Protostellar jets and planet-forming disks: Witnessing the formation of Solar System analogues with interferometry

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Publications

Refereed first-author publications:

4. *Dust masses of young disks: constraining the initial solid reservoir for planet formation.* **Tychoniec Ł.**, Manara C. F., Rosotti G. P., van Dishoeck E. F., Cridland A. J., Hsieh T., Murillo N. M., Segura-Cox D., van Terwisga S. E., Tobin J. J., 2020, A&A, 640, 19.

3. *Chemical and kinematic structure of extremely high-velocity molecular jets in the Serpens Main star-forming region.* **Tychoniec Ł.**, Hull C. L. H., Kristensen L. E., Le Gouellec V. J. M., van Dishoeck E. F., 2019, A&A, 632, 101

2. *The VLA nascent disk and multiplicity survey of Perseus protostars (VANDAM). IV. Free-free emission from protostars: links to infrared properties, outflow tracers, and protostellar disk masses.* **Tychoniec Ł.**, Tobin J.J., Karska A., Chandler C., Dunham M. M., Harris R. J., Kratter K. M., Li Z., Looney, L. W., Melis C., Pérez L. M., Sadavoy S. I., Segura-Cox, D., van Dishoeck E. F., 2018, ApJS, 238, 19.

1. *The VLA nascent disk and multiplicity survey of Perseus protostars (VANDAM). III. Extended radio emission from protostars in Perseus.* **Tychoniec Ł.**, Tobin J.J., Karska A., Chandler C., Dunham M. M., Li Z., Looney L. W., Segura-Cox D., Harris R. J., Melis C., Sadavoy S. I., 2018, ApJ, 852, 18.

Other refereed publications:

10. *Complex organic molecules in low-mass protostars on Solar System scales. I. Oxygen-bearing species.* van Gelder M. L., Tabone B., **Tychoniec Ł.**, van Dishoeck E. F., Beuther H., Boogert A. C. A., Caratti o Garatti A., Klaassen P. D., Linnartz H., Müller H. S. P., Taquet V., 2020, A&A, 639, 87.

9. *The VLA/ALMA nascent disk and multiplicity (VANDAM) survey of Orion protostars. II. A statistical characterization of Class 0 and Class I protostellar disks.* Tobin J. J., Sheehan P. D., Megeath S. T., Díaz-Rodríguez A. K., Offner S. S. R., Murillo N. M., van 't Hoff M. L. R., van Dishoeck E. F., Osorio M., Anglada G., Furlan E., Stutz A. M., Reynolds N., Karnath N., Fischer W. J., Persson M., Looney L. W., Li Z., Stephens I., Chandler C. J., Cox E., Dunham M. M., **Tychoniec Ł.**, Kama M., Kratter K., Kounkel M., Mazur B., Maud L., Patel L., Perez L., Sadavoy S., Segura-Cox D., Sharma R., Stephenson B., Watson D. M., Wyrowski F., 2020, ApJ, 890, 130.

8. *The VLA/ALMA nascent disk and multiplicity (VANDAM) survey of Orion protostars I. Identifying and characterizing the protostellar content of the OMC2-FIR4 and OMC2-FIR3 regions.* Tobin J. J., Megeath S. T., van 't Hoff M.L.R., Diaz-Rodriguez, A. K., Reynolds N., Osorio

M., Anglada G., Furlan E., Karnath N., Offner S. S. R., Sheehan P. D., Sadavoy, S. I., Stutz A. M., Fischer W. J., Kama M., Persson M., Di Francesco J., Looney L. W., Watson D. M., Li Z., Stephens I., Chandler C. J., Cox E., Dunham M. M., Kratter K., Kounkel M., Mazur B., Murillo N. M., Patel L., Perez L., Segura-Cox D., Sharma R., **Tychoniec Ł.**, Wyrowski F., 2019, ApJ, 886, 6.

7. *Characterizing magnetic field morphologies in three Serpens protostellar cores with ALMA.* Le Gouellec V. J. M., Hull C. L. H., Maury A. J., Girart J. M., **Tychoniec Ł.**, Kristensen L. E., Li Z., Louvet F., Cortes P. C., 2019, ApJ, 885, 106.

6. *The mass evolution of protostellar disks and envelopes in the Perseus molecular cloud.* Andersen B. C., Stephens I. W., Dunham M. W., Pokhrel R., Jørgensen J. K., Frimann S., Segura-Cox D., Myers P. C., Bourke T. L., Tobin J. J. **Tychoniec Ł.**, 2019, ApJ, 873, 54.

