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## The infrared spectrum of massive protostars: circumstellar disks and high mass star formation

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# List of Publications

## Refereed Publications

1. *High-resolution Infrared Spectroscopy of Hot Molecular Gas in AFGL 2591 and AFGL 2136: Accretion in the Inner Regions of Disks around Massive Young Stellar Objects*  
**Barr, A. G.**, Boogert, A., DeWitt, C. N., Montiel E., Richter, M. J., Lacy, J. H., Neufeld, D. A., Indriolo, N., Pendleton, Y., Chiar, J., Tielens, A. G. G. M. (2020), ApJ, 900, 104
2. *The H<sub>2</sub>O Spectrum of the Massive Protostar AFGL 2136 IRS 1 from 2 to 13  $\mu$ m at High Resolution: Probing the Circumstellar Disk*  
Indriolo, N., Neufeld, D. A., **Barr, A. G.**, Boogert, A. C. A., DeWitt, C. N., Karska, A., Montiel, E., Richter, M. J., Tielens, A. G. G. M. (2020), ApJ, 894, 107
3. *Molecular complexity on disc scales uncovered by ALMA: Chemical composition of the high-mass protostar AFGL 4176*  
Bøgelund, E. G., **Barr, A. G.**, Taquent, V., Ligterink, N. F., Persson, M., Hogerheijde, M. R., van Dishoeck, E. F. (2019), A&A, 628, A2
4. *High-resolution SOFIA/EXES Spectroscopy of SO<sub>2</sub> Gas in the Massive Young Stellar Object MonR2 IRS3: Implications for the Sulfur Budget*  
Dunsee, R., Boogert, A., DeWitt, C. N., Montiel, E., Richter, M. J., **Barr, A. G.**, Blake, G. A., Charnley, S. B., Indriolo, N., Karska, A., Neufeld, D. A., Tielens, A. G. G. M. (2018), ApJL, 868, L10
5. *Infrared Detection of Abundant CS in the Hot Core AFGL 2591 at High Spectral Resolution with SOFIA/EXES*  
**Barr, A. G.**, Boogert, A., DeWitt, C. N., Montiel E., Richter, M. J., Indriolo, N., Neufeld, D. A., Pendleton, Y., Chiar, J., Dunsee, R., Tielens, A. G. G. M. (2018), ApJL, 868, L2

## Submitted Publications

1. *H<sub>2</sub>O Absorption in Circumstellar Disks of Massive Protostars at High Spectral Resolution: Full spectral survey results of AFGL 2591 and AFGL 2136*  
**Barr, A. G.**, Boogert, A., Li, J., DeWitt, C. N., Montiel E., Richter, M. J., Indriolo, N., Pendleton, Y., Chiar, J., Tielens, A. G. G. M. (2021), ApJ, Submitted
2. *Surveying the Inner Structure of Massive Young Stellar Objects in the L Band*  
**Barr, A. G.**, Li, J., Boogert, A., Lee, A., DeWitt, C. N., Tielens, A. G. G. M. (2021), A&A, Submitted

# Curriculum Vitae

Born in Paisley, I grew up in the neighbouring city of Glasgow, in Scotland, United Kingdom. There I attended Hutchesons' Grammar School for the entirety of my school education. Towards the end of my schooling I had yet to decide which course I wished to take at university. Enjoying the sciences, and being good at chemistry, I considered a career as a biologist; as it happened, at the last minute I decided that a career in astronomy would suit me better, although I had no real education in physics. Influenced by my father, I had a general interest in astronomy, but never really knew what it entailed to be an astronomer. In my last year of school I tried physics and found that it came naturally. So my application to the University of Glasgow to undertake a degree in Physics and Astronomy, was accepted.

Not surprisingly, at the beginning of my university degree, I struggled, after only beginning to learn physics the year before. I felt somewhat inferior in comparison to the other more vastly learned students, not realising that everyone would quickly become lifted to the same level. During the third year of my bachelor's degree, encouraged by my dad, I sent out emails approaching various astronomers at various institutes, asking if I could do a summer internship with them. I think only one of them replied: Dr Dimitris Stamatellos from the University of Central Lancashire. I am still very grateful for this, as this was a fundamental moment in my life for many reasons. There I was introduced to the topic of star and planet formation, and did a computer simulation project investigating the effect of metallicity on disk fragmentation. There I also first got the idea to come to the Netherlands, as a visiting Dutch astronomer told me how good Dutch astronomy is, particularly in education.

Still, I doubted if I would be good enough to pursue a master's degree after I completed my bachelor's (the thought of doing a PhD never crossed my mind), and indeed I graduated from my Bachelor's with a 2:2, the Scottish equivalent of a C grade. Not very impressive! Thankfully, after being rejected from the University of Amsterdam, somehow I was unconditionally accepted into a master's programme at Leiden University.

