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Report on the ESO workshop

Towards New Frontiers: the Astrochemical Journey from Young Stellar Nurseries to Exoplanets

held at ESO Headquarters, Garching, Germany, 10–14 March 2025

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Understanding the chemical composition of young prestellar and protostellar systems is key to unveiling the origin of planetary systems. In recent years, high-sensitivity observations at different wavelengths have revealed unexpected molecular complexity in cold cores, discs, and forming planetary systems. This workshop brought together about 90 researchers working on interstellar chemistry, protostellar evolution, disc chemistry and exoplanetary atmospheres to discuss the chemical evolution from clouds to planets. Key goals included identifying robust molecular tracers, understanding chemical inheritance, and bridging observations with laboratory and theoretical work. Particular focus was given to the synergy between the planet formation communities and those studying planetary atmospheres, highlighting the need for a shared language and cross-disciplinary collaboration. The programme featured invited reviews, contributed talks and poster sessions, along with breakout discussions and open question sessions that encouraged interactive and inclusive exchanges. These discussions emphasised the importance of combining chemical models with advanced observations from current and future facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA), the ALMA Wideband Sensitivity Upgrade, the James Webb Space Telescope (JWST), the Square Kilometre Array Observatory, the Next Generation Very Large Array, and ESO's Extremely Large Telescope. The workshop successfully set the stage for future collaborations, paving the way toward a unified understanding of the chemical processes that shape planetary systems.

Motivations

Characterising the chemical composition of young prestellar and protostellar systems and understanding their evolution is crucial to unveiling the chemical heritage of forming planets. Over the past few years, significant progress has been made, thanks to large observational campaigns using millimetre (mm) and centimetre (cm) telescopes (for example, the IRAM 30-metre telescope, the Atacama Large Millimeter/submillimeter Array [ALMA], the Northerrn Extended Millimetre Array [NOEMA], the Green Bank Telescope, and the Very Large Array [VLA]) and the new mid-infrared capabilities of JWST.

A few pressing questions frame this research:
– How much of the molecular content in prestellar and protostellar systems is reprocessed or preserved in later stages?
– How does the chemical composition of exoplanets reflect the conditions of their formation environments?
– Which open questions can we address with upcoming facilities?

Figure 1. Conference picture of the participants in front of the ESO Supernova Planetarium & Visitor Centre, Garching.