5. *The Herschel-PACS legacy of low-mass protostars: the properties of warm and hot gas components and their origin in far-UV illuminated shocks.* Karska A., Kaufman M. J., Kristensen L. E., van Dishoeck E. F., Herczeg G. J., Mottram J. C., **Tychoniec Ł.**, Lindberg J. E., Evans N. J. II, Green J. D., Yang Y., Gusdorf A., Itrich D., Siódmiak N., 2018, ApJS, 235, 30.

4. *ALMA observations of dust polarization and molecular line emission from the Class 0 protostellar source Serpens SMM1.* Hull C. L. H., Girart J. M., **Tychoniec Ł.**, Rao R., Cortés P. C., Pokhrel R., Zhang Q., Houde M., Dunham M. M., Kristensen L. E., Lai S., Li Z., Plambeck R. L., 2017, ApJ, 847, 92.

3. *Against the biases in spins and shapes of asteroids.* Marciniak A., Pilcher F., Oszkiewicz D., Santana-Ros T., Urakawa S., Fauvaud S., Kankiewicz P., **Tychoniec Ł.**, Fauvaud M., Hirsch R., Horbowicz J., Kamiński K., Konstanciak I., Kosturkiewicz E., Murawiecka M., Nadolny J., Nishiyama K., Okumura S., Polińska M., Richard F., Sakamoto T., Sobkowiak K., Stachowski G., Trela P., 2015,Planetary and Space Science, 118, 256.

2. *High-resolution 8 mm and 1 cm polarization of IRAS 4A from the VLA nascent disk and multiplicity (VANDAM) survey.* Cox, E. G., Harris, R. J., Looney, L. W., Segura-Cox, Dominique M., Tobin J. J., Li Z., **Tychoniec Ł.**, Chandler C. J., Dunham M. M., Kratter K., Melis C., Perez L. M., Sadavoy S. I., 2015, ApJ, 814, L28.

1. *Far-infrared CO and H_2O emission in intermediate-mass protostars.* Matuszak, M., Karska, A., Kristensen, L. E., Herczeg G. J., **Tychoniec Ł.**, van Kempen T. A., Fuente, A., 2015, A&A, 578, 20.

Non-refereed publications:

1. Chemical and kinematic complexity of the very young star-forming region Serpens Main observed with ALMA. **Tychoniec Ł.**, Hull C. L. H., Tobin J. J., van Dishoeck E. F., 2018, Astrochemistry VII: Through the Cosmos from Galaxies to Planets, in Proceedings of the International Astronomical Union, IAU Symposium, Volume 332, pp. 249-253.

Curriculum Vitae

I was born in the city of Nowogard in north-west Poland, on 25th of January 1992, to Jolanta and Edward Tychoniec. From my dad I inherited a passion for stargazing, from my mom a curiosity for math and science; from both of them an appreciation for a spiritually-oriented life. My ridiculously successful older sister Agata, set a path that for me seemed natural to follow: that of a constant drive for new challenges. My younger brother Krzyś, taught me most that I know about patience, selfless love and compassion, qualities that I later appreciated as essential for a human being.

I was blessed with a house and high-school environment that allowed me to explore my interest and opportunities. Mrs. Aldona Kopycińska helped me to get an early start at peculiarities of European Union law system, Mrs. Marta Maziarz and Mrs. Izabella Koladyńska saw my inclination to delve into philoshopical discussions, and patiently convinced me to explore this path. Ft. Marek Gajowiecki sparked in me an enthusiasm not only in rock music and Dark Tower series, but also in theology. Those efforts allowed me to become a finalist of both Theology and Philosophy Olympiad in 2010. It all seemed that a path of a true humanist is right in front of me. Therefore I enrolled for a B.A. in International Relationships at Adam Mickiewicz University (AMU) in Poznań. However, this path has proven not to be fertile, and after one year I decided to explore my lifelong passion for astronomy, one of the most philosophical of sciences, in a more professional way – I started a BSc and further on a MSc in Astronomy at Astronomical Observatory in AMU in Poznań.

Years 2011-2016 that I spent on studying astronomy were exciting as I first got to experience professional observations in Borówiec Observatory on the outskirts of Poznań, and collaborate in a first scientific project on studying asteroids of the Solar System with Dr. Anna Marciniak. One of my career defining moments was when I met Dr. Agata Karska during the 1st year of my master studies, as she offered me to work on a project studying young massive stars with the Herschel Space Observatory. An exploration of the origin of stars and planets with a space telescope, was extremely exciting for me and I jumped on this with all enthusiasm I had, however this would not happen without an all-important nudge by my colleague Monika Matuszak. This resulted in my first international collaboration with Dr. Antoine Gusdorf at Observatoire de Paris. In the break between first and second year of my masters I participated in the Leiden/ESA Astrophysics Program for Summer Students in Leiden working with Dr. John Tobin on Very Large Array observations of young protostars in the Perseus molecular cloud. This has also become a topic of my master thesis I finished in Poznań under supervison of Dr. Karska and Dr. Tobin. During my studies I also became a