During my master's programme, I continued my interest in star and planet formation with a project with Ewine van Dishoeck. This was studying the hot core AFGL 4176 through complex organic molecules detected with the Atacama Large Millimetre Array (ALMA). For my next project I approached Xander Tielens, who would later become my PhD supervisor. I still remember one of the first things Xander said to me: 'Astronomy is all about having fun'. My thought then was, 'this is the supervisor for me!' And it hasn't changed since. Thankfully he took me under his wing and I

worked with observations from the Stratospheric Observatory for Infrared Astronomy (SOFIA), again focusing on high mass star formation, but this time on ultracompact ionised hydrogen regions and their dust properties. I enjoyed it very much and grew in confidence such that undertaking a PhD did not seem like such an insurmountable task.

One day walking into Xander's office he announced, 'I have a project'. This project eerily combined the two research projects that I had done. Studying molecules in hot cores and SOFIA observations; this time I would be working in the infrared wavelength regime, and with absorption lines instead of emission lines.

Throughout my PhD research I have analysed the first full spectral survey of the mid-infrared region of hot cores at high spectral resolution. This was for two sources, AFGL 2591 and AFGL 2136. I have also been involved in the proposal writing for the spectral surveys of W3 IRS5 and NCG 7538 IRS1, which will extend this work to more objects. In addition to this, I was the PI for the  $L$  band survey of a sample of massive protostars (chapter 5 of this thesis) after a serendipitous discovery of organic emission lines in AFGL 2591 at  $3\ \mu\text{m}$ .

Now that my PhD has come to an end, so has my time as an astronomer. My next ambition is to embark on a career path as a physicist outside of the area of academia.

# Acknowledgements

Reflecting at the end of this PhD process, there are many people that deserve to be acknowledged and thanked for making my PhD what it was.

First I want to say thank you to my PhD supervisors, Adwin Boogert and Xander Tielens for working with me on this great project, and supporting me so well throughout it. Adwin, I have learned a lot from you over these past years; thank you for your patience and encouragement. And to Xander, what else can be said other than, 'you are so good'.

I would also like to thank the EXES Hot Core Survey team, Matt, Curtis, Ed, Nick, David, Yvonne and Jialu, for all your input into this thesis. Particular thanks go to the EXES instrument team for obtaining the EXES data, and the many hours spent trying to improve the data quality to get it to what we needed it to be. Also thanks to John Lacy for the acquirement and reduction of the TEXES data, as well as your input into the internally heated disk model.

For the smooth running of the observatory, without which would have made it impossible to get this work done, I want to thank the IT department, Erik, Eric, David and Leonardo, for always being available and finding quick solutions to every which computer problems. As important are the observatory secretaries, particularly Marjan, Evelijn and Alexandra for having answers to all my questions and being willing to accommodate any wishes.

I would like to say thank you to all the members of the ISM group (& co): Daniel, Pablo, Pedro, Kim, Mihal, Sanjana, Jordy, Dario, Cameron, Alessandra, Arthur, Cornelia, Liz, Marcelo, Morgan, Kirstin, Sasha, Olivia and Raymond. A group held together with the glue of cheese, and tomato (and pineapple for Liz), our bi-weekly pizza meetings attracted many others with an interest in the ISM (or Dominoes).

For my office mates over the past years, whether master's or PhD student, thank you for being so quiet and making the office a pleasant and productive place to work. Pablo, Christian, Merel, Martijn, Benoit, Michael, Keith, and Yu Gu, I enjoyed sharing an office with you guys. And of course, thank you to Collins and Patricia for cleaning it everyday.

For those special few at the observatory that I got to know better over the past 4 years, I want to say a particular word for. Xavier, being one of your paranymphs was really special and fun! Jordy, I enjoyed fighting over pepperoni pizza with you, and I hope your new job in Colorado will be a satisfying new chapter in your life. Mihal, I am happy that we got to start our PhDs at the same time, and after the 4 years consider you a real friend. I am glad you are staying in the Netherlands. I would also

like to remember Maolin, who very tragically passed away just as we were beginning to become friends.

Coming to the end, I of course want to thank all of my family and friends for their amazing support. Especially, thank you to Tom for the translation of my summary. And to Tjitze for being a listening ear about the stuff that's there but not really. I am very grateful for having such a great family; my mum and dad and sister Rachel. Mum and dad, without your sacrifices sending me to a good school, I doubt I would be where I am today.

And saving the best until last, my dearest wife Gerdy, truly there is no one better for me in this whole world. You know how important you were in getting this thesis finished; the endless encouragements you gave, being constant in my ups and downs, and all your very wise insights and practical advice. I am really really excited for our next season together!