave plate with effective retardation of $\lambda/2$, mirror M4 with 10\% lower refracting indices as well as a perfect common path:

$$
M[M3 + HW P + M4(-10\%) + CP]_{z=45^\circ} =
\begin{pmatrix}
0.8803 & -0.0258 & 0 & 0 \\
-0.0258 & 0.8803 & 0 & 0 \\
0 & 0 & 0.5163 & -0.7126 \\
0 & 0 & 0.7126 & 0.5163
\end{pmatrix}.
$$  \hspace{1cm} (4.33)

All these examples of non-perfect surfaces or retardation are subject to a strong spectral dependence (not visible in the matrices (4.28) to (4.33)) caused by the spectral dependent polarisation of aluminium (M3 and M4), see also Fig. 4.20. The retardation error of the half-wave plate leads to the introduction of $U$ polarisation, which can be seen in the $(t_{31})$ matrix elements and in Fig. 4.20. The strength of this oblique polarisation is of course very low ($|U/I| \lesssim 0.3\%$) but not negligible. The strong wavelength dependent residual polarisation can therefore not be corrected to zero for the whole spectral range by the compensator glass plate anymore, since the glass plate produces more or less a flat polarisation versus wavelength.

Nevertheless, by use of the glass plate the instrumental polarisation can be corrected to values very close to zero in $Q/I$ and $U/I$ for a selected wavelength range. For example, the polarisation of the whole instrument can be kept below 0.006\% in $Q/I$ and in $U/I$ at 800 nm for a half-wave plate with a retardation error of +3\% and refracting indices of mirror M3 which are 10\% lower than "not affected" aluminium. The inclination angle of the polarisation correction glass plate is then $\phi = 24.4^\circ$ and the rotation angle is $\theta = 85^\circ$. Although it is not necessary to reduce the polarisation to such a low level and neither for both polarisation directions $Q/I$ and $U/I$ at once, since only one direction can be measured, it is a good example to show how important the polarisation compensator plate is and how powerful its use is.

In Fig. 4.20 the two Stokes parameters $Q/I$ and $U/I$ are plotted for the several combinations of defects described in the previous matrices. The whole optical train from M3 to the last folding mirror is regarded except the compensator plate. The left plot shows $Q/I$ and the right $U/I$. The zenith angle is 45°. The solid lines are the ideal case of no material or retardation deviations. The dashed lines stand for a retardation error of
+3% and the dot-dashed lines for −3%. For the $Q/I$ plot, the error of M3 is above, and the error of M4 is below the solid line. For $U/I$ the error of M3 is that with the larger absolute value, whereas the error of M4 is given by the lines which are closer to the zero line.

Fig. 4.20: Instrument polarisation $Q/I$ (left) and $U/I$ (right) as a function of wavelength for the design with the crossed mirrors M3 + HWP + M4 and the whole following common path optics. Explanations are given in the text.

Non perfect materials in the common path It has to be expected that the surfaces of the silver coated mirrors change their optical properties with time. This has an effect on the complex diffraction index $n = n_r - i \cdot n_i$ of the coating. An example for the total path (without compensator plate) with refraction indices of silver which are 10% lower than the theoretical is simulated. The mirrors M3 and M4 as well as the half-wave plate are left with the theoretical surface and retardation properties, respectively. The Mueller matrix for the described configuration is presented as follows:

$$
\begin{pmatrix}
0.8830 & -0.0231 & 0 & 0 \\
-0.0231 & 0.8830 & 0 & 0 \\
0 & 0 & 0.4587 & -0.7541 \\
0 & 0 & 0.7541 & 0.4587 
\end{pmatrix}
$$

(4.34)

The Stokes parameters for the whole spectral range from 600 to 1000 nm are plotted in Fig. 4.21.

Comparing Fig. 4.21 with Fig. 4.19 shows that the difference for the polarisation is almost just an offset between the two $Q/I$ plots. This can be corrected with the compensator plate to the same instrumental polarisation as it was with perfect silver mirrors. Optimised for the whole spectral range the Mueller matrix for the whole train with compensator plate yields again a similarly low polarisation as for the perfect silver surfaces:

$$
\begin{pmatrix}
0.8830 & -0.0231 & 0 & 0 \\
-0.0231 & 0.8830 & 0 & 0 \\
0 & 0 & 0.7541 & -0.8541 \\
0 & 0 & -0.8541 & 0.7541 
\end{pmatrix}
$$

(4.35)
4.2. Polarisation studies for VLT-SPHERE

Fig. 4.21: Stokes parameters for the whole instrument from mirror M3 through the common path without polarisation compensator plate for 10% lower diffraction indices of silver.

\[
\begin{pmatrix}
0.8203 & 0.0049 & 0 & 0 \\
0.0049 & 0.8203 & 0 & 0 \\
0 & 0 & 0.4263 & -0.7008 \\
0 & 0 & 0.7008 & 0.4263
\end{pmatrix}
\] (4.35)

and the Stokes parameters for the whole spectral range are given in Fig. 4.22. To compensate the slightly enhanced polarisation due to the 10% lower refracting indices of silver the inclination angle of the compensator plate has to be enhanced by 1° from 30° to 31°.

Non-normal incidences The half-wave plate shows also a retardation effect for non-normal incidence e.g. in the converging/diverging beam near the F/15 primary focus. This retardation effect depends on the design of the half-wave plate. We consider here a super achromatic half-wave plate from Halle, Berlin which has the following properties (according to Halle):

For rays with an angle of 2° with respect to the principle ray (maximum for a F/15 beam) the retardation is larger or smaller by up to ±0.017 wave at 600 nm or ±0.010 wave at 1000 nm. In the plane of incidence angles \((x, y)\) the retardation has a quadrant structure, where opposite quadrants have the same sign (e.g. +) in the retardation error while the two other quadrants have the opposite sign (e.g. -). Between the quadrants the retardation errors go through zero. Due to the symmetry properties of this effect, it cancels out for an incident beam where the light has for all incident angles \((x, y)\) the same polarisation, e.g. the 5% polarisation from mirror M3.
4.2. Polarisation studies for VLT-SPHERE

Fig. 4.22: Stokes parameters for the whole instrument from mirror M3 through the common path with polarisation compensator plate for 10% lower diffraction indices of the silver coatings. The inclination angle of the compensator plate has been enhanced to 31°.

Due to the non-normal incidence on M1 and M2 for rays reflected near the outer mirror edges a tangential polarisation of up to 0.3 % is introduced. In Stokes Q or U this polarisation has a similar quadrant structure as the incident angle dependent retardation effect of the half-wave plate. Thus, for a given telescope zenith angle the +U polarisation components from mirror M1 and M2 get for example a retardation by the HWP which is slightly too high, while the —U component gets a retardation which is too low. For linear polarisation the effect cancels again, but for the cross-talks between linear and circular polarisation (Q — V, U — V) the effects from the different quadrants add up and depend on the azimuth angle. However, when averaging over the entire mirror surfaces, then the cross-talk terms $t_{42}, t_{43}, t_{24}, t_{34}$ are at least a factor 2 smaller than the error for the retardation offset discussed above. Further, it has to be considered, that this effect acts only on the much smaller polarisation component < 0.3 % introduced by the mirrors M1 and M2, so that the resulting effect is more than an order of magnitude smaller than the retardation error discussed above. Therefore, we will neglect in the following discussion the small errors introduced by the non-normal incidence onto the half-wave plate in the F/15 telescope beam.

4.2.5 Polarisation efficiencies

The optical components of the telescope degrade the level of measurable polarisation from a sky object due to cross-talk effects. Thus, we have to investigate the polarisation transfer
efficiency for the considered design. SPHERE-ZIMPOL is designed for the measurement of the linear polarisation from extra-solar planets and circumstellar regions. Of interest is therefore the resulting target polarisation signal.

The VLT-SPHERE telescope/instrument polarisation transfer efficiency for linear polarisation $E_{\text{pol}}$ is defined as ratio between the measured linear polarisation after the telescope $p_{\text{meas}}$ of a target on top and the original linear polarisation of the sky target $p_{\text{sky}}$, whereas $p_{\text{meas}}$ is the net polarisation, i.e. the instrumental polarisation is already corrected:

$$E_{\text{pol}} = \frac{p_{\text{meas}}}{p_{\text{sky}}}. \quad (4.36)$$

A measurement of the Stokes vector on the sky with ZIMPOL, $\vec{S}_{\text{sky}} = (I, Q, U, V)$, yields $\vec{S}_z = T \vec{S}_{\text{sky}}$, where $T$ is the Mueller matrix of the telescope/instrument. The instrument polarisation $\vec{S}_{\text{tel,Q,U,V}} = (T \vec{S}_0)_{Q,U,V}$ where $\vec{S}_0 = (I, 0, 0, 0)$ (the indices $Q, U, V$ mean, that only these components are considered). The net Stokes vector is then:

$$\vec{S}_{\text{meas}} = \vec{S}_z - \vec{S}_{\text{tel,Q,U,V}} = T \vec{S}_{\text{sky}} - (T \vec{S}_0)_{Q,U,V}. \quad (4.37)$$

$$\vec{S}_{\text{meas}} = \begin{pmatrix} t_{11}I + t_{12}Q + t_{13}U + t_{14}V \\ t_{21}I + t_{22}Q + t_{23}U + t_{24}V \\ t_{31}I + t_{32}Q + t_{33}U + t_{34}V \\ t_{41}I + t_{42}Q + t_{43}U + t_{44}V \end{pmatrix} - \begin{pmatrix} 0 \\ t_{21}I \\ t_{31}I \\ t_{41}I \end{pmatrix} = \begin{pmatrix} t_{11}I + t_{12}Q + t_{13}U + t_{14}V \\ t_{22}Q + t_{23}U + t_{24}V \\ t_{32}Q + t_{33}U + t_{34}V \\ t_{42}Q + t_{43}U + t_{44}V \end{pmatrix}. \quad (4.38)$$

$p_{\text{meas}}$ is defined as:

$$p_{\text{meas}} = \sqrt{(t_{22}Q + t_{23}U + t_{24}V)^2 + (t_{32}Q + t_{33}U + t_{34}V)^2 + (t_{42}Q + t_{43}U + t_{44}V)^2} \quad (4.39)$$

$$t_{11}I + t_{12}Q + t_{13}U + t_{14}V$$

and $p_{\text{sky}}$ is defined as:

$$p_{\text{sky}} = \sqrt{Q^2 + U^2 + V^2} \quad (4.40)$$

$$I$$

thus, the polarisation efficiency is given by the ratio of the measured polarisation degree $p_{\text{meas}}$ and the original polarisation degree on the sky $p_{\text{sky}}$:

$$E_{\text{pol}} = \frac{\sqrt{(t_{22}Q + t_{23}U + t_{24}V)^2 + (t_{32}Q + t_{33}U + t_{34}V)^2 + (t_{42}Q + t_{43}U + t_{44}V)^2}}{t_{11}I + t_{12}Q + t_{13}U + t_{14}V} \quad (4.41)$$

$$\sqrt{Q^2 + U^2 + V^2} \quad (4.42)$$

$$I$$

$$\sqrt{Q^2 + U^2 + V^2} \quad (4.43)$$
4.2. Polarisation studies for VLT-SPHERE

Assuming that the circular sky polarisation $V$ is negligible and only Stokes $Q$ and $U$ are measured ($\Rightarrow$ neglect all matrix elements with $t_{4*}$) $E_{\text{pol}}$ is simplified to:

$$E_{\text{pol}} = \frac{\sqrt{(t_{22}Q+t_{23}U)^2+(t_{32}Q+t_{33}U)^2}}{t_{11}I+t_{12}Q+t_{13}U}.$$  \hspace{1cm} (4.44)

Without loss of generality Stokes $Q$ and $U$ shall have the same value $p$, which is the linear polarisation in one arbitrary direction, and since $t_{11}I \gg t_{12}Q + t_{13}U$, one can write:

$$E_{\text{pol}} \approx \frac{p\sqrt{(t_{22}+t_{23})^2+(t_{32}+t_{33})^2}}{t_{11}I}.$$  \hspace{1cm} (4.45)

At the end this equation is simplified to:

$$E_{\text{pol}} \approx \frac{\sqrt{(t_{22}+t_{23})^2+(t_{32}+t_{33})^2}}{t_{11}\sqrt{2}}.$$  \hspace{1cm} (4.46)

For the case of the crossed mirrors, the whole common path and a best aligned polarisation compensator, the efficiency for linearly polarised light at 800 nm is:

$$E_{\text{pol}} = 0.8247.$$

In principle, if one is only interested in how a 100% $Q$-polarised light beam $\vec{S}_{\text{sky}} = (1, 1, 0, 0)$ is transmitted through the system, equation (4.44) changes into the very simple form:

$$E_{\text{pol}} \approx \frac{\sqrt{t_{22}^2 + t_{32}^2}}{t_{11}}.$$  \hspace{1cm} (4.47)

which is in our case at 800 nm $E_{\text{pol}} = 100\%$. If one wants to measure the $U$-polarisation on the sky only the second half-wave plate (HWP2) is rotated by 22.5° and the sky-$U$ signal is changed into a $Q$ signal and can therefore be measured with the same efficiency as the sky-$Q$ signal.

4.2.6 About Aluminium

Aluminium, when exposed to air forms rapidly an aluminium-oxide layer ($\text{Al}_2\text{O}_3$). Once formed, it protects the underlying aluminium from further oxidation. The thickness of the layer was measured during polarimetrie studies to be in the range of 20 to 55 Å when simply exposed to the atmosphere (Smith et al. (1985)). The oxide layer has practically no influence in reflectance for infrared light from about 6 μm to 180 μm (Smith et al. (1985)) but a high decrease in reflectivity for ultraviolet light. For example, at 121.6 nm a 17 Å thick layer reduces the reflectivity by a factor of two compared to the absence of an oxide layer.
4.2. Polarisation studies for VLT-SPHERE

The used complex refraction indices for Aluminium in the thesis were primarily based on the Kramers-Kroning analysis of reflectance measurements of ultra-high-vacuum films by Shiles et al. (1980). Ellipsometric measurements of the complex refraction index were performed by Mathewson & Myers (1971) leading to a determination of the indices comprising the oxide layer, because the measurements are performed using polarimetry. This would exactly be the way to get the refracting indices to calculate the induced polarisation, but unfortunately they are not available for such a dense grid of wavelengths, and an interpolation would comprise indeterminable uncertainties. Therefore, I decided to work with the indices from Shiles et al. (1980), knowing that the values differ slightly from the (for our purpose) more accurate numbers derived by the ellipsometric method from Mathewson & Myers (1971).

4.2.7 About Silver

The optical properties of silver were obtained by using polarimetric methods for the spectral range of 0.36 μm to 2.07 μm by Winsemius et al. (1976). They used polycrystalline silver of more than 99.999 % purity and measured the refracting indices \( n \) and \( k \) in vacuum using a polarimetric mode described in Beattie (1955). Because of the polarimetric method they used to determine the refraction indices for silver the indices are well suited for the purpose to calculate the polarimetric properties of the metal.

Nevertheless, one has to bear in mind, that it is not possible to use pure silver because silver reacts very willingly with sulfur and compounds of sulfur which are always present in the air. Therefore, the silver coated mirrors of the common path will be covered with protecting layers. But, up to now, little is known about the protection coatings which will be used for the silver mirrors in SPHERE and I therefore made all calculations for pure silver coatings.

4.2.8 Discussion

The presented Mueller matrix calculations give a good estimate about the instrumental polarisation, the cross-talk and the zenith dependent properties of single optical components but also for the whole train from the Nasmyth folding mirror M3 to the last mirror of the common path. It has been shown, how the rotation of M3 changes the introduced polarisation. The introduction of a super achromatic half-wave plate after M3 has demonstrated to stabilise the instrumental polarisation very accurately to a fixed value for all zenith distances. To reach this goal, it must be assured that the half-wave plate co-rotates with the zenith distance, but with only the half angular velocity. To compensate this (now stable) polarisation of the aluminium coated (and therefore strongly wavelength dependent) mirror, the solution with the “crossed mirror” M4 was presented and the Mueller matrix of the whole set of M3, half-wave plate and M4 was calculated for different zenith angles. It was shown, that this solution leads to a completely erasure of instrumental polarisation.

Further, the influence of the common path optics was calculated for the 11 silver coated mirrors and sketched for several refraction optics. Silver produces a spectrally much less
4.2. Polarisation studies for VLT-SPHERE

dependent polarisation and must therefore not be corrected with a similar “crossed mirror” solution. Nevertheless, also the common path optics introduce some polarisation, particularly the derotator, which must be corrected before an accurate ZIMPOL measurement can be obtained. This can be achieved with the polarisation compensator plate right in front of the ZIMPOL modulator.

Mueller calculus is very powerful and in principle the Mueller matrix of the whole telescope can be calculated for each wavelength and each configuration of the optical elements if the materials used are known well enough. Therefore, some possible errors were addressed and discussed. The conclusion is that only the uncertainties for the materials of M3 and M4 as well as the possible non-perfect retardation of the half-wave plate are of vital importance. A deviation of the surface properties of the common path components (mainly silver) has only the consequence of an offset of the instrumental polarisation, which can be corrected by different inclination angles of the compensator plate. Even if the compensator plate would differ from the theoretical surface properties only a different orientation of the plate would be the consequence. This holds for all optical components as long as there is no temporal and spectral feature introduced (ADC), i.e. as long as the instrumental polarisation is just variable in strength (up to a certain amount) but more or less constant for all zenith distances (time) and for the wavelength, it can be compensated by the glass plate.
Part II

Polarimetry of the solar system gas planets
Chapter 5

Theoretical aspects

Radiation from an unresolved, centrosymmetric star is normally unpolarised due to the fact that many photons, each polarised in one “arbitrary” direction, escape from the source towards the observer with no preferred polarisation direction. The average of the polarisation directions of all photons from the star detected by the observer results in zero polarisation.

In spite of this, many stars are strongly polarised and even used as high polarisation standard stars for the calibration of polarimetric measurements (for example in Serkowski (1974)). This is mostly not an intrinsic polarisation but rather produced on the way between the star and the observer. Non-centrosymmetric interstellar dust particles in the line of sight can be aligned in one preferred direction, due to a magnetic field. Different absorption cross sections for different polarisation directions can therefore result in a net polarisation at the observers place as described for example in Serkowski’s work on interstellar polarisation (Serkowski (1973)).

But also an intrinsic polarisation of a star can occur if the star is not centrosymmetric. An unresolved star of ellipsoid shape produces polarised light (Serkowski (1970)) on the order of up to about 1% (Al-Malki et al. (1999)).

On a spatially resolvable star like the Sun, one can measure polarised light at some regions on the Sun, at the location of a sunspot for instance due to the Zeeman effect or at the solar limb due to scattering polarisation. Nevertheless, integrated over the whole Sun the resulting polarisation is close to zero. Kemp et al. (1987) measured in 1986 that the disc integrated linear polarisation of the Sun is lower than 2·10^{-7} in the visual.

These examples are typical for producing polarised light in astronomy and have one common property – the violation of symmetry. Hence, one can say, that polarisation in astronomy is likely where asymmetry is present. In the cases above, different absorptions for different polarisation states, non centrosymmetric shape of a star, scattering at a limb and magnetic fields are the reasons for asymmetry.

The Zeeman effect and the non-centrosymmetric shape of a star are rather the reason for the generation of polarised light at the origin of the emitted photons, whereas scattering and different absorption influence the polarisation state of light anywhere between the source and the detector. The interstellar absorption for different polarisation directions is strongly dependent on the amount of interstellar dust between the source and the detector, thus on distance. Strong interstellar polarisation occurs mainly for stars with distances much larger than 100 pc (Krautter (1980)) dependent on the galactic coordinates (Serkowski (1973)). Being interested in the polarisation signal of a planet, scattering will
be the main reason for the generation of polarised light.