proficient barista (a professional coffee maker) in Brisman Kawowy Bar in Poznań. Working with a coffee legend Mateusz Gaca, who led me to become a 5th Polish Barista in 2015, and future World Barista Champion Agnieszka Rojewska, was a unique experience, and I was on a brink of choosing a career path of a professional barista. However, the determination of Dr. Karska, and also financial support from stipends of Polish Ministry of Higher Education and AMU, allowed me to fully focus on scientific research.

I was admitted to the PhD program in Leiden Observatory in Netherlands to work with Prof. dr. Ewine van Dishoeck on star and planet formation in 2016. One of my first tasks was to assist in preparation of the first scientific observations of star-forming regions on the James Webb Space Telescope (JWST). Although it was not meant for me to witness the excitement of a JWST launch and first data delivery during my PhD, I learned plenty about infrared astronomy and experienced working in a large collaboration within MIRI European Consortium.

My first research projects were a continuation of VLA studies of radio jets in Perseus that I started during my masters. My first paper explored the ionized component of the jet, finding exciting evidence for cosmic rays production in protostars. A second paper, aside from providing a very extended survey dataset on radio emission from protostars, also opened a path that determined my next main interest: planet-forming disks. We used the data to provide an updated estimate of protostellar disk masses. This chapter, without a doubt inspired by sharing an office with disk expert Dr. Sierk van Terwisga, resulted in an exciting outcome: disks in young systems are more massive than their mature counterparts, and the planets could form very early. This work prompted a collaboration with Dr. Carlo Manara, Dr. Giovanni Rosotti, and Dr. Alex Cridland on the relation between the disk masses and exoplanets. This comparison showed that planets must form early, and it delivered for me a first press release. My PhD was also revolving around Atacama Large Millimeter/submillimeter Array (ALMA). Through a collaboration with Dr. Charles Hull and Dr. Lars Kristensen we explored the nature of young protostellar jets in Serpens. This also triggered a lot of fruitful discussion with Dr. Benoit Tabone and helped to put in motion a final work on the molecular tracers of physical components of the protostellar systems with Dr. Merel van 't Hoff and Martijn van Gelder.

During the first three years of my graduate program I was a Teaching Assistant for Galaxies and Cosmology, course led by Dr. Jacqueline Hodge. I also had the privilege to supervise together with my colleague Martijn van Gelder, two master students: Micha Heilman and Yuan Chen. As the excitement for the JWST launch heated up I was an expert speaker at the JWST MasterClass in Toruń and at the Dutch JWST day. On my final year I co-ran with Dr. Alex Cridland a Star Formation and Disk Coffee meeting. I had opportunity to present my research in Puerto Varas in Chile, Pasadena in California, USA, and many virtual conferences during pandemic times.

I will continue my career as a Research Fellow at the European Southern Observatory in Garching, Germany, pursuing ALMA studies of young protostellar systems, while getting experience at using Very Large Telescopes at Paranal, and eagerly awaiting launch of the JWST in the fall of 2021.

Acknowledgements

As this journey called PhD comes to an end, I want to take this opportunity to acknowledge everyone who helped me to get here. In all honesty, this was an outcome that didn't seem very likely for me many times across this endeavor. I can admit that if it wasn't for all the people who believed in me when I didn't, and who constantly put their money on me against all odds, I wouldn't make it. Thank you! Dziękuję! Below I will try to thank some of you in person, but I am grateful to everyone who even briefly lifted me up along the way.

Moving to a different country can be a challenge, which was made a lot nicer, thanks to two awesome flatmates who helped me to settle in, Andrej and Iva, I will always think fondly about our year at Lasserstraat! You both without a blink dragged me into your social circle, which resulted in many parties, new friendships and I didn't have time to feel alone during my first year. Andrej, I still miss your cooking!

At the very beginning, support from Agata Karska and John Tobin was essential for me to choose the path of a professional astronomer. Agata, thank you for betting on me early on, investing your time and resources so I can get a fast-track into high-level research. Antoine Gusdorf, thanks for being my first foreign collaborator and showing me that doing science can't be so scary. John, I will be always indebted for trusting me with the impressive VANDAM dataset, and for your support over the years. Chat, Lars, Carlo, Migo, Henrik, Valentin, Giovanni, Tien-Hao, Nadia, Tyler, Mario, Yao-Lun, Dominique, Tom, thank you for various scientific and non-scientific discussions and advice. Leiden/ESA Astrophysics Program for Summer Students (LEAPS) was a life-changing event for me not only for scientific reasons, which cemented my dedication to star-formation and to interferometry but also for a social life, which made me feel that I can fit in in an international environment. Thanks, LEAPS 2015, both organizers and fellow students!

