Molecular complexity in protostellar and protoplanetary disks
around Sun-like stars
(PhD project, Università di Firenze)

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SYNOPSIS

A key open question in astrochemistry is how chemical complexity builds up along the formation process of Sun-like stars from prestellar cores to protoplanetary disks and ultimately to planets. Is the chemical composition of planets inherited from the prestellar and protostellar stages? Or does it reflect chemical processes occurring in the disk? Are organic molecules efficiently formed in disks and via what mechanism(s)?

The present PhD thesis project aims at investigating the physical structure and the chemical content of planet-forming disks by analysing molecular lines and continuum emission at 20-200 au scales. We will reduce and analyse (sub-)millimeter single-dish and interferometric data taken in the context of the NOEMA-SOLIS and ALMA-FAUST (co-PI: C. Codella) Large Programs and the ALMA-DOT chemical survey (PI: L. Podio), plus complementary new data taken with the NOEMA and ALMA interferometers. The disk chemical composition will be reconstructed along its evolution from the protostellar to the protoplanetary stage and will be compared with that observed in comets, which preserve a nearly pristine record of the Solar Nebula composition.

The thesis is part of the H2020 MSCA Innovative Training Network Project AstroChemical Origins (www.aco-itn.org), with PI C. Ceccarelli (IPAG, France) and with INAF-Osservatorio Astrofisico di Arcetri one of the ACO nodes (under the supervision of C. Codella). The ACO ultimate goal is to reconstruct the early history of the Solar System (SS) by comparing presently forming solar-type planetary systems with the small bodies of the SS. The comparison will be based on the most advanced astrochemical knowledge, which will be developed by the interdisciplinary ACO team.

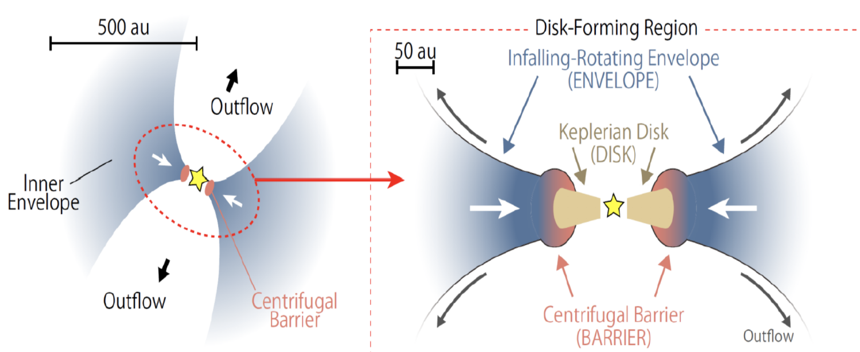
CONTEXT: FROM PROTOSTARS TO PLANETARY SYSTEMS

After just two decades from the first discovered exoplanet, the field of exoplanets has reached maturity. The two most striking results have been the almost ubiquitous presence of planetary systems around Main Sequence stars and the overwhelming diversity of system architectures. Both of these findings strongly motivate the quests of the origins of such diversity and the existence of the astrophysical conditions for habitability. Said that, what is the next step? The future is enlightened by a breakthrough discovery: planets start to form already during the protostellar phases (about 10^5 yr) and even more so in the protoplanetary (> $10^{5\text{-}6}$ yr) stages. This discovery has been possible thanks to the ALMA millimetre array which delivered to us the first resolved images of disks showing gaps and rings which are thought to be the signatures of the presence of forming planets embedded in the disk. It is then mandatory to investigate the physical and chemical properties of the first stages of a Sun-like star, and to compare them with what found in our Solar System to unveil the origin of planets.

This PhD project is focused on the initial phases of planet formation and the build-up of the chemical complexity of the young disks, where Solar Systems will form. Understanding the evolution of solids and gas in disks and the disk-star-planet interaction is the key to clarify the process of planet formation, the properties and architecture of planetary systems and finally to address the question of how common is the evolutionary path bringing to planetary systems supporting life.

