Mind the gap : gas and dust in planet-forming disks

Marel, N.

List of publications

Refereed Publications

1. **van der Marel, N.**; van Dishoeck, E.F.; Bruderer, S.; Andrews, S.M.; Pontoppidan, K.M.; Herczeg, G.J.; van Kempen, T.; Miotello, A. *Resolved gas cavities in transitional disks inferred from CO isotopologues with ALMA.* subm. to A&A. **(Chapter 7)**

2. Pinilla, P.; **van der Marel, N.**; Pérez, L.M.; van Dishoeck, E.F.; Andrews, S.M.; Birnstiel, T.; Herczeg, G.J.; Pontoppidan, K.M.; van Kempen, T. *Testing particle trapping in transition disks with ALMA.* A&A, in revision. **(Chapter 4)**

3. **van der Marel, N.**; Pinilla, P.; J. Tobin; T. van Kempen; S. Andrews; L. Ricci; T. Birnstiel. *A concentration of centimeter-sized grains in the Oph IRS 48 dust trap.* ApJL, in press (arXiv: 1508.01003). **(Chapter 3)**

4. Rapson, V. A.; Sargent, B.; Sacco, G.; Kastner, J. H.; Wilner, D.; Rosenfeld, K.; Andrews, S.; Herczeg, G.; **van der Marel, N.**. *A Combined Spitzer and Herschel Infrared Study of Gas and Dust in the Circumbinary Disk Orbiting V4046 Sgr.* ApJ, in press (arXiv: 1507.05574).

5. van Kempen, T. A.; Hogerheijde, M. R.; van Dishoeck, E. F.; Kristensen, L. E.; Belloche, A.; Klaassen, P. D.; Leurini, S.; San Jose-Garcia, I.; Aykutalp, A.; Choi, Y.; Endo, A.; Frieswijk, W.; Harsono, D.; Karska, A.; Koumpia, E.; **van der Marel, N.**; Nagy, Z.; Pérez-Beaupuits, J. P.; Risacher, C.; van Weeren, R. J.; Wyrowski, F.; Yildiz, U. A.; Güsten, R.; Boland, W.; Baryshev, A. *Outflow forces in intermediate mass star formation.* A&A, in press (arXiv: 1507.01973).

6. **van der Marel, N.**; van Dishoeck, E. F.; Bruderer, S.; Perez, L. M.; Isella, A. *Gas density drops inside dust cavities of transitional disks around young stars observed with ALMA.* 2015, A&A, 579, 106. **(Chapter 6)**

7. Yildiz, U. A.; Kristensen, L. E.; van Dishoeck, E. F.; Hogerheijde, M. R.; Karska, A.; Belloche, A.; Endo, A.; Frieswijk, W.; Güsten, R.; van Kempen, T. A.; Leurini, S.; Nagy, Z.; Pérez-Beaupuits, J. P.; Risacher, C.; **van der Marel, N.**; van Weeren, R. J.; Wyrowski, F. *APEX-CHAMP+ high-J CO observations of low-mass young stellar objects. IV. Mechanical and radiative feedback.* 2015, A&A, 576, 109Y

8. Follette, K. B.; Grady, C. A.; Swearingen, J. R.; Sitko, M. L.; Champney, E. H.; **van der Marel, N.**; Takami, M.; Kuchner, M. J.; Close, L. M.; Muto, T.; and 53 coauthors. *SEEDS Adaptive Optics Imaging of the Asymmetric Transition Disk Oph IRS 48 in Scattered Light.* 2015, ApJ, 798, 132F

9. **van der Marel, N.**; van Dishoeck, E. F.; Bruderer, S.; van Kempen, T. A. *Warm formaldehyde in the Ophiuchus IRS 48 transitional disk.* 2014, A&A, 563, 113V **(Chapter 8)**

10. Bruderer, S.; **van der Marel, N.**; van Dishoeck, E. F.; van Kempen, T. A. *Gas structure inside dust cavities of transition disks: Ophiuchus IRS 48 observed by ALMA.* 2014, A&A, 562, 26B **(Chapter 5)**

11. **van der Marel, N.**; Kristensen, L. E.; Visser, R.; Mottram, J. C.; Yildiz, U. A.; van Dishoeck, E. F. *Outflow forces of low-mass embedded objects in Ophiuchus: a quantitative comparison of analysis methods.* 2013, A&A, 556, 76V