The two Dutchies who became my main resort for science questions, life problems, shared difficulties, board games, and late-night drinks. Arthur, I never stopped being impressed with your knowledge and intelligence, thank you for your tireless help with 'easy' questions. Merel, your kind heart and compassion dragged me through the hard parts of this journey, thanks for the company during all the ALMA deadlines and all the insights on disks and chemistry. Thank you both for being fantastic traveling companions, through Chile, California, and Sweden! I'm sure this is not over yet!

I was very lucky to be a part of a large, diverse, and friendly research group. Sierk, your knowledge is beyond the limit, I greatly enjoyed our discussions on countless topics, thanks for your help with statistics and setting first steps in the disk territory. Christian, my fellow coffee geek, we ran a small revolution in the observatory and had some nice coffee-hunting excursions, it was great fun! Danna, you were one of the first friends I made in the Netherlands, I was lucky to have you around! Alex, thanks for timeless geek-outs at

the borrels, and for insights during my exoplanetary endeavor. Pooneh, I wish we shared more time in and outside the observatory, your positive attitude is so contagious. Benoît, I was so excited to welcome another outflow aficionado in the group, thank you for being a fun and always an enthusiastic companion. Martijn, thank you for your help and support, co-supervision of students together was a great adventure! Thanks also for being a helpful and patient neighbor, whenever I lost my keys. Giovanni, thank you for your insights and mentoring. Niels, till the next borrel. Daniel, thank you for your patience in answering all the questions to an ALMA beginner. Anna, I'm looking forward to our Paranal reunion. Nadia, thanks for all the practical insights on how to do better science, Alice, I'm still waiting for a karaoke duel, and good luck with the new band, Leon, Margot, Kirstin, Shota, thanks for countless coffee breaks, Jeroen, thanks for all the jokes and lunch discussions, Gleb, I always enjoyed your visits at 504.

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Sterrewacht is much bigger than a research group and I especially appreciate people with whom I could share Friday borrels, King's Birthdays, Leiden Ontzet, and countless other parties. Kirsty, what are the odds?! Mantas, greatest micro-parties at your place. Eleonora, Fran, Gwen, Leindert, Marta, Matus, Alex, Marina, Sarah, Jerry, Jordy, Maria Cristina, Turgay, Dilovan, Nico, Anna, Fraser, Sanjana, Gabriela, Volkert, and many others, thanks for being around!

Chiel, thanks for getting me into squash! Lisanne, thank you for supporting us during our wedding. Chummy crew: Jaap and Corrie, I can't express enough how important your lovely coffee house was during this PhD, kind of a safe haven from which I always left with a little bit more enthusiasm to fight another day. Dario and the Monkeys: Hiddo and Dario, thanks for bringing me back to my old hobby of playing guitar, I had fun exploring my 'rock & roll' side. Dario, I am so glad we fulfilled our goal and played at the BBQ!

I was always looking forward to coming back to Poland, especially to Poznań, however, 2020 brought me a surprise and I had to stay there for 4 months: Oskar, Patryk, thank you for letting me in and for sharing a home office, through games of LoL, board games and morning coffees. Thank you to all with whom we managed to get in touch, despite the distance Uran and Agata, Kamila and Max, Michu, Marika i Jan, all people at Brisman Coffee, Krycha, Dawid, Grześ i Madzia, Szopen, Mery, I was always excited to see you all!

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I am grateful to those who supported me in my early years and encouraged me to follow my dreams: Mom and Dad, thank you for sharing the passion for stargazing and math, my

sister Agata, thanks for teaching me what ambition and hard work mean, my brother Krzyś for teaching me so much so early in my life. Szymon, my young godson, for helping me rediscover my child's passion for the cosmos. Staś, welcome to the world! Can't wait to spam you with astronomy books!

I left this to the very end but in many ways, it is the most important paragraph: Marta, my wife. When we met, I told you that in a few months I need to leave abroad to do a PhD in astronomy, but you didn't run away. We made a bold and somewhat crazy choice to spend the next four years 1000 kilometers apart. Not only we made it, but our relationship thrived and I was delighted to say 'I do' to you a month before the end of my time in Leiden. It is impossible to overstate your role in getting this thesis done, with your unconditional support, your confidence in me, and your patience. Having you designing this beautiful cover is my honor. I'm so excited to start our new life in Germany! Kocham Cię!