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Unveiling the third dimension: vertical structure as a probe of planet formation conditions

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Publications

Refereed publications as first author

1. *High turbulence in the IM Lup protoplanetary disk. Direct observational constraints from CN and C₂H emission*
Paneque-Carreño, T., Izquierdo, A. F., Teague, R., Miotello, A., Bergin, E. A., Loomis, R., van Dishoeck, E. F., 2024, *Astronomy & Astrophysics*, 684, A174.
2. *Directly tracing the vertical stratification of molecules in protoplanetary disks*
Paneque-Carreño, T., Miotello, A., van Dishoeck, E. F., Tabone, B., Izquierdo, A. F., Facchini, S., 2023, *Astronomy & Astrophysics*, 669, A126.
3. *Vertically extended and asymmetric CN emission in the Elias 2-27 protoplanetary disk*
Paneque-Carreño, T., Miotello, A., van Dishoeck, E. F., Pérez, L. M., Facchini, S., Izquierdo, A. F., Tychoniec, L., Testi, L., 2022, *Astronomy & Astrophysics*, 666, A168.
4. *Spiral arms and a massive dust disk with non-Keplerian kinematics: Possible evidence for gravitational instability in the disk of Elias 2-27*
Paneque-Carreño, T., Pérez, L. M., Benisty, M., Hall, C., Veronesi, B., Lodato, G., Sierra, A., Carpenter, J. M., Andrews, S. M., Bae, Jaehan, Henning, Th., Kwon, W., Linz, H., Loinard, L., Pinte, C., Ricci, L., Tazzari, M., Testi, L., Wilner, D., 2021, *The Astrophysical Journal*, 914, 2, 88.

Submitted publications as first author

1. *Vertical CO surfaces as a probe for protoplanetary disk mass and carbon depletion*
Paneque-Carreño, T., Miotello, A., van Dishoeck, E. F., Rosotti, G., Tabone, B., submitted to *Astronomy & Astrophysics*.

Refereed publications as co-author

1. *Gravitational instability in a planet-forming disk*
Speedie, J., Dong, R., Hall, C., Longarini, C., Veronesi, B., **Paneque-Carreño, T.**, Lodato, G., Tang, Y., Teague, R., Hashimoto, J., accepted for publication in Nature.
2. *Angular momentum transport via gravitational instability in the Elias 2-27 disc*
Longarini, C., Lodato, G., Clarke, C. J., Speedie, J., **Paneque-Carreño, T.**, Arrigoni, E., Curone, P., Toci, C., Hall, C., 2024, *Astronomy & Astrophysics*, 686, L6.
3. *CI traces the disk atmosphere in the IM Lup protoplanetary disk*
Law, C. J., Alarcón, F., Cleeves, L. I., Öberg, K. I., **Paneque-Carreño, T.**, 2023, *The Astrophysical Journal Letters*, 959, 2.
4. *The Disc Miner. II. Revealing gas substructures and kinematic signatures from planet-disc interaction through line profile analysis*
Izquierdo, A. F., Testi, L., Facchini, S., Rosotti, G. P., van Dishoeck, E. F., Wölfer, L., **Paneque-Carreño, T.**, 2023, *Astronomy & Astrophysics*, 674, A113.
5. *Mapping protoplanetary disk vertical structure with CO isotopologue line emission*
Law, C. J., Teague, R., Öberg, K. I., Rich, E. A., Andrews, S. M., Bae, J., Benisty, M., Facchini, S., Flaherty, K., Isella, A., Jin, S., Hashimoto, J., Huang, J., Loomis, R. A., Long, F., Muñoz-Romero, C. E., **Paneque-Carreño, T.**, Pérez, L. M., Qi, C., Schwarz, K. R., Stadler, J., Tsukagoshi, T., Wilner, D. J., van der Plas, G., 2023, *The Astrophysical Journal*, 948, 1.
6. *Deuterium-enriched water ties planet-forming disks to comets and protostars*
Tobin, J. J., van't Hoff, M. L. R., Leemker, M., van Dishoeck, E. F., **Paneque-Carreño, T.**, Furuya, K., Harsono, D., Persson, M. V., Cleeves, L. I., Sheehan, P. D., Cieza, L., 2023, *Nature*, 615, 7951.
7. *Dynamical mass measurements of two protoplanetary discs*
Lodato, G., Rampinelli, L., Viscardi, E., Longarini, C., Izquierdo, A., **Paneque-Carreño, T.**, Testi, L., Facchini, S., Miotello, A., Veronesi, B., Hall, C., 2023, *Monthly Notices of the Royal Astronomical Society*, 518, 3.
8. *A dichotomy in group II Herbig disks. ALMA gas disk height measurements show both shadowed large vertically extended disks and compact flat disks*
Stapper, L. M., Hogerheijde, M. R., van Dishoeck, E. F., **Paneque-Carreño, T.**, 2023, *Astronomy & Astrophysics*, 669, A158.
9. *Gas temperature structure across transition disk cavities*
Leemker, M., Booth, A. S., van Dishoeck, E. F., Pérez-Sánchez, A. F., Szulágyi, J., Bosman, A. D., Bruderer, S., Facchini, S., Hogerheijde, M. R.,

