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A song of ice and gas: the formation and evolution of complex organic molecules

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Citation

Chen, Y. (2026, February 24). *A song of ice and gas: the formation and evolution of complex organic molecules*. Retrieved from <https://hdl.handle.net/1887/4292644>

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

Publications

Refereed publications as first author

1. *CoCCoA: Complex Chemistry in hot Cores with ALMA. The chemical evolution of acetone from ice to gas*
Chen, Y., Garrod, R. T., Rachid, M., van Dishoeck, E. F., Brogan, C., Loomis, R., Lipnicky, A., McGuire, B. A., 2025, *Astronomy & Astrophysics*, 696, A198. (Chapter 4)
2. *JOYS+: The link between the ice and gas of complex organic molecules. Comparing JWST and ALMA data of two low-mass protostars*
Chen, Y., Rocha, W. R. M., van Dishoeck, E. F., van Gelder, M. L., Nazari, P., Slavicinska, K., Francis, L., Tabone, B., Ressler, M. E., Klaassen, P. D., Beuther, H., Boogert, A. C. A., Gieser, C., Kavanagh, P. J., Perotti, G., Le Gouellec, V. J. M., Majumdar, L., Güdel, M., and Henning, T., 2024, *Astronomy & Astrophysics*, 690, A205. (Chapter 3)
3. *CoCCoA: Complex Chemistry in hot Cores with ALMA. Selected oxygen-bearing species*
Chen, Y., van Gelder, M. L., Nazari, P., Brogan, C. L., van Dishoeck, E. F., Linnartz, H., Jørgensen, J. K., Hunter, T. R., Wilkins, O. H., Blake, G. A., Caselli, P., Chuang, K.-J., Codella, C., Cooke, I., Drozdovskaya, M. N., Garrod, R. T., Ioppolo, S., Jin, M., Kulterer, B. M., Ligterink, N. F. W., Lipnicky, A., Loomis, R., Rachid, M. G., Spezzano, S., and McGuire, B. A., 2023, *Astronomy & Astrophysics*, 678, A137. (Chapter 2)

Submitted publication as first author

1. *JOYS+: An overview of the ice features in the COM fingerprint range (6.8–8.8 μm)*
Chen, Y., van Dishoeck, E. F., Francis, L., Slavicinska, K., Tychoniec, Ł., van Gelder, M. L., Boogert, A. C. A., Schravendijk, C. A. F., Beuther, H., Caratti o Garatti, A., Eenhorst, E. K. H., Gieser, C., Henning, Th., Güdel, M., Le Gouellec, V. J. M., McClure, M. K., Narang, M., Nazari, P., Reyes, S. D., Tolman, M., and Yang, Y.-L., submitted to *Astronomy & Astrophysics*. (Chapter 5)

Refereed publications as co-author

1. *Expanding the ice inventory of NGC1333 IRAS 2A with INDRA using JWST observations: Tracing organic refractories and beyond*