12. **van der Marel, N.**; van Dishoeck, E. F.; Bruderer, S.; Birnstiel, T.; Pinilla, P.; Dullemond, C. P.; van Kempen, T. A.; Schmalzl, M.; Brown, J. M.; Herczeg, G. J.; Mathews, G. S.; Geers, V. *A Major Asymmetric Dust Trap in a Transition Disk.* 2013, Science, 340, 1199V **(Chapter 2)**

13. Yildiz, U. A.; Kristensen, L. E.; van Dishoeck, E. F.; Belloche, A.; van Kempen, T. A.; Hogerheijde, M. R.; Güsten, R.; **van der Marel, N.**. *APEX-CHAMP+ high-J CO observations of low-mass young stellar objects. III. NGC 1333 IRAS 4A/4B envelope, outflow, and ultraviolet heating.* 2012, A&A, 542, 86Y

14. Cuppen, H. M.; Penteado, E. M.; Isokoski, K.; **van der Marel, N.**; Linnartz, H. *CO ice mixed with CH_3OH: the answer to the non-detection of the 2152 cm-1 band?* 2011, MNRAS, 417, 2809C

15. Öberg, K. I.; **van der Marel, N.**; Kristensen, L. E.; van Dishoeck, E. F. *Complex Molecules toward Low-mass Protostars: The Serpens Core.* 2011, ApJ, 740, 14O

Conference Proceedings

1. **van der Marel, N.**; van Dishoeck, E. F.; Bruderer, S.; Perez, L. M.; Isella, A. *Gas cavities inside dust cavities inferred from ALMA observations* IAUS, 314, in press (2015), ed. J. Kastner

2. van Dishoeck, E. F.; **van der Marel, N.**; Bruderer, S.; Pinilla, P. *Quantifying the gas inside dust cavities in transitional disks: implications for young planets* 'Revolution in Astronomy with ALMA: the 3rd year' (2015)

3. **van der Marel, N.**; van Dishoeck, E. F.; Bruderer, S.; Birnstiel, T.; Pinilla, P.; Dullemond, C. P.; van Kempen, T. A.; Schmalzl, M.; Brown, J. M.; Herczeg, G. J.; Mathews, G. S.; Geers, V. *Planet formation in action: resolved gas and dust images of a transitional disk and its cavity* IAUS, 299, 90 (2014), ed. M. Booth, B.C. Matthews, J.R. Graham

Curriculum Vitae

I was born on February 2nd, 1986, in Groningen. Six months later my parents moved to the south of the Netherlands, to a village in the neighbourhood of Eindhoven, where I spent my childhood. With my father being a physicist, I was introduced early on to funny consequences of physics and scientific experiments. I was addicted to books, and spent almost all my time on reading about a large variety of topics, including volcanoes, dinosaurs, animals, mountains, ancient history and of course: stars and planets. With all those interests, who could have known that I would end up studying astronomy? I went to the gymnasium called Christiaan Huygens College when I was 12, choosing the scientific track with mathematics, physics and chemistry, but also Latin and Greek, which kept my interest for the full six years. Analyzing and translating classical texts was the same for me as solving a mathematical or physics puzzle, and I graduated with the highest marks for both the scientific and the classical courses. My dreams for the future floated between becoming a (children's) book writer, a teacher and 'completely clueless'. The job perspectives convinced me to look into studying physics at university rather than classical languages. During one of the university days I heard about the possibility of studying astronomy on the side, and my childhood memories of the beautiful star images returned.

I decided to study physics and astronomy at Leiden University, starting Fall 2004. Unlike most of my fellow students, who disliked either the lab experiments at physics or the large uncertainties in astronomy, I continued being fascinated by both disciplines and was unable to make a choice between the two. In my second year I joined the observing trip to the Isaac Newton Telescope at La Palma for a week of learning how to operate a telescope, and I was gripped: being on top of a mountain with state of the art technology, looking at data that nobody else had seen before, was the most exhillarating feeling I had ever had. In my bachelor research project in the third year I got introduced to astrochemistry, doing laboratory infrared spectroscopy on interstellar ice mixtures in the Sackler Laboratory. In addition to my course work I became very active in the study society De Leidsche Flesch, as member of several committees, main editor of Eureka! magazine and board member. The lessons I have learnt during those years on social interaction, networking, organization and writing form an indispensable part of my development, and as a scientist I am still taking the advantages of those years.