- Paneque-Carreño, T.**, Sturm, J. A., 2022, *Astronomy & Astrophysics*, 663, A23.
10. *Constraining protoplanetary disc mass using the GI wiggle*
Terry, J. P., Hall, C., Longarini, C., Lodato, G., Toci, C., Veronesi, B., **Paneque-Carreño, T.**, Pinte, C., 2022, *Monthly Notices of the Royal Astronomical Society*, 510, 2.
 11. *A dynamical measurement of the disk mass in Elias 227*
Veronesi, B., **Paneque-Carreño, T.**, Lodato, G., Testi, L., Pérez, L. M., Bertin, G., Hall, C., 2021, *The Astrophysical Journal Letters*, 914, 2.
 12. *Predicting the kinematic evidence of gravitational instability*
Hall, C., Dong, R., Teague, R., Terry, J., Pinte, C., **Paneque-Carreño, T.**, Veronesi, B., Alexander, R. D., Lodato, G., 2020, *The Astrophysical Journal*, 904, 2.

Published books (science outreach)

1. *Universo Según Carlota: Galaxias lejanas y materia oscura*
Paneque-Carreño, T., 2024, in press, Editorial Planeta Chile.
2. *Universo Según Carlota: Vida extraterrestre y exoplanetas*
Paneque-Carreño, T., 2023, Editorial Planeta Chile.
3. *Universo Según Carlota: Agujeros negros y explosiones estelares*
Paneque-Carreño, T., 2024, Editorial Planeta Colombia.
Paneque-Carreño, T., 2022, Editorial Planeta Chile.
4. *Universo Según Carlota: Asteroides y estrellas fugaces*
Paneque-Carreño, T., 2022, Editorial Planeta Colombia.
Paneque-Carreño, T., 2021, Editorial Planeta Chile.

Curriculum Vitae

I was born on the 15th of November, 1997, in Madrid, Spain. My parents, originally from Cuba and Chile, where in Spain doing their PhD studies in molecular genetics (dad) and immunology (mum). We stayed in Spain for five years, during which I bonded with my godparents and their sons, whom to this day are a second family to me. In January of 2003 we moved to Glasgow, Scotland where my parents worked as postdoctoral investigators. I started school without knowing a word of english, but thanks to the excellent public system managed to learn how to read, write and speak within the first six months. During our first years in Glasgow my two brothers where born. My life at this point was filled with books, I greatly enjoyed reading fantastic literature and the library was my favorite place. At school I was interested in all topics, from maths to english and also, at the insistence of my dad, learnt how to play the violin.

In April of 2007 my family moved to Chile. On one hand it was great to reconnect with my family from my mother's side, but it was very hard for me to leave my friends and life in Glasgow. After some struggles I managed to feel comfortable in my new high school and joined a program called PENTA UC. PENTA is an initiative of Universidad Católica in Chile that focuses on students with academic talent, offering classes on topics beyond the high school curriculum. Through PENTA I discovered robotics, computer science, astronomy and complex math. While for a long time my intention was to study to become a school teacher, I had a never ending curiosity and wished to also be a life-long student, therefore I decided to become a scientist like my parents, but in the topic of astronomy.

In March of 2014 I enrolled in the faculty of physical and mathematical sciences of Universidad de Chile. Here I was one of over 800 first year students interested in various engineering and scientific majors. I didn't know much about astronomy beyond the fact that it was a branch of physics that studied the processes of objects in the universe. My first approach was on the topic of planet formation and it filled me with curiosity and eagerness to learn more on the subject. During the four years of my undergraduate I worked as teaching assistant to various physics classes, my favorite being Mechanics, which was taught in the third semester and introduced cylindrical and spherical coordinates. During the weekends I worked as assistant professor in PENTA courses and volunteered as referee to a nation-wide robotics competition. I graduated from Astronomy in December of 2017 and, filled

with impostor syndrome, doubted about following an academic career beyond the bachelor. Thankfully my friends pushed me to apply for a Master degree and I was accepted to start in March of 2018 at Universidad de Chile.

The Master degree changed my view of academia and my place in it. I worked with Prof. Dr. Laura Pérez on the analysis of new ALMA data from the protoplanetary disk surrounding the young star Elias 2-27. At that point Prof. Dr. Myriam Benisty was also working at Universidad de Chile and both her and Laura became excellent role models of what it means to be a woman in academia. I became involved in the Dustbusters collaboration, which allowed me to travel in early 2019 to Università degli Studi di Milano and the University of Leicester to work alongside Prof. Dr. Giuseppe Lodato and Dr. Cassandra Hall in the modelling of gravitational instabilities. During these visits I also met the person who would become one of my PhD supervisors, Dr. Anna Miotello.

