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Organic molecules in protostellar and protoplanetary disks observed with ALMA on Solar System scales

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Abstract – 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)? Here, we present in a nutshell the state-of-the-art of how observations performed using the ALMA interferometer can shed light on the chemical content of planet-forming disks by analysing molecular lines and continuum emission at 20-200 au scales. More specifically, we will review the recent results on two archetypal young disks around: (i) the HH212 protostellar disk (about 10^5 yr), and more evolved DG Tau protoplanetary disk (about 10^6 yr). We will show how the disk chemical composition will be investigated along its evolution from the protostellar to the protoplanetary stage and how it can be compared with that observed in comets, which preserve a record of the pristine Solar Nebula composition.

Keywords: Complex Organic Molecules; Star Formation

Riassunto – Una delle questioni chiave ancora aperte in astrochimica è come la complessità chimica aumenti lungo il processo di formazione di stelle simili al Sole, partendo da nubi prestellari, passando dai dischi protoplanetari per arrivare ai pianeti. Alla luce di questo si pone la domanda: la composizione chimica dei pianeti è ereditata dagli stadi prestellari e protostellari? O riflette invece i processi chimici che si verificano nel disco stesso? Ancora: le molecole organiche si formano in modo efficiente nei dischi e, nel caso, tramite quale meccanismo/i? In questo contributo presentiamo brevemente lo stato dell'arte di come le osservazioni di emissione di righe molecolari, eseguite utilizzando l'interferometro ALMA su scale spaziali di 20-200 au, possano far luce sulla composizione chimica dei dischi destinati a formare i pianeti. Nello specifico, esamineremo i recenti risultati riguardanti due giovani dischi archetipici: (i) il disco protostellare HH212 (con un età di circa 10^5 anni), e quello protoplanetario DG Tau (circa 10^6 anni). Mostreremo come la composizione chimica del disco può essere seguita lungo la sua evoluzione dallo stadio protostellare a quello protoplanetario e come può essere confrontata con quella delle comete, che conservano una memoria della composizione iniziale della Nebulosa Solare.

Parole chiave: Molecole Organiche Complesse; Formazione Stellare

1. The formation of a Sun-like star and its planetary system

Making a long and complex story short and simple, star formation is the process by which an interstellar dense molecular cloud forms in some Myr stars with planetary systems. Briefly, we can identify three main stages (see e.g., André *et al.* 2000, Caselli & Ceccarelli 2012, and references therein): (1) *prestellar cores*: such objects are clumps with a typical size of about 0.1–0.01 pc located inside the filaments of molecular clouds; they slowly accrete matter towards the center under the gravitational force counteracted by the magnetic field. Cores are dense ($n_{H2} > 10^4$ cm^{-3}) and cold (less than 10 K); (2) *protostars:* they are the central objects which are accreting material from the collapsing core through an equatorial infalling-rotating disk. Protostars (also called *Class 0-I* phases) are deeply embedded ($n_{H2} > 10^8$ cm^{-3}) and obscured by the large infalling envelope. The angular momentum is removed thanks to the ejection of high-velocity and highly collimated protostellar atomic and molecular jets. (3) *Class II-III young stars*: after about 10^6 yr, the natal molecular core is almost entirely dissipated and the star, which already accreted almost all the gas enters the Main Sequence stage, and it is surrounded by a protoplanetary disk, where the dust coagulation process becomes more and more efficient, ending eventually with a planetary system. In principle, the ingredients to make a planet like our own Earth are simple: a relatively small rocky body, at the right distance from the host star, with a not too thick atmosphere rich in volatiles and capable of developing the so-called interstellar complex organic molecules (iCOMs; O-bearing species with at least 6 atoms) chemistry. In practice, it is yet unclear how common a System like our own is. As a matter of fact, searches for exoplanets have shown (i) the almost ubiquitous presence of planetary systems around Main Sequence stars, and (ii) a large degree of diversity in the planetary systems architecture and chemical contents. Understanding the formation of planetary systems and the chemical processing of the volatiles that will form their atmospheres is thus key to understand the origins of the Solar System. The recent Nobel Prize assigned in 2019 to Michel Mayor and Didier Queloz on the discovery of an exoplanet orbiting a solar-type star is a milestone celebrating the work done so far in this field. Said that, during the last years, the ALMA (Atacama Large Millimeter Array: https://www.almaobservatory.org) (sub-)mm array observations of disks revolutionised our comprehension of planet formation with a breakthrough discovery: planets start to form already during