For my master studies I chose the new master program Astronomy & Instrumentation, a collaboration between Leiden University and Delft University, as a way to continue working on topics in both astronomy and physics. I did a minor research project on molecular outflow observations with Ewine van Dishoeck, Lars Kristensen and Ruud Visser; a major research project on polarization effects in infrared interferometry with Walter Jaffe and Remko Stuik in the optical laboratory; and an observing project at the IRAM 30m telescope on complex organic molecules in young protostars with Karin Öberg and Lars Kristensen. Observational research became my passion, and when I got the opportunity to work as PhD student with Ewine van Dishoeck on an entirely new project on transitional disks with the recently commissioned ALMA telescsope I took it without further doubt.

As PhD student I discovered the real world of astronomical research: the stress of ALMA and ESO proposal deadlines, the large numbers of papers to read, the telescope and instrument manuals, the enormous amounts of data, the frustrations of data analysis, but also the excitement about new discoveries, the joy of solving puzzles, the relief of finishing a paper

and the interaction with astronomers all over the world. I presented my work at conferences in Toledo, Washington, Grenoble, Hamilton, Puerto Varas, Hawaii, Victoria, Heidelberg, Santiago, Bonn, Cambridge, Kiel and Atlanta, and visited institutes of MPE, ESAC, ETH, ESO Munich and Santiago, Beijing University, Harvard CfA, Ann Arbor, IAC La Palma, Caltech, IfA Hawaii, PUC Chile and NRC Canada. I also went observing at some of the most beautiful locations in the world at CARMA, William Herschel Telescope and APEX. Back in Leiden I was teaching assistant of Bernhard Brandl's course on Observing techniques, main organizer of the Astronomy Olympiad for high school students, member of the social committee and I organized a Lorentz Center workshop on the link between theory and observations of transitional disks together with Paola Pinilla. I gave public talks in many places in the Netherlands on astrochemistry, planet formation and ALMA during these years. I also had the privilege of (co)supervising three master students (Sierk Terwisga, Roman Tatch and Bart Verhaar), and I feel very proud that Sierk will start as PhD student in Leiden at my departure, continuing on the topic of my research, the transitional disks. After my PhD defense I will start my next job as Beatrice Watson Parrent Fellow at the University of Hawaii in Honolulu.

Acknowledgements

The years as a member of the Leiden Observatory have been a truly exciting experience and I feel extremely lucky that I had the opportunity to work here as PhD student. I owe the joy of these years and the success of my PhD to many more people than I can thank in these few pages, but I would like to point out a few people that were of particular importance for me.

First of all I would like to thank my supervisors, both before and during my PhD: without you I would never have started or finished. Lars, you were the first person giving me the confidence that I would be smart enough for a PhD position and I can not thank you enough for your praising and encouraging words that have led to me continuing in research. Simon, your never-ending patience in explaining me basic physics and radiative transfer were truly incredible. Paola, thank you so much for endlessly clarifying the details of theoretical modeling, I really enjoyed all of our discussions on interpreting the models and the observations (and the uncertainties in both). Bruno and Joanna, thank you for your help with getting started on radiative transfer modeling. Geoff M., you demonstrated your teaching skills during the year you were in Leiden, guiding me into disk and dust analysis and leaving me confident with the remark that you had taught me all you knew. I owe most of all to the person who pushed me but left me all the freedom to find my own limits, who always told me to enjoy the weekend or my holidays when I sent e-mails outside working hours and who gave me a desk full of inspiration: thank you for the wonderful years together.

I would not have been half as successful if it had not been for the amazing environment of Leiden Observatory. I will truly miss the Kaiser lounge, the coffee breaks, the borrels, the social events and all the other things that made this such a stimulating work place. A big thank you goes to the computer group: Erik, David, Aart, Niels, Leonardo: I could always knock at your door with the most trivial computer questions. Equally important is the work from the secretaries: Liesbeth, Anita, Alexandra, Jacqueline, Els, Jeanne, Debbie: thank you for making everything run so smoothly. Also special thanks to the Allegro group in Leiden for all the help with ALMA: Michiel, Tim, Pamela, Markus, Attila, Remo, Luke and Ian.