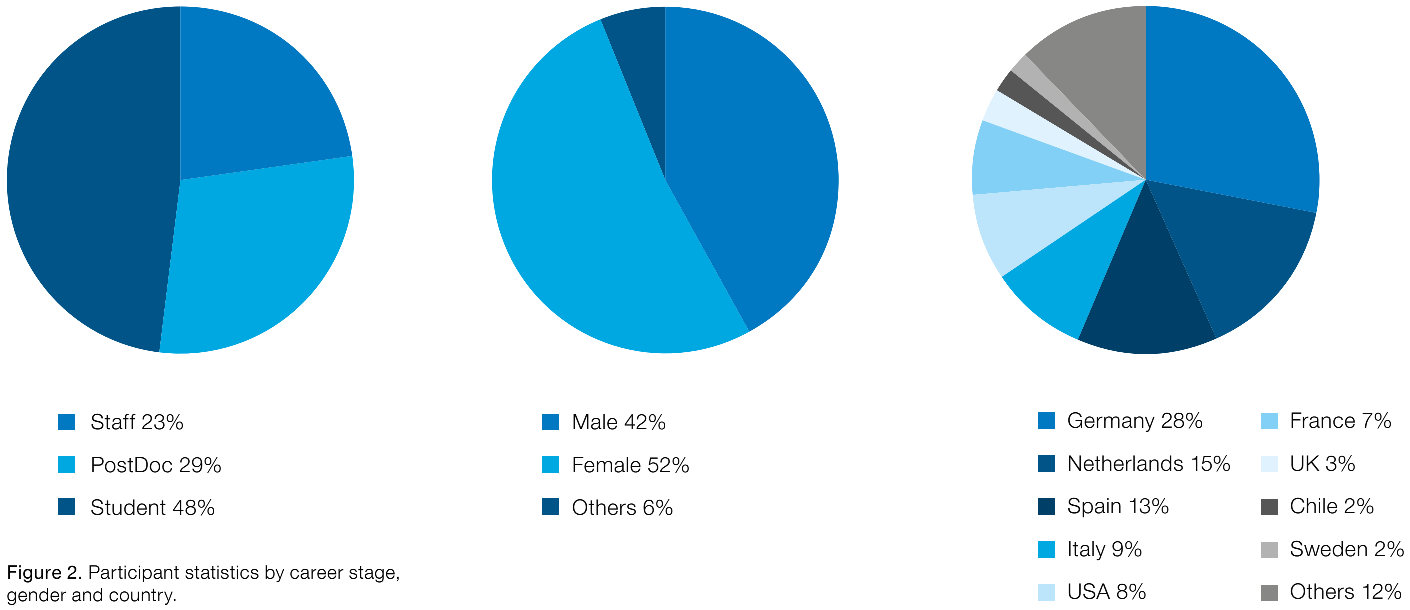

Figure 2. Participant statistics by career stage, gender and country.

This workshop brought together observers and modellers working across various stages of star and planet formation to investigate these questions and build connections between the star formation and exoplanet communities (Figure 1). A major aim was to delineate current observational limitations and offer valuable insights to the community on future ESO facilities and upgrades, such as the ALMA Wideband Sensitivity Upgrade (WSU) and ESO's Extremely Large Telescope (ELT), and future cm instruments such as the Next Generation VLA (ngVLA) and the Square Kilometre Array Observatory (SKAO). The workshop's multi-wavelength and multi-field nature offered a distinctive perspective within the field.

Summaries of talks and highlights from sessions

The workshop[1] covered the chemistry of i) prestellar cores, ii) protostars, iii) accretion and ejection mechanisms, and iv) discs, Solar System objects and exoplanets. Time was also dedicated to future facilities, laying the groundwork for a multi-wavelength and multi-community dialogue.

The workshop started with a review of starless/prestellar core chemistry. High-sensitivity observations at mm and cm wavelengths have revealed unexpected molecular complexity in cold clouds, driven by both gas-phase and grain-surface processes. Contributed talks showed new discoveries and how laboratory and computational studies traced the formation of interstellar ices. Key open questions remain: i) what causes variations in species abundances and detection? ii) how are they spatially and kinematically distributed? and iii) how to improve nitrogen-bearing species modelling?

The second session addressed protostellar ejection and accretion mechanisms. It was shown that: i) young discs show vertical and radial chemical distribution and accretion events warm them, shifting snowlines outwards; ii) accretion streamers may transport fresh material into discs, potentially triggering shocks; and iii) disc winds may influence dust growth and chemical mixing. These processes are crucial for shaping protostellar chemistry and serve as astrochemical laboratories for testing molecular formation routes. The connection between accretion streamers and outbursting events and the origin of streamers is still unclear. Multi-line, kinematic studies are essential to fully characterise these environments.

The third session focused on hot cores and hot corinos, the paradise for astrochemists, being chemically rich environments. Note that not all protostars show rich molecular inventories and different chemical content. Understanding what drives this diversity, whether physical, environmental, or evolutionary, is challenging. The role of the proto-solar nebula and the potential prebiotic role of detected molecules were discussed. Integrated astrochemical modelling, involving both chemists and observers, is vital for interpreting these data.

The rest of the workshop explored the chemistry of planet-forming discs and the link to Solar System bodies and exoplanets. ALMA and IRAM's NOEMA observations have enabled a detailed chemical characterisation of discs. Almost 30 molecules have been detected, representing about 10% of known interstellar molecules. Astrochemical models are crucial for connecting these observations to the disc physical and chemical history. For instance, the CS/SO ratio may serve as a probe of the elemental C/O ratio. However, many assumptions need to be made and chemical abundances of nascent planets are not well understood.

Solar System objects offer complementary insights into planetary system formation: planets and satellites represent the end-products of the formation process, while comets and meteorites preserve pristine material from the earliest stages. These bodies can be explored by *in-situ* space missions that, along with ground-based observations, provide unique chemical diagnostics. However, comparisons between cometary and disc chemistry are challenging, owing to limited statistics and observational biases. Deuteration ratios (for example, D/H) remain powerful tracers of chemical origins and inheritance, though interpretations remain complex, as illustrated by ongoing debates about the role of comets/meteorites in delivering water to Earth.