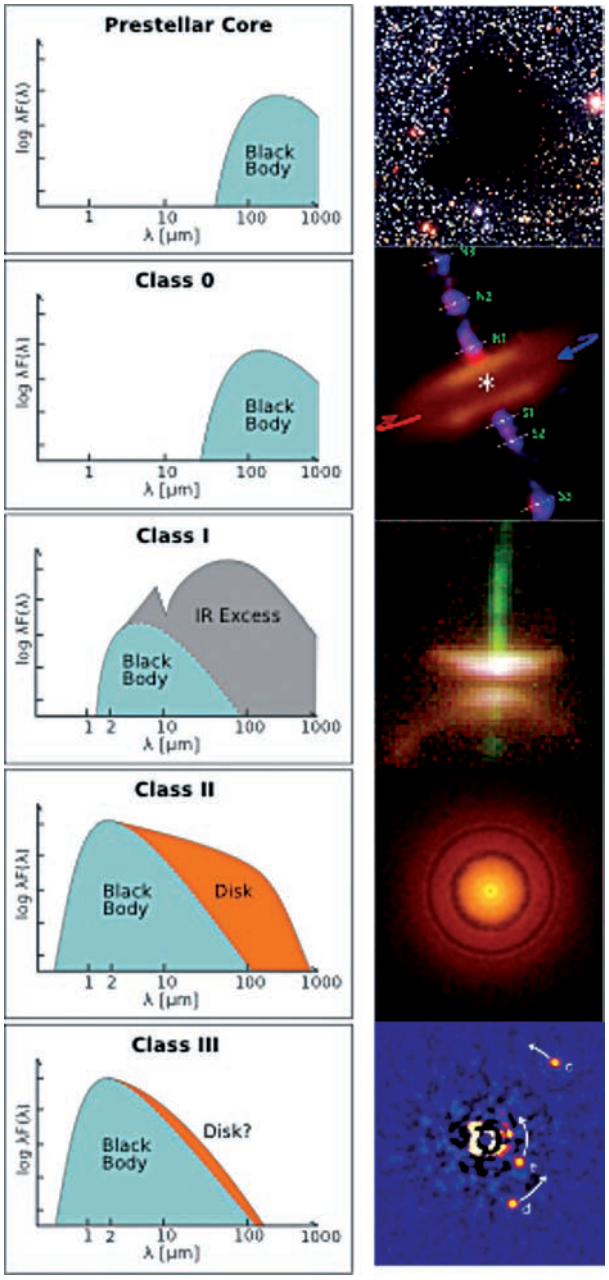

Fig. 1. Adapted from Bianchi *et al.* (2019b). Left panels: Spectral energy distributions (SEDs) of different evolutionary stages of the formation of a Sun-like star. Right panels: Real images of objects in the different evolutionary phases as observed using different telescopes at different wavelengths. The dark cloud B68 as observed by VLT/FORS1 (Credit:ESO). The Class 0 protostar HH212-mm in Orion as imaged by ALMA Lee *et al.* (2017b). HH30 is the Class I object, observed by the Hubble Space Telescope (Credit: Chris Burrows (STScI), the WFPC2 Science Team and NASA/ESA). The Class II object is an ALMA view of the protoplanetary disc surrounding the TW Hydrae star (Credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO). Finally, the Class III object is represented by the system HR 8799 associated with three orbiting planets (Keck II telescope); Credit: Marois *et al.* (2010).

the protostellar phases hence before to reach the protoplanetary stage. As a matter of fact, the unprecedented combination of high sensitivity and high-spatial resolution (down to fews au) provided by ALMA has allowed to image in details protoplanetary disks, which are far to be as simple as imagined before: gaps, rings, and spirals are common, which are thought to be the signature of the earliest phases of planet formation (e.g. Sheehan & Eisner 2017; Fedele *et al.* 2017). It is then mandatory to investigate the physical and chemical properties of young disks around Sun-like analogs, and to compare them with what found in our Solar System.