I have had the privilege of working in a fantastic group, which has expanded over the years that I was here. From being the only person 'not in WISH' to being amongst a mix of astrochemists, disk observers, star formation experts and modelers: there would always be somebody around to ask questions, discuss the life and the universe over lunch, enjoy brain storm sessions and sports during our legendary group retreats and have a beer after work. Many thanks to my current and former group members: Catherine, Paola, Magnus, Alan, Anna, Agata, Irene, Mihkel, Maria, Daniel, Christian, Niels, John, Vianney, Xiaohu, Nadia, Joe, Davide, Kenji, Koju, Umut, Jeanette, Lars and Ruud. Many other people in the Observatory have contributed to fantastic times here: my former office mate Edith (the hamster, the light sabre and our crazy holiday in northern Italy), Matthew (always time for a discussion with a beer), Nico (still impossible to practice Spanish with you) and all the other people I was hanging out with: Tiffany, Marissa, Matteo, Andra, Berenice, Renske, Heather, Anton, Gustavo, Wendy, Maria, Francisco, Sylvia, Edwin, Henry, Remco, Allison, Mason, Nicola, Marco, Mattia, Grainne, Lucie, Jayne, Steven and Jesse and many many more.

None of the work in this thesis would have been possible without the help of my collaborators. Kees, your drive and enthusiasm for problems ('That is so cool!') is infectious, and I feel honored that you were willing to become my second promotor. Greg, I always enjoyed our conversations, your 'minor' comments, my visit in Beijing and our observing run at La

Palma ('Let's observe it again to make sure'). Laura and Andrea, sharing our transitional disk ALMA data has been really insightful and I hope to continue working together on ALMA observations. Sean and Klaus, I really appreciate your critical view on several of my papers ('I am a stickler on titles'). Luca, you were not only a great teacher in dust observations, but also a wonderful friend ('Italians always complain about everything'). Til, thank you for explaining me countless times about the consequences of the dust evolution. Geoff B., many thanks for our useful discussions during ALMA deadline and for helping me to continue working in astronomy in the United States. Jonathan, I can't wait to get started in Hawaii.

One of the most rewarding experiences during my PhD was public outreach: telling non-astronomers about my work truly was the best test of my knowledge or in the words of Einstein: *"If you can't explain it simply, you don't understand it well enough"*. Therefore, I thank all the audiences I have had during public talks for their stimulating questions. My deepest gratitude for Marieke Baan, Richard Hook and Luis Calçada for all their help on the press release on the IRS 48 dust trap. Special thanks also to the co-organizers of the Astronomy Olympiad: Jens, Renske, Berenice and Irene, it was a pleasure to work with you.

During the years I have made many amazing friends amongst astronomers all around the world. Ilse, I can only say: you rock! I am so glad we became such good friends while climbing the PhD ladder together, and now both continuing in fellowships in the United States, solving planet formation together as we promised each other. Stefano A., I will never forget our epic hike to the volcanoe in Chile. Mihkel and Matteo, thank you for driving me around in Hawaii. Tiffany and Demerese, I owe you for showing me around in beautiful California. And so many more people that I have met over the years: Carlo, Giovanni, Rosina, Wlad, Melissa, Agnes, Ciro, Rafael, Rosina, Antonio, Sascha, Thayne, Mark, Marco T., Sebastian P., Gijs, Sarah, James, Giuseppe, Ruobing, Zhaohuan, Andres and Stefano F.

Also outside astronomy I have been fortunate to be surrounded by good friends. Mesa and Magda, I am so happy that years after our time at the Vrijheidslaan we are still in touch. I owe a lot to the study society De Leidsche Flesch. Special thanks to my dear fellow board members: Marinus, Ilse, Anton, Frank and Gonny, for all the good times that we have had. Jelmer, Guus and Mette, thank you for all the good times together after our 'SPIN' years. Several other friends: Marina, Adrienn, Erica, Babak, it is great to have met you! Jarno, even though we are no longer together, I thank you for the support you have given me over the years. My dearest Dita, getting to know you is one of the best things happening to me in 2014: thank you for all the evenings together, the laughs and cries we shared, the motivation you gave me to start running and most of all that you are always there for me.

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Finally, I would not have been anywhere without my wonderful family. My grandmother Dolly, even though she did not make it to this day, I know she is with me as she has always been. My aunts, uncles and cousins: Harry, Marjan, Sjoerd, Rion, Willem, Imma, Dick, Rosemarie, Bert, Piet, Suzanne, Wouter, Reinier, Alba, Manuel, Eva, Daniel and Fareeda; thank you for being part of our family.

My dear brothers, Floris and Ivo, you have followed your hearts looking for adventure all over the world and I am so proud of what you have accomplished. I am also really happy that you are joining me at the defence as my paranymphs. Special thanks to Floris and Killian for the beautiful cover design! Most of all I thank my parents for their eternal love and support for any decision that I have made in my life. You have made me the way that I am and I am truly grateful for that. Pappa en mamma, ik hou van jullie.