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## **Spectroscopic characterization of exoplanets : from LOUPE to SINFONI**

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### **Citation**

Hoeijmakers, H. J. (2017, November 23). *Spectroscopic characterization of exoplanets : from LOUPE to SINFONI*. Retrieved from <https://hdl.handle.net/1887/57507>

Version: Not Applicable (or Unknown)

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**Author:** Hoeijmakers, Jens

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**Date:** 2017-11-23

## LIST OF PUBLICATIONS

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### REFEREED PUBLICATIONS

1. **Hoeijmakers, H. J.**; de Kok, R. J.; Snellen, I. A. G.; Brogi, M.; Birkby, J. L.; Schwarz, H. *A search for TiO in the optical high-resolution transmission spectrum of HD 209458b: Hindrance due to inaccuracies in the line database.* *A&A*, 575A, 20H (2015)
2. Ridden-Harper, A. R.; Snellen, I. A. G.; Keller, C. U.; de Kok, R. J.; Di Gloria, E.; **Hoeijmakers, H. J.**; Brogi, M.; Fridlund, M.; Vermeersen, B. L. A.; van Westrenen, W. *Search for an exosphere in sodium and calcium in the transmission spectrum of exoplanet 55 Cancri e.* *A&A*, 593A, 129R (2016)
3. **Hoeijmakers, H.J.**; Arts, M. L. J.; Snik, F.; Keller, C. U.; Stam, D. M.; Kuiper, J. M. *Design Trade-Off and Proof of Concept for LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth.* *Optics Express*, 24, 21435-21453 (2016)
4. Khalafinejad, S.; von Essen, C.; **Hoeijmakers, H. J.**; Zhou, G.; Klocová, T.; Schmitt, J. H. M. M.; Dreizler, S.; Lopez-Morales, M.; Husser, T.-O.; Schmidt, T. O. B.; Collet, R. *Exoplanetary atmospheric sodium revealed by orbital motion. Narrow-band transmission spectroscopy of HD 189733b with UVES.* *A&A*, 598A, 131K (2017)
5. **Hoeijmakers, H.J.**; Snellen, I. A. G.; van Terwisga, S. E. *Searching for reflected light from  $\tau$  Boötis b with high-resolution ground-based spectroscopy: Approaching the  $10^{-5}$  contrast barrier.* Accepted for publication in *A&A* (2017)

### CONFERENCE PROCEEDINGS

1. **Hoeijmakers, H. J.**; Snik, F.; Stam, D. M.; Keller, C. U. *LOUPE: Spectropolarimetry of the Earth from the surface of the Moon.* European Planetary Science Congress 2014, EPSC Abstracts, Vol. 9, id. EPSC2014-574
2. Khalafinejad, S.; Hoeijmakers, H.J. *Searching for exo-planetary atmospheric sodium around the active star, HD 189733 with UVES.* IAU General Assembly, Meeting #29, id.2255364 (2015)



## CURRICULUM VITAE

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I was born on the 8<sup>th</sup> of July of the year 1990, in the city of Zwolle, the Netherlands. In 1992, my parents moved (me) to the rural town of Zonnemaire (which incidentally is the birthplace of Prof. Pieter Zeeman, known for winning the Nobel Prize in Physics together with Hendrik Lorentz in 1902 for his discovery of spectral line splitting in the presence of a magnetic field), where I attended elementary school. Growing up in the 1990's, I witnessed the development of new technologies such as personal computing, the internet and mobile communication which have fundamentally altered society. This also was a decade of discovery in astronomy and planetary science, which saw the continued robotic exploration of Mars, the thriving of the Hubble Space Telescope as well as the discovery of the first extra-solar planets. I remember being captivated by the promise of the Cassini/Huygens mission that was scheduled to arrive at Saturn in 2004. At the time of writing, this spacecraft is making its final plunge into Saturn's atmosphere, ending thirteen years of ground breaking discoveries that include the striking resemblance of Titan's cryogenic climate to the climate of Earth and the exciting potential for extraterrestrial life in warm water oceans below the frozen surface of Enceladus. Being at the receiving end of all this exciting progress, I attended high school at the Pontes Pieter Zeeman College where my interest in physics and astronomy was finally cemented.