2. The protostellar stage: the HH212 laboratory

At the protostellar stage, observations of disks are hindered by the presence of many kinematical components which may hide their chemical content, e.g. the surrounding envelope and the outflow. To date only one protostellar disk, rotating around HH212-mm, has been chemically characterised on a Solar System scale. The HH 212 star forming region, in the L1630 cloud in Orion B, is a perfect school case study to illustrate the complexity of the environment around a young Class 0/I protostar. All the components mentioned in Sect. 1 have been imaged (e.g. Lee *et al.* 2014, 2017ab, 2019; Codella *et al.* 2014, 2018, 2019): a central object obscured by the envelope, a disk, and a jet driving an outflow. More specifically, Fig. 2-Left shows the $C^{34}S$(7-6) emission which traces the high-density cavity walls opened by the fast jet, traced by the CO(6-5) emission at 691.5 GHz. *Note that this is the first time that a bipolar jet is imaged in the CO(6-5) line on spatial scales smaller than 100 au towards a Class 0 protostar.*

Figure 2-Right shows a zoom-in of region around the star: $C^{17}O$(3-2) is tracing an envelope which is clearly elongated along the equatorial plane, which is normal to the jet direction. The envelope is clearly rotating suggesting the presence of a hidden rotating protostellar disk. On the other hand, imaging these regions with simple molecules, such as CO or CS (even their rarer isotopologues), is paradoxically hampered by their high abundances and, consequently, high line opacities which do not allow the observers to disentangle all the emitting

