



Universiteit
Leiden
The Netherlands

The sky is made of lava: how lava worlds reveal their interiors through their atmospheres

Buchem, C.P.A. van

Citation

Buchem, C. P. A. van. (2025, September 5). *The sky is made of lava: how lava worlds reveal their interiors through their atmospheres*. Retrieved from <https://hdl.handle.net/1887/4259796>

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/1887/4259796>

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

The Sky is Made of Lava

How lava worlds reveal their interiors through their atmospheres

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 vrijdag 5 september 2025
klokke 11:30
door

Christiaan Pieter Augustijn van Buchem

geboren te Parijs, Frankrijk
in 1995

Promotores: Prof.dr. I.A.G. Snellen

Prof.dr. W. van Westrenen

Vrije Universiteit Amsterdam

Copromotor:

Dr. Y. Miguel

Promotiecommissie:

Prof.dr. A. Vidotto

Prof.dr. E. F. van Dishoeck

Prof.dr. M. Hogerheijde

Dr. T. Lichtenberg

Rijksuniversiteit Groningen

Dr. M. Min

Netherlands Institute for Space Research

ISBN: 978-94-6473-883-4

Cover: Reinier Cedric van Buchem

Printed by: Proefschriften.nl

“La seule chose que nous ayons à craindre,
c’est que le ciel nous tombe sur la tête!”

“The only thing we have to fear
is that the sky will fall on our heads!”

– *Asterix et Obelix*, René Goscinny

CONTENTS

1	Introduction	1
1.1	Hell on (super-) Earth	1
1.2	Why do we care?	4
1.2.1	(exo)Planets	4
1.2.2	Lava Planets	7
1.3	How did we do it?	9
1.3.1	Observing hot-rocky exoplanets	9
1.3.2	Modelling hot-rocky exoplanets	13
1.4	What did we find?	17
2	LavAtmos: An open-source chemical equilibrium vaporization code for lava worlds	23
2.1	Introduction	24
2.2	Methodology	26
2.3	Validation	31
2.4	Discussion	39
2.5	Conclusion	41
	Appendices	42
2.A	Deriving the partial pressure equation	42
3	Sensitivity of Dry Lava Planet Atmospheric Emission Spectra to Changes in Lava Compositions	45
3.1	Introduction	46
3.2	Method	47
3.2.1	Melt compositions	48
3.2.2	Equilibrium chemistry	50
3.2.3	Star-planet systems	52
3.2.4	Radiative transfer	53
3.2.5	Pseudo-2D model	55
3.3	Results	55
3.3.1	The anatomy of a BSE vapour atmosphere	57
3.3.2	TiO ₂ variation	58
3.3.3	SiO ₂ variation	62
3.3.4	Alkali variation	65
3.3.5	Observability of potential targets	69
3.4	Discussion	71
3.4.1	Melt compositions	71
3.4.2	Assumptions made in our model	71
3.4.3	Surface temperature degeneracy	73
3.5	Conclusion	73
	Appendices	75
3.A	Melt compositions	75

3.B	Opacity data	77
3.C	Stellar spectra	77
3.D	Pseudo-2D atmosphere	77
3.E	SiO ₂ activity changing with alkali abundances	77
4	LavAtmos 2.0: Incorporating volatile species in vaporisation models	83
4.1	Introduction	84
4.2	Methods	87
4.2.1	Workflow	87
4.2.2	Model validation	89
4.3	Results	90
4.3.1	Effect of pure volatile atmospheres	90
4.3.2	Effects of a complex volatile atmosphere	96
4.4	Implications for a 55-Cnc e-like atmosphere	97
4.4.1	Vaporised partial pressure comparison between LavAtmos 2.0 and the volatile-free vaporisation method	102
4.4.2	The effect of lava oceans on atmospheric volatile species	105
4.5	Discussion	108
4.5.1	Effect of water on melt activities	108
4.5.2	Water in melt as a source of oxygen	110
4.5.3	How to identify a surface lava ocean from atmospheric composition	110
4.6	Conclusion	111
	Appendices	112
4.A	Effect of complex volatile atmospheres on vaporised species . .	112
5	The effect of H⁻ continuum on Lava Planet Emission Spectra	119
5.1	Introduction	120
5.2	Methods	121
5.2.1	Forward model	121
5.2.2	H ⁻ opacity	122
5.3	Results	123
5.3.1	Adding H to a lava planet atmosphere	128
5.3.2	Sensitivity to temperature	131
5.4	Discussion	134
5.5	Conclusion	135
	Appendices	136
5.A	Opacities	136
	English summary	151
	Nederlandse samenvatting	155
	Publications	159

Curriculum Vitae	161
Acknowledgements	163