In September 2008 I enrolled to the bachelor programme of astronomy at Leiden University, which I completed in 2011. During this time I became a member of the Rino foundation, who performs classroom physics demonstrations at high schools throughout the Netherlands. I was a member of the board for one year and performed demonstrations at over 40 schools. I continued my education by starting the instrumentation track of the astronomy master programme in 2011. This included regular visits to the Technical University of Delft where I attended courses related to planetary science, image analysis, signal processing and optics. I did both my research projects in Leiden, starting with the application of the cross-correlation technique at optical wavelengths to search for molecules in the atmosphere of a hot Jupiter in the group of Prof. dr. Ignas Snellen, followed by a project to prototype an instrument aboard a lunar lander to observe the Earth as if it were a living exoplanet, supervised by Dr. Frans Snik and Prof. dr. Christoph Keller. I graduated Cum Laude and was awarded the Huygens fellowship, allowing me to start a Ph.D. program in Leiden under the combined supervision of Dr. Frans Snik and Prof. dr. Ignas Snellen with the goal of interfacing between exoplanet observations and instrument development. During my Ph.D. I anal-

ysed optical, high-dispersion spectroscopic transit observations of two hot Jupiters to search for absorption by molecular species and reflected starlight. I developed and tested a prototype for the Lunar Observatory for Unresolved Polarimetry of Earth (LOUPE), demonstrating that spectropolarimetric characterization of Earth as a living exoplanet can be performed using a small, robust instrument from the lunar surface. Finally, I applied the new Molecule Mapping technique on integral-field spectroscopy observations of the  $\beta$  Pictoris system by the SINFONI spectrograph and showed that high-contrast integral field spectroscopy can be used at medium spectral resolution to confidently detect molecules in hot young gas giants and that it can be used to constrain their fundamental parameters.

As of November 2017 I will be working as a post-doctoral researcher in the groups of David Ehrenreich, Christophe Lovis and Kevin Heng at the University of Geneva and the University of Bern, Switzerland. I will continue to use spectroscopic observations to characterize exoplanets, and make use of the many new and exciting instruments that are due to be deployed over the course of the coming years.

## ACKNOWLEDGEMENTS

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A Ph.D. thesis is the direct result of multiple years of hard work, in which the way forward is often unclear, the lessons that need to be learned are abstract and ill defined, and the rewards of which are uncertain. The ability to do a Ph.D. depends on many more years of preparation during which you need to gather enough knowledge, evolve your understanding, acquire inspiration and most of all cultivate your motivation. It is therefore highly contingent on the people around you, and I would like to thank everyone who has contributed in making this possible.

In the first place I would like to thank my colleagues: Andrew, Emanuele, Geert-Jan, Henriette, Jayne, Javi, Matteo, Remco, Sara, Sebastiaan and so many others (exoplanets is a growing field) with whom I had the pleasure to work together. I have seen all of you face up to the realities of academic life in your own ways and circumstances and I have drawn a lot of inspiration from all of you. Thanks for the productive, collaborative and inspiring times together, and I wish you the best of success in all your works.

Ricardo, Vincent and Steven, I have greatly enjoyed our contribution to the demise of so many bachelor students while TAing the planetary systems course (remember that double FOR-loop?). Thanks for a great time and especially for teaching me a thing or two about Python.

Emanuele, thanks for the often hilarious times we had together. Your departure from 434 caused a steep decline in the gezelligheid of our office (but also its messy-ness, everyone knows that I keep my desk absolutely spotless). I wish you the best of luck in your new career and I am sure that you will do great stuff. At least you will drive a larger car than what Andy and I will drive, combined. Be sure to lock it well.