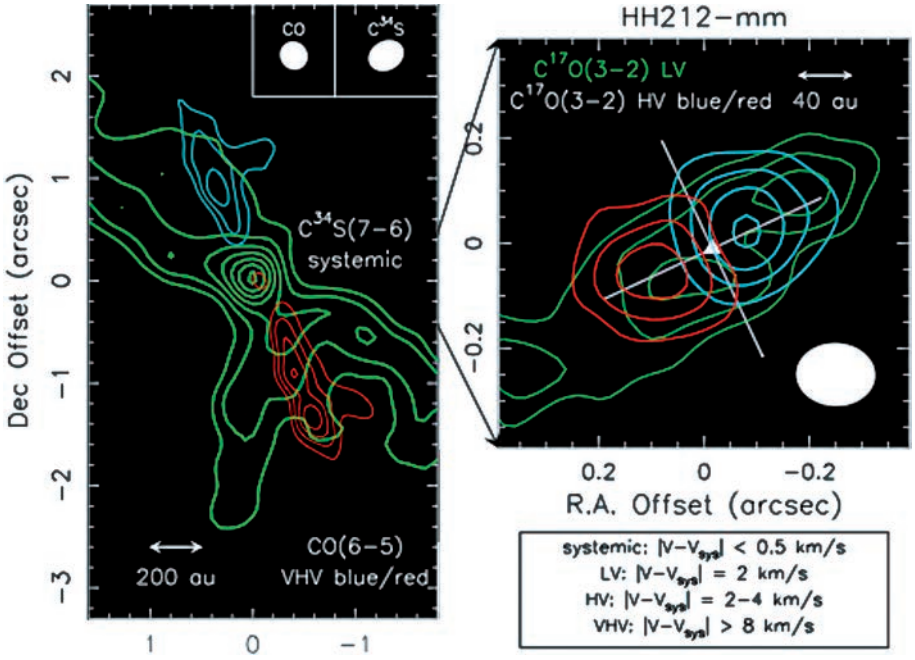

Fig. 2. Adapted from Codella *et al.* (2019). Left Panel: The HH 212 protostellar system as imaged by ALMA using different line tracers (CO, $C^{17}O$, $C^{34}S$) and different emission velocities (labelled depending on the shift with respect the systemic velocity Vsys = +1.7 km s^{-1}). The maps are centered at the position of the HH212-mm protostar: $\alpha_{J2000} = 05^h\,43^m\,51.404^s$, δ_{J2000} = -01° 02' 53.11". Blue/red contours plot the very high-velocity (VHV) blue/redshifted CO(6-5) jet. The $C^{34}S$(7-6) emission traces the asymmetric cavity at systemic velocity (green contours). The filled ellipses show the synthetized beams (HPBW). Right Panel: Zoom-in of the central region: $C^{17}O$(3-2) low-velocity (LV) emission (green contours), overlaid to the blue/red high-velocity (HV). The white cross (oriented to illustrate the direction of the CO(6-5) jet and consequently the equatorial plane) indicates the position of the protostar (white triangle).

components at these small scales. iCOMs observations are fundamental not only to investigate the link between the Solar System and its protostellar phases. In addition, they provide an instructive tool to disentangle the various components at down to scale of tens of au, allowing us to study the complex processes leading to a star surrounded by its planetary system.

In the panels of Figure 3 we show the dust continuum emission (orange; at 350 GHz) towards HH212 as observed using ALMA: the protostellar disk is clearly resolved. On top of continuum, white contours illustrate the spatial distribution of several iCOMs such as CH_3OH, CH_3CHO, t-HCOOH: these maps reveal (i) that the iCOMs emission is associated with the disk, and (ii) it is not confined towards the equatorial plane of the disk but, on the contrary, peaks above and below it (e.g. Lee et al. 2019; Codella *et al.* 2019). In principle, this

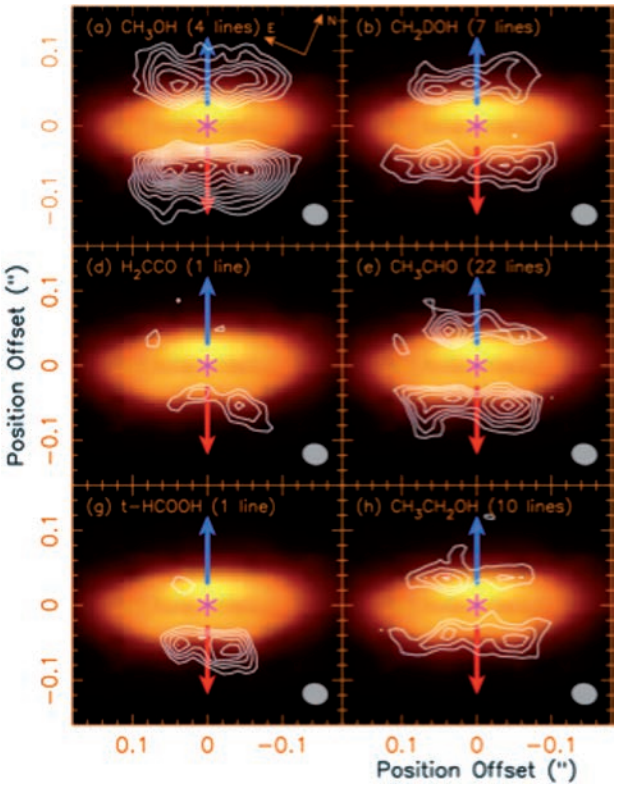

Fig. 3. Adapted from Lee *et al.* (2019). The HH 212 protostellar disk as imaged by ALMA using continuum emission at about 350 GHz (orange scale): an edge-on disk with a radius of about 40 au is observed. The equatorial midplane is dark, indicating continuum optically thick emission. The maps are centered at the position of the HH212-mm protostar: α_{J2000} = 05^h 43^m 51.404^s, δ_{J2000} = -01° 02' 53.11". The spatial resolution is about 10 au. Blue and red arrows indicate the direction of the bipolar jet as traced by CO(6-5), see Fig. 2. White contours trace, in each molecule, emission due to different iCOMs.