In this chapter we discuss the scattering of light and how polarisation can be produced in a planetary atmosphere, whereas in the next chapters the measured polarisation of planets is discussed in detail. The short summary about scattering of light is just a rough abstract, since more detailed descriptions can be found in several textbooks, like in van de Hulst (1980) or in Chandrasekhar (1950).

5.1 Scattering of light

When Maxwell wrote his set of fundamental equations describing electromagnetism it came to a surprise to him and his contemporaries that these differential equations had waves as solution which were propagating with the speed of light. What had electromagnetism to deal with light? After the work of Lorentz, Hertz and Zeeman the only conclusion was that a unifying theory was found between electromagnetism and optics. With this unification of electromagnetic fields and light a lot of phenomena in optics could be described using Maxwells electromagnetic theory. The phenomenon of scattering was such an application.

Scattering of an electromagnetic wave is in principle a re-emission of the wave by a charged particle after very short time. The electric field vector of the incident wave, $\vec{E}$, accelerates a free electron according to

$$m\ddot{r} = -e\vec{E}. \quad (5.1)$$

Since the incident electric field is oscillating with the angular frequency $\omega$,

$$\vec{E}(t) = \vec{E}_0 e^{i(\omega t + \delta)}, \quad (5.2)$$

the acceleration changes sign with a frequency of $2\omega$. Accelerated charges radiate electromagnetic waves (Jackson (1962)) dependent on the scattered direction. Thus, the incident wave is re-emitted.

The charged particles are mostly electrons and one can distinguish between scattering by a free and a bound electron. If the accelerated charge is a free electron the scattering is of Thomson type and if the electrons are bound further distinctions are made. If the incident wave has a wavelength much larger than the scatterer (atom, molecule, ...) then the scattering is of Rayleigh type. For wavelengths smaller than and comparable with the size of the (spherical) scatterer the related scattering is of Mie type. For the case of Rayleigh scattering the incident electric field can be treated as a homogeneous field for the entire scatterer, which leads to a simplification of the scattering theory. The scattered intensity for the Rayleigh case is strongly wavelength dependent ($\propto \lambda^{-4}$).

For the case where the electron is bound in an atom, equation (5.1) must be completed with an additional term accounting for the "circling" of the electron around the atomic nucleus. This semi-classical description of the atom leads to a harmonic oscillation of the electron in three directions described by the angular frequency $\omega_0$. Thus, equation (5.1) changes into the following type:

$$m\ddot{r} + \omega_0^2 m\dot{r} = -e\vec{E}. \quad (5.3)$$
5.2 Scattering geometry of planets and the second order scattering effect

This is a non homogeneous differential equation which can be solved for the accelerations in $x$ and $y$ directions for the incident light travelling along the $z$ axis.

With the accelerations one can calculate the radiation of the light for each direction according to the theory of electrodynamics. Collett (1993) derives then the Stokes parameters for the scattered light dependent on the scattering direction.

Scattering at a planetary atmosphere is mostly scattering by atoms, molecules and aerosols and less by free electrons. Whereas the scattering by atoms and molecules is of Rayleigh type, aerosols, which can be much larger (Morozhenko & Yanovitskii (1973)), scatter according to the Mie theory.

5.2 Scattering geometry of planets and the second order scattering effect

Scattered light can be polarised. Light from our solar system planets reaching the Earth is mainly scattered solar light, thus, under certain circumstances, polarisation should be measured.

For planets one introduces the phase angle $\phi$, which is the angle between planet-Sun and planet-observer. It has therefore nothing to do with the phase of a wave. The phase angle $\phi$ reaches from $0^\circ$ (opposition) to $180^\circ$ (conjunction).

All outer gas planets of our solar system can only be observed under small phase angles from Earth. The maximum phase angle for Jupiter is $\approx 11.7^\circ$, for Saturn $\approx 6.4^\circ$, for Uranus $\approx 3.2^\circ$ and for Neptune it is $\approx 2.0^\circ$. Small phase angles means that the planets are observed under a back scattering geometry and back scattered light (after one scattering) has no preferred orientation of the electric field vector, thus, is unpolarised. Therefore, observing one of the four giant gas planets should always result in a very low polarisation and for opposition the polarisation should be zero (van de Hülst (1980)).

But already Lyot (1929) observed for example the polarisation on Jupiter when the planet was at opposition. He also observed different polarisation strengths at the Jovian poles compared to the equatorial regions indicating different atmospheric properties for the two regions. Nevertheless, for exact opposition no atmosphere would produce polarisation for single back scattering. Thus, multiple (Rayleigh) scattering must occur to produce polarisation at opposition (van de Hülst (1980)). A hint to multiple scattering was also that the polarisation direction was mostly oriented in radial direction in Lyot's observations.

Particularly photons scattering twice can produce a significant amount of polarisation for planets at opposition:

**Second order scattering effect** Assume the geometry of opposition. Light from the Sun shall be reflected by the planetary atmosphere and then detected by an observer on Earth. Suppose that each photon is scattered twice before it can escape from the atmosphere and be detected by the observer. Photons which scatter in forward or backward directions first must scatter the second time in backward and forward
5.2. Scattering geometry of planets and the second order scattering effect

direction, respectively, to be detected by the observer. Hence, no polarisation would arise because each polarisation direction is equally probable.

Light scattered the first time in perpendicular direction is polarised perpendicularly to the scattering plane. The second scattering towards the Earth doesn’t change the polarisation state of the light, thus it is still perpendicular to the first scattering plane. It leads to no net polarisation if all perpendicular first scatterings are equally probable and all photons reach the observer after the second scattering. This is the situation for the centre of a planetary disc at opposition if the atmosphere is homogeneous.

As already mentioned, polarisation always occurs when the symmetry is violated. This is the case at the planetary limb where the sunlight is incident at grazing angles. Consider again photons incident at a homogeneous planetary atmosphere at the limb of the planet, say, at the northern limb. Forward and backward scattering produces again no polarisation. Scattering upwards results in an enhanced probability of escaping from the atmosphere because of decreasing density. Scattering downwards means traversing towards higher density, which results in a higher possibility of being scattered multiple times or being absorbed. Only light scattering left or right and then back to the observer results in being polarised perpendicularly to the limb. For better comprehension Fig. 5.1 shows a sketch of the scattering geometry. The vertical density distribution is in this example the asymmetry.

![Fig. 5.1](image.png)

Fig. 5.1: Sketch of the second order scattering effect as described in the text for a planet in opposition. The incident light is undergoing two scatterings at a grazing angle at the limb of the planet. Light scattered back to the observer is polarised perpendicularly to the limb. The solid arrows designate the polarisation directions of the light whereas the dashed lines indicate the propagation direction of the light. Points 1 and 2 are the positions where the scattering occurs.

The second order scattering effect produces polarisation perpendicularly to the limb for opposition geometry. This effect is described by van de Hulst (1980). The first mea-
5.2. Scattering geometry of planets and the second order scattering effect

Measurements of the second order scattering effect for Uranus and Neptune are presented in Schmid et al. (2006b), Joos & Schmid (2007) and in this thesis.
Chapter 6

Polarimetric measurements of the solar system gas planets

The main driver for ZIMPOL within the planet finder-instrument is the fact that light reflected by a planetary atmosphere can be polarised.

The amount of polarisation, the polarisation degree, depends on the phase angle and on the atmosphere of the planet. Since we neither know the composition of an extra-solar planet's atmosphere nor the phase angle of the observed extra-solar system, an observer searching for a polarised signal of an extra-solar planet doesn't know what he is looking at. Nevertheless, it is possible to make some assumptions.

The highest possibility for an extra-solar planet to be detected by means of polarimetry is a large gas planet (Jupiter-sized) at a "convenient" separation to its harbouring star. Convenient means that the planet is not to far away from the star in order to reflect enough light but as far as to be distinguishable from the star. In addition, an atmosphere of the extra-solar planet which produces a lot of polarisation, similar to that of Uranus or Neptune (Schmid et al. (2006b); Joos & Schmid (2006); Joos & Schmid (2007)) or the polar regions of Jupiter (Smith & Tomasko (1984); Joos et al. (2005)) is desirable.

From radial velocity observations we know that most detected exo-planets up to day are Jupiter-sized planets (or larger) orbiting their star in very close distances (Marcy et al. (2005) and http://exoplanet.eu).

Extra-solar planets are also found by measuring an eclipse caused by the planet transit in front of its star (transiting). Much less planets are found with this method compared with the radial velocity method, but the few planets found are also large and near to their parent star.

From the parameters of the detected extra-solar planets (size or mass and semi-major axis of the orbit) one could credulously assume that the close orbits and the large sizes and masses of the found planets is a generic property. But to understand why predominantly "hot-Jupiters" have been detected one has to look at the probabilities of detecting an extra-solar planet by the means of radial velocity (Benz et al. (2005)) and transit.

The radial velocity method measures the Doppler shift of the star light, caused by the wobbling of the star around the centre of gravity of the star-planet system. High radial velocities are easier to detect. High radial velocities are caused by planets with large mass (moves the centre of gravity further away from the centre of the star) and small separations (causes a faster circling around the centre of gravity). Therefore, hot-Jupiters have a higher probability to be detected by radial velocity method.
Let's make a short example, how the radial velocity depends on the distance of the star and the planet: A Jupiter-Sun system causes a radial velocity for the Sun of about 12 m/s, if the mean distance of Jupiter to the Sun is 5.2 AU. Would Jupiter instead be at a distance of only 1 AU, the radial velocity would rise to about 28 m/s or, at a distance of 20 AU it would decrease to about 6 m/s.

But also for the transiting method large (not necessarily heavy) and close-in planets are due to simple geometric reasons the most promising candidates to be detected.

These two cases show that with the mentioned detection methods it is most probable to detect hot Jupiters, which doesn’t mean at all that the majority of extra-solar planets are of this type. The best counter evidence that there are also Jupiters at larger separations from the central star is, of course, Jupiter.

If we have a look at our giant planets at large separations from the Sun, i.e. Jupiter, Saturn, Uranus and Neptune, we find that they all gas planets with deep hydrogen, helium and methane atmospheres (Lunine (1993); Karkoschka (1998)), whereas the inner planets from Mercury to Mars are rocky planets. From the polarimetric point of view, giant extra-solar gas planets are the best candidates to be detected (Schmid et al. (2006a)). Therefore, we observed our giant gas planets to determine the polarimetric properties of their atmospheres.

Jupiter is at a mean distance of 5.2 AU from the Sun and Neptune at about 30 AU. This means that those planets are always seen from Earth under a very small phase angle, i.e. in a backscattering situation. The maximum phase angle for Jupiter is about 11°. Under such small angles the expected polarisation, integrated over the whole planetary disc is only on the order of 0.5%, as measured by Morozhenko & Yanovitskii (1973) for a phase angle of 10° at 7200 Å and not directly comparable with the possibly high polarisation due to large phase angles of extra-solar planets. Nevertheless, knowing more about the polarisation properties of our gas planets helps extrapolating the expected, disc integrated, polarisation of a similar extra-solar planet. Further, accurate measurements are needed to compare model results with them.

For these reasons, disc resolved spectropolarimetric and imaging polarimetric measurements where made for the four giant gas planets Jupiter to Neptune. We were also seeking to detect an anticipated limb polarisation of planets which scatters mostly Rayleigh like, due to a second order scattering effect, see van de Hulst (1980). The spectropolarimetric measurements and results of our four giant gas planets are presented in the following sections.
6.1 What is known about polarimetry of gas planets up to now

Uranus & Neptune Because of the large distance of these two planets and because of the very small phase angles under which they can be observed, only few polarimetric measurements of the two planets have been obtained up to now.

Michalsky & Stokes (1977) have measured the temporal variation of the Uranus whole-disc polarisation in the visual spectrum, i.e. aperture polarisation. They measured the disc integrated polarisation for various phase angles from 1975 to 1976. At the maximum of the phase angle (at \(\approx 3^\circ\)) they measured a positive polarisation in the blue (\(\lambda_c = 4500\,\text{Å}\)) of about 0.05%. Whereas for phase angles around 1° a negative polarisation of about \(-0.01\%\) was measured. For the red part of the spectrum (\(\lambda_c = 6650\,\text{Å}\)) a flatter phase curve was measured with a maximum polarisation of about 0.02% at the maximum phase angle and also \(-0.01\%\) at 1° phase angle.

Schempp & Smith (1984) obtained disc integrated high spectral resolution spectropolarimetry of Uranus for the methane absorption line at 6818.8 Å. They measured the polarisation degree \(p = \sqrt{Q^2 + U^2} \approx 5\%\) in the line core of the absorption line.

Jupiter Jupiter is the most frequently and accurately observed gas planet by means of polarimetry because of its apparent size.

Lyot (1929) and Dollfus (1957) made polarimetric observations of Jupiter in visible light during several nights over many years. They found a very small polarisation at the centre of the disc for opposition and a polarisation on the order of \(-0.5\%\) for the maximum phase angle. For the polar regions they measured a positive and enhanced polarisation of up to 7% which was not dependent on the phase angle. They found variations (up to 1%) of the polarisation degree (\(p\)) at each polar region from day to day. In 1923 the polarisation at the South Pole was larger than at the North Pole, in 1926 they were equal (Lyot (1929)) and in 1955 the polarisation in the North was larger than in the South (Dollfus (1957)). The equatorial region was always found to be small from the centre of the disc until 0.15 – 0.2 diameters from the limb, where the amounts and orientations changed from day to day. An average of 19 nights yielded an enhanced polarisation (\(\Delta p = 0.13\%\)) at the western limb (Lyot (1929)). Neither Lyot nor Dollfus found a polarisation structure coinciding with the band structure of Jupiter.

Hall & Riley (1974) observed Jupiter in ultra-violet showing that the polarisation in the disc centre is comparable with the visual measurements but that near the poles the polarisation is larger at shorter wavelengths. There were no polarised disc features (belts and zones) observed. There was already an enhanced polarisation detected at the limbs, not only at the poles but also at the equatorial limbs. The polarisation direction was always perpendicular to the limb. These measurements
6.1. What is known about polarimetry of gas planets up to now

indicated that multiple scattering must occur to produce the radial polarisation.
Pioneer 10 and Pioneer 11 delivered polarimetric data of Jupiter for phase angles
of 40° – 150° (Smith & Tomasko (1984)). Pioneer measured polarisation degrees of
up to 50% at the poles of Jupiter but still no polarised structure correlating with
the band structure for lower latitudes.

Wolstencroft & Smith (1979) measured the polarisation in the methane band at
7250 Å to be enhanced compared to the adjacent higher albedo regions. They mea-
sured the disc integrated spectropolarimetric signal.

**Saturn** Pioneer 11 obtained polarimetric measurements of Saturn for phase angles reach-
ing from 15° to 160°. Only the intermediate and low latitudes were observed but not
the poles. An increasing polarisation was measured towards the limbs and higher
latitudes. The disc centre displayed a positive polarisation (perpendicular to the
scattering plane) of about 10% at a phase angle of 100°. Further, zonal variations
of the polarisation were observed (Tomasko & Doose (1984)).

The measurements presented here for Uranus and Neptune are the first of their kind.
In the literature no disc resolved spectropolarimetry of Uranus and Neptune was found,
nor were publications found about disc resolved spectropolarimetry of Jupiter. Only
disc integrated spectropolarimetry was measured by Wolstencroft & Smith (1979) and
by Smith & Wolstencroft (1983). Hence, the measurements of Jupiter presented in this
thesis are the first of its kind.

The same applies to our measurements of Saturn, where no measurements of disc
resolved spectropolarimetry have been published before. Only one paper about disc in-
tegrated spectropolarimetry has been found in the literature by Smith & Wolstencroft
(1983).

Our disc resolved spectropolarimetric measurements of the giant gas planet are very
important for future comparisons of scattering models comprising polarimetry of the plan-
etary atmospheres.
6.2 Instrument, observations and data reduction

During two nights in 2003, on November 29 and 30, polarimetric observations of our giant gas planets were made at the ESO 3.6 m telescope at La Silla, Chile. During the same run spectropolarimetric observations (Joos & Schmid (2007)) and imaging polarimetry (Schmid et al. (2006b)) were accomplished. In this thesis the spectropolarimetric data are presented.

In Table 6.1 the phase parameters for the planets for the 29./30. November 2003 are summarised:

<table>
<thead>
<tr>
<th>parameter</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>apparent diameter</td>
<td>$33.58''$, $35.91''_e$</td>
<td>$18.60''_p$, $20.23''_e$</td>
<td>$3.51''$</td>
<td>$2.24''$</td>
</tr>
<tr>
<td>phase angle</td>
<td>$10.4^\circ$</td>
<td>$3.7^\circ$</td>
<td>$2.8^\circ$</td>
<td>$1.7^\circ$</td>
</tr>
<tr>
<td>position angle of the South Pole</td>
<td>$-154^\circ$</td>
<td>$173^\circ$</td>
<td>$78^\circ$</td>
<td>$169^\circ$</td>
</tr>
<tr>
<td>centre to South Pole distance</td>
<td>$16.78''$</td>
<td>$8.27''$</td>
<td>$1.62''$</td>
<td>$0.97''$</td>
</tr>
</tbody>
</table>

Table 6.1: Planetary phase parameters for the 29./30. November 2003. The subscripts $p$ and $e$ stand for "polar" and "equatorial". The planetary parameters are taken from "The Astronomical Almanac 2003".

In the next three sections the instrument setup, the observations and the data reduction are described in detail for the case of spectropolarimetry.

6.2.1 Instrument

The used telescope is the ESO 3.6 m telescope in La Silla, located at an altitude of 2400 m above sea level. It was commissioned in 1977 and completely upgraded in 1999. The mounting is equatorial of horseshoe/fork type. The diameter of the primary mirror is 3.566 m and the focal ratio is f/8.09. This yields an image scale at the primary focal plane of 7.12''/mm. Interchangeable instruments can be attached at the Cassegrain focus.

We used EFOSC2 (ESO Faint Object Spectrograph and Camera 2). EFOSC2 is a multi-mode Cassegrain imager and grism spectrograph which can be equipped with a Wollaston prism and a rotatable super achromatic half-wave plate for linear polarimetry and spectropolarimetry.

The instrumental setup for spectropolarimetry contains an entrance slit at the prime focus and a collimator lens to make the light beam parallel. The polarimetric components follow, which are a half-wave plate and a polariser. A grism disperses the light spectrally onto a field lens, which produces an image of the slit at the CCD. The setup is shown in Fig. 6.1 and summarised in Tabl. 6.2. For the sake of completeness the setup for imaging polarimetry is given too.

The used spectrographic slits had widths of 0.5'' (slit#0.5) and 1.5'' (slit#1.5), respectively. The slits were divided into slit-lets of 19.7'' length at a period of 42.2'' by a special mask. The slit masks are called Wollaston masks and are oriented perpendicularly to the long slit. The Wollaston masks are needed because the Wollaston beam splitter produces two orthogonally polarised beams out of one unpolarised, i.e. produces two images on the
6.2. Instrument, observations and data reduction

**EFOSC 2: A schematic diagram of the instrument**

![Schematic diagram of EFOSC 2](http://www.ls.eso.org/lasilla/sciops/3p6/efosc/docs/Efosc2Diagram.html)

Fig. 6.1: Layout of EFOSC2 from http://www.ls.eso.org/lasilla/sciops/3p6/efosc/docs/Efosc2Diagram.html.

CCD out of one. Therefore, at least half of the slit must be occulted to avoid superposition of the two polarisation directions, see also Fig. 6.2.

For changing the polarisation direction to be measured, for example from $+Q$ to $-Q$ or to $\pm U$, a super achromatic half-wave plate was used. Rotating the half-wave plate by an angle $\varphi$ yields a flip of the measured polarisation by $2\varphi$, e.g. rotating the half-wave plate by $45^\circ$ yields an exchanging from $+Q$ to $-Q$ directions, and vice versa.