Sara, we go way back and you have been one of my closest friends even though we have done our Ph.D.'s in different countries. Thanks for inviting me to your wedding and for making me part of your family. During these years you have experienced the sometimes chilling realities of national borders and life abroad. The meanings of privilege and belonging become clear only when they are absent, but I have always seen you beat back and succeed where others don't. I wish you and your family all the happiness, wisdom, health and success, and I hope that we will get the opportunity to work together more in the future.

Paula, you have been able to withstand a lot of adversity over the past years and arguably you are the most motivated person I know. Now after facing up to pretty much every form of barrier a student can be faced with, I am so happy to see that you are approaching the level of productivity that you have

been striving for. I'd like to thank you for the many reflective conversations that we have had and for being a great friend during this entire process. I hope that your success will take flight and bring you where you want to go.

Ainil, thank you for the great literary input that you have given me over the years. I hope that we can continue our literary exchanges so please remember to keep an eye on your pigeon hole on occasion. I wish you the best of luck with the final stages of your Ph.D., and also a lot of joy with Tofan and Faiz. Both Faiz and you two are totally awesome, so I am confident that this should not be a problem.

Nazreen, we met by chance when organising a dinner party. I am so grateful that this was a success, but sad that circumstances prevented us from doing more. I have always enjoyed our Wednesday teas, dinners and the lectures that we attended together. I wish you and Tahar the best of health, wisdom and peace in your marriage; you deserve no less. Do try to finish your thesis. If you can stand by your work and shed a little light on an age-old enigma, however little, it will be rewarded in the end.

Fadwa, thanks for the many LUMC meet-ups and for introducing me to a lot of great Sudanese tastes.

My Iranian friends: Afsaneh, Behrooz, Elham, Faezeh, Yazdan, Mina, Rokhsareh, Sara and many others (and yes, also Hendrik and Thomas, you are Iranians too now, like it or not). Before meeting you I barely appreciated the international and multi-cultural environment that surrounds a university like that of Leiden. I would deeply like to thank you for your endless friendliness and hospitality and overall payeh-ness for dragging me into this amazing network and for being a part of it. Not in the least I would like to thank you for preparing me for, and hosting me during my visits to your allegedly dangerous and hostile homeland. As far as I could tell, in reality it is quite the opposite. You have a truly amazing heritage. Be sure to keep it with you whether you end up in the Netherlands (I'm totally rooting for you) or wherever else you may settle.

Thomas and Elham, I am still regularly amazed by the circumstances of how our friendship came into being. I'm sure that even Hafez would find it difficult to put into words your bravery and perseverance. Thanks for letting me be part of your adventure, not in the least the part that takes place in the kitchen. Finding Earth-like exoplanets is almost as hard as making tahchin, but I am sure that I will be successful one day, without burning down anybody's house.

In this context I would also like to mention the Damavand Fellowship. Doing a Ph.D. is a bit like climbing a mountain for the first time. You reach the summit blinded by snow and fog, only to realize that the hard part is just about to begin. Even though I spent only a short time with most of you, this adventure was exhilarating and inspiring in so many ways, and I do hope to repeat it some time.

Also thanks to my friends from Rino and beyond: Erik, Rick, Rick, Yorick (you see? that's confusing), Hiske, Inge, Jasper, Kari, Noelia, Rosa, Timmy, Willem and everyone else who has phased in and out of filmhuis over the years. Though our parting of ways and the tragic loss of our headquarters at the Hooigracht, Rijnsburgerweg and Oude Vest have somewhat decreased the frequency at which we watch movies nowadays, I have always loved our get-togethers and I hope that we can keep doing them in the future.