- Rayalacheruvu, P., Majumdar, L., Rocha, W. R. M., Ressler, M. E., Giri, P. R., Maitrey, S., Willacy, K., Lis, D. C., **Chen, Y.**, Klaassen, P. D., 2025, *The Astrophysical Journal Supplement Series*, 281, 51.
2. *Sulfur oxides tracing streamers and shocks at low-mass protostellar disk-envelope interfaces*
Liu, X.-C., van Dishoeck, E. F., Hogerheijde, M. R., van Gelder, M. L., **Chen, Y.**, Liu, T., van't Hoff, M., Drozdovskaya, M. N., Artur de la Villarmois, E., Mai, X.-F., Tychoniec, Ł., 2025, *Astronomy & Astrophysics*, 701, A141
 3. *HDO ice detected toward an isolated low-mass protostar with JWST*
Slavicinska, K., Tychoniec, Ł., Navarro, M. G., van Dishoeck, E. F., Tobin, J. J., van Gelder, M. L., **Chen, Y.**, Boogert, A. C. A., Drechsler, W. B., Beuther, H., Caratti o Garatti, A., Megeath, S. T., Klaassen, P. D., Looney, L. W., Kavanagh, P. J., Brunken, N. G. C., Sheehan, P., Fischer, W. J., 2025, *The Astrophysical Journal Letters*, 986, L19.
 4. *JWST Observations of Young protoStars (JOYS): Overview of program and early results*
van Dishoeck, E. F., Tychoniec, Ł., Rocha, W. R. M., Slavicinska, K., Francis, L., van Gelder, M. L., Ray, T. P., Beuther, H., Caratti o Garatti, A., Brunken, N. G. C., **Chen, Y.**, Devaraj, R., Geers, V. C., Gieser, C., Greene, T. P., Justtanont, K., Le Gouellec, V. J. M., Kavanagh, P. J., Klaassen, P. D., Janssen, A. G. M., Navarro, M. G., Nazari, P., Notsu, S., Perotti, G., Ressler, M. E., Reyes, S. D., Sellek, A. D., Tabone, B., Tap, C., Theijssen, N. C. M. A., Colina, L., Güdel, M., Henning, Th., Lagage, P.-O., Östlin, G., Vandenbussche, B., Wright, G. S., 2025, *Astronomy & Astrophysics*, 699, A361.
 5. *JWST Observations of Young protoStars (JOYS): Overview of gaseous molecular emission and absorption in low-mass protostars*
van Gelder, M. L., Francis, L., van Dishoeck, E. F., Tychoniec, Ł., Ray, T. P., Beuther, H., Caratti o Garatti, A., **Chen, Y.**, Devaraj, R., Gieser, C., Justtanont, K., Kavanagh, P. J., Nazari, P., Reyes, S. D., Rocha, W. R. M., Slavicinska, K., Güdel, M., Henning, T., Lagage, P.-O., and Wright, G., 2024, *Astronomy & Astrophysics*, 692, A197.
 6. *JWST detections of amorphous and crystalline HDO ice toward massive proto-stars*
Slavicinska, K., van Dishoeck, E. F., Tychoniec, Ł., Nazari, P., Rubinstein, A. E., Gutermuth, R., Tyagi, H., **Chen, Y.**, Brunken, N. G. C., Rocha, W. R. M., Manoj, P., Narang, M., Thomas Megeath, S., Yang, Y.-L., Looney, L. W., Tobin, J. J., Beuther, H., Bourke, T. L., Linnartz, H., Federman, S., Watson, D. M., and Linz, H., 2024, *Astronomy & Astrophysics*, 688, A29.
 7. *JWST Observations of Young protoStars (JOYS): Linked accretion and ejection in a Class I protobinary system.*
Tychoniec, Ł., van Gelder, M. L., van Dishoeck, E. F., Francis, L., Rocha, W. R. M., Caratti o Garatti, A., Beuther, H., Gieser, C., Justtanont, K., Linnartz, H., Le Gouellec, V. J. M., Perotti, G., Devaraj, R., Tabone, B., Ray, T. P., Brunken,

- N. G. C., **Chen, Y.**, Kavanagh, P. J., Klaassen, P. D., Slavicinska, K., Güdel, M., and Östlin, G., 2024, *Astronomy & Astrophysics*, 687, A36.
8. *JWST Observations of Young protoStars (JOYS+): Detecting icy complex organic molecules and ions. I. CH₄, SO₂, HCOO⁻, OCN⁻, H₂CO, HCOOH, CH₃CH₂OH, CH₃CHO, CH₃OCHO, and CH₃COOH.*
Rocha, W. R. M., van Dishoeck, E. F., Ressler, M. E., van Gelder, M. L., Slavicinska, K., Brunken, N. G. C., Linnartz, H., Ray, T. P., Beuther, H., Caratti o Garatti, A., Geers, V., Kavanagh, P. J., Klaassen, P. D., Justtanont, K., **Chen, Y.**, Francis, L., Gieser, C., Perotti, G., Tychoniec, Ł., Barsony, M., Majumdar, L., Le Gouellec, V. J. M., Chu, L. E. U., Lew, B. W. P., Henning, T., and Wright, G., 2024, *Astronomy & Astrophysics*, 683, A124.
9. *JOYS+: Mid-infrared detection of gas-phase SO₂ emission in a low-mass protostar. The case of NGC 1333 IRAS 2A: Hot core or accretion shock?*
van Gelder, M. L., Ressler, M. E., van Dishoeck, E. F., Nazari, P., Tabone, B., Black, J. H., Tychoniec, Ł., Francis, L., Barsony, M., Beuther, H., Caratti o Garatti, A., **Chen, Y.**, Gieser, C., Le Gouellec, V. J. M., Kavanagh, P. J., Klaassen, P. D., Lew, B. W. P., Linnartz, H., Majumdar, L., Perotti, G., and Rocha, W. R. M., 2024, *Astronomy & Astrophysics*, 682, A78.
10. *Which molecule traces what: Chemical diagnostics of protostellar sources.*
Tychoniec, Ł., van Dishoeck, E. F., van't Hoff, M. L. R., van Gelder, M. L., Tabone, B., **Chen, Y.**, Harsono, D., Hull, C. L. H., Hogerheijde, M. R., Murillo, N. M., and Tobin, J. J., 2021, *Astronomy & Astrophysics*, 655, A65.