can have two explanations: the disk has a vertically extended gaseous atmosphere there is not molecular emission on the disk midplane; (2) the disk midplane disk is optically thick and obscures the methanol emission behind it so that only the disk atmosphere CH_3OH emission can escape. Further observations are needed to clarify this point. In any case, this pioneering work on HH212 shows enriched chemistry associated with the disk surface layers, with the detection of a number of complex organic molecules, e.g. CH_3OH (with an abundance with respect to H_2 of ~10^{-7}), HCOOH (~10^{-9}), CH_3CHO (~10^{-9}), $HCOOCH_3$ (~10^{-9}), NH_2CHO (~10^{-10}) (e.g. Codella *et al.* 2018, 2019, Lee *et al.* 2017ab, 2019). These abundances are larger than that observed at the protoplanetary stage (see Sect. 3). This chemical enrichment may be due to slow shocks occurring at the interface between the infalling envelope and the forming disk (e.g. Sakai *et al.* 2014). The scenario obtained for HH 212 needs to be confirmed by further observations on a statistical sample.

3. The protoplanetary stage

In the last years there have been a number of surveys dedicated to assess the molecular content of protoplanetary disks, targeting mostly simple bi- and tri-atomic molecules such as CO, CN, CS, H_2O, HCO^+, DCO^+, N_2H^+, HCN, DCN (e.g. Fedele *et al.* 2013, Guilloteau *et al.*, 2016, Öberg *et al.*, 2011, Podio *et al.* 2013). At difference the content of simple to complex organic molecules is still poorly known, because of their lower gas-phase abundances (< 10^{-8}). According to disk models this is due to the fact that iCOMs are frozen on the icy mantles of dust grains in the cold disk interior and only a tiny fraction of them is released in gas-phase through thermal or photo-/CR- desorption (e.g., Walsh *et al.* 2014; Loomis *et al.* 2015). Hence, (complex) organic molecules in protoplanetary disks remain hidden in their ices and can be unveiled only through interferometric observations at high sensitivity and resolution, e.g. with ALMA. Their detection is key for two main reasons: (1) to estimate the fraction of C, O, and N atoms which are trapped in organic molecules. While it is thought that most of these atoms are on ices (in the form of, e.g., H_2O, CO_2, CO), there is the possibility that organic molecules trap a significative amount of them, as also suggested by recent observations of comets in the Solar System (e.g. Fulle *et al.* 2019). This in turn may affect the location of the snowlines and the C/O ratio in the disk. (2) To understand if the chemical compo-

