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From midplane to planets : the chemical fingerprint of a disk

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Citation

Eistrup, C. (2018, October 16). *From midplane to planets : the chemical fingerprint of a disk*. Retrieved from <https://hdl.handle.net/1887/66260>

Version: Not Applicable (or Unknown)

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

Cover Page



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Author: Eistrup, C.

Title: From midplane to planets : the chemical fingerprint of a disk

Issue Date: 2018-10-16

PUBLICATIONS

Refereed Publications

Setting the volatile composition of (exo)planet-building material. Does chemical evolution in disk midplanes matter?

C. Eistrup, C. Walsh, E. F. van Dishoeck, 2016, *A&A* , 595, 83.

Molecular abundances and C/O ratios in chemically evolving planet-forming disk midplanes

C. Eistrup, C. Walsh, E. F. van Dishoeck, 2018, *A&A* , 613, 14.

Formation of cometary O₂ ice and related ice species on grain surfaces in the mid-plane of the pre-Solar nebula

C. Eistrup, C. Walsh, 2018, *A&A* , *in press*

Publications in preparation

Matching protoplanetary disk midplane chemical evolution to cometary compositions

C. Eistrup, C. Walsh, D. Carr, M. Drozdovskaya, E. F. van Dishoeck, *A&A In prep*

Refractory carbon depletion leading to super-stellar C/O in planetary atmospheres

A. J. Cridland, **C. Eistrup**, E. F. van Dishoeck, *MNRAS In prep*

Hot-Jupiter atmospheric compositions formed from a chemically evolved disk mid-plane

S. Notsu, **C. Eistrup**, H. Nomura, C. Walsh, *A&A In prep*

CURRICULUM VITAE

I was born on 4 July 1988 in Hørsholm, Denmark to Kirsten and Carl Eistrup. I grew up with my little sister, Astrid, and dogs in the house. My childhood and teenage years were filled with weekly activities, as I was boy scouting, sailing, rowing, playing basketball, dancing and playing the contrabass. I was not particularly talented in any of the disciplines, but I gave them all my full commitment. I came to like sports and physical exercise, I learned perseverance, and especially rowing built my physical stamina. I also grew accustomed to spending much time away from home and meeting new people constantly.

My primary school physics teacher at Hørsholm Skole, Jens Terkelsen, inspired me much and got me enrolled in a LEGO robotics competition, and with that I learned my first basic programming. I continued on a scientific path in high school at Birkerød Gymnasium, where Niels Erik Wegge and Hanne Gjerløff opened up a world of physics and astronomy to me, and taught me to solve physics and astronomy textbook problems. I vividly remember how Niels Erik caught the attention and interest of the entire classroom during his lessons, how the Big Bang, CERN physics and Einstein's relativity permeated our curriculum, and how he kept us up-to-date on the frontiers of science. As a final project, Niels Erik provided me with exoplanet radial velocity data for me to analyse, and with that exoplanetary science and an eagerness to search for life in space became clear interests for me to further pursue.

I enrolled as a physics undergraduate student at the Niels Bohr Institute at the University of Copenhagen, and I was inspired by both CERN physics and exoplanets. For my undergraduate final project I was supervised by Dr. Uffe Graae Jørgensen on a project about transiting exoplanets. As the loud and talkative person that I am, and with a growing fascination with and understanding of science, I caught on to the idea of teaching physics, during my undergraduate studies. Thus, upon earning my degree at age 21, I went into teaching physics and astronomy at my old high school for a year. And what an experience! Seeing the fascination in my students' eyes when I went through the newest scientific results, their puzzled faces when faced with something seemingly inexplicable, and their excitement when they finally understood it, or suddenly succeeded in deducing or calculating the correct results themselves, sparked an incredible eagerness in me to continue to teach, pass on excitement and inspire people around me and everywhere, with science.

With my mind set to return to teaching at a later point, I continued my studies as a Master's student in physics and astronomy at the Niels Bohr Institute. As a

part of it, I went to Hawai'i, USA for a semester to study astronomy as an exchange student at the University of Hawai'i at Manōa. Here, I took part in the activities at the NASA Astrobiology Institute, along with, among others, Dr. Karen Meech and Dr. Bo Reipurth, and I had my first experience with theoretical astrochemistry in a course taught by Prof.dr. Ralf Kaiser. Back in Copenhagen, I decided to explore yet another exoplanetary detection method as my Master's degree final project, and did this project on gravitational microlensing, again supervised by Dr. Uffe Graae Jørgensen.