Submitted publications as co-author

1. *JOYS: Launching and destruction of dust in protostellar jets. The case of BHR71-IRS1 with JWST/MIRI*
Tychoniec, Ł., Francis, L., Navarro, M. G., Vorster, J. M., van Dishoeck, E. F., Caratti o Garatti, A., Assani, K., Le Gouellec, V. J. M., Tabone, B., Klaassen, P. D., Janssen, A. G. M., Justtanont, K., Harsono, D., Nazari, P., Reyes, S. D., Slavicinska, K., Gieser, C., Bourke, T., Yang, Y.-L., Nisini, B., Giannini, T., Beuther, H., Devaraj, R., Ray, T. P., Brunken, N. G. C., **Chen, Y.**, van Gelder, M. L., submitted to *Astronomy & Astrophysics*.
2. *JOYS: Linking the molecular ice and gas-phase composition towards the high-mass hot core IRAS 18089-1732*
Gieser, C., Rocha, W. R. M., **Chen, Y.**, Slavicinska, K., van Dishoeck, E. F., Nazari, P., Francis, L., Beuther, H., Reyes, S. D., Caratti o Garatti, A., Klaassen, P. D., Vorster, J. M., Navarro, M. G., submitted to *Astronomy & Astrophysics*.
3. *Measuring accretion rates onto high-mass protostars with JWST*
Reyes, S. D., Beuther, H., van Dishoeck, E. F., Gieser, C., Caratti o Garatti, A., Tychoniec, Ł., Kavanagh, P. J., Klaassen, P. D., Justtanont, K., Francis, L., Le Gouellec, V. J. M., Devaraj, R., Ray, T. P., **Chen, Y.**, Rocha, W. R. M., van Gelder, M. L., submitted to *Astronomy & Astrophysics*.

4. *JOYS+*: Analyses of OCN^- , N_2O , NO , and complex cyanides in ices. Thermal processing results in modest enhancement of OCN^- ice
Nazari, P., Brunken, N. G. C., **Chen, Y.**, Slavicinska, K., van Dishoeck, E. F., Rocha, W. R. M., Boogert, A. C. A., Navarro, M. G., Le Gouellec, V. J. M., Francis, L., Tychoniec, Ł., Caratti o Garatti, A., Gieser, C., Greene, T. P., Kavanagh, P. J., submitted to *Astronomy & Astrophysics*.

Curriculum Vitae

Twenty-eight years ago, I was born on the 4th of May, the Youth Day in China, which was established to commemorate the patriotic May Fourth Movement in 1919. Although both of my parents were born and bred in the north, they migrated to the tropical city of Guangzhou in the early 1990s, which is where I grew up.

The first fifteen years of my life had nothing to do with astronomy, and the reason was simple: you have very little chance to pay attention to the night sky in a metropolis* with a rainy climate, towering buildings, and severe light pollution. After entering secondary school at 12, I became a boarding student and couldn't hang out with my playmates after school anymore. I gradually lost contact with them and focused more on my studies instead. Luckily, I inherited my parents' talent for taking exams and was admitted to one of the best high schools in the province—Guangdong Experimental High School, the place where all the stories began.

I still clearly remember the moment when my attention was captured by a photo in the admission brochure. It was a photo of the award ceremony of Chinese National Astronomy Olympiad (CNAO) in 2012. Everyone in the photo was smiling so brightly that I couldn't help imagining myself as one of them. As a result, I joined the astronomy club (SSAA[†]) in the first month of school. It turned out that SSAA is such an amazing student club that it became the best part of my school life. There were two academic lessons per week taught by second-year students, where I was able to learn basic astronomy from scratch. When the lessons switched from introducing the seasonal night sky to learning theories and equations, the class began to thin out. However, I was one of the few who stayed on, not only because I found astronomy interesting, but also because I was deeply touched by the enthusiasm and devotion of those senior students. I had been studying hard to meet the expectations of people around, but never thought about chasing a dream of my own. For a 15-year-old teen, nothing could be more exciting than exploring the scenery off the beaten track.

