



Universiteit  
Leiden  
The Netherlands

## High-contrast imaging polarimetry of exoplanets and circumstellar disks

Holstein, R.G. van

### Citation

Holstein, R. G. van. (2021, October 13). *High-contrast imaging polarimetry of exoplanets and circumstellar disks*. Retrieved from <https://hdl.handle.net/1887/3217115>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/3217115>

**Note:** To cite this publication please use the final published version (if applicable).

# High-contrast imaging polarimetry of exoplanets and circumstellar disks

Rob Gerardus van Holstein

**Cover design:**

Bottom right: Total-intensity image of the star DH Tau A and its substellar companion DH Tau B. Top left: Linearly polarized intensity image of the same system, revealing the circumstellar disk of DH Tau A and the polarization signal from DH Tau B that indicates the presence of a disk around this companion. The images are presented in Chapter 5 and were taken with SPHERE-IRDIS at ESO's Very Large Telescope located on Cerro Paranal.

# High-contrast imaging polarimetry of exoplanets and circumstellar disks

## Proefschrift

ter verkrijging van  
de graad van doctor aan de Universiteit Leiden,  
op gezag van rector magnificus prof. dr. ir. H. Bijl,  
volgens besluit van het college voor promoties  
te verdedigen op woensdag 13 oktober 2021  
klokke 11.15 uur

door

Rob Gerardus van Holstein

geboren te Delft, Nederland  
in 1990

Promotor:	Prof. dr. C. U. Keller	
Co-promotor:	Dr. ir. F. Snik	
Promotiecommissie:	Prof. dr. H. J. A. Röttgering (voorzitter)	Universiteit Leiden
	Prof. dr. I. A. G. Snellen (secretaris)	Universiteit Leiden
	Prof. dr. H. M. Schmid	ETH Zürich
	Prof. dr. I. E. E. Kamp	Rijksuniversiteit Groningen
	Prof. dr. M. K. Kupinski	University of Arizona
	Dr. J. Milli	Université Grenoble Alpes

Printed by: Gildeprint

ISBN: 978-94-6419-315-2

An electronic copy of this thesis can be found at <https://openaccess.leidenuniv.nl>.

© Rob G. van Holstein, 2021

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Polarimetry to study circumstellar disks and substellar companions . . . . .	2
1.2	High-contrast imaging . . . . .	6
1.2.1	Components of a high-contrast imager . . . . .	6
1.2.2	Differential imaging techniques . . . . .	10
1.3	Polarimetry . . . . .	10
1.3.1	Description of polarized light . . . . .	11
1.3.2	Polarization measurements with the double difference . . . . .	11
1.3.3	Instrumental polarization effects and polarization aberrations . . . . .	12
1.4	Outline of this thesis . . . . .	13
1.5	Outlook . . . . .	16
	References . . . . .	18
<b>2</b>	<b>Polarimetric imaging mode of VLT/SPHERE-IRDIS II: Characterization and correction of instrumental polarization effects</b>	<b>23</b>
2.1	Introduction . . . . .	24
2.2	Conventions and definitions . . . . .	26
2.3	Optical path and instrumental polarization effects of SPHERE-IRDIS . . . . .	27
2.3.1	SPHERE-IRDIS optical path . . . . .	27
2.3.2	Instrumental polarization effects of optical path . . . . .	30
2.4	Mathematical description of complete optical system . . . . .	31
2.5	Instrumental polarization effects of instrument downstream of M4 . . . . .	35
2.5.1	Calibration measurements and determination of model parameters . . . . .	35
2.5.2	Results and discussion for internal source calibrations . . . . .	37
2.6	Instrumental polarization effects of telescope and M4 . . . . .	43
2.6.1	Calibration measurements and determination of model parameters . . . . .	43
2.6.2	Results and discussion for unpolarized star calibrations . . . . .	44
2.7	Polarimetric accuracy of instrument model . . . . .	48
2.8	Correction of science observations . . . . .	51
2.8.1	Correction method . . . . .	51
2.8.2	Correction of images of circumstellar disk of T Cha . . . . .	54
2.8.3	Improvements attained with correction method . . . . .	55
2.8.4	Limits to and optimization of polarimetric accuracy . . . . .	58
2.8.5	Data-reduction pipeline including correction method . . . . .	61
2.9	Summary and conclusions . . . . .	61
2.A	Computation of parallactic, altitude, HWP, and derotator angles from FITS-headers . . . . .	62
2.B	Gradient in flux of internal calibration measurements . . . . .	63
2.C	Graphs of model fits of internal calibration measurements . . . . .	65
2.D	Determination of normalized Stokes parameters and graphs of model fits of unpolarized star observations . . . . .	69