TWO EVOLUTIONARY STAGES, TWO APPROACHES

Protostellar disks: ALMA FAUST. The research activity of the Arcetri group is focused on the study of Sun-like star forming regions through dedicated observational campaigns using both single-dish telescopes and interferometers in the millimetre range. These have provided a rich baggage of information on the chemical diversity of protostellar solar analogs down to Solar System scales (< 50 au). Figure 3 shows the structure of the Solar-like Class 0/I protostars: the envelope, the outflow, and the inner keplerian disk. These regions are probed by different molecules which can be observed at different frequencies (from sub-mm to cm). The current breakthrough question is to understand how much of the molecular complexity develops during the formation of stars and is available in the disks to be incorporated into the forming planets. Some recent key publications are De Simone et al. 2017, Podio et



al. 2015, 2019, Bianchi et al. 2017, 2019, Favre et al. 2018, Codella et al. 2017, 2019). Our proof-of-concept have already been conducted for a few sources and a few molecules: time is now ripe for a systematic study of much more sources and much more species, via an observational large program with ALMA. Indeed, our team obtained the first ALMA Large Program on astrochemistry: the FAUST project (Fifty AU Study of the Chemistry in the Disk/Envelope System of Sun-like Protostars; PIs: Ceccarelli, Chandler, Codella, Sakai, Yamamoto; 150 hrs, http://faust-alma.riken.jp). With the ALMA LP FAUST, we attack the issue of the chemical diversity of young Solar-like systems at planet-formation scales. The ALMA LP FAUST (co-led by INAF) is the first ALMA LP to reveal and quantify the variety of the chemical composition (including the so called interstellar Complex Organic Molecules -iCOMs, i.e. O-bearing species with at least 6 atoms), of the envelope/disk system of a large sample of Solar-like protostars (10^4-10^5 yr). Such chemical variety will add a new dimension to the diversity of planetary systems, and we expect that it will have a substantial impact on studies of planet (Solar System included) formation.

Protoplanetary disks: ALMA-DOT. The FAUST observations of protostars (10^4-10^5 yr) are complemented by high angular resolution (~10 au scales) observations of more evolved disks (10^6 yr) acquired as part of the ALMA chemical survey of Disk-Outflow sources in Taurus (ALMA-DOT) (ALMA Cycle 4 to 7, PI: L. Podio). These are disks showing dust substructures (rings, gaps, cavities, spirals) which may be produced by protoplanets embedded in the disk. The chemistry of protoplanetary disks is difficult to probe observationally due to the low gas-phase abundance of molecules, in particular of iCOMs which are mostly frozen on the ice mantles of dust grains in the disk midplane. It is only with the advent of millimetre interferometers such as ALMA that we started to unveil the molecular content of planet-forming disks at unprecedented angular resolution/sensitivity. In particular, we have detected a few simple organics such as formaldehyde (H_2CO), methanol (CH_3OH), and formic acid (HCOOH). Recent Arcetri-led projects on protoplanetary disk chemistry (Podio et al. 2019, Garufi et al. 2019) have shown that H_2CO show a peak of emission beyond the CO snowline, R_{CO} (i.e. where CO froze onto the dust grains, at $T_{dust} < 20$ K) and at the edge of the millimetre dust continuum. This suggests efficient formation of organic molecules in the outer disk by CO hydrogenation on the grain surfaces beyond R_{CO}. Moreover, in the disk of DG Tau the H_2CO-ring is located beyond a dust-ring, with a change of orientation of the continuum polarization, supporting a tight link between the disk chemistry and the dust properties (Podio et al. 2019). These pilot projects paves the way to a large campaign to characterise the molecular content of protoplanetary disks and to comprehend the organic composition inherited by the planets assembled in the disks.

PhD ACTIVITY AND TRAINING

In general, I will analyse millimetre observations from both ALMA FAUST and ALMA-DOT datasets. The results are expected to pave the way to follow ups which I will lead preparing ad-hoc observational proposals as PI. One of the first goal of the PhD project is to acquire experience in reducing and analysing single-dish and interferometric (sub-)millimeter wavelengths data. Following the ACO Grant Agreement, I plan to spend 6 months of my PhD activity (plausibly the second half of the second year of the PhD project) at the IRAM institute in Grenoble (France). The attention will be focused on protostellar and protoplanetary disks imaged on Solar System scale. In particular, it is mandatory to learn how to analyse high-spatial IRAM-NOEMA, VLA, and ALMA images using the GILDAS and CASA data reduction tools. Single-dish observations (IRAM-30m, GBT) will be also used. I will also learn how to interpret the collected forest of lines thanks to the available spectroscopic catalogues (JCMT, CDMS, NIST). The analysis of emission due to several molecules will be done also in light of quantum-chemistry calculations of the coefficient rates of the chemical reactions occurring in space, provided by the chemical nodes inside ACO. The study of the line profiles will be fundamental to disentangle the different kinematical components playing in the protostellar scenario (disk, jets, outflow cavities, extended envelopes, infalling material).