Driven by strong curiosity, I devoted most of my free time to learning astronomy. After only three months of study, I placed among the top 20 in the high school division of a provincial astronomy competition. Several months later, I became a finalist of CNAO and won a silver medal right before my 16th birthday—it took me only eight months to progress from a beginner to a medalist. Even now, I can hardly imagine how enthusiastic I was at that time. At the end of my first year in high school, I took over the astronomy club as the vice president, and attended a nationwide astronomy summer school in Beijing. From then on, I set my sights on majoring in astronomy. However, only a handful of universities in China offered astronomy programs at that time, and admission to most of them was very competitive. In the final semester, I gradually began to struggle under the prolonged high intensity of studies, and finally fell ill on the eve of the college entrance examination (also known as *Gaokao*). However,

*Guangzhou is the third largest city in China with a population of over 20 million.

[†]“SS” is the abbreviation for my high school's name (in Chinese), and “AA” is the abbreviation for “astronomy association”.

I never thought about giving up, and somehow my prayers were answered. I delivered my best performance in Gaokao and gained admission to my dream school—Peking University, of which the anniversary happens to be on the same day as my birthday.

Heavy is the head that wears the crown. Although it was a great honor to be a student of PKU, it was not easy to survive there. Since the Department of Astronomy is part of the School of Physics, astronomy students usually take classes together with physics students, many of whom are medalists of National and even International Physics Olympiads. For someone like me with neither a strong aptitude for physics[‡] nor any experience in physics competitions, it was a nightmare to keep up with fellow students. Fortunately, as soon as I started my campus life, I made up my mind to pursue graduate study abroad to engage with the forefront of astronomical research, and my determination to achieve this goal kept me from falling into despair. In my second year, I joined Prof. Gregory Herczeg's group and received basic research training. To prepare for my PhD applications, I also pursued a summer internship with Dr. Lumila Carone at the Max Planck Institute for Astronomy (MPIA) in 2018. In the subsequent fall, I traveled to the University of Michigan, Ann Arbor to conduct my bachelor thesis project on chemical modeling of protoplanetary disks with Prof. Edwin Bergin. These experiences not only equipped me with essential research skills, but also taught me how to navigate life abroad.

The four years I spent as an undergraduate were demanding yet fulfilling, but the ending was not as favorable as that of my high school—I was not able to get admitted to any of the US PhD programs, and instead, I enrolled in a master's program at Leiden University in the fall of 2019. This transition turned out to be a better choice for my career development than what I had planned. At Leiden Observatory, I had the opportunity to do my first master's research project in the group of Prof. Ewine van Dishoeck, who is referred to as *the Queen of Astrochemistry* in the community. Thanks to this experience, I rejoined her group as a PhD student in late 2021. According to the initial Education & Supervision Plan, my PhD research was supposed to study the formation of complex organic molecules in both the gas and the solid phases using ALMA and JWST—yes, my PhD progressed exactly as planned (though probably not as fast as expected). After years of delay, JWST was successfully launched two months after I started my PhD, and I was therefore able to work on first-hand JWST data just after finishing my first ALMA project. In the last year of my PhD, I was very lucky to be granted observing time of both ALMA and JWST as the Principle Investigator (PI), which, as far as I'm concerned, is one of the highest “honors” an observer can receive. I would not have reached this point if I had not chosen to come to Leiden, where I met such a professional and supportive group. Currently, I'm starting a postdoc position in the Center for Astrochemical Studies (CAS) at Max Planck Institute for Extraterrestrial Physics (MPE). I will keep exploring the icy and gaseous worlds of interstellar molecules using the most powerful telescopes in human hands.

Time flies. I still remember it was a clear night in late October of 2012 that I recognized Orion for the first time. Thirteen years later, I'm finally approaching the completion of my doctoral degree. It's been a long journey, beginning with dreams and hopes, but soon filled with challenges, uncertainties, and moments of self-doubt. I considered quitting more than once, yet somehow I arrived here, where I can contentedly say to my fifteen-year-old self: I have seen the scenery you once longed for.

[‡]Both of my parents majored in Chinese language and literature (yes, nothing to do with STEM).

Acknowledgements

In Chinese, my name Yuan(缘) refers to fortunate encounters shaped by both destiny and coincidence. Throughout this journey, I have been very lucky to cross paths with many great people, whose guidance, support, and encouragement have brought me to where I am today. I would like to express my sincere gratitude to everyone who has illuminated my path, including those who may not be individually acknowledged here.