2.E Calculation of accuracies of fit and uncertainties in determined parameters	74
References . . . . .	75
<b>3 Calibration of the instrumental polarization effects of SCExAO-CHARIS' spectropolarimetric mode</b>	<b>79</b>
3.1 Introduction . . . . .	80
3.2 Mathematical description of complete optical system . . . . .	81
3.2.1 Optical path of SCExAO-CHARIS . . . . .	81
3.2.2 Mueller matrix model of optical path . . . . .	83
3.3 Measurements and data reduction . . . . .	85
3.4 Results . . . . .	87
3.4.1 Instrumental polarization effects of the HWP and derotator . . . . .	87
3.4.2 Instrumental polarization of the telescope . . . . .	90
3.5 Conclusions and outlook . . . . .	91
References . . . . .	92
<b>4 Combining angular differential imaging and accurate polarimetry with SPHERE-IRDIS to characterize young giant exoplanets</b>	<b>95</b>
4.1 Introduction . . . . .	96
4.2 Measurement technique . . . . .	98
4.3 Observations . . . . .	99
4.4 Data reduction . . . . .	100
4.4.1 Construction of total-intensity $I_Q$ - and $I_U$ -images . . . . .	102
4.4.2 Construction of Stokes $Q$ - and $U$ -images . . . . .	104
4.5 Results . . . . .	108
4.6 Discussion . . . . .	109
4.7 Conclusions . . . . .	111
References . . . . .	111
<b>5 A survey of the linear polarization of directly imaged exoplanets and brown dwarf companions with SPHERE-IRDIS: First polarimetric detections revealing disks around DH Tau B and GSC 6214-210 B</b>	<b>113</b>
5.1 Introduction . . . . .	114
5.2 Target sample and observations . . . . .	116
5.2.1 Target sample . . . . .	116
5.2.2 Observations . . . . .	117
5.3 Data reduction . . . . .	120
5.4 Extraction of polarization of companions: Detection of polarization of DH Tau B . . . . .	122
5.5 Results . . . . .	129
5.5.1 Detection of intrinsic polarization of DH Tau B . . . . .	129
5.5.2 Likely detection of intrinsic polarization of GSC 6214 B . . . . .	134
5.5.3 Detection of interstellar polarization from 1RXS J1609 B . . . . .	136
5.5.4 Upper limits on polarization of other companions . . . . .	138

5.5.5	Detection of circumstellar disks of DH Tau, GQ Lup, PDS 70, $\beta$ Pic, and HD 106906 . . . . .	140
5.6	Modeling of polarization from circumsubstellar disks . . . . .	143
5.6.1	Setup of the radiative transfer model . . . . .	143
5.6.2	Origin of the spatially integrated polarization . . . . .	144
5.6.3	Dependence on the inner radius and surface density . . . . .	146
5.7	Discussion . . . . .	148
5.7.1	Circumsubstellar disks, rotational periods, and formation of DH Tau B, GSC 6214 B, and GQ Lup B . . . . .	148
5.7.2	Circumsubstellar disks of 1RXS J1609 B, HD 106906 b, and PDS 70 b . . . . .	150
5.7.3	Atmospheric asymmetries of the companions . . . . .	151
5.7.4	Confirmation and further characterization of the disks of DH Tau B and GSC 6214 B . . . . .	152
5.8	Summary and conclusions . . . . .	153
5.A	Cosmetic correction of spurious structure in <i>Q</i> - and <i>U</i> -images . . . . .	155
5.B	Systematic errors due to bad pixels . . . . .	155
5.C	Retrieval of total intensity through ADI: Upper limit on polarization of $\beta$ Pic b . . . . .	157
5.D	Retrieval of total intensity through PSF fitting: Upper limit on polarization of HD 19467 B . . . . .	161
5.E	Contrast curve of $\beta$ Pic data . . . . .	165
	References . . . . .	166
<b>6</b>	<b>Circular polarimetric imaging at planetary system scales by hacking SPHERE-IRDIS: Full-Stokes observations of the asymmetric nebula surrounding VY CMa</b>	<b>171</b>
6.1	Introduction . . . . .	172
6.2	Observing scheme for measuring circular polarization . . . . .	174
6.2.1	SPHERE-IRDIS' polarimetric mode for linear polarimetry . . . . .	175
6.2.2	Observing scheme for measuring circular polarization . . . . .	178
6.3	Test observations of VY CMa . . . . .	179
6.4	Instrumental polarization effects of circular-polarization measurements .	180
6.4.1	Mueller matrix model and setup of calculations . . . . .	181
6.4.2	Polarimetric efficiency . . . . .	181
6.4.3	Instrumental polarization . . . . .	184
6.4.4	Crosstalk . . . . .	185
6.4.5	Effect of uncertainty of retardance of UT and M4 . . . . .	186
6.5	Data reduction . . . . .	187
6.6	Calibration of crosstalk from data of VY CMa . . . . .	192
6.6.1	Identification of spurious signals due to uncorrected crosstalk .	192
6.6.2	Constraining retardance of UT and M4 from data . . . . .	193
6.7	Linear and circular polarization of VY CMa and its nebula . . . . .	196
6.7.1	Spatially unresolved stellar polarization . . . . .	196
6.7.2	Spatially resolved polarization of nebula . . . . .	198

6.8 Conclusions . . . . .	200
6.A Additional figures . . . . .	202
References . . . . .	205
<b>7 Polarization-dependent beam shifts upon metallic reflection in high-contrast imagers and telescopes</b>	<b>207</b>
7.1 Introduction . . . . .	208
7.2 Conventions and definitions . . . . .	210
7.2.1 Polarization of light . . . . .	210
7.2.2 Metallic reflection . . . . .	212
7.3 Beam shifts from polarization ray tracing . . . . .	215
7.4 Explanation of beam shifts and comparison to polarization ray tracing . . . . .	218
7.4.1 Spatial Goos-Hänchen shift . . . . .	220
7.4.2 Angular Goos-Hänchen shift . . . . .	223
7.4.3 Spatial Imbert-Federov shift . . . . .	226
7.4.4 Angular Imbert-Federov shift . . . . .	229
7.5 Discussion . . . . .	231
7.5.1 Polarization structure in the PSF due to beam shifts . . . . .	232
7.5.2 Effect of beam shifts on polarimetric measurements . . . . .	233
7.5.3 Size of beam shifts for various mirror materials and wavelengths . . . . .	235
7.5.4 Mitigation of beam shifts . . . . .	237
7.6 Conclusions . . . . .	238
References . . . . .	239
<b>English summary</b>	<b>241</b>
<b>Nederlandstalige samenvatting</b>	<b>245</b>
<b>List of publications</b>	<b>249</b>
<b>Curriculum vitae</b>	<b>253</b>
<b>Acknowledgments</b>	<b>255</b>