



Universiteit
Leiden
The Netherlands

Novel approaches for direct exoplanet imaging: Theory, simulations and experiments

Por, E.H.

Citation

Por, E. H. (2020, December 11). *Novel approaches for direct exoplanet imaging: Theory, simulations and experiments*. Retrieved from <https://hdl.handle.net/1887/138516>

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/1887/138516>

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

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/138516> holds various files of this Leiden University dissertation.

Author: Por, E.H.

Title: Novel approaches for direct exoplanet imaging: Theory, simulations and experiments

Issue date: 2020-12-11

Novel approaches for
direct exoplanet imaging
theory, simulations and experiments

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op vrijdag 11 december 2020
klokke 12:30 uur

door

Emiel Hugo Por

geboren te Zoetermeer, Nederland
in 1992

Promotor: prof.dr. Christoph Keller
Co-promotor: dr. Matthew Kenworthy

Promotiecommissie:

prof. dr. Huub Röttgering	Universiteit Leiden
prof. dr. Ignas Snellen	Universiteit Leiden
prof. dr. Simon Portegies Zwart	Universiteit Leiden
dr. Rebecca Jensen-Clem	University of California, Santa Cruz
dr. Olivier Guyon	University of Arizona

Cover design: the designed pupil-plane masks for (left) an apodizing phase plate coronagraph with an annular dark zone for the SCExAO/Subaru instrument, and (right) an apodized-pupil Lyot coronagraph for the LUVOIR-A telescope. Both masks were optimized using algorithms developed during my PhD.

Keywords: coronagraph, wavefront sensing, optimization, Python

ISBN: 978-94-6361-500-6

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

©Emiel H. Por, 2020

To Mom and Dad,
for without your advice,
your patience,
and your love,
I would not be who I am today.

Contents

1	Introduction	1
1.1	Star and planet formation	3
1.1.1	From molecular cloud to young stellar system	3
1.1.2	Pathways for planet formation	5
1.1.3	Atmospheric composition and biomarkers	6
1.2	Observational techniques for finding planets	6
1.2.1	Transit photometry	7
1.2.2	Radial velocity	9
1.2.3	Astrometry	9
1.2.4	Direct imaging	10
1.3	Anatomy of a high-contrast imaging instrument	10
1.3.1	The coronagraph	14
1.3.2	The wavefront control system	31
1.3.3	Image post processing	34
1.4	This thesis	35
1.5	Future outlook	37
2	Optimal design of apodizing phase plate coronagraphs	49
2.1	Introduction	50
2.2	Linearization, discretization and correction	51
2.2.1	Linearization	51
2.2.2	Discretization	53
2.2.3	Speed improvements	53
2.2.4	Tilt correction	55
2.3	Case studies	56
2.3.1	D-shaped dark zones	56
2.3.2	Annular dark zones	59
2.4	Conclusions	65
3	The SCAR coronagraph I	67
3.1	Introduction	68
3.2	Modal filtering using single-mode fibers	71
3.2.1	Nulling in single-mode fibers	71
3.2.2	Single-mode fiber arrays using microlenses	73

3.3	Coronagraphy with a single-mode fiber array	76
3.3.1	Conventional coronagraphy	76
3.3.2	Direct pupil-plane phase mask optimization	77
3.4	Single-mode fiber coronagraph properties	84
3.4.1	Fiber mode field diameter	84
3.4.2	Throughput and inner working angle	84
3.4.3	Spectral bandwidth	88
3.4.4	Tip-tilt sensitivity and stellar diameter	88
3.4.5	Sensitivity to other aberrations	88
3.5	Comparison to the vortex coronagraph	91
3.6	Conclusion	97
4	The SCAR coronagraph II	101
4.1	Introduction	102
4.2	Optical setup details and first results	104
4.2.1	Lab setup description	104
4.2.2	Fiber alignment procedure	106
4.2.3	Apodizing phase plate designs	106
4.2.4	Liquid crystal plate	108
4.2.5	Lab setup results	108
4.3	Tolerance simulation analysis	116
4.3.1	Fiber alignment tolerance	117
4.3.2	MLA surface	118
4.3.3	Fiber mode shape	119
4.3.4	FIU Monte Carlo analysis	120
4.4	Conclusions	122
5	High Contrast Imaging for Python (HCIPy)	125
5.1	Introduction	126
5.2	Core functionality	127
5.2.1	Coords, Grids and Fields	128
5.2.2	Field generators and visualization	129
5.2.3	Fourier transforms	129
5.2.4	Mode bases	130
5.3	Optical systems	131
5.4	Adaptive optics	132
5.4.1	Atmospheric modeling	132
5.4.2	Wavefront sensing	133
5.4.3	Wavefront control	134
5.5	Coronagraphy	136

5.6	Miscellaneous	137
5.6.1	Polarization	137
5.6.2	Performance	137
5.7	Conclusions	141
5.7.1	Overview	141
5.7.2	Future plans	141
6	Origin of the asymmetry of the wind-driven halo	145
6.1	Introduction	146
6.2	Description of the observed asymmetry	146
6.3	Interference between scintillation and temporal error	149
6.4	Simulations of the effect	153
6.5	Conclusions	155
7	Phase-apodized-pupil Lyot coronagraphs	161
7.1	Introduction	162
7.2	Overview of the numerical optimization problem	164
7.2.1	Problem definition	164
7.2.2	Simplification and convexification	168
7.2.3	Symmetry considerations	170
7.2.4	Tip-tilt correction for one-sided dark zones	170
7.3	Parameter study for point-symmetric dark zones	171
7.4	Parameter study for one-sided dark zones	174
7.4.1	Contrast, inner working angle and central obscuration ratio	177
7.4.2	Achromatization and residual atmospheric dispersion	178
7.5	Case studies for VLT/SPHERE and LUVOIR-A	179
7.5.1	VLT/SPHERE	179
7.5.2	LUVOIR-A	183
7.5.3	Performance	183
7.6	Conclusions	187
7.7	Appendix: The full optimization problem	188
8	First laboratory demonstration of the PAPLC	191
8.1	Introduction	192
8.2	PAPLC with deformable mirror	194
8.2.1	Monochromatic performance	194
8.2.2	Broadband performance	195
8.3	Simultaneous high-order wavefront sensing	197
8.3.1	Principle	197

8.3.2	Empirical modal response and reconstruction	201
8.3.3	Sensitivity to photon noise	203
8.4	Laboratory demonstration	204
8.4.1	The THD2 bench	204
8.4.2	Coronagraphic performance	207
8.4.3	Phase-retrieval wavefront sensor	212
8.5	Conclusions	222
	English summary	225
	Nederlandse samenvatting	229
	Curriculum Vitae	233
	Acknowledgments	235