Erik, I distinctly recall the many late night therapy sessions that we treated ourselves to. These occasionally ended in throwing household objects through the room in agony as well as countless hours not spent on sleep. However it seems that we are each finding our respective ways, and I wish you the best of luck and happiness. I would also like to thank you for recently -after 9 years of my mockery and refusal- making clear the beauty of mathematics. Apparently it allows one to understand the meaning of complex physical equations without understanding neither the notation nor the meaning of a single variable (these things had indices and curly brackets all over the place, mind you). That was really impressive. It is indicative of your intelligence and I am pretty sure that you will turn anything in your future career into spicy, thinly sliced grilled meat.

René, a scientific career has many similarities with a career in the music industry: You always need to be passionate, you always need to search for opportunities and collaborations and you are always in the trenches, convincing people of the value of your work and relying on their willingness to help you move forward. You can struggle for years with what seems little progress, trying to achieve that big success which may never come. We have always been in a friendly competition of who of us will conquer the world first. Although this thesis is a big step forward, I can't help but feel that all bets are still off. In any case, make sure to make that *début* happen, as I am really looking forward to it. And if all our endeavours turn out fruitless in the end, we can still go back to building aeroplanes, or perhaps to running an orchestra in a rural town.

This brings me to the folks at Nut en Uitspanning. Ik heb vaak duidelijk gemaakt in de reservetijd te zitten, aangezien de rit van en naar Leiden aanzienlijk is en dat werkdruk alsmede sociale verplichtingen in de jaren niets dan toenemen. Desalniettemin was ik in staat om regelmatig te genieten van de repetities en onze vele optredens. Een waardevolle uitlaat voor het stadse, studenten, en academische leven. Ook jullie wens ik veel speel plezier en alle goeds toe in de toekomst.

I estimate that I have lived with over 50 housemates during my 9 years here in Leiden, and trying to name you all would result in awkward omissions, so I will not. Thanks for making Klik 23a a happy, quiet, easy-going and for the most part tidy place to live. I have always enjoyed our house as a place where interesting, diverse and nuanced ideas come together, mixed with a

healthy dose of humour, good cooking (for most of you, that is) and a lot of gezelligheid. I have none but good memories and will miss this aspect of student life dearly.

Next, I would like to thank my two promoters: Frans, many thanks for spicing up my time here with insane space-faring hyperspectral polarimetry projects. I loved the way in which we could inter(re)act promptly and flexibly under ever so exciting and unpredictable dynamic circumstances. If there's anything that I've learned, it's that enthusiasm and pragmatism are key to the success of any project. That's why LOUPE is not going to die any time soon, unless perhaps it actually gets to fly to the Moon.

Ignas, you did not lose patience even when I spent six full months scrolling through thousands of aperture traces in IRAF. You taught me how to look pragmatically at raw data. Without this skill, a student could spend months on a troublesome dataset without real progress, while the raw data tells you all you need to know. You spent many hours going over plots, papers, proposals and presentations and have taught me how important it is to not only do good science, but also how to present it well. Thanks for bringing me to this point, and I am very excited to carry these foundations with me to my new colleagues in Switzerland.

These pages would not be complete without thanking the countless organizations and institutions who made, and continue to make this research possible. Especially Leiden Observatory, on whose efficient management I and so many other students and researchers rely on on a daily basis. Also ESO, whose instruments, facilities and archives are at the cradle of much of this research, and the Dutch and European governments and society at large, who have created the climate and provided the financial means that are needed for fundamental research to take place. Science can only be done by a few people, while so many others are working hard to create the necessary boundary conditions. This always needs to be acknowledged.

Finally, I would dearly like to thank my parents and family for supporting me throughout my education and work in Leiden as well as before. You encouraged me to learn and work hard, and always made sure that I had the means and the space to follow my dreams. Hence you supported me even when I decided that it was a great idea to spend my life chasing rocks floating around distant stars (instead of a real job that actually has tangible use), and even if it meant that I should go to a distant country to get even better at it. We are a close family that pulls together in good times as well as in bad times when it is most important. I will miss you, but I know that you will make Switzerland feel less far away than it actually is.