



**Universiteit
Leiden**
The Netherlands

**Tracing life through light: towards detecting life on
exoplanets with spectroscopy and spectropolarimetry**
Mulder, W.

Citation

Mulder, W. (2026, April 2). *Tracing life through light: towards detecting life on exoplanets with spectroscopy and spectropolarimetry*. Retrieved from <https://hdl.handle.net/1887/4300414>

Version: Publisher's Version

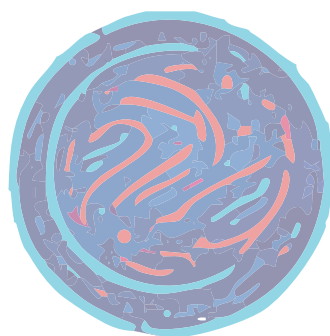
License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/4300414>

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

TRACING LIFE THROUGH LIGHT

TOWARDS DETECTING LIFE ON EXOPLANETS
WITH SPECTROSCOPY AND SPECTROPOLARIMETRY



WILLEKE MULDER

Tracing life through light

Towards detecting life on exoplanets with spectroscopy and spectropolarimetry

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof. dr. S. de Rijcke,
volgens besluit van het college voor promoties
te verdedigen op donderdag 2 april 2026
klokke 10:00 uur

door

Willeke Mulder

geboren te Hengelo, Nederland
in 1993

Promotores: Prof. dr. I. A. G. Snellen
Prof. dr. C. U. Keller
Co-promotor: Dr. ir. F. Snik
Promotiecommissie: Prof. dr. M.P. van Exter
Prof. dr. A. Vidotto
dr. N. van der Marel
Prof. dr. W. Sparks University of Maryland
Prof. dr. B.-O. Demory University of Bern

Printed by: Gildeprint

ISBN: 978-94-6496-510-0

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

Cover design:

The cover reflects the title of and my journey during my PhD - tracing life through light, both in science and in spirit. Just as we search for signs of life beyond our planet, we also learn to keep following the light through moments of darkness, stumbling yet moving forward toward understanding. This cover was designed by the author using Adobe Illustrator, aided by AI.

© Willeke Mulder, 2026

*Those who claim to be entirely unbiased often conceal their prejudices the deepest;
acknowledging bias is the first step toward equity.*

Contents

1	Introduction	3
	<i>The revolutionary hunt for exoplanets and characterising atmospheres</i>	3
1.1	Exoplanet detection methods	3
1.1.1	Radial-velocity method	3
1.1.2	Transit photometry	4
1.1.3	Direct imaging	5
1.2	From detecting to characterizing exoplanets	6
1.2.1	Transmission spectroscopy	7
1.2.2	Emission spectroscopy	7
1.2.3	High-resolution Doppler spectroscopy	7
1.2.4	Atmospheric models & retrievals	8
1.3	Current and future research in exoplanetary science	8
1.3.1	Observational probes of planet formation history	8
1.3.2	Working towards the search for extraterrestrial life	10
	<i>Observing the Earth as an Exoplanet using spectropolarimetry</i>	11
1.4	Definitions for polarimetry	12
1.4.1	Jones formalism	12
1.4.2	Stokes and Mueller formalism	13
1.4.3	Scattering and phase matrix	15
1.5	Sources of polarisation	17
1.5.1	Surface reflection	17
1.5.2	Atmospheric refraction and scattering	19
1.5.3	Differential absorption	19
1.6	The measurement of polarisation	20
1.6.1	Classical polarimeter	21
1.6.2	Instrumental polarisation & cross-talk	22
1.6.3	Polarisation modulation	22
1.7	Spectropolarimeters	24
1.7.1	TreePol & FlyPol	24
1.7.2	Life Signature Detection Polarimeter	26
1.8	This dissertation	28
I	Characterising atmospheres through spectroscopy	31
2	Atmospheric characterisation of brown dwarf atmospheres	33
2.1	Introduction	34
2.2	Sample selection	35
2.2.1	J0835	35

2.2.2	J0501	38
2.2.3	J0500	39
2.3	Observations and data reduction	39
2.3.1	Observations	39
2.3.2	Data reduction	39
2.4	Atmospheric modelling	40
2.4.1	Retrieval framework	40
2.4.2	Likelihood and correlated noise	41
2.4.3	Pressure–temperature profile	42
2.4.4	Chemical Composition	43
2.5	Results & Discussion	44
2.5.1	Chemical Composition	46
2.5.2	Free chemistry versus equilibrium chemistry	51
2.5.3	Thermal Profile	53
2.5.4	Surface gravity	54
2.5.5	Rotational velocity	55
2.6	Conclusions and future work	55
2.A	Posterior distributions of atmospheric retrievals	57
2.A.1	Atmospheric retrieval of J0835	57
2.A.2	Atmospheric retrieval of J0501	58
2.A.3	Atmospheric retrieval of J0500	59
2.B	Best Fitting Spectra	60
2.C	Cross-correlation analysis of various abundances	61

II Observing the Earth as an exoplanet using spectropolarimetry 63

3	Spectropolarimetric measurements of life from a hot-air balloon 65
3.1	Introduction 66
3.2	Methods 68
3.2.1	Polarisation 68
3.2.2	The normalised difference vegetation index 69
3.3	Instrumental set-up 69
3.4	Results 71
3.5	Conclusion & discussion 76
3.6	Acknowledgements 78
4	Diffraction effects from spatial polarisation modulators 81
4.1	Introduction 82
4.2	Full-Stokes spectropolarimeter 83
4.2.1	Polarimetry 83
4.2.2	Spectroscopy 84
4.2.3	Spectropolarimeter principle and prototype design 85
4.2.4	Discrepancies between observations and theory 87
4.3	Numerical simulation including Fresnel diffraction 87

4.3.1	Fresnel propagation of a monochromatic wavefront	88
4.3.2	Response to a fully polarised light source	90
4.3.3	Response to an unpolarised light source	92
4.4	Measurements using LSDPol prototype set-up	93
4.4.1	Change of intensity modulation due to modulator-slit distance	93
4.4.2	Influence of increasing distance on the $m = 0$ diffraction order	94
4.4.3	Influence of increasing distance on the $m = \pm 1$ orders	95
4.5	Conclusions	96
4.6	Acknowledgements	96
5	Polarisation-dependent Talbot diffraction in spatial polarisation modulators	99
5.1	Introduction	100
5.2	Theory behind spatial phase modulators	103
5.2.1	Diffraction effects beyond the SPM ($z > 0$)	105
5.2.2	Definition of our spatial phase modulators	107
5.3	Polarisation transformation and intensity maps via Mueller Matrix formalism	108
5.4	Numerical Fresnel diffraction simulation	111
5.4.1	Simulation set-up	112
5.4.2	Wavefront at the focus ($z=0$)	113
5.4.3	Wavefront propagation beyond the focus ($z>0$)	115
5.5	Application in full-Stokes spectropolarimetry	118
5.6	Conclusions and discussion	121
5.7	Talbot carpet for different incident polarisation states	124
	Bibliography	126
	English summary	133
	Nederlandse samenvatting	137
	Curriculum vitae	141
	List of publications	143
	Acknowledgments	145