<table>
<thead>
<tr>
<th>Spectropolarimetry</th>
<th>Imaging polarimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slit (Spectropolarimetric mask)</td>
<td>Wollaston mask</td>
</tr>
<tr>
<td>Collimator</td>
<td>Collimator</td>
</tr>
<tr>
<td>Half-wave plate</td>
<td>Half-wave plate</td>
</tr>
<tr>
<td>Wollaston prism (20&quot;)</td>
<td>Filters</td>
</tr>
<tr>
<td>Grism</td>
<td>Wollaston prism (10&quot; or 20&quot;)</td>
</tr>
<tr>
<td>Shutter</td>
<td>Shutter</td>
</tr>
<tr>
<td>Field lens</td>
<td>Field lens</td>
</tr>
<tr>
<td>CCD</td>
<td>CCD</td>
</tr>
</tbody>
</table>

Table 6.2: Setup at EFOSC2 for spectropolarimetry and imaging polarimetry, respectively
6.2. Instrument, observations and data reduction

The polariser is a Wollaston prism. It splits the (unpolarised) image of an object into 2 images of orthogonal polarisation directions I|| and I⊥ (the ordinary and extraordinary beam). The 2 images are separated with respect to the location where the unpolarised image would have been in absence of the prism. They are offset by 20″ on the CCD.

The orientation of the image separation caused by the polariser, can be changed by rotating the Wollaston prism in its wheel. In EFOSC2 the prism is aligned so as to split the image either along the x- or the y-axis of the CCD. But, since the dispersion axis at EFOSC2 is always along the y-axis on the CCD the two spectra must be split along the x-axis for spectropolarimetry.

![Diagram of spectropolarimetry setup]

**Fig. 6.2:** Setup for spectropolarimetry. Left: spectroscopic long slit with occultation mask dividing the slit into 5 slit-lets. Right: same as left but with the Wollaston prism and grism introduced after the slit. The Wollaston splits the image of the slit horizontally whereas the grism disperses the light vertically. The object at the left is now spectrally re-imaged and polarimetrically divided at the right image (indicated with PS1 and PS2). The nominal position of the slit-lets is indicated for orientation reasons. (Figure from the EFOSC2 site: http://www.ls.eso.org/lasilla/sciops/3p6/efosc/docs/Efosc2PolarElements.html)

The employed grism (EFOSC2 grism#5) covers the wavelength range of 5200 - 9350 Å and provides a spectral resolution of 12.8 Å for a 1′′ wide slit.

The detector is a Loral/Lesser, Thinned, AR coated, UV flooded, MPP chip with a ESO-FIERA controller (ESO CCD#40). The CCD Size is 2048 × 2048 pixels with a pixel size of 15 μm × 15 μm. At the focal plane this leads to an image scale per pixel of 0.157″ × 0.157″ and a wavelength scale of 2.06 Å per pixel. The useful field size is 5.2′ × 5.2′. The full well capacity is reached with 104'000 electrons/pixel and the dark current is measured to 7 electrons/pixel/hour. A pixel is saturated at 65535 ADU.
6.2.2 Observations

Measurements with different orientations of the spectrographic slits were made depending on the target. For this the whole instrument was rotated. For Uranus the celestial orientations were North - South and East - West, whereas for Neptune only the North - South orientation was measured. Jupiter and Saturn were observed with the slits in North - South and in East - West directions in planetary coordinates.

The linear polarisation was measured in a standard way as described in Tinbergen & Rutten (1992) with sets of four exposures taken with half-wave plate position angles of 0°, 22.5°, 45° and 67.5°, respectively. Three sets were taken for each slit orientation and all planets (except Jupiter North, where only two sets could be used) in order to enhance the signal-to-noise.

For a measurement of an object in Q direction two independent exposures (with the same integration time) must be made with half-wave plate position at 0° and 45°. These two exposures lead to four long-slit spectrograms of the same object: \( I_\parallel (0°) \), \( I_\perp (0°) \), \( I_\parallel (45°) \) and \( I_\perp (45°) \), where the \( \parallel \) and \( \perp \) signs stand for the parallel and perpendicular or ordinary and the extra-ordinary beams on the CCD and the angle in brackets for the position of the half-wave plate. For the measurement in U direction again two exposures must be done, one with the half-wave plate at 22.5° and one at 67.5°. Again, this leads to four spectrograms of the same object, namely: \( I_\parallel (22.5°) \), \( I_\perp (22.5°) \), \( I_\parallel (67.5°) \) and \( I_\perp (67.5°) \). Thus, to obtain the three Stokes parameters \( I \), \( Q \) and \( U \), four exposures are necessary leading to eight spectrograms of the object. In principle a Stokes Q or U measurement could be achieved with one exposure since this yields the two orthogonally polarised spectrograms of the object. But the combination of two measurements with different half-wave plate orientations (different by 45°) leads to a reduction of the gain effects of the instrument and temporal transmission effects due to the atmosphere as described in Tinbergen & Rutten (1992).

One exposure was 30 s for Uranus, 50 s for Neptune, 3 s for Jupiter and 5 s for Saturn. The effective seeing for our spectropolarimetric data was about 1" as derived from the width of the spectra of the standard stars.

The polarisation zero point of the instrument was derived and corrected from an unpolarised (HD 14069) and a polarised (BD +25°727) standard star. The instrumental polarisation was found to be less than 0.2%. According to the EFOSC2 documentation the instrumental polarisation should be less than 0.1% for the central parts of the CCD (http://www.ls.eso.org/lasilla/sciops/3p6/efosc/). The polarisation angle calibration should be accurate to about \( \theta \approx \pm 2° \).

To determine the readout noise bias observations were made with the shutter closed and integration time zero. To examine the response of the CCD flat field spectra were obtained by exposing an internal calibration lamp. For the wavelength calibration the emission spectrum of an internal helium-argon lamp was recorded with known wavelengths of the emission lines.
6.2.3 Data reduction

In this section the data reduction scheme for spectropolarimetry is described in detail. The data were reduced with the ESO-MIDAS software package.

- All bias frames were investigated. The bias showed a profile similar to a step function, i.e. the left part of the CCD had a mean value of 201 and the right part one of 207.2. This is caused by different readout electronics for the left and the right side of the CCD. No evident structure was found besides the common readout noise. Therefore, it was decided to create an artificial bias frame with the same image dimensions as the original bias frames but with the shape of a flat step function with the value 201 for the left and 207.2 for the right part of the CCD. This artificial bias was saved and used later to be subtracted from the science frames.

- The flat-field frames were prepared. Averages were created and normalised to one.

- The bias was subtracted from all scientific frames. No dark current was subtracted, since the CCD creates a dark current of only 7 electrons/pixel/hour, which is negligible. Neither were the frames corrected for flat field effects. This, because the reduction of polarimetric measurements is differential and therefore, flat field effects were supposed to be corrected 'automatically' when reducing the polarimetric frames in the standard way. Nevertheless, flat field correction was tested but no significant improvement was established. More details about the flat fields later in this section.

- Each spectropolarimetric frame contains two spectra of the same object, the ordinary and the extra-ordinary. These two spectra were extracted out of the image and saved as separate frames.

- The wavelength calibration was achieved by using the reference frame of the spectrum of a helium-argon lamp. According to the reference frame, all science spectropolarimetric frames were calibrated to a wavelength step-size of 2 Å, i.e. the spectral direction was binned into 2 Å steps.

- During the reduction, it is important to accurately align the different planetary spectra (e.g. $I_{\parallel}(0^\circ)$, $I_{\perp}(0^\circ)$, $I_{\parallel}(45^\circ)$, and $I_{\perp}(45^\circ)$) to a precision of about 1/10 of a pixel in spatial direction. This high precision is required because a small misalignment would produce a spurious polarisation signal (say positive) at one limb and an opposite polarisation signal (negative) at the other limb of the long-slit spectrum. This is particularly important for Uranus and Neptune where the intensity gradient at the planetary limbs is very steep. For an accurate alignment, it has to be taken into account, that the Wollaston has some dispersive power. The resulting ordinary and extra-ordinary spectra are therefore slightly bended with a curvature which differs between the two beams. This alignment was achieved with the help of the standard star observations from which the wavelength dependent spatial position of the spectra could be determined with sufficient precision. Involved
tests have demonstrated that the alignment procedure yields to a position precision of better than 0.2 pixels from the very blue to the most red end of the spectrum. This high accuracy could only be reached for scientific spectra in celestial North-South direction. For East-West oriented spectrographic slits the precision was lower, namely about 0.4 pixels. This is probably because the standard stars were recorded in celestial North-South direction and for the scientific East-West direction a tiny bending of the whole EFOSC2 system caused probably different bended spectra compared to the calibrating standard stars. This caused a non perfect overlap of the discussed bended spectra between the scientific and the standard star measurements. To facilitate the alignment procedure, the frames were oversampled in spatial direction to a tenth of a pixel.

- All sets of the identical observations were averaged to reduce the noise error. It was important that all the frames belonging together (e.g. the $I_{\parallel}(0^\circ)$ of the first set and the $I_{\parallel}(0^\circ)$ of the additional sets) had the appropriate spectral and spatial information at the same pixel coordinates. This was achieved by shifting the whole spectrum of each set forth or backwards to an accuracy of better than 0.07 of a pixel. This was done for all half-wave plate position angles and for the ordinary and extra-ordinary beams.

- Before starting with the intrinsic polarisation reduction, i.e. the evaluation of the Stokes parameters, the polarisation offset due to instrumental effects and the polarisation zero angle must be known. These informations were obtained from the reduction of the standard stars HD14069 (zero pol. standard) and BD+25°727 (high pol. standard) and the comparison of the measured polarisation degree and polarisation angle with the data from the literature (Turnshek et al. (1990)). The polarisation degree of the zero pol. standard star was measured to be 0.22% (literature: 0.11%) and the polarisation angle of the high pol. standard star was measured to -28.2° (literature: +33.8°). For both stars the wavelength region of 6000Å to 8000Å was investigated. The polarisation angle difference of 62° is the offset angle which the measured data must be corrected for. In addition, a wavelength dependent retardation effect of the half-wave plate was considered too. It is a smooth deviation of a perfect $\lambda/2$ retarder which must be added to the measured offset of 62° yielding the spectral dependent correction angle $\varphi(\lambda)$.

- The intrinsic polarisation reduction was processed by calculating the normalised Stokes parameter $p_Q = Q/I$ as follows:

$$p_Q = \frac{R - 1}{R + 1} \quad \text{with} \quad R^2 = \frac{I_{\parallel}(0^\circ)/I_{\perp}(0^\circ)}{I_{\parallel}(45^\circ)/I_{\perp}(45^\circ)}.$$  \hspace{1cm} (6.1)

To yield Stokes $p_U = U/I$ the 0° in the formula above has to be exchanged by 22.5° and the 45° by 67.5°.

- Up to now the orientation of $Q$ and $U$ are in the coordinates of the instrument. To adjust this coordinate system to the celestial system the zero point for the
6.2. Instrument, observations and data reduction

The polarisation angle must be set according to the calculated zero angle offset from the high pol. standard star. This is in principle a rotation in the $Q - U$ plane:

\[
\begin{align*}
Q/I & \to Q'/I = Q/I \cos(2\varphi) - U/I \sin(2\varphi) \\
U/I & \to U'/I = U/I \cos(2\varphi) + Q/I \sin(2\varphi),
\end{align*}
\]

where $Q'$ and $U'$ denote the rotated and $Q$ and $U$ the original Stokes parameters.\(^1\)

- The total linear polarisation degree $p$ and the polarisation angle $\Theta$ are given by:

\[
p = \sqrt{p_Q^2 + p_U^2}
\]

\[
\Theta = 0.5 \cdot \text{atan}(p_U/p_Q).
\]

- After the correction for the polarisation zero point angle the polarisation angle was computed again and compared to the literature value to make sure that sign errors had not crept in. It was found, that the polarisation angle calibration is accurate to about $\Theta \approx \pm 2^\circ$.

- After the reduction an interference pattern introduced by the CCD for $\lambda > 7000$ Å was found with a full amplitude of about 5% at 7500 Å and about 10% at 8200 Å of the mean intensity level. The differential data reduction for the polarisation reduces these fringes to a full amplitude level for $Q/I$ of $\Delta p \approx 0.3$% at 7500 Å and $\approx 0.5$% at 8200 Å. In the intensity and polarisation spectra the fringes are visible as quasi-periodic pattern with a periodicity of about $15 - 20$ Å. We have tried to reduce the fringe pattern with the available flat field calibrations. Some improvement was achieved for the intensity spectrum but not for the polarisation spectrum. Spectral binning turned out to be much more efficient. This averaged out the periodic pattern and produced much smoother intensity and polarisation spectra. As the spectral features in our gas planets are very broad, the loss in spectral resolution was acceptable. With this method the spurious fringe pattern vanished almost completely and in addition a significantly improved S/N per bin was obtained for the polarisation spectrum. Even with no fringes a similar spectral binning would have been necessary for an analysis of the polarisation spectrum in order to have sufficient S/N. For these reasons, we have binned all spectropolarimetric data into 30 Å bins.

- The intensity spectra of all four planets were corrected and calibrated for the CCD efficiency with the albedo spectrum of Karkoschka (1994).

All presented polarimetric data for Uranus and Neptune as well as for Jupiter and Saturn are subject to the same convention about the sign of the Stokes parameters. Positive $Q/I$ is used for light polarised parallel to the spectrographic slit, whereas negative sign

\(^1\) Henceforth, $Q$ and $U$ always refer to the rotated Stokes parameters and the apostrophe ' will be left away.
6.2. Instrument, observations and data reduction

of $Q/I$ is for light polarised perpendicularly to the slit. This means, that if the signal is positive and the slit is oriented in North-South direction, then the light is polarised in North-South direction too. Positive $U/I$ is polarised in a direction that is rotated by $45^\circ$ in counter-clock direction relative to the slit.
6.3 Spectropolarimetry of Uranus and Neptune

The spectropolarimetric observations of Uranus and Neptune were taken on November 29 in 2003. The spectrographic slits are much longer than the diameters of the planets which are about 3.5\" for Uranus and 2.2\" for Neptune. Thus, we obtained “long-slit” spectropolarimetry for both planets. For Uranus a slit width of 0.5\" and for Neptune one of 1.5\" was used.

For Uranus and Neptune a clear limb polarisation has been detected (Joos & Schmid (2007); Schmid et al. (2006b)). The strength of the polarisation was for the whole limb more or less the same and everywhere perpendicular to the limb. This is unlike Jupiter where the strength of the limb polarisation is characterised by a strong difference between polar and equatorial limb regions (Hall & Riley (1976); Smith & Tomasko (1984); Braak et al. (2002); Joos et al. (2005)).

The limb polarisation can be explained by a second order scattering effect which is expected to occur for reflecting atmospheres seen near phase angle \( \alpha = 0^\circ \) (backscattering) where Rayleigh-type scattering processes are dominant (see van de Hülst (1980)).

Disc resolved spectropolarimetry of Uranus and Neptune is presented in the following sections. The data cover a wavelength range from 5300\( \text{Å} \) to 9300\( \text{Å} \) which includes strong methane absorption bands. Strong absorption bands correspond to large opacity jumps in the scattering atmospheres and corresponding polarisation effects may be expected for the reflected light.

6.3.1 Spectropolarimetric structure of Uranus

For Uranus we have taken 5300 to 9300\( \text{Å} \) long-slit spectropolarimetry with the slit oriented in N-S and E-W direction in the celestial coordinate system (Fig. 6.3). The N-S slit position extends roughly along the equator of Uranus. Henceforth, measurements taken with this slit position are called “equatorial” with the definition of West and East limbs or longitudes on the planet as indicated in Fig. 6.3.

The E-W slit extends from the South Pole over the equator to northern latitudes roughly along the central meridian of Uranus. Measurements from this slit orientation will be referred to as “meridional”.

Figure 6.3 illustrates the exact slit positions and the selected regions: four limb regions East, West, South and North\(^2\) (0.628\" long black boxes), two central slit regions (0.942\" long white boxes), as well as the two spectropolarimetric signals obtained by integrating over 7.85\" along the equatorial and the meridional slit. These selected regions are denoted as limb, central part and total slit.

Already our ground based images reveal a strong asymmetry between the brighter South Pole and darker northern latitudes which are well resolved as band structures in HST images (e.g. Karkoschka (2001); Rages et al. (2004)), but no strong longitudinal features are seen for Uranus (see also press release STScI-PRC2004-05).

\(^2\) All the following orientations East, West, South and North refer always to the planetary coordinates.
6.3. Spectropolarimetry of Uranus and Neptune

Fig. 6.3: Uranus i-band images with the slit in celestial N-S (left) and E-W (right) orientation. N is up and E is left. The black boxes indicate the “limb” sections of the long-slit spectropolarimetry and the white boxes the “central” regions. Also shown are the positions of the South Pole and the equator with the West limb indicated according to the planetary coordinates defined by Seidelmann et al. (2002). At the time of our observations the diameter was 3.51", the phase angle 2.8°, the position angle of the South Pole was 78° and the distance of the South Pole from the disc centre was 1.62". (The planet parameters were taken from “The Astronomical Almanac 2003”, see also Tabl. 6.1.)

Spectroscopic structure and spectral albedo $A(\lambda)$

Spectroscopically (Fig. 6.5, top panel), our data show mainly the strong methane (CH$_4$) absorption bands, which are well known for Uranus (e.g. Baines & Bergstralh (1986); Karkoschka (1994)). Also clearly visible is the telluric absorption due to the A-band at 7590 Å. Further, the enhanced limb brightening in the methane bands is well visible in our data and illustrated (in Fig. 6.5) by the normalised limb intensity to albedo ratio.

An albedo spectrum is constructed from our data. For this we averaged first the total slit spectra in equatorial and meridional direction and then normalised the result to the geometric albedo spectrum of Karkoschka (1994) multiplying our spectrum with a smooth correction function which accounts for the instrumental efficiency curve. This procedure yields a well defined full disc albedo spectrum $A(\lambda)$ as plotted in Figs. 6.4 and 6.5.

Spectral regions were selected in order to quantify the albedo and the polarisation. The selected regions, which represent strong absorption bands (M1 – M7) and the higher albedo regions (C1 – C5) in between, are indicated in Fig. 6.4 and listed in Table 6.3.

A clear difference of the spectral structure of the limb was found when compared to the albedo spectrum $A(\lambda)$. This is shown in Fig. 6.5 where the normalised ratio between the average of the West and East limb spectra and the albedo spectrum is plotted. The ratio is enhanced in all CH$_4$ bands indicating that absorption is less deep for the limb regions. This is equivalent to the statement that deep absorption bands of Uranus show a limb brightening effect as observed e.g. by HST in Karkoschka (2001).
6.3. Spectropolarimetry of Uranus and Neptune

Fig. 6.4: Albedo spectrum of Uranus with the illustration of the chosen spectral sections for the continuum or high albedo regions C1 – C5 and the deep methane absorption bands M1 – M7. The sections are the same for Uranus and for Neptune.

Spectropolarimetry for the equatorial slit

Spectropolarimetry for the equatorial slit may be considered as representative for the “average” planetary disk of Uranus because the bright South Pole region and the faint northern latitudes are not included in these observations. The peculiarities of these special regions are discussed in the following subsection.

Spectropolarimetry of the equatorial cut through Uranus is plotted in Figure 6.5 as normalised Stokes Q/I and U/I spectra ($p_Q(\lambda)$ and $p_U(\lambda)$ respectively). Normalised Stokes polarisation spectra are in principle defined as $p_Q = Q/I = (I_0 - I_90)/(I_0 + I_90)$ where $I_0$ is the intensity for the linear polarisation parallel to the slit and $I_90$ perpendicular to the slit and $p_U = U/I = (I_{45} - I_{135})/(I_{45} + I_{135})$ for tilted polarisation directions relative to the slit. Nevertheless, during the reduction, a different calculation of the Stokes parameters was applied in order to reduce gain and temporal effects, as already described in Sect. 6.2. There exists in our data no significant difference between the polarisation signal of the western and eastern limbs and therefore only the average of the two limb polarisation spectra is plotted here. Fig. 6.5 includes further the polarisation spectra of the central part and the average for the entire slit. All limb plots can be seen in appendix A.1.