First and foremost, I would like to thank my supervisors, Ewine and Harold, for offering me the opportunity to pursue my PhD, and InterCat, the Center for Interstellar Catalysis at Aarhus University, for providing me the funding over the four years. Ewine, thank you for always taking time out of your busy schedule to meet with me, read my manuscripts, and teach me how to give good presentations. You never lost faith in me, even when my progress was slower than expected. I know from your mentorship that you genuinely hope we can find our own place in academia, rather than simply meeting the requirements to graduate. It was a privilege to be one of your last PhD students, and I hope I have not let you down. Harold, I regret that I did not take more initiative to interact with you before your passing. Thank you for running the Laboratory for Astrophysics, which has been continuously fueling our observational research by providing important lab spectra.

During my six years at Leiden, I also received generous help from many senior group members. Łukasz and Martijn, thank you for guiding me through my first master's project step by step. Martijn, I'm very happy to have you as my co-promoter at my defense! I owe so much to your guidance and dedication. Thank you for staying in the group as a postdoc so that our time overlapped for longer, although I felt sorry that you were always copied on the emails Ewine sent me. Pooneh, I learned a lot from you, not only about doing research, but also about how to grow into an independent researcher. Will, I couldn't imagine how I would have moved forward without your pioneering studies. Thank you for always being patient and helpful whenever I had questions. Łukasz, it was amazing that our paths crossed again, and it is a privilege to have you in the group as an expert in both ALMA and JWST. Logan, thank you for sharing your scripts and humor, both of which are necessary to my life.

The companionship with my fellow students has also meant a lot to me. Katie, you are one of the best people I have met, both as a friend and as a researcher. I will miss our chats about everything and nothing. Nashanty, I love your hearty laugh, even when you were teasing me at the NOVA Fall School. Julia, your diligence and efficiency are truly admirable. I was lucky to have you as the co-mentor of our master's student Kelly. Chen and Yanling, I fondly remember the dinners we shared, the PhD events we attended, and the concert and volleyball matches we watched together.

Beyond those I worked with closely, I would also like to thank the rest of the Leiden-Garching group: Alice, Andrew, Sierra, Nicolás, Franciele, Zak, Xunchuan, Lisa, Marina, Andrés, Margot, Ardjan, Lukas, Teresa, Giulio, Pranjal, Marissa, Milou, for the time we shared at L-G telecons, group retreats, and conferences over the world.

Thank you for broadening my knowledge of disks, jets, simulations and experiments. Femke, Lukas, Tobias, and Mulan, welcome to the group—the torch is now in your hands. Special thanks to other faculty members, Serena, Michiel, Melissa, Nienke, Ko-Ju, Thanja, for keeping astrochemistry thriving at Leiden. Alessia and Josh, thank you for your hard work as TAs for SSE. I learned a lot from working with you. Beth and Karin, you are both fast learners; good luck with your future duties!

Outside Leiden, I also received warm hospitality and valuable guidance. Liv, Karin, Andrew, and all the InterCat folks, thank you for organizing the seminars and hosting us warmly at the yearly retreat. Greg, thank you for supporting me all the way until I got my PhD. I was so lucky to have you as my first academic mentor. Ted, it was my pleasure to see you again after graduation. Doing the bachelor's thesis project with you was the start of my astrochemistry journey. Brett, thank you for your wonderful ALMA data, which became the backbone of this thesis, and for taking care of my JWST program as the US Admin Co-I. Rob, thank you for all the simulation results and your detailed replies to my questions, which made my observational studies much more meaningful. Of course, thank you Silvia, for recognizing my work and offering me the postdoc position in your group. I would also like to express my gratitude to the professors, researchers, and students I met in China. Thank you for your warm welcome and financial support. I really enjoyed our academic discussions and social activities, and I hope to be able to return your kindness in the future.

As someone who spent a lot of time cooking and sleeping, my life outside academia was not very colorful. Even so, I would like to thank my Chinese colleagues for dining out together, which has been an important part of my spare time. Yapeng, Xuechen, Shunsheng, Zhenlin, thank you for your guidance in both life and research. Also thanks to many of my neighbors and friends, with whom I spent enjoyable holidays.

Before closing, I would like to thank my parents, for always respecting and supporting my decisions, even though I chose a less conventional path. Thank you for being my harbor whenever I need to return. As the only child, I wish I could spend more time with you. Finally, thank you—myself—for staying grounded and keeping moving forward, no matter how slow the pace. It was not easy to pursue a PhD abroad, alone, and during the pandemic, but you made it. May the road ahead be kind to you.