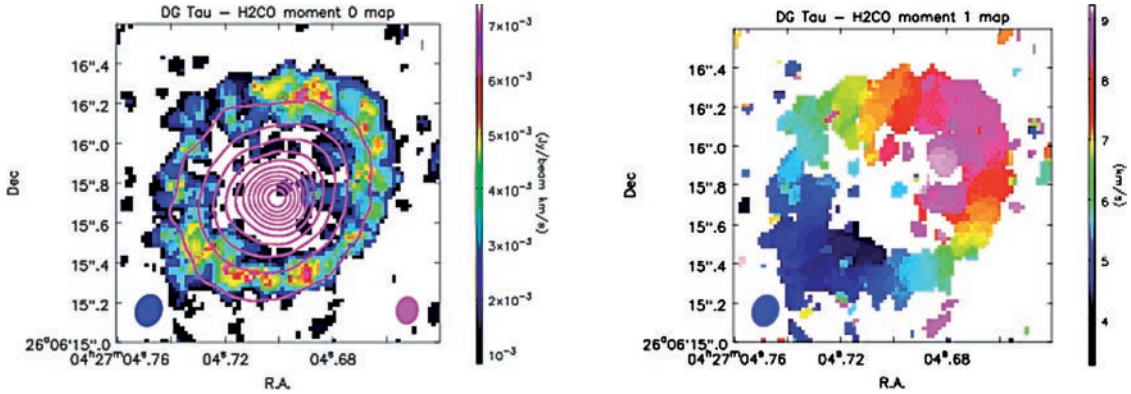

Fig. 4. Adapted from Podio *et al.* (2019): The protoplanetary disk around the Class II source DG Tau. Left panel: H_2CO line emission (in color scale) originates from a ring located at the edge of the 1.3 mm dusty disk (magenta contours). The blue and magenta ellipse in the bottom left and right corner indicate the synthesized beam for H_2CO and the dust continuum, respectively. Right panel: H_2CO velocity map showing the typical rotation pattern in a disk (Vsys = +6.3 km s^{-1}).

sition of planets is inherited from the prestellar and protostellar stages or if instead reflects chemical processes occurring in the disk. Thanks to ALMA a few simple organics have been imaged in disks. Among them, formaldehyde (H_2CO) and methanol (CH_3OH) are key to investigate organics formation. While H_2CO can form both in gas-phase and on grains, CH_3OH forms exclusively on grains.

An illustrative example are the first resolved ALMA images of H_2CO in a few nearby prototypical protoplanetary disks, i.e. DM Tau (Loomis *et al.* 2015), TW Hya (Qi *et al.* 2013, Öberg *et al.* 2017), HD 163296 (Carney *et al.* 2017, 2019), DG Tau (Podio *et al.* 2019), and DG Tau B (Garufi *et al.* 2020). This allows us for the first time to infer the H_2CO abundance and distribution in disks and to constrain the mechanism(s) that forms this simple organic, one of the bricks for the formation of complex organic and prebiotic molecules. The H_2CO radial intensity profiles in these disks show common characteristics: (i) the depression (or lack) of emission in the inner disk; (ii) an emission peak located outside the CO snowline; (iii) emission beyond the mm dust continuum (with a peak at the edge of the continuum in the case of DG Tau, TW Hya, and HD 163296) (see e.g., Fig. 4). The observed distribution of H_2CO suggests that most of it is formed in the disk midplane due to freeze-out of CO beyond the CO snowline, and its subsequent hydrogenation on the icy grains. This means that ice chemistry is efficient in the outer regions of disks and should also produce methanol as well as other complex organics, which are then partly released in gas-phase. Besides H_2CO, only a few of them has been so far detected, i.e. cyanoacetylene and methyl cyanide (HC_3N, CH_3CN, Öberg *et al.* 2015), methanol (CH_3OH, Walsh *et al.* 2016), and formic acid (HCOOH, Favre *et al.* 2018). Typical abundances are: ~10^{-12} - 10^{-10} (H_2CO), ~10^{-12} - 10^{-11} (CH_3OH, HCOOH, HC_3N), ~10^{-13} -10^{-12} (CH_3CN).

4. Future perspectives

To conclude, in order to understand if the chemical content of protoplanetary disks is inherited from the early star formation stages and is then passed to the forming planets, it is crucial:

1. to image iCOMs emission in a large sample of protostellar disks on a Solar System scale, to compare the emission with that observed in HH212. Answers are expected soon from the FAUST ALMA Large Program (Fifty AU STudy of the chemistry in the disk/envelope system of Solar-like protostars; http://faust-alma.riken.jp). It will be instructive also to increase the number of complex molecular species detected in protoplanetary disks obtaining spatially resolved images;

2. to compare the chemical composition of protostellar and protoplanetary disks with that of Solar System objects (the final stage of Sun-like stars formation process). Comets are ideal for this purpose, as they sample the pristine composition of the outer Solar System. A comparative study of the 67P comet with two Solar-like protostellar systems, IRAS16293-2422B and SVS13-A, shows similar abundances of NH_2CHO and $HCOOCH_3$, and in general of CHO-, N- and S-bearing species, suggesting inheritance from the pre-solar phase (Bianchi *et al.* 2019a, Drozdovskaya *et al.* 2019). These promising results need to be confirmed by further comparative studies.

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