The data show that the Q/I polarisation is positive and high at the limbs and close to zero for the central region. Essentially no signal is visible for the U/I data, indicating that the orientation of the polarisation is everywhere parallel to the slit equivalent to a limb polarisation perpendicular to the limb. The U/I spectra give a good representation of the noise errors in the data, which are particularly large in the deep absorption bands at the longest wavelength $\lambda > 8500$ Å, where the photon statistics are poor.

The Q/I polarisation spectrum for the equatorial limbs displays a clear overall decrease
Fig. 6.5: Spectropolarimetry of Uranus for the equatorial slit. Top panel: geometric albedo spectrum $A(\lambda)$. Second panel: normalised ratio between the limb intensity spectrum and the geometric albedo spectrum $A(\lambda)$. Third panel: normalised Stokes $Q/I$ polarisation spectra for the average of the western and eastern limb regions (solid line), the central part (dotted line) and the total slit (dashed line). Bottom panel: same as third panel but for Stokes $U/I$. 
of the polarisation level with wavelength. Further, the limb polarisation is enhanced in the deep CH\textsubscript{4} absorption bands when compared to the adjacent continuum or spectral regions with higher albedo.

Table 6.3 gives the measured polarisation for the N, S, E, and W limbs for selected wavelength regions. The listed values are flux weighted average values $\langle Q/I \rangle = \Sigma Q/\Sigma I$, where $\Sigma I$ and $\Sigma Q$ are summed over intensity flux and polarisation flux, respectively for the selected spatial bin and wavelength interval.

In the methane bands the limb polarisation decreases from about 2.6\% in the band at 5400 Å (M1) to about 0.9\% in the broad, deep band centred at 8900 Å. The measured limb polarisation for the continuum (or high albedo regions) is about 2\% at 5500 Å, and less than 0.4\% for the C5-region at 8270 Å, except for the North limb where the polarisation for C5 is significantly higher.

It should be noted, that the level of polarisation in Fig. 6.5 and Table 6.3 depends on the seeing conditions and the size and position of the spatial bin, selected for the averaging. However, the relative wavelength dependence of polarisation for a given limb section depends very little on spatial position, and therefore on the selected slit region and the seeing conditions. Uncertainties in the polarisation values of Table 6.3 due to photon noise are about $\Delta \langle Q/I \rangle = \pm 0.10\%$, except for the narrow interval M3 and the longest CH\textsubscript{4} wavelength intervals M6 and M7, where $\Delta \langle Q/I \rangle = \pm 0.20\%$.

<table>
<thead>
<tr>
<th>feature</th>
<th>wavelength [Å]</th>
<th>albedo</th>
<th>$\langle Q/I \rangle$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>West</td>
<td>East</td>
</tr>
<tr>
<td>C1</td>
<td>5827 - 5883</td>
<td>0.59</td>
<td>1.88</td>
</tr>
<tr>
<td>C2</td>
<td>6300 - 6400</td>
<td>0.48</td>
<td>1.59</td>
</tr>
<tr>
<td>C3</td>
<td>6755 - 6794</td>
<td>0.41</td>
<td>1.40</td>
</tr>
<tr>
<td>C4</td>
<td>7442 - 7565</td>
<td>0.32</td>
<td>0.89</td>
</tr>
<tr>
<td>C5</td>
<td>8215 - 8320</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>M1</td>
<td>5368 - 5459</td>
<td>0.37</td>
<td>2.68</td>
</tr>
<tr>
<td>M2</td>
<td>5732 - 5788</td>
<td>0.40</td>
<td>2.41</td>
</tr>
<tr>
<td>M3</td>
<td>6180 - 6200</td>
<td>0.13</td>
<td>2.45</td>
</tr>
<tr>
<td>M4</td>
<td>6627 - 6699</td>
<td>0.21</td>
<td>1.84</td>
</tr>
<tr>
<td>M5</td>
<td>7174 - 7358</td>
<td>0.06</td>
<td>1.55</td>
</tr>
<tr>
<td>M6</td>
<td>7933 - 8034</td>
<td>0.05</td>
<td>1.27</td>
</tr>
<tr>
<td>M7</td>
<td>8369 - 8453</td>
<td>0.06</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table 6.3: Limb polarisation $(Q/I)$ for Uranus for the West, East, South and North limb and selected wavelength intervals (column 2). Column 3 gives the averaged albedo $A(\lambda)$ for the corresponding interval.
6.3. Spectropolarimetry of Uranus and Neptune

Peculiarities for the meridional slit

Uranus, close to its equinox which is on the 7th of December 2007, shows currently an intensity asymmetry from the bright South pole to the darker northern latitudes which is particularly strong in the methane bands. This intensity asymmetry is also obvious in the HST-images of Karkoschka (2001) or Rages et al. (2004).

A clear peculiarity was found for the northern latitudes in the spectropolarimetric signal. Figure 6.6 compares the Q/I limb spectropolarimetry of the northern latitudes with the average of the three other limb regions, East, South and West, which are very similar and can be taken together. The northern latitudes show for wavelengths longer than about 6000 Å a no polarisation minimum for spectral regions with high albedo. Thus, the normalised polarisation spectrum Q/I for the northern limb is essentially featureless and displays just a steady decrease in polarisation with wavelength.

Fig. 6.6: Comparison between Q/I polarisation spectra of the northern limb of Uranus (thick line) and the average of the other three limb regions (thin line).

According to our data the darker northern latitudes show, when compared to the other limbs, for λ < 6000 Å a higher overall polarisation and for λ > 6000 Å a higher polarisation for the inter band regions. It was carefully investigated whether this result could be due to a misalignment or another spurious effect. It was found, that the maximum error in misalignment for the polarimetric data reduction produces an effect on the order of only 0.05. Based on such tests I conclude that the described Stokes Q/I polarisation peculiarities of the northern limb are real.

Fitting the limb polarisation spectrum

It was found, that the $Q/I = p_Q(\lambda)$ polarisation spectra for Uranus show a clear overall decrease of the polarisation level with wavelength. Further, the polarisation is enhanced in the deep CH$_4$ absorptions bands, when compared to the adjacent higher albedo spectral regions, except for the red part of the northern limb spectropolarimetry.
In order to quantify the wavelength and albedo dependence of the limb polarisation, a fit of the polarisation spectra with a simple linear relation with respect to the wavelength \( \lambda \) and the albedo \( A(\lambda) \) was formulated:

\[
p_{Q}(\lambda)\,[\%] = c_1 + c_2 \cdot \lambda[\mu m] + c_3 \cdot A(\lambda) .
\]  

(6.5)

The parameters \( c_1, c_2, \) and \( c_3 \) can then be determined with a least square procedure. Particularly good fits were obtained for the spectral region from 5300 \( \AA \) to 7500 \( \AA \) (see Fig. 6.7).

![Fig. 6.7: Fits to the equatorial limb polarisation spectrum compared to the measured spectrum (thin line). The thick line is a best fit for the spectral region 5300 - 7500 \( \AA \) and the dotted line for 7700 - 9300 \( \AA \).](image)

The best fit to the equatorial limb polarisation for the wavelength region 5300 - 7500 \( \AA \) is:

\[
p_{Q}(\lambda)\,[\%] = 8.4 - 9.1 \cdot \lambda[\mu m] - 2.2 \cdot A(\lambda).
\]  

(6.6)

The standard deviation of the fit is less than 0.1 \%. The largest deviations are due to the telluric absorption bands at 6870 \( \AA \) (B-band) and 7200-7300 \( \AA \) (water absorption) which were not corrected in the albedo spectrum. Due to the uncorrected A-band absorption at 7590 \( \AA \), the upper boundary of the least square fitting procedure was fixed to 7500 \( \AA \).

The fit to the longer wavelength region 7700 \( \AA \) to 9300 \( \AA \) yields a flatter wavelength dependence and a stronger albedo dependence \((c_1 = 6.0, c_2 = -5.6 \) and \( c_3 = -4.5 \)).

**Spatial sampling and full slit signal**

According to a simple analytic model for Rayleigh scattering atmospheres (see e.g. Schmid et al. (2006b); van de Hulst (1980)) the limb polarisation feature is expected to be a narrow, strongly peaked feature along the limb. In our data this narrow peak is not resolved due to the seeing limited \((\approx 1''\) resolution). Therefore, the apparent strength of the limb polarisation \( p_{Q}(\lambda) \) depends strongly on the not so well defined seeing conditions during the observations. In addition, also the slit width must be considered which defines the spatial region over which the intensity and Stokes fluxes are sampled. For Uranus, a narrow slit \((0.5''\) was employed which caused only a small degradation of the polarisation signal.
Choosing a radial bin for the quantification of the limb polarisation is an arbitrary procedure. For this reason it is reasonable to employ the polarisation signal integrated over the entire slit to quantify the limb polarisation. A fit according to Eq. (6.5) to the total slit spectropolarimetry of the equatorial slit as given in Fig. 6.5 yields the parameters $c_1 = 3.6$, $c_2 = -3.8$, and $c_3 = -1.3$ (again for the spectral region 5300 – 7500 Å).

In Sect. 6.3.3 we derive a correction factor which accounts for the seeing and the spatial sampling of our observations.

### 6.3.2 Disc profiles for Uranus

The spectropolarimetric data can be employed to investigate the intensity and polarisation profiles through the disc of Uranus for any wavelength interval covered by our observations, a kind of centre to limb profiles. Since the slit is much longer than the planet’s diameter our data provide profiles roughly along the equator (equatorial slit) and profiles from the South Pole to high northern latitudes (meridional slit).

![Uranus disc profiles](image)

**Fig. 6.8:** Uranus equatorial (solid lines) and meridional (dashed lines) disc profiles for the high albedo wavelength range 5827 Å to 5883 Å (C1). The panels give the flux $I(x)/I_0$ (top), the normalised Stokes parameter $Q(x)/I(x)$ (middle), and the Stokes flux $Q(x)/I_0$ (bottom).
Again, the analysis is focused on the spectral regions C1 - C5 (high albedo regions) and M1 - M7 (strong methane bands) as defined in Table 6.3.

Fig. 6.8 shows an example for disc profiles for the C1 region around 5850 Å. Fig. 6.9 shows the same as Fig. 6.8 but for the methane band at 5760 Å (M2). Both figures show profiles for the equatorial and the meridional direction. The flux of the disc profiles was normalised at the disc centre $I_0 = I(x = 0') = 1$ and also the Stokes flux $Q$ is expressed in percentage of $I_0$.

![Disc Profiles](image)

**Fig. 6.9:** Uranus equatorial (solid) and meridional (dashed) disc profiles for the methane band centred at 5760 Å (M2). The panels give the flux $I(x)/I_0$ (top), the normalised Stokes parameter $Q(x)/I(x)$ (middle) and the Stokes flux $Q(x)/I_0$ (bottom).

### Disc profiles for the intensity

The intensity profiles show some pronounced differences between the equatorial and the meridional directions as well as between different spectral regions. All equatorial profiles are essentially symmetric while the meridional profiles are rather asymmetric, showing a brighter South Pole when compared to the northern latitudes (see Fig. 6.9). This
asymmetry is particularly strong in the deep methane bands. In this section a relationship between intensity profile structure and albedo is presented for both slit orientations.

The equatorial cuts have a Gaussian-like profile for the high albedo bands (Fig. 6.8) and flat top profiles for the deep absorptions (Figs. 6.9 and 6.10). The flat top profiles can be explained as not well resolved limb brightening effect.

These intensity features of Uranus are also clearly present in imaging studies based on high resolution HST observations (e.g. Karkoschka (2001); Rages et al. (2004)). Compared to the HST data, we can only see the strongest spatial features due to the much lower spatial resolution of our data. However, the spectropolarimetric data yield disk profiles for any spectral region in the covered wavelength range and therefore our data are particularly well suited to investigate the systematic behaviour of the asymmetry and the limb brightening for Uranus.

<table>
<thead>
<tr>
<th>feature</th>
<th>$\Delta_{\text{mer}}$</th>
<th>$\Sigma_{\text{eq}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>-0.017</td>
<td>-0.082</td>
</tr>
<tr>
<td>C2</td>
<td>-0.030</td>
<td>-0.019</td>
</tr>
<tr>
<td>C3</td>
<td>-0.008</td>
<td>0.019</td>
</tr>
<tr>
<td>C4</td>
<td>0.038</td>
<td>0.048</td>
</tr>
<tr>
<td>C5</td>
<td>0.102</td>
<td>0.035</td>
</tr>
<tr>
<td>M1</td>
<td>0.031</td>
<td>0.070</td>
</tr>
<tr>
<td>M2</td>
<td>0.079</td>
<td>0.039</td>
</tr>
<tr>
<td>M3</td>
<td>0.095</td>
<td>0.375</td>
</tr>
<tr>
<td>M4</td>
<td>0.141</td>
<td>0.149</td>
</tr>
<tr>
<td>M5</td>
<td>0.160</td>
<td>0.529</td>
</tr>
<tr>
<td>M6</td>
<td>0.102</td>
<td>0.467</td>
</tr>
<tr>
<td>M7</td>
<td>0.156</td>
<td>0.341</td>
</tr>
</tbody>
</table>

Table 6.4: Uranus meridional asymmetry parameter $\Delta_{\text{mer}}$ and limb brightening parameter $\Sigma_{\text{eq}}$ at the equatorial regions for spectral features C1 – C5 and M1 – M7 as defined in Table 6.3.

In order to quantify the asymmetry between South and North and the limb brightening effect, first a symmetric disk profile is constructed as reference profile $I_{\text{ref}}(x)$ for Uranus by averaging all 5 equatorial continuum profiles (C1 – C5) and their mirrored profiles (mirrored at $x = 0\degree$). As next step, the relative deviation $\delta(x)$ is determined for the equatorial and meridional profiles from the reference profile by calculating

$$\delta(x) = \frac{I(x) - I_{\text{ref}}(x)}{I_{\text{ref}}(x)}.$$  

(6.7)

Due to the normalisation, the deviation in the middle of the profiles is for all profiles $\delta(x = 0\degree) = 0$. Strong signals in $\delta(x)$ are obtained for $x \approx \pm 1\degree$. The averages of the deviations $\langle\delta(x)\rangle$ are calculated for all four planetary orientations on the disk selecting
profile regions around $x \approx 1''$. The selected regions correspond to the "grey" boxes in Fig. 6.3, defined by:

$$
\delta_{W,S} = \langle \delta(x) \rangle \quad \text{for} \quad -1.41'' < x < -0.47''
$$

$$
\delta_{E,N} = \langle \delta(x) \rangle \quad \text{for} \quad +0.47'' < x < +1.41'' .
$$

Based on this, the meridional asymmetry parameter is calculated:

$$
\Delta_{\text{mer}} = \delta_S - \delta_N
$$

and the equatorial limb brightening parameter:

$$
\Sigma_{\text{eq}} = \delta_W + \delta_E,
$$

which are given in Table 6.4 for the wavelength intervals C1 - C5 and M1 - M7. Large values indicate a strong asymmetry between South and North or a strong limb brightening. Figure 6.10 illustrates the asymmetry for the central meridian and the equatorial limb brightening for the most extreme case, the M5 absorption band at 7270 Å.

It should be noted that the absolute values of $\Delta_{\text{mer}}$ and $\Sigma_{\text{eq}}$ contain little diagnostic information, because they depend on the seeing and the size of the chosen spatial interval. More interesting information is obtained from the relative strength of the $\Delta_{\text{mer}}$ and $\Sigma_{\text{eq}}$

![Fig. 6.10: Disk intensity profile for the methane absorption M5, showing the strongest asymmetry between South and North (dotted line) and equatorial limb brightening (solid) effect. For comparison the symmetric reference profile $I_{\text{ref}}$ is plotted in addition (Gaussian-like).](image)

parameters for different wavelength bands. They are all affected in a similar way by the limited spatial resolution. The data show a tight anti-correlation between the meridional asymmetry parameter $\Delta_{\text{mer}}$ and albedo $A$ as well as between limb brightening $\Sigma_{\text{eq}}$ and $A$ which is illustrated in Fig. 6.11.
6.3. Spectropolarimetry of Uranus and Neptune

The HST observations of Uranus described by Karkoschka (2001) also clearly show that the intensity asymmetry and limb brightening are particularly strong in the methane bands. However, the presented long-slit spectroscopy allows to select any particular wavelength band for a centre-to-limb profile analysis. To my knowledge, the dependence of the asymmetry and limb brightening effect on the albedo has not been described previously. The asymmetry between South Pole and northern latitudes is of course a seasonal effect of Uranus.

To investigate the properties of the scattering layers in Uranus and Neptune via the limb brightening effect, it would be desirable to have long-slit spectroscopy with a spatial resolution as offered by HST.

**Disc profiles for the polarisation**

Disc profiles for the polarisation are obtained for the normalised Stokes parameter $Q(x)/I(x)$ (short: $Q/I$) and the Stokes flux $Q(x)/I_0$ (short: $Q$), where positive values indicate a polarisation parallel to the slit or perpendicular to the limbs. A few examples are plotted in Figs. 6.8 and 6.9.

As already described in the previous sections, the polarisation is low in the centre of the disc and high at the limb at all wavelengths of our spectrum. Typically, $Q/I$ increases steadily with radius $r = |x|$ and reaches a constant value around $r \approx 2''$, where the photon noise starts to dominate the measurements. The Stokes flux $Q$ increases from $r = 0''$ until

---

**Fig. 6.11:** Uranus meridional asymmetry parameter $\Delta_{mer}$ vs. albedo (top) and limb brightening $\Sigma_{eq}$ vs. albedo (bottom) for high albedo spectral regions C1 – C5 (□) and methane absorption bands M1-M7 (○).
about $r \approx \pm 1.5''$ and decreases together with the intensity profile further out to zero. This behaviour is in agreement with the imaging observations described in Schmid et al. (2006b).

For the equatorial slit observations all $Q/I$ and $Q$ disc profiles are essentially symmetric and they have roughly the same spatial structure (Figs. 6.8, 6.9 and in appendix A.2). Only the strength of the polarisation signal shows a clear wavelength dependence.

For the meridional slit there is an obvious asymmetry in the $Q/I$ polarisation signal. For most spectral regions the $Q/I$ polarisation is typically 30% higher at the northern limb than at the South limb (Tab. 6.3, Figs. 6.8, 6.9 and appendix A.2). The asymmetry is particularly strong for the inter band regions C4 and C5. This effect was also described in Sect. 6.3.1, where the spectropolarimetric signal for the southern and northern limb is compared.

Surprisingly, the $Q$-flux profiles in meridional direction are rather symmetric (Figs. 6.8, 6.9 and appendix A.2). Thus, the higher intensity $I$ at the South pole, combined with the lower normalised polarisation $Q/I$ yield together a Stokes flux $Q$ at a similar level as for the darker but higher polarised northern latitudes. Whether this is a fortuitous coincidence or an indication of a planet-wide homogeneous haze layer producing everywhere more or less the same limb polarisation flux remains to be investigated.

All profiles for the selected wavelength ranges C1 - C5 and M1 - M7 are presented in appendix A.2.

### 6.3.3 Seeing corrected limb polarisation parameters for Uranus

For comparison with models and future observations of Uranus it appears useful to derive well defined parameters for the strength of the limb polarisation. In particular, such values should be corrected for the polarisation cancellation introduced by the seeing and the averaging effects due to the finite slit width.