Finally, the meeting aimed to strengthen collaboration between the exoplanet atmosphere and planet formation communities. To date, over a dozen chemical species have been detected in about 30 exoplanets, revealing wide diversity. Thanks to new JWST data, all major elemental reservoirs and many carbon species are now observed, moving beyond water as the sole probe. Improved models are needed to obtain a holistic view, to connect the atmospheric composition with planetary interiors and dynamics. Elemental ratios (for example, C/O) offer valuable insight into the planet formation conditions, but disc models remain uncertain and degenerate, and atmospheric characterisation is still highly model-dependent. In summary, connecting these datasets requires close collaboration across subfields.

The observing telescopes

Throughout the evolutionary pathway from cloud to planets, several telescopes can be used extensively, from infrared to radio wavelengths, to infer the chemico-physical properties at each stage of evolution. We explored the role of several facilies in the field.

JWST has opened up a new avenue in the chemical characterisation of icy mantles in prestellar cores, protostars, discs and exoplanet atmospheres, providing a full ice inventory. Contributed talks also explored sulphur and nitrogen reservoirs, whose main ice carriers remain elusive and the role and impact of mixed ices and porous grains on the chemistry evolution.

In the mm regime, ALMA and NOEMA continue to revolutionise astrochemistry. One of ALMA's key goals in the 2030 roadmap is to unravel the origin of chemical complexity. The planned ALMA WSU will double to quadruple the bandwidth, improving spectral coverage and speed (making it 2.25–4.7 times faster). This will significantly enhance molecular line surveys, reducing the compromise between spectral resolution and bandwidth.

Although complex molecules are typically observed at mm wavelengths, the cm regime is gaining attention. Observations at radio wavelengths allow carbon chains to be detected and dust opacity to be overcome. Facilities such as the SKAO and ngVLA will offer unprecedented resolution and sensitivity, further advancing our understanding of astrochemistry.

Finally, the potential of ESO's ELT for exoplanetary atmosphere characterisation was presented. Instruments like the ArmazoNes high Dispersion Echelle Spectrograph (ANDES), the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI), and the Mid-infrared ELT Imager and Spectrograph (METIS) will enable detailed studies of nearby terrestrial planets using high-resolution spectroscopy. While JWST has begun this work, the ELT will dramatically expand our capabilities, potentially detecting biosignatures and tracing the planetary inheritance of chemical material.

Main conclusions and ways forward

The workshop highlighted both exciting progress and pressing open questions: How much molecular content is inherited from earlier stages? Which tracers best connect disc chemistry to exoplanet atmospheres? What processes shape, preserve, or erase chemical fingerprints over time?

Despite these challenges, the field is advancing rapidly. With the arrival of ALMA WSU, the SKAO, ngVLA, and the ELT, we are entering a transformative era. However, progress depends not only on instrumentation but also on cross-disciplinary collaboration. Chemists, modellers and observers must join forces, sharing tools and a common language, not only within their fields but also bridging disc formation and exoplanet atmosphere research. This synergy is key to building a comprehensive picture through advanced observations and up-to-date chemical networks and astrochemical models.

Breakout sessions and the collection of open questions fostered interactive, engaging, and respectful discussions that were widely appreciated by participants.

Demographics

The scientific organising committee (SOC) sought fair representation from the community. We invited 10 speakers: six reviews on science topics and four overviews of facilities. Selection was based purely on expertise, resulting in a 30:70 male-to-female speaker ratio. The final participant demographics showed approximately 50% female attendance, and a high proportion of early-career scientists, especially PhD students (see Figure 2).

We limited in-person participation to 80 to ensure engagement and discussion, but attendance reached nearly 90, with active involvement in sessions and discussions. We believe this reflects both the strong interest in the topic and the workshop's accessibility, aided by low registration fees.

Slides from most talks, the detailed programme, the list of posters, and the composition of the organising committees are available at the workshop website[2].

Acknowledgements

We warmly thank all participants, both in-person and remote, for their active engagement. We are grateful to the SOC and the local organising committee for their fundamental and invaluable contributions. We thank the ESO Supernova Planetarium & Visitor Centre for the possibility to visit the free exihibition during the workshop, encouraging team building and social activities. Special thanks go to ESO's Directorate for Science for financial and logistical support, without which this workshop would not have been possible.

Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2025/tnf/programme.html
[2] Workshop website: https://www.eso.org/sci/meetings/2025/tnf.html