Nearing the end of my Master's, Dr. Jes Kristian Jørgensen at the University of Copenhagen suggested I applied to enter the PhD program at Leiden Observatory. My interests at that time were still very much on the detection of exoplanets, and the search for biosignatures. Thus, I applied for two exoplanetary PhD projects in Leiden, as well as a somewhat more peripheral project on the chemistry of planet formation with Prof.dr. Ewine van Dishoeck and Dr. Catherine Walsh. I thought it would be interesting to explore the astrochemistry I learned in Hawai'i further, and I was fortunate enough to be offered the astrochemistry position.

My PhD started with me emerging into an entire new field: star formation, planet formation and protoplanetary disks. A world of disk -and astrochemical models, and ALMA data and results being discussed over coffee and lunch. Like many beginnings, this was not an easy one. But my PhD project evolved in interesting ways. I went from exploring some of the astrochemistry that takes place before planets start forming, to making connections to what is detected in exoplanet atmospheres, and in comets nowadays. Importantly, I realised that as a theoretical astrochemist working with disks and planet formation chemistry, and with a strong interest in and intention to couple this to planets, I was somewhat floating in-between more traditional scientific communities, focusing on different fields of science (from star formation to disks to planet formation and to exoplanets) using different means and observing in different wavelengths. This has led to many interesting discussions, new ideas and a platform from which I feel that I can contribute to multiple scientific fields at the same time. In that context, I have been privileged to meet many brilliant and talented scientists, amongst others Kamber, Tim, Jenny, Ryan, Thomas, Dr. Steffen Kjær Jacobsen, Dr. Richard Teague, Dr. Sebastiaan Krijt, Dr. Myriam Telus, Dr. Bertram Bitsch, Dr. Ágnes Kóspál, Prof.dr. Fred Ciesla, Prof.dr. Christoph Mordasini, Prof.dr. Hubert Klahr and Prof.dr. Anders Johansen, and to travel to many interesting meetings in many places around the world to present my work.

I am now so lucky that I can pursue some of my research ideas, as an Origins Postdoctoral Fellow, first for two years at University of Virginia in Charlottesville, US, working with among other Dr. Rob Garrod and Prof.dr. Eric Herbst, and subsequently for two years at Chalmers University of Technology in Gothenburg, Sweden, with Prof.dr. Jonathan Tan. I hope that I will be able to make an impact to advance the scientific fields of planet formation, planets and exoplanets.

With my heart still beating loudly to share the world of, and fascination with science with people everywhere, I have been fortunate enough to be introduced to Universe Awareness at Leiden Observatory during my PhD. UNawe has helped me become a better communicator, story-teller, and, through that, also a better

scientist. With skills learned from working with UNAWE, I took up the challenge of condensing my research interests down to a three-minute pitch, and with that I won the Leiden heat of the FameLab 2017 science communication competition, and was subsequently invited to talk about my research at NEMO Science Center for the Museum Night in Amsterdam 2017.

I will continue to communicate and inspire people with astronomy, everywhere I go. Becoming a scientist, doing research and being in touch with the frontiers of astronomy have made me a better communicator. Communicating my research, and why science is exciting and important, in turn, has made me a better scientist. For me, research and communication go hand-in-hand, and are both very important parts of my job, and my identity, as a scientist.

ACKNOWLEDGEMENTS

I may be the author of this PhD thesis, but it is the product of countless interactions and discussions with, suggestions from, support by, and answers to questions by many, many people. Each and everyone whom I have encountered on my way from arriving at Leiden Observatory, and until printing my thesis have affected me, and hence my thesis, in one way or another.

Catherine and Ewine. I deeply appreciate that you have stood by my side throughout these four years. I have found my research difficult, and becoming an expert in astrochemical modelling has been extremely challenging and hard work for me. You have taught me astrochemistry from scratch and till where I am now, even though I assume that I was not always an easy PhD student to advise and guide. Yet, you gave me space, but also both encouraged and pushed me at critical times so I could accomplish and be proud of this thesis, and you allowed me, not only to engage with all the different scientific communities relevant to my research interests, but also to devote precious time and energy to my outreach. Thank you for making me the scientist I am today!