For this reason, we first determine the flux weighted mean polarisation for a line (slit) through the centre of the planet $\langle Q/I \rangle_{\text{line}}$. This is calculated according to $\langle Q/I \rangle_{\text{line}} = \Sigma Q/\Sigma I$, where $\Sigma Q$ and $\Sigma I$ are the polarisation flux $Q(x)$ and flux $I(x)$ summed up along the entire slit. The slit integrated polarisation $\langle Q/I \rangle_{\text{line}}$ is of course significantly lower than the values derived for a small limb region given in Table 6.3 or shown in Fig. 6.5 for the equatorial slit.

The seeing introduced by the Earth's atmosphere causes a polarisation cancellation effect. As explained in detail in Schmid et al. (2006b) components, e.g. the $+Q_{\text{sky}}$ components at the equatorial limbs and the $-Q_{\text{sky}}$ components at the northern and southern limbs overlap and cancel each other if the seeing is substantial, say seeing $\geq 0.5$ Rp$_{\text{planet}}$. A second effect of the seeing is that the signal from regions adjacent to the slit spill into the slit. This averages down the measurable limb polarisation. In addition, there is also a reduction of the integrated limb polarisation due to the finite slit width. For Uranus this is a small effect, because the data were obtained with a very narrow slit of 0.5''.

For our observations the seeing-limited resolution was determined to be 1.09'' at 6000 Å and 1.00'' at 8000 Å taken from observations of standard stars observed with the same
6.3. Spectropolarimetry of Uranus and Neptune

setup. However, the seeing conditions can change on short time scales, introducing uncertainties on the order of ±0.1" to ±0.2".

This effect of polarisation cancellation due to the limited resolution was modelled in Schmid et al. (2006b) and seeing correction factors for the imaging polarimetry were determined. These calculations have been prepared for observations through a 0.5" wide slit and obtained essentially the same seeing dependence as for the imaging polarimetry. From these simulations it was found that the measurable polarisation is reduced by a factor 0.96 due to the width (0.5") of the slit and a factor of 0.76 due to the seeing of 1" when compared to the intrinsic limb polarisation integrated along a slit through the disc centre.

Thus, in Table 6.5 corrected values are given for the intrinsic limb polarisation \(\langle Q/I\rangle_{\text{corr}}\) for Uranus by multiplying the measured values \(\langle Q/I\rangle_{\text{line}}\) with a factor of 1.37. The uncertainty in this correction factor is about ±0.15 mainly due to the not precisely defined seeing. For the intrinsic limb polarisation other error sources like photon noise or the calibration of the polarisation data are less important.

<table>
<thead>
<tr>
<th>feature</th>
<th>(\langle Q/I\rangle_{\text{corr}}) [%]</th>
<th>equatorial</th>
<th>South</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.90</td>
<td>1.02</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>0.80</td>
<td>0.99</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>0.66</td>
<td>0.90</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>0.41</td>
<td>0.57</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>0.18</td>
<td>0.24</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>1.47</td>
<td>1.46</td>
<td>1.85</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>1.26</td>
<td>1.40</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>1.61</td>
<td>1.46</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>1.01</td>
<td>1.13</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>1.15</td>
<td>0.95</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>M6</td>
<td>0.88</td>
<td>0.75</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>M7</td>
<td>0.71</td>
<td>0.46</td>
<td>1.08</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5: Line (slit) integrated, seeing corrected polarisation \(\langle Q/I\rangle_{\text{line}}\) for the equatorial and meridional slits through the centre of Uranus for the selected spectral features (Table 6.3). The listed values are corrected (measured values \(\times 1.37\); see text) for the seeing and the employed slit width of our observations.

The same correction factor can also be applied to the fit of the slit integrated spectropolarimetric signal along the equator, determined in Sect. 6.3.1. Thus, the corrected fit for the intrinsic equatorial full slit polarisation for the spectral region 5300 to 7500 Å can be given by:

\[
p_Q(\lambda) = 4.9 - 5.2\lambda [\mu\text{m}] - 1.8A(\lambda). \tag{6.11}
\]
6.3. Spectropolarimetry of Uranus and Neptune

6.3.4 Spectropolarimetric structure of Neptune

Spectropolarimetry of Neptune was obtained with a North-South oriented slit and almost the same instrument set-up as for Uranus. The only difference was the slit width of 1.5", compared to the 0.5" for Uranus. We also define three slit regions for Neptune, a northern and a southern limb section of 0.625" each, a central region of 0.942" and an integrated "total slit" of 4.71" length as shown in Fig. 6.12.

At the time of our observations, Neptune had a diameter of 2.24". Compared to this size the width of the slit of 1.5" and the seeing conditions of about 1" are large and not well suited to resolve spatial features on the planetary disc. Almost the entire planet was contained in the N-S slit except for the eastern and western limbs. With higher spatial resolution observations it was shown that Neptune displays also a limb brightening effect similar to Uranus (e.g. Hammel et al. (1989); Baines & Hammel (1994)).

![Fig. 6.12: Intensity image of Neptune in the i-band with North-South slit position. North is up and East is left. The South Pole is marked with a dash. The grey stripe indicates the position of the slit. The black boxes show the "limb" area and the white box the "central part". At the time of our observations the diameter was 2.24", the phase angle 1.7°, the position angle of the South Pole 169° and the distance of the South Pole from the centre of the disc was 0.97".](image)

Despite the bad resolution of our Neptune observations a clear polarisation signal is detected. This is shown in Fig. 6.13, which presents the spectropolarimetry of Neptune in a similar form as for Uranus (Fig. 6.5). The albedo spectrum $A(\lambda)$ was constructed with a normalisation to the Neptune albedo spectrum of Karkoschka (1994). Spectroscopically, Neptune is very similar to Uranus (see Karkoschka (1998)).

The spectropolarimetric signal of Neptune for the average of the northern and southern limbs is qualitatively also very similar to Uranus (Fig. 6.13). The $Q/I$ polarisation spectrum is high and positive at the limbs, or parallel to the slit, but is low in the disc centre and essentially zero for the $U$ direction. $Q/I$ shows an overall decrease in polarisation towards longer wavelength and an enhanced polarisation in the strong methane bands, when compared to the adjacent continuum or higher albedo regions. The level of the measured limb polarisation for Neptune is significantly lower than for Uranus because
6.3. Spectropolarimetry of Uranus and Neptune

Fig. 6.13: Spectropolarimetry of Neptune for the slit in North-South direction. Top panel: geometric albedo spectrum $A(\lambda)$. Middle panel: normalised Stokes $Q/I$ polarisation spectra for the average of the North and South limb regions (solid line), the central part (dotted line) and the entire slit (dashed line). Bottom panel: Same as the middle panel but for Stokes $U/I$.

The planetary disc is spatially worse resolved.

The spectropolarimetry for the central region shows a weak and negative $Q/I$ polarisation spectrum. This can easily be understood as polarisation signal from the eastern and western limb which spills into the central slit region. As the eastern and western limb polarisations are oriented perpendicularly to the limb, they produce a perpendicular (negative) signal for the North-South slit. The slit integrated polarisation is small because of the small spatial resolution. For spatially unresolved observations with a slit which is wider than Neptune, a total net polarisation close to zero is expected, because the centrosymmetric polarisation structure of Neptune, as seen in Schmid et al. (2006b) would produce an almost perfect cancellation of positive and negative polarisation features.

Parameters for the limb polarisation of Neptune are given in Table 6.6. Due to the
fact that Neptune is spectroscopically very similar to Uranus, the same spectral features were investigated. The mean albedo for the spectral intervals was determined from the albedo spectrum $A(\lambda)$. The limb polarisation is only given for the average of the northern and southern limb regions. The two measurements are averaged because no significant difference is detectable between North and South.

The measured limb polarisation of Neptune is significantly lower than for Uranus. This is due to the much lower resolution or to the slit width and the much larger size of the seeing disc with respect to the size of the planet. Beside this, the limb polarisation of Neptune seems to behave qualitatively similarly to Uranus.

Since the spatial resolution of our observation is poor, it is not possible to deduce reliable parameters for the intrinsic limb polarisation of Neptune. However, the imaging polarimetry presented in Schmid et al. (2006b) indicates that the intrinsic limb polarisation of Neptune is about 1.5 times higher than that of Uranus.

<table>
<thead>
<tr>
<th>feature</th>
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<th>$\langle Q/I \rangle_{NS}$</th>
<th>$\langle Q/I \rangle_{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.49</td>
<td>0.85</td>
<td>0.37</td>
</tr>
<tr>
<td>C2</td>
<td>0.37</td>
<td>0.80</td>
<td>0.36</td>
</tr>
<tr>
<td>C3</td>
<td>0.30</td>
<td>0.77</td>
<td>0.34</td>
</tr>
<tr>
<td>C4</td>
<td>0.22</td>
<td>0.62</td>
<td>0.29</td>
</tr>
<tr>
<td>C5</td>
<td>0.14</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>M1</td>
<td>0.32</td>
<td>1.22</td>
<td>0.52</td>
</tr>
<tr>
<td>M2</td>
<td>0.33</td>
<td>1.09</td>
<td>0.48</td>
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<tr>
<td>M3</td>
<td>0.11</td>
<td>1.08</td>
<td>0.47</td>
</tr>
<tr>
<td>M4</td>
<td>0.16</td>
<td>0.97</td>
<td>0.42</td>
</tr>
<tr>
<td>M5</td>
<td>0.06</td>
<td>0.83</td>
<td>0.38</td>
</tr>
<tr>
<td>M6</td>
<td>0.05</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>M7</td>
<td>0.05</td>
<td>0.67</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 6.6: Limb polarisation $\langle Q/I \rangle$ in [%] for Neptune for the average of the North and South limbs $\langle Q/I \rangle_{NS}$ and for the total meridional slit $\langle Q/I \rangle_{t}$, for selected wavelength intervals. Column 2 gives the averaged albedo $A(\lambda)$ for the corresponding interval.

**Fitting the polarisation spectrum of Neptune**

A fit to the limb polarisation spectrum of Neptune is presented for a quantitative description. The same procedure is applied as described in Sect. 6.3.1. This yields for Neptune for the average of the North and South limb polarisation spectrum and the wavelength range of 5300 - 7500 Å the fit:

$$p_Q(\lambda) [%] = 3.35 - 3.35 \cdot \lambda [\mu m] - 1.10 \cdot A(\lambda).$$

(6.12)
6.3. Spectropolarimetry of Uranus and Neptune

It is interesting to note, that the fit parameters for Neptune behave like $c_1 \approx -c_2$ and $c_1 \approx -3c_3$. These are almost identical proportionalities as derived for the limb polarisation in Uranus. This indicates that the wavelength and albedo dependence of the limb polarisation is very similar for Neptune and Uranus.

For the red end of the North-South spectropolarimetry (7700 - 9300 Å) the derived parameters are $c_1 = 1.75$, $c_2 = -1.15$ and $c_3 = -2.75$. For the longer wavelength region the wavelength dependence is flatter and the albedo dependence stronger.

Fig. 6.14: Fits to the North-South limb polarisation spectrum of Neptune compared to the measured spectrum (thin line). The thick line is a fit for the spectral region 5300 - 7500 Å and the dotted line for 7700 - 9300 Å.
6.4 Imaging polarimetry of Uranus and Neptune

As mentioned, also imaging polarimetry of the giant gas planets was achieved during the same run at La Silla observatory. But, as imaging polarimetry was not the main assignment of the author, it will not be discussed here in this thesis, but can be read in Schmid et al. (2006b). Only some major results will be presented here in order to give an impression about the imaging polarimetry observations of Uranus.

Fig. 6.15: Imaging polarimetry of Uranus in the i band with indicated position of the South pole, the equator and the geometrical limb. Left: Stokes Q image with positive polarisation at the western and eastern limbs and negative polarisation at the South Pole and the northern latitudes. Right: As left but now a composite of Stokes Q and U yielding the radial polarisation $Q_r$ perpendicular to the planet's limb according to formula (6.13). The grey scale is normalised to the peak intensity $I_{peak}$ and spans the range from -0.5% (black) to +0.5% (white).

Several filters were used for imaging polarimetry, such as Bessel R, Gunn i and z, as well as some narrow band filters centred at the strong methane absorption bands. Fig. 6.15 shows imaging polarimetry of Uranus from the same run in La Silla. It shows a symmetric butterfly pattern of the Stokes Q image in the left panel, where white indicates positive polarisation, i.e. at the western and eastern limbs and black denotes negative polarisation (at the South Pole and at the northern latitudes). The left image already shows that the polarisation direction is perpendicular to the limb because positive polarisation direction is vertical and negative is horizontal. Even a better evidence of polarisation oriented perpendicularly to the limb is achieved by computing the radial polarisation $Q_r$ from Stokes Q and U according to:

$$Q_r = +Q \cos(2\phi) + U \sin(2\phi),$$  \hspace{1cm} (6.13)

where $\phi$ is the polar angle counted clockwise from celestial north (West limb) of a given
position \((x, y)\) on the planetary disc with respect to the centre of the disc \((0, 0)\), \(\phi = \arctan(x/y)\).

The radial polarisation is positive if the polarisation is perpendicular to the limb and negative if parallel. The right panel of Fig. 6.15 shows the white signal along the limb of Uranus indicating a polarisation perpendicular to the planet’s limb. This confirms the evidence of a second order scattering effect in Uranus’ atmosphere also proved by spectropolarimetric observations.
6.5 Discussion of the polarimetric data from Uranus and Neptune

In the following two sections the polarimetric data are discussed and comparisons between the spectropolarimetry and the imaging polarimetry of Uranus and Neptune are made.

6.5.1 Comparison between spectropolarimetry and imaging polarimetry

The R, i and z-band imaging polarimetry of Uranus and Neptune reported in Schmid et al. (2006b) reveals the same overall polarisation behaviour as the spectropolarimetric data presented here. Both, imaging polarimetry and long-slit spectropolarimetry, show for Uranus and Neptune essentially no polarisation in the disk centre and a strong limb polarisation with a position angle perpendicular to the limb.

Already the polarimetric images taken in a few, mainly broad-band, filters define a general trend, that the limb polarisation is lower for longer wavelengths. However, the wavelength dependence of the limb polarisation is described in much more detail with the long-slit spectropolarimetry presented in this thesis. From spectropolarimetry it is obvious that there is not only a decrease in the limb polarisation with wavelength but also a very tight anti-correlation with the albedo.

The spectropolarimetry and the imaging polarimetry of Uranus and Neptune yield further results which are complementary. Very interesting is the spectropolarimetric result that the relatively dark northern latitudes of Uranus have a higher level of polarisation $Q/I$ when compared to the other limbs. This result is not seen with the imaging polarimetry in Schmid et al. (2006b) due to the delicate alignment requirements for the images with opposite polarisation in the data reduction process.

The imaging polarimetry was taken under better seeing conditions ($0.8''$) and the spatial resolution was not further degraded by a wide slit, as it was for Neptune in the spectropolarimetric measurements. Therefore, the imaging polarimetry allowed to derive a seeing corrected limb polarisation average for both planets, indicating that the intrinsic limb polarisation for Neptune is about a factor of $\approx 1.5$ higher than for Uranus.

A good quality test of the data analysis provides the comparison of the derived intrinsic limb polarisation of Uranus from imaging polarimetry and spectropolarimetry. For this, the derived values for the disk averaged limb polarisation $\langle Q_r/I \rangle$ are converted from imaging polarimetry (equation 6.13) into the slit (line) averaged limb polarisation $\langle Q/I \rangle_{\text{line}}$ as obtained from the spectropolarimetric data. This conversion depends somewhat on the radial dependence of the intensity and the limb polarisation. However, the simple model results presented in Schmid et al. (2006b) indicate that a conversion relation $\langle Q_r/I \rangle \approx 1.6 \langle Q/I \rangle_{\text{line}}$ is adequate for the expected centre to limb profiles.

Thus, the converted parameters for the intrinsic limb polarisation of Uranus from the filter polarisation is $\langle Q/I \rangle_{\text{line}}^{\text{corr}} = 0.53\%$ for the $\lambda_{673}$-filter (albedo=0.32); 0.59 % for the $\lambda_{729}$-filter, corresponding to M5, (albedo=0.05); 0.46 % for the i-filter (albedo=0.19) and 0.27 % for the z-filter (albedo=0.12).
6.5. Discussion of the polarimetric data from Uranus and Neptune

In Fig. 6.16 the limb polarisation $(Q/I)_{\text{line}}^{\text{corr}}$ and the albedo from the filter polarimetry are compared with the spectropolarimetry. The broad band filters $i$ and $z$ lie between the values for the reddest wavelength intervals $C5$ and $M6$ and $M7$ as expected for a broad band average. Also for the narrow band filter $\lambda_{673}$ located in wavelength between $M4$ and $C3$ the agreement is quite good. Only for the $\lambda_{729}$ filter the measured polarisation from the filter polarimetry is significantly lower than the spectropolarimetric results ($M5$). As described in Schmid et al. (2006b), the accuracy of the measurement in this filter is particularly low due to the low signal to noise. Thus, it may be concluded that the agreement between imaging polarimetry and spectropolarimetry is good, except for the low quality $\lambda_{729}$-filter observations.

This gives confidence that the analysis and the applied seeing corrections are consistent for the two data sets.

![Fig. 6.16: Seeing corrected, full slit polarisation for the equatorial slit of Uranus vs. albedo from Table 6.5. The circles are the high albedo regions (C1 – C5) and the triangles are the methane absorption bands (M1 – M7). The dotted line gives the full slit polarisation at 6000 Å and the dashed line at 7000 Å, according to Eq (6.11). The filled squares denote the measured polarisation with the four filters from previous observations in Schmid et al. (2006b) (broad band filters $i$ and $z$ and the narrow band filters centred at 673 and at 729 nm).](image)

6.5.2 Limb polarisation and atmosphere models

The properties of the limb polarisation for Uranus and Neptune can be summarised as follows:

- higher polarisation for shorter wavelength
6.5. Discussion of the polarimetric data from Uranus and Neptune

- enhanced polarisation in the methane bands when compared to the inter band regions
- in Uranus a higher inter band polarisation for the darker northern latitudes when compared to the bright South Pole.

According to simple Rayleigh scattering models a limb polarisation is expected for scattering atmospheres with some amount of Rayleigh-type scattering.

However, for homogeneous (semi-infinite) Rayleigh scattering atmospheres one does not expect an enhanced limb polarisation in deep absorption bands (Schmid et al. (2006b)) except for a small range of single scattering albedos around 0.8 and 1.0 corresponding to geometric albedos between 0.3 to 0.79. A tight anti-correlation between polarisation and albedo is obtained for models with finite Rayleigh scattering layers above diffusely reflecting ground layers or deeper layers with different albedos (Schmid et al. (2006b)). This can easily be understood as a constant amount of Rayleigh scattered radiation producing the limb polarisation, combined with an albedo dependent contribution of unpolarised light from diffusely reflecting lower layers.

The limb brightening effect, which shows also an anti-correlation with albedo, points to a similar stratification in the atmosphere of Uranus and Neptune. As predicted by Belton & Price (1973) and illustrated by e.g. Hammel et al. (1989) or Sromovsky (2005), only inhomogeneous scattering atmospheres with a single scattering opacity increasing with depth will show a limb brightening.

It is well known that Uranus and Neptune have optically thin scattering haze layers high in the atmosphere. This finding is based on careful analyses and modelling of the albedo spectrum, centre to limb profiles and other multi-wavelengths studies of these planets (e.g. Baines & Bergstralh (1986); Hammel et al. Hammel et al. (1989); Baines & Smith (1990); Baines & Hammel (1994); Sromovsky (2005)).