After successfully defending my Master thesis virtually during the 2020 pandemic, I moved to Germany in November of 2020 to start my PhD at the European Southern Observatory with Anna. In parallel, I worked with the group led by Prof. Dr. Ewine van Dishoeck at Leiden Observatory, as my position was shared between both institutions. I was introduced to the amazing world of astrochemistry, the various temperatures (brightness, kinetic, effective, rotational) that confused me for a long time and the power of understanding the conditions of emission for the gas observations that I was working with. We uncovered and dived deep into the vertical structure of protoplanetary disks, discovering new avenues and methods to understand the conditions of planet formation through the surfaces traced by molecular gas observations.

In parallel to the scientific production, since early 2020 I started to dedicate a large portion of my “spare” time to do astronomy outreach on social media. I began uploading videos in spanish to different social media platforms explaining astronomy concepts and when I was in Germany my following numbers grew unexpectedly. Currently I have over one million followers accross platforms, have written four astronomy outreach books for a juvenile audience that are used as reading materials in schools in Chile and was named UNICEF good will ambassador in Chile. To me, scientific outreach is a key part of my scientific research, as it helps me to use the astronomical knowledge to give back to society and promote critical thinking. I also think it is a way of connecting with my initial wish to be a teacher, only that instead of a blackboard I appear on a telephone screen.

In September of 2023 I left Germany and moved to the Netherlands to complete my last PhD year at the University of Leiden and work in person with people that for years had been virtual collaborators. Now, after my thesis defence I will continue doing astronomical research through a joint fellowship of 51 Pegasi b and Michigan Society of Fellows at the University of Michigan in the group of Prof. Dr. Ted Bergin.

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My experience during this PhD has been largely filled by support, encouragement and collaboration. The list of people that have been part of this would be too long to put here, however I will do my best to name some of the key players.

First, some words for my nuclear family. Mamá y Papá you have always been my biggest supporters and shown me unconditional love that no amount of geographical distance can stop. To my not-so-little siblings, Carlos and Miguel, I am beyond proud of watching you both grow and conquer every challenge that you face. Huge recognition for my large extended family, but particularly to both my abuelitas, Nivia and Norma son mi inspiración máxima.

I was fortunate to divide my PhD between the European Southern Observatory in Garching working directly with Anna Miotello and Leiden Observatory with Ewine van Dishoeck. Anna, I appreciated our weekly meetings and your concern from the very first day. Even in a pandemic lockdown you were always present and available to have a conversation on science and life. It has been a delight to be a founding member of the Miotello group that will for sure grow largely in the coming years. Ewine, your sharp thoughts and experience always sparked new ideas in our research meetings. It has been very inspiring to learn astrochemistry with you. I am thankful to both my advisors for trusting me not only in my research, but also in my outreach endeavours and for being present in some of the key moments of my life both personal and professional.

To some of the many amazing people I worked with during these four years. My first office mate and favourite brazilian, Cami, it was lovely sharing this PhD adventure with you, the good and the bad. Luca, it has been all laughs with you since the first day, I thank you for your sincerity and constant support and I am so happy I will now get to see you every time I go to Chile! Victor, I will always look forward to having one of our talking sessions and I hope in the future we get to share more time together again. Andrés, from the start we got on great talking about kinematics and trying to figure out how to do crazy science, there is still a lot of work to be done! Gemma, Sam, Stephen, Simon, Juliet, Amanda, you were some of my closest friends at ESO and I hope the future brings us more opportunities to make new memories. Nelma, I appreciate your unwavering support and dedication, ESO would not have been the same without you. To all the ESO SPF team, Aashish, Domi, Alice, Rik, Adrien, Haochang, Pietro, Chi

Yan, Hala, Mari-Liis, Enrique, Carlo, Justyn, Claudia, Marta, Claudio, Karina, Leonardo, it has been amazing to be part of the Monday meetings all these years! To my fellow collaborators around the world, Rich, Giovanni, Benoit, Ilse, Myriam, Stefano, Ted solving science challenges together has been a delight.

Even though we only shared physical office space for the last year, the Leiden team was fundamental throughout this period. Margot, you have been my guide in the world of physical-chemical models and my dutch best friend, I am very grateful for all your kindness. Sierra and Alice, as postdocs in the team you were great support and role models, I am excited to keep collaborating and crossing paths with you both in the US. Lucas, Ardjan, Milou, Marissa, Andrew, Nashanty, Martijn, Lisa, Melissa, Michiel, Nienke, Will, Logan, Katie and Lukasz, thank you for welcoming me first virtually and then in person to the land of marvellous cheese, stroopwafels and bitterballen.

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To the huge online community that follows @terepaneque, the boys and girls that read my books and the teachers that take me to their classrooms I deeply value your trust. Together we are building a brighter and better future through scientific education and critical thinking.

Finally, to the person that has held my hand every step of the way. Sacha, home is wherever you are. Your constant trust and love has pushed me through the bad times and celebrated in the good ones, I can't wait for the next chapter in our story to begin.