My research group in Leiden (and Garching) has counted so many people over four years. Thanks to Magnus, Mihkel, Joe, John, Maria, Irene, Xioahu, Kenji, Niels, Ko-Ju, Vianney, Daniel, Anna, Paolo, Stefano, Alvaro, Andreas and Sierk for countless coffees, L-G telekon discussions, and for making the corridor such a relaxed, yet lively place place to work. Special shout-outs to Arthur, Alan and Daniel for your programming help and advise when I was new to Python and much else down that alley. Merel, I have enjoyed our discussions in the office, and when trying to decipher scripture. Nadia, you are ever positive and patient, also when faced with me getting started with an ALMA proposal. Nadia, Paola and Nienke, I have appreciated your understanding, empathy and warm hugs when times were tough. And Łukasz: a small step for a barista has been a giant LEAP(S) for coffee at Leiden Observatory. Thanks for being appropriately snobbish about coffee, and for coffee crawls during which significant parts of this thesis were written. Lastly, Alex, it was good to get even more spirit of planets and planet formation into the group. My corridor was also shared with people from the laboratory. Jeroen, Danna and Pablo it has been much fun to know actual lab people. Vincent, see you in D.C.! Michał, another person with passions in both astronomy and CrossFit, keep going as you are. And Kirstin, the original hipster at Leiden Observatory, and fellow dog-lover. You're a weird and amazing person, I look forward to running into you again at the other side of the pond!

Andrew, Mike, Chris, Eva, Aayush and Mieke, we shared a crazy and fun first-

year experience, and we have had many great moments since then. Aayush, Mieke, Ann-Sofie, Allison and Ricardo H., those many strolls outside brought the needed energy back on so many afternoons. Thank you to Marcelo and Liz for a delicious drink of Delirium Tremens that lead to the pink elephant on my conference posters. It has become an important part of my presentations at meetings. I also had the pleasure of spending a year of my time in Leiden sharing roofs with Nico and Ann-Sofie. Nico, you and Wijnand have been ever laughing, ever loving, ever direct, and ever comforting towards me back then. I wish you happy lives together! Ann-Sofie, tak! Tak for at vi kunne skælde ud og brokke os til hinanden på dansk, over forskningen og livet. Tak for alle gåturene, al kaffen og øllene. Tak for alt lindy hopperiet. Tak for alt det sjove, det irriterende, alle de gode grin, og fordi du gad lytte og give mig svar, hårdt for usødet. Tak også til Eva, Chris og Henriette, det har været en god og sjov tid med stor dansk tilstedeværelse i Leiden. Henry, tak for korrekturlæsningen og |RUM|-tiden. Luke and Valeriya, the Haguespers. You two are amazing! Luke, your “English” is completely incomprehensible, but I appreciate that you came to Val’s rescue on the dance floor, when my attention was elsewhere.

Being a PhD student in Leiden gives you a country-wide network of colleagues. Claudia, Edgar, Veronica, Kaustubh, Lukas, Kataryna and many others, you all made the PEPSci meetings exciting and fruitful, yet there was a casual and friendly atmosphere surrounding the meetings that made me look especially forward to them all. During my visits to the University of Leeds I have come to know the astronomy graduate students there. Alice, Abi, James and the rest of you, I have felt so welcome in Leeds because of you, and I enjoyed all the discussions! Shotasan and Hideko-san, it has been a pleasure and very interesting collaborating with you both! I also had the honor of serving as Assistant Coordinator of the NOVA Network 2. Carsten Dominik, Rik van Lieshout, Ignas Snellen and Eleanor Spring, it has been a pleasure to co-organise the meetings with you, and thanks to the entire network for your engagement during the meetings.

It was not clear to me throughout my PhD that I would continue in academia afterwards, as other career ideas also caught my interest. However, the professional career advice from Prof.dr. Edwin Bergin, Prof.dr. Karin Öberg, Dr. Nikku Madhusudhan, Dr. Jes Jørgensen and Dr. Ilsedore Cleeves helped me decide to continue in academia, and also helped me shape and sharpen my research ideas and plans. Special thanks to Madhu for always being patient, for having time, and for always looking on the bright side of life with a smile and a laugh. You suggested I do outreach next to being a scientist, rather than vice versa, and I am now confidently following that advice. Lastly, Ted! Thank you for believing in me and my research proposal, and for your tireless reference letter writing.

My PhD was made more exciting because I could mix it with astronomy outreach, which was made possible through Universe Awareness. Thank you to Pedro, Tibusay, Jorge, Michael, Kyra, Rafa, Bruno (and Fatima), Audrey (and Maciej), Wouter, Erik (and Martha), Thilinah and George for introducing me to the world of UNawe. Sarah, Edward, Sævar, Mathieu and Oana, you also inspired me with new outreach ideas. All of you helped me understand what good astronomy outreach is, and how it can be done. You were a large part of the reason for my success

in the FameLab science communication competition in 2017! Kyra and Rafa, you guys have meant so much to me, the trips to Spain have been fantastic, and every time I see you is a new adventure - Rafa, a f***ing hot dance! Ricardo G.: your introduction to podcasts helped me to make a good one for astronomy outreach. Your enthusiasm is contagious! Singapore Science Center, and UNAWA Singapore Coordinator Gerardyn, I appreciate you having me twice to give exoplanet talks to the interested children. It was much fun, exciting and inspiring to be there, and I hope to come back!