With the newly detected limb polarisation of Uranus and Neptune it would now be possible to test the existing models with radiative transfer calculations including polarisation. It should not be expected that the atmospheric models have to be radically changed for Uranus and Neptune due to the polarisation signal. However, one may expect that an analysis including the scattering polarisation would provide important new insights on the scattering properties for the aerosol particles in the haze layers of these planets.
6.6  Spectropolarimetry of Jupiter and Saturn

During the run in Nov. 2003 at La Silla observatory also imaging polarimetry and spectropolarimetry of Jupiter and Saturn were obtained. The spectropolarimetric data of Jupiter and Saturn are presented in this thesis because no such data have been described in the literature up to now. For Jupiter, spectropolarimetry of the northern polar regions was acquired on November 29th, whereas on the 30th the southern, eastern and western parts were taken. All spectropolarimetric measurements of Saturn were made on November 29th. For Jupiter, both slit orientations (N-S and E-W) are presented, whereas for Saturn only the N-S direction is treated. For each mentioned region of the two planets three sets of polarisation measurements were taken, except for Jupiter North, where only two sets could be used. To remember, one set of polarisation measurements consists of four expositions with the different positions of the half-wave plate at 0°, 45°, 22.5° and 67.5° (see also section 6.2).

The diameters of the planets were larger than the length of the slit. Therefore, “long-slit” polarimetry does not cover an entire cut through the planet as for Uranus and Neptune. Nevertheless, with two slit positions it was possible to cover nearly the whole planet diameter for Jupiter in North-South and the whole diameter for Saturn in N-S direction. For Jupiter in E-W direction only the limb regions were measured. The positions of the slits can be seen in Figs. 6.17 and 6.23.

Disc resolved spectropolarimetry along the slits are presented for the wavelength range of 5300 to 9300 Å which includes strong methane absorption bands.

The slit width was for Jupiter and Saturn 0.5”. The spectrographic slits were aligned along the central meridian or the equator of the planets, respectively and not oriented along the celestial directions as it was the case for Uranus and Neptune.

The coordinate systems used for Jupiter and Saturn are projections of the planetary spheres on a Cartesian system, i.e. the centre of the apparent planetary disc has the \((x = 0, y = 0)\) coordinates. Towards planetary North and West it is counted positively and towards South and East negatively.

Albedo spectra are constructed from our data. For this, the intensities along the spatial directions of each slit orientation (N, S, E and W for Jupiter, N and S for Saturn) were averaged, multiplied with a smooth correction function which accounts for the instrumental efficiency and then normalised to the geometric albedo spectrum of Karkoschka (1994). On the other hand, no correction for telluric absorption, such as the A-band at 7590 Å, the B-band at 6870 Å or water absorption bands between 7200 and 7300 Å were done.

Comparisons of the polarimetric signals from the higher albedo regions with the methane absorption bands are made. For this, special spectral regions are selected after the same scheme as it was done for Uranus and Neptune. Five high albedo regions (C1 – C5) and seven methane absorption bands (M1 – M7) are chosen for further investigation (see Fig. 6.18). The selected features defined in Table 6.7 are used for Jupiter and for Saturn. The high albedo regions have all the same spectral width of 100 Å each, whereas the methane regions differ depending on the width of the absorption band. The albedo

---

3 Orientations for Jupiter and Saturn are always given for the coordinate systems of the planets, i.e. North (N) refers to the northern region of the planets (the same for South, East and West).
values for both planets are also given in Table 6.7 for the envisaged spectral domains.

<table>
<thead>
<tr>
<th>feature</th>
<th>wavelength</th>
<th>albedo Jupiter</th>
<th>albedo Saturn</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>6000 - 6100</td>
<td>0.58</td>
<td>0.55</td>
</tr>
<tr>
<td>C2</td>
<td>6300 - 6400</td>
<td>0.57</td>
<td>0.58</td>
</tr>
<tr>
<td>C3</td>
<td>7420 - 7520</td>
<td>0.50</td>
<td>0.59</td>
</tr>
<tr>
<td>C4</td>
<td>8230 - 8330</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>C5</td>
<td>9150 - 9250</td>
<td>0.38</td>
<td>0.49</td>
</tr>
<tr>
<td>M1</td>
<td>5380 - 5450</td>
<td>0.58</td>
<td>0.48</td>
</tr>
<tr>
<td>M2</td>
<td>6180 - 6200</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>M3</td>
<td>7240 - 7300</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>M4</td>
<td>7830 - 8000</td>
<td>0.35</td>
<td>0.44</td>
</tr>
<tr>
<td>M5</td>
<td>8380 - 8440</td>
<td>0.40</td>
<td>0.48</td>
</tr>
<tr>
<td>M6</td>
<td>8600 - 8670</td>
<td>0.21</td>
<td>0.26</td>
</tr>
<tr>
<td>M7</td>
<td>8810 - 9000</td>
<td>0.07</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 6.7: Spectral regions defined for the Jupiter and Saturn disc profiles with the appropriately averaged albedo values.

The next sections describe the polarimetric data for Jupiter and Saturn. First, Jupiter is discussed and then Saturn. For both planets we start with spatial cuts (disc profiles) parallel to the slit orientations. The cuts are constructed for the selected spectral ranges as defined in Tabl. 6.7. Secondly, spectropolarimetry is presented. This contains besides the flux spectrum also the linear polarisation spectrum in Stokes Q/I. The spectra are always given for a selected spatial region of the planet, for example the limb region or the total slit, etc. The flux spectra are corrected for the instrumental efficiency (like for Uranus and Neptune) but are left in arbitrary units.

6.6.1 Disc profiles for Jupiter

The orientation on the Jovian disc is divided into two parts depending on the orientation of the spectrographic slits, in N-S and in E-W, respectively. Since Jupiter had a diameter of \( \approx 34'' \) in polar and \( \approx 36'' \) in equatorial direction, respectively, but the slit length was about 20'', only selected parts of the planet could be measured at once. The exact positions of the slits during the measurements on 29th and 30th of November 2003 are indicated in Fig. 6.17, where also the nominal limb and the South Pole are marked. The northern slit starts at 2'', the southern at 1'', the eastern at 12.8'' and the western at 10.7'' distance from the centre of the Jovian disc. This indications refer to the usable parts of the slit.

In principle, a slit length of nearly 20'' was achieved since the geometric length of the slit was 19.7''. But, because of the already mentioned (Sect. 6.2.3) dispersive power of the Wollaston prism and the different curvature of the ordinary and extra-ordinary beams and the following required alignment procedure, not the whole length of the slit could
be used. But also because of stray light at the edges of the slit, the outermost parts of the slits must be cut away and are therefore not usable. Because of this, the geometrical northern and southern limbs are not that well mapped as it was the case for Uranus or Neptune (where the slit was much longer than the planetary diameter) or as it is for the western and the eastern limbs of Jupiter. The South polar region comes up with less spatial information than the North Pole.

Fig. 6.17: Acquisition image of Jupiter to demonstrate the position of the spectrographic slits (white). The nominal limb and the South Pole are indicated in the image (black). North is up and East is left.

Similar to the Uranus measurements, cuts through the Jovian disc along the spectrographic slits for different spectral regions are presented. Fig. 6.18 can be used to compare the selected spectral regions, C1 – C5 and M1 – M7, with the whole albedo spectrum.

Although not the whole planet diameter was captured within one slit, the data from two slits are combined to create the disc profile and for the N-S direction nearly the whole planet along the central meridian was covered. Where no information is available, i.e. where parts of the planet were not covered by the slit aperture, the sections in the profiles are left blank.

There are two main differences in the presentation mode compared to the former of Uranus. First, no spatial binning is processed anymore, thus, the full obtained resolution is presented. Secondly, instead of drawing error bars for $Q/I$ the error is computed for the entire profile and an upper and a lower curve of the polarisation signal is plotted. Hence, the real value lies in between. The error is computed the same way as it was for Uranus, i.e. in principle the photon noise is considered.

**North-South direction**

The N-S direction on Jupiter is affected by intensity and spectral features due to the belt and zone structure. Whether this impacts the polarimetric signals or not is also a
6.6. Spectropolarimetry of Jupiter and Saturn

subject of this section. The slit was pointed once over the northern hemisphere with only a small part reaching beyond the northern limb and the other time over the southern half of Jupiter. Only about 3\" at the very centre of the Jovian disc and 0.3\" at the South Pole are not captured within our measurements, see also Fig. 6.17.

In Fig. 6.19 a profile for the high albedo region C1 from 6000 to 6100 Å is plotted. In the intensity plot the belt structure is clearly visible, particularly in the southern hemisphere. Since the central part of Jupiter is not available, the intensity is normalised to the intensity $I_0$ of the most central pixel, which is the pixel at $-1\"$. The dotted vertical lines at the limbs indicate the positions for the southern limb (Is) and the northern limb (In) which are used in the next section for spectropolarimetry. The profiles for the normalised linear polarisation parallel to the slit $Q/I$ (solid lines) and the Stokes $U/I$ (dashed lines) are plotted in the middle panel. An evident difference in the polarisation strength is visible between South and North. On the South polar region a peak value of about 10% of $Q/I$ is reached, whereas a maximum of about 8% is present at the northern limb. This asymmetry is present in all spectral regions. In the red part of the spectrum this difference is even stronger than for the "blue" C1 region (see also appendix A.3 and Table 6.8). This asymmetry was also observed by Lyot (1929). In addition also $U/I$ is plotted (dashed line). There is no significant $U/I$ signal visible along the central meridian, except at the polar regions where it increases at the South Pole and decreases in the north polar region. This effect is small and it is not clear whether it is real or not. In the lower panel the polarised flux $Q$ is plotted as a percentage of $I_0$.

As it is evident from Fig. 6.19 the polarisation signal $Q/I$ towards the disc's centre is negative (about -0.45%). The negative polarisation is due to the relatively large phase angle under which Jupiter was observed at the end of November 2003. The phase angle was $\alpha = 10.4^\circ$, which is close to the maximum phase angle for Jupiter $\alpha_{\text{max}} = 10.7^\circ$. Morozhenko & Yanovitskii (1973) observed the central part (10") of the Jovian disc at different phase angles and determined the polarisation to be at about -0.45% for a phase
6.6. Spectropolarimetry of Jupiter and Saturn

Fig. 6.19: Spatial cut for the high albedo region C1 from 6000 Å to 6100 Å through Jupiter along the central meridian from South to North. South is left and North is right. The upper panel shows the intensity normalised to $I_0$. The dotted vertical lines show the regions which are selected for the limb spectrum in the next section (“ls” for the southern and “ln” for the northern limb). In the middle panel the normalised polarisation, Stokes $Q/I$ (solid line) and $U/I$ (dashed line), is plotted in percent. The two curves each give an error estimate. The lower plot is the polarised flux normalised to $I_0$.

angle of $\alpha = 10^\circ$ at 6200 Å. Dollfus (1957) measured in 1952 Jupiter’s central region to have a polarisation of -0.6% at 6500 Å. Jupiter was observed that time under a phase angle of $\alpha = 10.7^\circ$, thus, both measurements were processed at phase angles very close to that of November 2003. Hence, the negative polarisation reported here is in agreement with previous “aperture” polarimetry.

Looking at the polarisation behaviour of the north- and south equatorial belts ($2'' < |y| < 6''$), clearly visible in the intensity image of Fig. 6.19, there is hardly something to notice for the $Q/I$ signal. The polarisation $Q/I$ drops dramatically when traversing from the poles towards equatorial latitudes, becomes negative and rises then smoothly (becomes less negative) towards the equator correlating with the spatial position of the belts. The position of the equatorial zone could not be measured with our observations,
but, according to previous measurements from Dollfus (1957), Hall & Riley (1976) and Joos et al. (2005) it is expected that the polarisation in the disc centre is similar to the adjacent belts. This means, that there is no obvious difference in $Q/I$ between equatorial belts and equatorial zone visible from our measurements.

For the polarised flux $Q$ it is much more evident, that it increases (becomes less negative) for the dark equatorial belts and decreases again towards the brighter equatorial zone. For the C1 region the difference in polarised flux between the lowest $Q$-flux region at $-9^\circ$ in the South and $8^\circ$ in the North to the enhanced equatorial belt regions is about $0.22 - 0.25\%$ of the peak flux $I_0$. This effect of slightly enhanced polarisation flux $Q$ on the positions of the equatorial belts is visible for all selected spectral regions (appendix A.3). This means, that the polarised flux $Q$ is less negative in the dark equatorial belts compared to the bright equatorial zone.

**East-West direction**

The disc profiles in East-West direction show different features compared to the meridional data not only in intensity but particularly for the polarisation signals. The profiles cover the whole spatial range from the inner edge of the slit-lets out to $\pm 20^\circ$. The “inner” edge is slightly different for the eastern and the western slit-lets. The eastern starts at $-12.8^\circ$ and the western at $10.7^\circ$.

In Fig. 6.20 one can see, that the intensity profile is steeper in the East. This phenomenon is visible for all 12 spectral regions and is mainly due to the relatively large phase angle of our observations. The dotted vertical lines denote the positions of the eastern (le) and the western (lw) limb regions used in the next section for the spectropolarimetry. Further, there is a very low $Q/I$ signal in the East. Similar to the N-S cuts an upper and a lower border, given by the error calculation, confine the $Q/I$ profile. At the position of the nominal eastern limb at $-18^\circ$ the polarisation is about $0.4\% (\pm 0.2\%)$, whereas at the western limb the polarisation at $18^\circ$ is significantly higher and reaches $2.7\% (\pm 0.35\%)$. It can be seen, that at both limbs the steep increase of $Q/I$ begins at $17^\circ$ distance from the centre of the disc and reaches the maximum value at about $\pm 18.5^\circ$.

Both limbs show a minimum polarisation at about $16^\circ < |x| < 17^\circ$ of $0.06\% (\pm 0.09\%)$ in the East and $0.1\% (\pm 0.1\%)$ at the western limb.

Unlike the N-S profiles, the Stokes $U/I$ profiles are for reasons of clarity not shown here.

In the panel at the bottom the polarised flux $Q$ decreases from the central parts towards the limb, but then, shortly before reaching the nominal limb, there is a small increase in polarised flux of comparable magnitude for both sides. Because of the different slope in the descent of the intensity, a different normalised polarisation arises in the East compared to the West. This is a very interesting feature which is visible in most spectral regions (appendix A.3). This rising in polarised flux occurs at the furthermost limb, where the solar radiation is incident nearly tangential to the planet. This thin, high atmospheric layer must therefore contain Rayleigh scatterers responsible for the second-order scattering effect, whereas in the lower atmosphere the contribution of diffuse reflection by clouds dominates.
Fig. 6.20: Disc profile along the equator of Jupiter from East to West for the high albedo region C1. "le" and "lw" in the intensity plot mark the "limb east" and the "limb west" regions which are chosen for the spectra at the limbs in the next section. Same denotation as in Fig 6.19.
6.6. Spectropolarimetry of Jupiter and Saturn

6.6.2 Spectropolarimetric structure of Jupiter

Spectropolarimetry for Jupiter with the slit oriented in N-S and E-W direction were obtained for the spectral range of 5300 to 9300 Å. Similar to the observations and presentations of Uranus and Neptune, spectropolarimetric plots of selected spatial regions are discussed in the following for Jupiter.

Spectropolarimetry for the N-S direction

The polarimetric spectra for the northern and southern limb regions of Jupiter are plotted in Fig. 6.21. The data were selected from a limb region $15'' < |y| < 16.5''$ (cf. Fig. 6.19) in the North (solid lines) and in the South (dotted lines). The planetary limb

![Graph showing spectropolarimetric data for Jupiter](image)

Fig. 6.21: Spectropolarimetry of Jupiter at the North (solid line) and at the South polar region (dotted line). The chosen spatial regions are for both polar areas $15'' < |y| < 16.5''$. is at $\pm 16.8''$. This means, that the furthermost limbs are not completely reached in our
spectropolarimetry, but this is probably only a minor effect, since the maximum of the polarisation flux is at about \(|y| = 15.5''\) (can be seen in Fig. 6.19) and therefore well inside the slit. The reason why the limbs are not reached is because of the alignment problem already discussed in Sect. 6.2.3.

Fig. 6.21 shows in the upper panel the flux spectrum in arbitrary units. For the selected region at the poles an averaged photon flux of about \(3 \cdot 10^6\) photons per binning element (30 Å x 1.5'') are obtained. It is dominated by the strong methane absorption bands around 7270 Å (M3) and 8900 Å (M7) and the telluric O2-absorption (A-band) at 7590 Å. The southern spectrum shows an increase towards the blue unlike the northern spectrum. In the middle panel Stokes \(Q/I\) is plotted in percentage.

There are some clear differences between the two polarisation spectra but also some common properties:

- The southern limb has an overall higher polarisation than the northern limb.

- The northern \(Q/I\) spectrum shows a decrease towards longer wavelengths. This is much less the case for the southern spectrum. The southern \(Q/I\) spectrum is nearly constant at a level of \(\approx 8\%\) in the wavelength range from 5300 to about 7000 Å and begins to decrease only further on.

- Both \(Q/I\) spectra show a slight enhancement in the methane absorption bands. The increase of polarisation for the southern slit is larger than for the northern, except in M6 and M7.

Since the selection of regions on Jupiter is somewhat arbitrarily a more physical definition of areas on Jupiter is considered. As visible in Fig. 6.19 there are regions along the slit, where the polarised flux is positive (towards the limb) and where it is negative (towards the centre). Such a distinction between the direction of the polarised flux offers a reasonable criterion for comparisons with other observers. Therefore, the zero-point \(y_0\) of the polarised flux was determined for each spectral region for the northern and the southern hemisphere. \(y_0\) was found to be wavelength dependent and to lie between 10.8'' < \(|y_0| < 13.7''\), where \(Q > 0\) for \(|y| > y_0\) and \(Q < 0\) for \(|y| < y_0\) (\(y\) is the radial position in arcsec in N-S direction and \(y_0 = y_0(\lambda)\) is wavelength dependent).

The polarised fluxes from the regions between \(y_0\) and the edges of the slit are averaged and divided by the appropriate intensities obtaining for each spectral region 4 polarisation signals: \(Q/I\) for the northern hemisphere with positive polarisation \((N_p)\) and with negative polarisation \((N_n)\) and \(Q/I\) for the southern hemisphere also with positive \((S_p)\) and negative \((S_n)\) polarisations.

These four regions are called positive polarisation at the poles and negative polarisation at intermediate latitudes here and the polarisation degrees for all selected spectral regions are presented in Table 6.8.

---

4 The northern limb could in principle be reached unlike the southern, but for reasons of better comparability the same regions were chosen for North and South.
Spectropolarimetry for the E-W direction

In the following spectropolarimetry of Jupiter taken with the spectrographic slits in E-W direction is presented. Only little of the equatorial parts is caught inside the slits oriented in E-W direction. These measurements were taken simultaneously with two adjacent slit-lets, one over the eastern and the other over the western part of the equatorial latitude, while the central part (22") was occulted by the Wollaston mask (see Fig. 6.2). This is different compared to the meridional slit positions. There, each position was taken as single measurement one after the other.

Since there were two different slit-lets used for the scientific observations but only one was used for the calibration measurements of the standard stars, the precision of aligning the spectra (Sect. 6.2.3) is maybe less accurate for the East-West observations compared to the North-South data.

![spectropolarimetric plot](image)

**Fig. 6.22:** Spectropolarimetric plot of the eastern (solid line) and western limbs (dotted line) of Jupiter for the regions of 17" < |x| < 19". In the upper panel the flux is plotted. The lower panel gives the Stokes $Q/I$ spectrum for both limb regions.
In Fig. 6.22 a 2" wide limb region (17" < |x| < 19") along the equator is presented for the eastern and western limbs (cf. Fig. 6.20). The geometrical limb is at ±18".

The polarimetric case for the equatorial limbs of Jupiter is completely different to the polar regions. This special Jovian polarimetric distribution was also reported in several earlier observations, such as by Lyot (1929).

For the eastern limb the polarisation at these longitudes is very low over the whole spectral range ((Q/I) ≈ −0.28%). On the western limb a significant polarisation is present. Stokes Q/I decreases from 2% at 5300 Å to nearly 0% at the position of the methane band M3 and starts to increase again to 2% at the blue wing of the deep absorption band at 8900 Å (M7). Inside the M7 band, the polarisation rises abruptly to a peak of about 5% and down again to about 2% after the methane band.

In Tabl. 6.8 the limb polarisation signals for the North, South, East and West limbs of Jupiter are listed. These are not the peak polarisation signals but spatial averages for the areas: 15" < |y| < 16.5" for North and South and 17" < |x| < 19" for East and West. The polarisation signals are flux weighted values \( \langle Q/I \rangle = \Sigma Q/\Sigma I \), where \( \Sigma I \) and \( \Sigma Q \) are summed over intensity flux and polarisation flux, respectively for the selected spatial bin and wavelength interval.

<table>
<thead>
<tr>
<th>feature</th>
<th>N limb</th>
<th>S limb</th>
<th>E limb</th>
<th>W limb</th>
<th>Q/I [%]</th>
<th>pos. &amp; neg. polaris. reg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>6.76</td>
<td>8.18</td>
<td>0.29</td>
<td>1.61</td>
<td>3.00</td>
<td>-0.46 3.88 -0.54</td>
</tr>
<tr>
<td>C2</td>
<td>6.32</td>
<td>8.09</td>
<td>-0.21</td>
<td>1.26</td>
<td>2.88</td>
<td>-0.49 4.03 -0.57</td>
</tr>
<tr>
<td>C3</td>
<td>4.62</td>
<td>7.51</td>
<td>-0.05</td>
<td>0.68</td>
<td>2.40</td>
<td>-0.55 4.06 -0.62</td>
</tr>
<tr>
<td>C4</td>
<td>3.70</td>
<td>6.89</td>
<td>-0.54</td>
<td>1.55</td>
<td>2.02</td>
<td>-0.54 3.58 -0.59</td>
</tr>
<tr>
<td>C5</td>
<td>2.83</td>
<td>6.06</td>
<td>-0.54</td>
<td>2.02</td>
<td>1.42</td>
<td>-0.52 3.19 -0.59</td>
</tr>
<tr>
<td>M1</td>
<td>7.61</td>
<td>8.20</td>
<td>-0.14</td>
<td>2.21</td>
<td>2.88</td>
<td>-0.38 3.58 -0.45</td>
</tr>
<tr>
<td>M2</td>
<td>6.95</td>
<td>8.59</td>
<td>0.17</td>
<td>1.38</td>
<td>3.10</td>
<td>-0.56 4.08 -0.65</td>
</tr>
<tr>
<td>M3</td>
<td>5.60</td>
<td>8.48</td>
<td>-0.22</td>
<td>0.12</td>
<td>2.91</td>
<td>-0.88 5.15 -0.98</td>
</tr>
<tr>
<td>M4</td>
<td>4.71</td>
<td>7.96</td>
<td>-0.47</td>
<td>1.68</td>
<td>2.48</td>
<td>-0.71 4.43 -0.81</td>
</tr>
<tr>
<td>M5</td>
<td>3.68</td>
<td>6.92</td>
<td>-0.58</td>
<td>1.92</td>
<td>2.06</td>
<td>-0.59 3.85 -0.62</td>
</tr>
<tr>
<td>M6</td>
<td>3.97</td>
<td>7.23</td>
<td>-0.23</td>
<td>2.35</td>
<td>2.37</td>
<td>-0.82 4.23 -0.91</td>
</tr>
<tr>
<td>M7</td>
<td>4.29</td>
<td>7.08</td>
<td>-0.30</td>
<td>4.54</td>
<td>2.77</td>
<td>-1.07 4.74 -1.15</td>
</tr>
</tbody>
</table>

Table 6.8: Polarimetric Q/I signals for all 12 selected spectral regions at the limbs of Jupiter (columns 2 to 5) and at the regions of positive polarisation at the poles and negative polarisation at intermediate latitudes ("pos. & neg. polaris. reg.", columns 6 to 9). All regions are explained and defined in the text.

In addition, North-South slit regions where the polarised flux is positive (positive polarisation at the poles) and regions where it is negative (negative polarisation at intermediate
latitudes) are investigated separately. Stokes $Q/I$ is computed for these regions and listed in Tabl. 6.8. They are presented in the four last columns in the table. These regions are labelled with an index $p$ for positive and an index $n$ for negative polarisation.
6.6.3 Disc profiles for Saturn

Saturn is inclined relatively to the ecliptic by about 26°. Therefore, in November 2003 the planet was tilted in such a way that the South Pole was visible from Earth but the northern latitudes were covered by the rings.

Equal to Jupiter, the chosen coordinate system of Saturn is a Cartesian with the origin (0,0) of the x-y axis at the geometric centre of the apparent disc counting positively in north and west directions. \( y \) is used for coordinates in N-S direction. The used units are arcsec.

Saturn had an apparent diameter along the central meridian of 18.6". Therefore, it was easily possible to cover the whole meridian from the northern limb of Saturn down to the South Pole with two separate slit positions. The northern slit is suitable covering the region from \( y = 0.9" \) to more than 13", whereas the southern slit covers the region from 1.2" down to -14.7". With suitable I mean again the part of the slit which is not affected by stray light and which has been corrected for the bending due to the Wollaston prism, as explained in Sect. 6.2.3.

![Fig. 6.23: Acquisition image of Saturn. The South Pole is marked with the black dash at the bottom and East is left. The two slit positions are marked with the two overlapping white rectangles. The geometric limb of Saturn is indicated as well as the edges of the A and the B ring.](image)

Fig. 6.23: Acquisition image of Saturn. The South Pole is marked with the black dash at the bottom and East is left. The two slit positions are marked with the two overlapping white rectangles. The geometric limb of Saturn is indicated as well as the edges of the A and the B ring.

Fig. 6.23 shows an acquisition image of Saturn. The South Pole is indicated at the bottom with a dash and East is left. The South Pole had an apparent distance from the southern limb of 1.03" (projection on the planetary disc along the central meridian). The two long white rectangles indicate the positions of the two slits over the planetary disc. It can be seen that the slits overlap and therefore, the whole spatial information along the central meridian is obtained.

From our measurements, it is difficult to localise all the separate rings by their boundaries. Nevertheless, in the acquisition image, the two main rings, the A and B ring are
clearly visible and distinguishable. The outer, darker ring is the A ring, and the inner, brighter ring is the B ring. Note, that in Fig. 6.23 bright is depicted as black and dark is displayed white. Accurate positions of the A and B rings are taken from Tholen et al. (2000) and the edges of the two rings are drawn in the acquisition image. The B ring extends from 1.53 to 1.95 times the equatorial radius of Saturn $r_S$ and the A ring from 2.03 to 2.26 $r_S$. The gap in between is the Cassini gap. Regarding the inclination of Saturn, the B ring extends from 6.3" to 7.9" and the A ring from 8.2" to 9.1".

The albedo spectrum for Saturn is slightly different when compared to Jupiter's albedo spectrum. The albedo of Saturn is affected by a decrease shortward of 7000 Å whereas the Jovian albedo shows a decrease of the high albedo regions towards the red end of the spectrum. Therefore, the positions of the selected wavelength regions C1 – C5 and M1 – M7 are shown by means of the appropriate Saturn albedo spectrum in Fig. 6.24, although the wavelength intervals for the 12 features have remained the same for Saturn. The positions of the ranges are drawn in bold ink and marked with the associated designation of the section.

![Saturn albedo spectrum with drawn and denominated positions of C1 – C5 and M1 – M7.](image)

**Fig. 6.24:** Saturn albedo spectrum with drawn and denominated positions of C1 – C5 and M1 – M7.

The polarimetric profiles for the North-South direction of Saturn cover a very diversified region. In the North, the ring system covers the planetary body from about 6.3" to 9.1" (measured as usual from the apparent disc centre). Further South, the profile crosses the equator down to the South Pole at -8.27". Since the apparent disc had a diameter of 18.6" along the central meridian, more than an arcsec around the South Pole is visible.

In Fig. 6.25 an example for a cut through Saturn is demonstrated for the “blue” spectral range C1 of our measurements. The upper panel shows the normalised intensity which is normalised to the central pixel of the disc. The hump towards the North signalises the enhanced reflection due to the rings. The precise position of the two main rings, the A and the B ring, are indicated with vertical dotted lines marked with the nomination of the ring. The dashed vertical lines indicate the spatial regions for which averaged
spectropolarimetry has been extracted. The ring material has similar albedos like the atmosphere varying between 0.4 and 0.6 (Tholen et al. (2000)).

![Graph](image)

Fig. 6.25: Spatial cut through Saturn along the central meridian from South to North. The South Pole is to the left and the northern latitudes to the right. The cut covers the spectral range C1 from 6000 Å to 6100 Å.

The polarisation $Q/I$ in the second panel is presented the same way as for Jupiter. An upper and a lower curve give an estimate of the error for $Q/I$. The polarisation signals exhibit an interesting shape. While the polarisation increment at the southern limb is expected from previous measurements (e.g. Gisler (2005)), there is a pronounced polarisation signal towards North peaking at mid-northern latitudes at about $4''$. This is about $2''$ south of the projection on the disc of the inner limb of the B ring, thus, a region which is not covered by the ring seen from Earth. On the other hand the polarised signal is very small and negative at the position of the ring system.

The peak polarisation reaches for the southern part of the disc about 1.6% at $-9''$. On the northern part it is even higher. With about 1.9% the highest polarisation along the central meridian is measured at $4.1''$. The polarisation does not vanish at the central
6.6. Spectropolarimetry of Jupiter and Saturn

parts of Saturn. A positive residual polarisation of about 0.4% is present at 0″.

The third panel is the same as the second but for \( U/I \). Stokes \( U/I \) is expected to be near zero but it shows an enhanced signal in the northern hemisphere coinciding with the enhancement of \( Q/I \). This correlation between \( Q/I \) and \( U/I \) is not visible for all spectral regions (cf. Figs. A.14 and A.15 in the appendix) but mostly present where also the \( Q/I \) polarisation is substantial. In the South there is no correlation between \( Q/I \) and \( U/I \). Only further towards the South there is a deviation from the mostly flat \( U/I \) profile, but this can be an instrumental effect due to the edge of the slit.

The polarised flux \( Q \) in the bottom panel exhibits a strong difference between South and North. Although the positions of the flux maxima coincide with the positions of the \( Q/I \) maxima the strengths are by far not equally evolved. The maximum of the \( Q \)-flux in the North is about 3 times higher than in the South. Nevertheless, this discrepancy in polarised flux leads to a nearly equal normalised polarisation \( Q/I \) because of the different intensities at \(-9″\) and at \(4″\). This asymmetry in polarised flux is not present for all wavelengths. It is mostly visible for the blue part of the spectrum (C1, C2, M1, M2, M3), whereas in the red end it vanishes.

The polarisation profiles for all selected wavelength regions on Saturn are presented in appendix A.5.

6.6.4 Spectropolarimetric structure of Saturn

Spectropolarimetry of any part of the slit in N-S direction on Saturn can be retracted and plotted with our data. But only a selection will be presented here and in appendix A.6. Five regions of special interest on Saturn are selected. Four of them are marked in Fig. 6.25 for reasons of visualisation:

1. South Pole (sp) The south polar region is chosen for the area \(-10″ < y < -8″\). It contains the South Pole and surroundings (Fig. 6.26).

2. central part (c) The central part is formed by the central \( 4″ \) from \(-2″\) to \(2″\).

3. intermediate northern latitude (i) An intermediate region with free sight onto the planetary atmosphere without occultation by the ring is chosen for \(3″ < y < 5″\). This area was selected because of the strong polarisation in this region seen in Fig. 6.25.

4. ring system (r) The summed fluxes of the A and the B ring are selected as ring system for \(6.3″ < y < 9.1″\) (Fig. 6.26).

5. total meridian (t) The total light from both slits reaching from \(-11″\) to \(11″\) forms the total meridian.

Fig. 6.26 presents spectropolarimetric plots of two selected regions of Saturn. The upper panels show the flux spectra in arbitrary units for the wavelength range from 5300 to 9300 Å. The lower panels display normalised Stokes \( Q/I \) spectra in percentage.
For the South Pole, the flux spectrum is like for Jupiter a spectrum mostly dominated by the methane absorption bands, particularly towards the red end of the spectrum. The flux spectrum for the ring system is different. The dominating absorption is given by the telluric A-band (7590 Å) and B-band (6870 Å). Only moderate absorption in the methane bands are present particularly at the positions of M3 and M7. This can be caused by stray light from the atmosphere of Saturn. Due to the low methane absorption the whole spectrum is flatter compared to the South Pole.

The polarisation spectrum $Q/I$ for the South pole is steep and more or less featureless for wavelengths shorter than about 7000 Å. At the position of the deep methane absorption around 7270 Å (M3) there is a polarisation feature, but not an enhancement as expected and present for Jupiter but a decrease of $Q/I$ of about 0.4%. This is interesting because at the methane band M7 the polarisation increases again above the polarisation of the high albedo regions. For the ring system the polarisation is for the whole spectral range negative with only small variations except the increase of negative polarisation in the deepest methane band M7. There, the $Q/I$ polarisation decreases from about $-0.2\%$ to less than $-0.5\%$. 

Fig. 6.26: Spectropolarimetric plots for Saturn. Left: the south polar region and right: the ring system in the north.
The Stokes $Q/I$ values of all five regions are presented in Table 6.9. In the first row the spectral features are listed. In the second row the polarisation signals $Q/I$ for the South Pole (sp), in the third row for the intermediate northern latitudes (i), in the forth row for the ring system (r), in the fifth row for the centre (c) and in the last row for the total central meridian (t) are given.

| features | $Q/I$ [%] |
| --- | --- | --- | --- | --- | --- |
| | sp | i | r | c | t |
| C1 | 1.39 | 1.60 | -0.07 | 0.34 | 0.53 |
| C2 | 1.17 | 1.22 | -0.16 | 0.29 | 0.39 |
| C3 | 0.68 | 0.30 | -0.13 | 0.14 | 0.15 |
| C4 | 0.47 | 0.00 | -0.19 | 0.14 | 0.04 |
| C5 | 0.28 | -0.20 | -0.20 | 0.18 | -0.03 |
| M1 | 2.05 | 2.16 | -0.19 | 0.44 | 0.70 |
| M2 | 1.21 | 1.65 | -0.12 | 0.38 | 0.52 |
| M3 | 0.39 | 0.57 | -0.20 | 0.21 | 0.15 |
| M4 | 0.41 | 0.13 | -0.19 | 0.14 | 0.07 |
| M5 | 0.36 | -0.05 | -0.19 | 0.20 | 0.05 |
| M6 | 0.25 | -0.13 | -0.19 | 0.20 | -0.01 |
| M7 | 0.36 | -0.41 | -0.39 | 0.25 | -0.17 |

Table 6.9: Stokes $Q/I$ for all 12 spectral features at different regions on Saturn: South Pole (sp) in row 2, the intermediate northern latitude (i) in row 3, the ring system (r) in row 4, the centre (c) in row 5 and the total slit (t) in row 6. The accurate positions are given in the text.

All polarisation spectra for the five selected regions on Saturn are presented in appendix A.6.
6.7 Summary and discussion for Jupiter and Saturn

Jupiter

Polarimetric cuts along Jupiter's central meridian have been presented for $Q/I$ and $U/I$. Jupiter shows a strong polarisation at the poles in $Q/I$ for all spectral features (C1 – C5 and M1 – M7). The polarisation is always stronger for the southern limb than for the northern, reaching maximum values up to 10%. For the central parts of the disc the polarisation is negative ($\approx -0.45\%$). The polarised flux $Q$ is less negative in the equatorial belts compared to the equatorial zone. The $U/I$ polarisation is less than 0.1% along the central meridian except at the very limbs where it deviates towards positive values in the South and negative in the North.

The spectropolarimetric plots for the polar regions show enhanced polarisation at the positions of the deep methane absorption bands and a different slope of the polarised spectrum for the northern and the southern hemisphere (the northern being steeper).

Comparing the positive (positive polarisation at the poles) and the negative polarisation regions (negative polarisation regions at intermediate latitudes) of the North and South slits reveals an obvious higher polarisation on the southern hemisphere of Jupiter for the positive polarisation flux ($N_p$ and $S_p$) but an almost equal negative polarisation for the regions of negative flux ($N_n$ and $S_n$).

Already Lyot (1929) measured a stronger polarisation at the poles of Jupiter compared to other regions of the disc at opposition. The reason for this asymmetry is, that the atmospheric structure or composition must differ for polar and equatorial regions (Coffeen & Hansen (1973)). At the poles Rayleigh scattering molecules lie in high altitudes layers above the clouds, whereas in equatorial regions only little Rayleigh scattering molecular gas lies above the Jovian clouds.

The equatorial cuts for Jupiter reveal a very low polarisation $Q/I$ at the eastern limb on the order of less than 1%, whereas the western limb shows a remarkable polarisation on the order of 2% for the blue spectra regions and up to 6% for the red. The same is visible in the polarised spectra. There is little coincidence of the $Q/I$ spectrum with the methane absorption bands in the east. It is rather flat and near zero. For the West the whole spectrum is enhanced and peaks in the strong methane band M7 with more than 5%.

There is an obvious difference between East and West in solar irradiation due to the rotation of Jupiter. The Sun rises on Jupiter's East rim (seen from Earth) and sets in the West, i.e. there is sunrise in the East and sunset in the West. This may cause a temperature gradient between East and West. It is possible that ice crystals in the East are re-sublimated into gas phase on the way to the West and scatter therefore Rayleigh like in the West but not in the East.

Saturn

The disc profiles for Saturn in N-S direction reveal an interesting polarisation shape.

At the South Pole an enhanced polarisation $Q/I$ is measured up to almost 2% in the blue with in general a slightly higher polarisation in the methane bands. In the red, the
enhancement of polarisation at the South Pole is barely visible. $U/I$ is less than about 0.2% for the blue and less than 0.4% for the red at the South Pole.

The central 4\" of the disc of Saturn correspond to a centro symmetric scattering geometry. A low polarisation is therefore expected. Averaged for the whole spectrum from 5300 to 9300 Å the Stokes $Q/I$ signal from -2\" to 2\" is 0.24\%, whereas the $U/I$ signal is essentially zero.

At the intermediate northern latitudes from 3\" to 5\" the $Q/I$ polarisation has a maximum in the blue but not visible for the red spectral features. For the same spectral features where $Q/I$ is enhanced also $U/I$ is increased at the same spatial position. This is an interesting effect which could be caused by reflections between atmosphere and rings.

In the deep methane absorption band (M7) where the atmosphere absorbs the major part of the light the rings appear relatively bright. Only a weak negative polarisation in $Q/I$ is measured for the rings but no effect is seen for $U/I$.

The polarised spectra for the South Pole shows interesting $Q/I$ features with a decrease in the methane band M3 and an increase in M7, the overall polarisation being positive. The $Q/I$ spectrum for the rings is flat and negative except at M7, there the polarisation drops from $-0.2\%$ to less than $-0.55\%$. This can be caused due to stray light from the atmosphere or a not opaque ring where atmospheric light is shining through as described in Dollfus (1996).

Spectropolarimetry of the intermediate northern latitudes shows a steep, negative slope for $Q/I$ from blue to red with enhancements in the methane bands M2 and M3. For M7 where the polarisation of the adjacent higher albedo regions is negative the polarisation drops inside the band from about $-0.2\%$ to lower than $-0.4\%$. 
Chapter 7

Polarimetry of extra-solar planets

The contrast of reflected light from an extra-solar planet to its central star depends on the size and the distance of the planet from the star and on the surface properties, i.e. the albedo. The self luminescence is dependent on the temperature of the planet's surface or atmosphere, respectively. Typical temperatures of self luminous planets correspond to radiation in the infrared regime. The temperature itself changes with the age of a planet, being higher for young planets and lower for older. Burrows et al. (1997) have calculated the luminosity of planets with different masses versus time, see Fig. 7.1. The luminosity is expressed relative to solar luminosity in a logarithmic scale.