My time in Leiden would not had been the same without CrossFit 071. Peter-Jan and Rob, I appreciate you welcoming me to the box, and trusting me to become a trainer, so I could give classes and share my CrossFit passion with all the great members of the box. To the team of trainers, to Mirte, Eline, Francette, Alex, Michał and all the other members of the box, it has always been putting a smile on my face, and butterflies in my stomach, to enter the box, and to conquer a WOD with y'all! Learning Dutch was a priority for me when I came to Leiden. I wanted to talk the local language with the Dutch and get in touch with the culture. But that is not easy, since the Dutch are now the best in the world (after the Danes) at English as second language, meaning everything is just much easier to do in English. One of the first people to bother speaking slow Dutch, so I could follow, was Kasper S.. Mannetje, you have been so patient with me and my funny Dutch, and you have given me so much. We have shared CrossFit og hiking, I gave astronomy lessons in Dutch to your students. We have had good coffees. You, and Pyne, have made me feel at home in Leiden, and I wish you two happy lives together. Other people to practice my Dutch on have been Simon, Cora, Desiree, Maks, Reinier, Martijn, Siroon, Thom, Elzemieke and Aart. I feel privileged to have gotten to know you all, I have enjoyed it so much. Leiden is not the first city to catch the newest trends. But Lindy Hop did arrive here during my time, thanks to Ron and Lotte, and learning swing-dancing has been much fun. Also, a few decent coffee places have opened in Leiden while I have been here, and I hope they will stay, because they are needed. Van Der Leur, and barista Anna, I have written so many pages of my thesis at your table, whilst sipping your delicious flat whites.

Leaving Denmark for a job in the Netherlands was both exciting and a scary. I was excited about moving abroad, but I also worried that I would lose contact with my friends in Denmark. Emil, tak for pool, for indsatsen med vores astro-podcast, og alt andet. Ubeskrivelige tider, BS! Ana, du er bare dejlige dig og du har altid været der, som dig. Du er som en ekstra søster for mig. Malte, du er sådan en fantastisk ven, du har været en enorm støtte gennem tiden, og vi har haft så mange fantastisk sjove og dejlige stunder sammen i så mange år nu. (Michael) Küffi, du og Schnathorst har en ganske særlig plads i mit hjerte, og du gør vores fælles astronomi rigere. Henrik and Sara, I gjorde mig til FCB fan, og I er fantastiske! Kasper M., du er skør og dejlig, om vi så har været i Leiden eller i Rotten. Og til alle jeres dejlige partnere, Cíntia, Nanna, Lisbeth, Giulia og Birgitte, og lille Aja og Alexander: jeg har været så glad for alle de gode tider, og glad for at lære jer at kende! Thank you all for visiting me, and for seeing me when I am in Denmark. For the calls and the texts. It has warmed my heart. I feel our friendships have

maybe even grown stronger, and I am now not afraid of losing contact with you, even though I am not returning to DK anytime soon.

Ook bedankt aan mijn Nederlandse familie, Lies, Ewout, Eric en Charissa. Jullie betekenen allemaal heel veel voor mij. Ik voel me bij jullie zo thuis. Ook met jullie hulp spreek ik nu beter Nederlands, bedankt voor jullie geduld. Ik zie er zo naar uit om met jullie de toekomst te ervaren.

Mor, far og Astrid. Jeg elsker jer alle tre! You have supported me to pursue science since I was young. You supported me in moving abroad, first to Hawai'i and then to Leiden. You encouraged me to take som big steps, to challenge myself. I miss you every day, but even being across the globe from each other doesn't mean I don't feel we are a small and loving family. Aarhus, Tisvilde and Singapore are all like homes to me, with all the lovely people around those places as well. In particular, Akhil you have made Singapore feel even more like home, likewise have the dear people at the Danish Seamen's Church. And really nice to also have you around now, Lars!

My personal life has changed dramatically since I arrived in Leiden. And that is in a large part because of one person: Iris. You have done so much for me. You have supported and helped me with translations and much more so I could write this thesis, and become better at outreach along the way. You have taught me Dutch. I love you, and I can't wait to explore the World with you during our lives together. And I also like our cats.