![Fig. 7.1: Evolution of the luminosity (in L☉) of solar-metalicity, M dwarfs and sub stellar objects vs. time (in yr). The stars, "brown dwarfs" and "planets" are shown as solid, dashed, and dot-dashed curves, respectively. The "brown dwarfs" are defined as objects that burn deuterium, while those which do not are designated as "planets." The masses (in M☉) label most of the curves, with the lowest three corresponding to the mass of Saturn, half the mass of Jupiter, and the mass of Jupiter, (Burrows et al. (1997)).](image)

It is clearly visible from Fig. 7.1 that planets at the age of our solar system radiate on the
order of less than $10^{-8}$ compared to the solar luminosity. This means that our evolved planets are poor in emission of thermal radiation and therefore hardly visible in extra-solar systems with the sensitivity of contemporary infrared detectors.

This makes it clear, that older, evolved planetary systems will most probably reveal their planets by reflected star light as it is the goal for SPHERE-ZIMPOL. The amount of reflected light is not directly dependent on the age of the planet but on other not less restricting parameters such as the phase angle, the albedo of the planet, the planet radius and the distance from the planet to the star.

A very important constraint is the phase angle. One has to expect an extra-solar system to be oriented arbitrarily in respect to the observer, i.e. the system can be oriented face-on, edge-on or at any orientation in between. For a face-on system the geometry is ideal, offering the whole time a phase angle of 90° for which the scattering polarisation is maximal. An edge-on arrangement provides only twice a year (exo-year) a perpendicular phase. In Fig. 7.2 two possible orientations are sketched. Left, a face-on system is drawn, with a planet orbiting the central star. For the observer of such a system, always a half of the visible planetary disc is illuminated and the phase angle is always 90°. This results in the highest possible polarisation signal indicated with a dash tangential to the orbit. The strength of the polarisation signal is for the entire planet orbit equal, whereas the polarisation direction is always perpendicular to the connecting line star-planet. On the right side, the geometry of an exo-system for an arbitrary inclination is presented. Here, it is obvious that the observable illumination changes and that the scattering geometry is also phase dependent. Therefore, the strength of the polarisation signal is also phase dependent.

![Fig. 7.2: Extra-solar system face-on (left) and under an arbitrary inclination (right). The planet is orbiting the central star with different visible illuminations dependent on the phase and different resulting polarisations.](image)

Phase angles near 90° are most promising to detect a planet due to two reasons: largest apparent distance to the central star and highest possible polarisation. This is always guaranteed in a face-on system. But looking at an edge-on configuration harbours the risk that when exposing, the planet is just visible under a small or very large phase angle ($\alpha \approx 0°$, $\alpha \approx 180°$). This would mean, that no polarised signal would be detectable at that time although a quarter exo-year later the best observing condition would be possible. For this reason, searching for extra-solar planets by means of polarimetry desires always an appropriate scheduling of the observations, i.e. if the observer knows the orbiting
period of the envisaged planet, for example from radial velocity observations, a dedicated observing plan can be elaborated.

The search for a polarimetrie signal of an extra-solar planet is challenging, because the polarisation at a planetary surface or atmosphere depends in a crucial way on the material in which the scattering takes place. It has also been shown in this thesis that the polarimetrie signals of Uranus, for example, change, depending on whether the scattered light coincides with methane absorption bands or not, or that the rings of Saturn show a completely different polarimetric “response” than the planetary body of Saturn, or the different polarisation of Jupiter between the polar caps and the equatorial regions.

Schmid et al. (2006a) summarise for all solar system planets and Titan the polarisation degree at a phase angle of 90°. In Fig. 7.3 the polarisation degree versus reflectivity in the R-band (≈ 0.65 μm) for the nine major solar system objects are presented.

![Polarisation degree for solar system objects in the R-band at a phase angle of 90° versus reflectivity (Schmid et al. (2006a)).](image)

Mercury and Mars with essentially no scattering atmosphere reveal a low polarisation on the order of 5 to 10% with a low reflectivity. This is probably typical for rocky surfaces where the light is reflected from a rocky surface. These kind of extra-solar planets will certainly not be the first detected by means of polarimetry.

But neither Venus nor Saturn are more promising candidates. Both come up with similar polarisation strengths as Mercury and Mars, although the reflectivity is much higher. Both are covered with a thick atmosphere reflecting a huge amount of the incident light, but the atmospheres are dominated by high lying clouds scattering the light diffusely, which diminishes the polarisation.

The Earth plays in a certain kind a special role. Because of the weather on Earth the scattering “material” changes from dry air to clouds, to oceans, deserts or polar ice caps. This has a large impact on the measured polarisation. Jupiter is similar to the Earth dominated by non homogeneous atmosphere. As seen in this thesis, the polarisation at
the polar caps of Jupiter is much larger than at the intermediate regions, thus, it depends strongly on the sight a possible exo-Jupiter would be observed from.

The probably best candidates for being detected by ZIMPOL within SPHERE are planets with an atmosphere similar to that of Uranus, Neptune and Titan. They are all surrounded by thick Rayleigh scattering layers producing high polarisation for perpendicular scatterings. Further the atmosphere is much more homogeneous than for the other planets. This makes them less dependent on the part of atmosphere which faces towards the observer.

From the presented polarimetric measurements of the giant gas planets in this thesis we can summarise the following aspects related to a possible detection of extra-solar planets by means of polarimetry:

- Jupiter and Saturn exhibit enhanced polarisation at the limbs indicating a Rayleigh scattering atmosphere at least at certain regions of the planets. Different sights onto the planets, however, can yield different polarisation strengths. For Jupiter there is a large difference in polarisation if seen onto the polar region compared to equatorial latitudes. For Saturn the ring system plays an important role, contributing with large albedo but with no polarisation. In addition at least Jupiter shows a clear but not overwhelmingly rise of polarisation in the methane absorption bands. These properties make extra-solar planets with similar atmospheric properties like Jupiter and Saturn possible candidates for the detections with SPHERE-ZIMPOL but not outstanding aspirants.

- In contrast to Jupiter and Saturn the planets Uranus and Neptune are of more homogeneous character. They exhibit an enhanced polarisation at all four measured limbs indicating a homogeneous Rayleigh scattering atmosphere probably over the whole planet. The enhanced polarisation in the methane absorption bands is considerable. These two properties are of outstanding importance for extra-solar planets to be detected with SPHERE-ZIMPOL. Polarimetric measurements with filters centred at the deep methane bands are most promising for a detection of extra-solar planets with atmospheric conditions similar to those of Uranus and Neptune.

The solar system offers a large variety of different kinds of planets with different polarisation properties. If this is not unique in the universe the probability to detect an extra-solar planet with ZIMPOL in the next few years is likely, but not easy!
Chapter 8

Final remarks

In the next decades many efforts will be undertaken to find more extra-solar planets by the “classical” means of measuring the radial velocity of the central star or by observing transits. But also more challenging enterprises to “see” extra-solar planets are in preparation and will start operating in a few years. SPHERE is only one of many promising projects to directly detect and analyse extra-solar planets. Different approaches to attain the goal are in preparation from ground and from space. A small selection of some projects shall be given here:

**Darwin** space project for infrared interferometry; a flotilla of four free-flying 3 m mirrors will detect and analyse Earth-like planets; launch foreseen in the middle of the next decade

**E-ELT** European Extremely Large Telescope; more “modest” project of the former planned OWL (OverWhelmingly Large telescope), ground based telescope of 30 to 60 m diameter (segmented), will be able to directly image extra-solar planets smaller than Jupiter

**JWST** the James Webb Space Telescope is the successor of the Hubble Space Telescope; segmented telescope of 6.5 m diameter optimised for the infrared; formation and evolution of planetary systems will amongst other goals, be investigated; launch is scheduled for 2013

**Kepler** single-mirror space telescope with 0.95 m aperture; space photometer optimised for transits of extra-solar planets, will observe 100’000 stars and search for transits caused by Earth-like planets; launch is scheduled for October 2008

**TPF** the Terrestrial Planet Finder consists of a coronagraphic and an interferometric subpart, both space based observatories:

a) TPF-C; the coronagraphic observatory is a visual single mirror of about 4 m diameter designed for the direct imaging of extra-solar planets

b) TPF-I; the interferometric system consists of multiple 3 to 4 m mirrors for detecting the heat radiation of extra-solar planets, similar to Darwin
The future of the Terrestrial Planet Finder is insecure due to shortening of funding.

The near future brings a lot of undertakings with good prospects to directly observe extra-solar planets of Jupiter size but also, with the new generations of extremely large telescopes (ELTs), extra-solar planets down to the size of the Earth. This is probably the first step in direction of answering the ancient question about the existence of other beings in the universe besides us.

In a letter to Herodot, Epikur speaks already in the third century before Christ about other worlds like he would have known about the discoveries that would happen very long time after his death:

*There are innumerable worlds, ours as well as others. (...) nothing argues against an infinite number of worlds. We must accept, that in all worlds there are creatures, plants and other things, like we behold in our world.*

I don’t know if Epikur really meant what he pronounced but nowadays we know that at least the first part of his speech is true and maybe also the second.
Appendix A

Additional plots

In this Appendix all generated plots of the discussed four planets are placed. It contains spectropolarimetric plots as well as the planetary profiles along the spectrographic slits.

In Appendix A.1 the spectropolarimetric plots of Uranus and Neptune are presented. All achieved orientations are shown, i.e. N-S and E-W for Uranus and N-S for Neptune.

In Appendix A.2 the planetary profiles of Uranus for N-S and E-W directions for all selected spectral regions (C1 - C5 and M1 - M7) are displayed.

For Jupiter and Saturn the order is inverted. First, in Appendix A.3, the profiles along the N-S and E-W directions for all spectral features are presented. Secondly, in Appendix A.4, spectropolarimetry for the four selected regions along the slits is demonstrated.

In Appendix A.5 the profiles for Saturn in N-S directions are shown for all spectral features.

The spectropolarimetry of Saturn for five selected regions is presented in Appendix A.6.
A.1 Spectropolarimetric plots for Uranus and Neptune

Spectropolarimetry for Uranus showing Stokes $Q/I$ and $U/I$ is presented in Figs. A.1 and A.2. All four limb regions and the total slits are demonstrated. The limb regions are, as defined in Section 6.3, the $0.628''$ wide sections of the spectrographic slit centred at the appropriate limb, indicated in Fig. 6.3 with the black boxes. The figures also show the spectropolarimetric plots for the total slit, which is the $7.85''$ long part of the slit centred at the middle of the planetary disc.

In Fig. A.3 the $Q/I$ and the $U/I$ spectropolarimetric plots for the northern and the southern limbs and also for the total slit of the Neptune measurements are shown. The limb regions are $0.628''$ wide each and the total slit is the $4.71''$ wide part of the slit, centred at the middle of the planetary disc.
Fig. A.1: First and second row show $Q/I$ polarisation spectra for Uranus at all four limb regions: West, East, South and North, as defined in Section 6.3 and shown in Fig. 6.3. Bottom row shows the $Q/I$ polarisation spectrum for the total equatorial and meridional slits.
Fig. A.2: First and second row show $U/I$ polarisation spectra for Uranus at all four limb regions: West, East, South and North, as defined in Section 6.3 and shown in Fig. 6.3. For the northern limb the scale to the negative part has been enlarged to show the whole plot. Bottom row shows the $U/I$ polarisation spectrum for the total equatorial and meridional slits.
A.1. Spectropolarimetric plots for Uranus and Neptune

Fig. A.3: Spectropolarimetric plots of Neptune. The two plots on the top show the limb positions North and South whereas the plots in the middle row show the total meridional slit $Q/I$ and $U/I$, respectively. The total slit is the average of the 4.71" long part of the slit. In the bottom row Stokes $U/I$ for the North and the South limb region are given. The regions are defined in section 6.3.4 and also shown in Fig. 6.12.
A.2 Polarimetric profiles for Uranus

In this section the polarimetric profiles (cuts in equatorial and meridional direction) for Uranus in the selected wavelength regions C1 – C5 and M1 – M7 are presented. In Figs. A.4 and A.5 the profiles are shown for the equatorial orientation and in Figs. A.6 and A.7 the same is shown for the meridional slit position. All images contain in the upper panel the normalised intensity. Normalised means, that the intensity value at the disc centre, $I_0$, is set to 1. The middle panels show the normalised Stokes $Q/I$ polarisation in percentage. There are also error bars indicated according to the photon noise. The lower panels show the polarised flux in $Q$ direction, i.e. parallel to the spectropolarimetric slit. The $Q$-flux is plotted in percentage of the intensity at the disc centre $I_0$.

Fig. A.4: Polarimetric profiles for Uranus in equatorial direction. Beginning with C1 (upper left) to M1 (bottom right).
A.2. Polarimetric profiles for Uranus

Fig. A.5: Polarimetric profiles for Uranus in equatorial direction. Beginning with M2 (upper left) to M7 (bottom right).
Fig. A.6: Polarimetric profiles for Uranus in meridional direction. Beginning with C1 (upper left) to M1 (bottom right).
A.2. Polarimetric profiles for Uranus

Fig. A.7: Polarimetric profiles for Uranus in meridional direction. Beginning with M2 (upper left) to M7 (bottom right).
A.3 Polarimetric profiles for Jupiter

In this section all profiles obtained for Jupiter are presented for the N-S orientation of the spectrographic slits (Figs. A.8 and A.9) and for the E-W orientation (Figs. A.10 and A.11). All selected wavelength regions from C1 – C5 and M1 – M7 are presented. In all plots the upper panels show the normalised intensities (normalised to the intensity $I_0$ of the most central pixel, at $-1\text{"}$), the middle panels contain the Stokes $Q/I$ polarisation signal with error indicated. For the N-S cuts additionally the Stokes $U/I$ polarisation is shown in the same panel like $Q/I$. There, $Q/I$ is plotted with a solid line and $U/I$ with a dashed line. The lower panels show the polarised $Q$-fluxes in percentage of $I_0$ such as in Fig. 6.19. For reasons of clarity, the polarised $U$-fluxes are omitted since the trend is visible from the normalised $U/I$ cuts.

For all presented plots a positive polarisation signal means always that the polarisation is parallel to the spectrographic slit, i.e. in N-S direction for the North and South plots and in E-W direction for the East and West plots.
Fig. A.8: Polarimetric profiles for Jupiter in N-S direction. Beginning with C1 (upper left) to M1 (bottom right).
Fig. A.9: Polarimetric profiles for Jupiter in N-S direction. Beginning with M2 (upper left) to M7 (bottom right).
A.3. Polarimetric profiles for Jupiter

Fig. A.10: Polarimetric profiles for Jupiter in E-W direction. Beginning with C1 (upper left) to M1 (bottom right).
A.3. Polarimetric profiles for Jupiter

Fig. A.11: Polarimetric profiles for Jupiter in E-W direction. Beginning with M2 (upper left) to M7 (bottom right).
A.4 Spectropolarimetric plots for Jupiter

Spectropolarimetric plots for Jupiter in N-S direction are presented in Fig. A.12. The spectrographic slit is divided into four regions: *limb, positive polarisation at the poles, negative polarisation at intermediate latitudes* and *total*. The polar limb regions extend from $15'' < |y| < 16.5''$ for North and South (cf. Fig. 6.19).

The *positive polarisation at the poles* region considers only positive polarised flux ($Q > 0$) and the *negative polarisation at intermediate latitudes* regards only negative polarised flux. The edge between positive and negative polarisation flux ($y_0$) is wavelength dependent. Therefore, the average edge value for the whole spectral range is taken. For the northern slit the edge is at 12.9" and for the southern slit at -13.3". For the *positive polarisation at the poles* the region is taken from 12.9" to 16.5" (North) and from -13.3" to -16.5" (South), respectively, and for the *negative polarisation at intermediate latitudes* it goes from 12.9" to 2" (North) and from -13.3" to -1" (South), respectively.

The region *total* is the total slit, from -16.5" to -1" (South) and from +2" to +16.5" (North).

The solid lines in the plots denote spectra of the northern hemisphere and the dotted lines stand for the southern. The upper panels describe the flux spectra in arbitrary units. The lower panels exhibit Stokes $Q/I$ in percentage.

Spectropolarimetric plots for Jupiter in E-W direction are presented in Fig. A.13. The spectra are divided in two parts: *limb* and *total*. The limb regions extend from $17'' < |x| < 19''$ (cf. Fig. 6.20), whereas the total means the “whole” slit for both orientations, East and West. In the East it extends from -20" to -12.8" and in the West from 10.7" to 20". The panels have the same arrangement as the panels for the N-S orientation.
A.4. Spectropolarimetric plots for Jupiter

Fig. A.12: Spectropolarimetric plots for Jupiter in N-S direction. The four slit regions limb, positive polarisation at the poles, negative polarisation at intermediate latitudes and total are explained in the text. The solid line denotes spectra from the northern slit and the dotted line stands for the southern slit.
Fig. A.13: Spectropolarimetric plots for Jupiter in E-W direction. The two slit regions *limb* and *total* are explained in the text. The solid line denotes spectra from the eastern slit and the dotted line stands for the western slit.
A.5 Polarimetric profiles for Saturn

In the next two figures the polarimetric profiles through Saturn from North to South are plotted as centre to limb profiles. The combination of the two slits reaches from -12″ to 12″. For $Q/I$ the profiles are not plotted long-wards of ±11″ because of the unsightly noise prevailing the domains beyond the nominal limb of 9.3″.

All 12 selected spectral sections are presented. In Fig. A.14 the high albedo sequences C1 - C5 and the first methane absorption band M1 are displayed. The 6 remaining CH$_4$ absorption bands M2 - M7 are plotted in Fig. A.15.

The upper panels show the normalised intensity (normalised to the intensity of the central pixel $I_0$). There, also the positions of the two main rings, the A and the B ring are indicated. The second panels represent the normalised Stokes $Q/I$ in percentage, the third panels the normalised Stokes $U/I$ in percentage whereas the lower panels show the $Q$ flux normalised to the central intensity $I_0$. 
A.5. Polarimetric profiles for Saturn

Fig. A.14: Polarimetric profiles for Saturn in N-S direction. Beginning with C1 (upper left) to M1 (bottom right).
Fig. A.15: Polarimetric profiles for Saturn in N-S direction. Beginning with M2 (upper left) to M7 (bottom right).
A.6 Spectropolarimetric plots for Saturn

Spectropolarimetric plots for Saturn with the slit in North-South direction are presented in Figs. A.16 and A.17. Five slit regions are chosen. An average over the whole slit (in principle two slits) from north to south is placed on the upper left corner of Fig. A.16. This plot contains the spatial region from -11" to + 11". Upper right shows the central 4" centred at the middle of the disc (from -2" to +2"). In the lower left corner the spectropolarimetric plots of the intermediate northern latitudes are plotted. This region from 3" to 5" is an area with high polarisation, as can be seen in Fig. 6.25. In the lower right corner the spectra for the A and B ring are presented for the region of 6.3" to 9.1". In Fig. A.17 spectropolarimetry of the South Pole is presented. This is a region from -10" to -8".

Each image consists of two panels. The upper panels show the flux in arbitrary units. The lower panels present Stokes Q/I in percentage.
Fig. A.16: Spectropolarimetric plots for Saturn in N-S direction. Upper left: total slit, upper right: central 4". lower left: intermediate region and lower right: ring system. Explanations in the text.
Fig. A.17: Spectropolarimetry for the South Pole of Saturn with the slit in N-S direction. The area is from $-10''$ to $-8''$. 
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Curriculum vitae

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