Astro2020 Science White Paper

Astrochemical Origins of Planetary Systems

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

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Abstract
Our Solar System is one of many, and Earth may be one of many habitable, and even inhabited, planets. Limiting our understanding of the latter is our lack of knowledge on how frequently temperate, rocky exoplanets have access to water and organic molecules, the basic ingredients for the origins of life. More generally, it s not clear what compositional diversity we should expect in exoplanets, and how these compositions depend on the details of planet formation and early evolution. We propose that these related factors, planet compositions and the chemical habitability of temperate exoplanets, be addressed through a combination of new facilities aimed at mapping out the volatile content of planet forming disks – the precursors of exoplanetary systems. This needs to be supplemented by supporting astrochemical laboratory experiments and by fostering community support for interdisciplinary scientific efforts. A holistic view of disk chemical compositions will enable a comprehensive understanding of the origins of observed planetary compositions, a predictive theory of planet formation and initial chemical conditions, and the development of probabilistic models of planet atmospheres and hydrospheres.

1 The astrochemical origins of exoplanet compositions

Planets form in disks of gas and dust around young stars. The chemical compositions of these disks direct or influence all stages and aspects of planet formation.To interpret observations of exoplanet locations, sizes, and densities across the HR diagram we need a predictive theory of planet formation, including nascent planet compositions, that takes into account the origins of their mass and chemical reservoirs. This requires a deep understanding of how disk chemical structure relates to planet formation and what those disk chemical structures are around stars of different kinds, from the early stages of protostellar disk formation – observations of disk dust structure shows that planet formation may be well on its way in disks as they emerge from their natal envelope [1] – up to disk dispersal a few million years later.

First, the overall chemical structure, and especially the division of volatiles between solids and gas across the disk, may regulate what kind of planets form in different locations [2]. A decreasing disk temperature with radius results in a series of condensation fronts, or snowlines, most notably of water between $< 1 - 10$ au [e.g. 3]. Snowlines affect the efficiency of the early stages of planet formation because they can enhance or stunt grain growth [4, 5, 6], and may therefore produce 'preferred' planet formation locations [7].

Second, snowline locations and other chemical gradients across planet-forming disks determine the volatile elemental compositions (C, O, N, S, P etc), and initial chemical compositions of planets. Snowlines change the elemental ratios in gas and dust across the disk, which is the idea behind a major interpretive framework for exoplanet compositions. This is aimed at relating the C/O ratios retrieved from exoplanet atmospheres to the gas or dust C/O ratio at their disk formation location [e.g. 8, 9, 10]. Through their impact on solid compositions, snowlines also affect the composition of planetesimals, which may provide secondary atmospheres to terrestrial exoplanets during analogs to our late heavy bombardment [11, 12, 13].

Finally, the disk chemical composition determines the organic composition of forming planets and planetesimals and therefore whether temperate planets are likely to be chemically habitable and hospitable to abiogenesis. Small organic molecules have been observed at all disk radii [14, 15, 16, 17]. Temperate planet volatile inventories may sample large swaths of the disk because of 1) volatile transport between different disk regions, and 2) bombardment of icy planetesimals formed beyond the snowline. Developing probabilistic models of temperate planet hydrospheres and atmospheres therefore requires knowledge of the chemistry across the disk.

In summary, whether aiming for a framework to interpret observed planet and exoplanet characteristics, or a predictive theory of planet formation and planetary habitability, we need to understand the chemical structures of disks within which planets form. Some aspects of these structures are accessible with existing observatories; ALMA has transformed our view of chemistry on scales of 10 au and larger in the past few years. Our understanding of chemistry on small scales, of the distribution of water, and of the planet-forming midplane remains limited, however. This white paper aims to set out observational, laboratory and theoretical priorities for addressing big unknowns in disk chemistry, and thus remove the roadblocks that are preventing us from developing a holistic theory of planet formation.

2 Observatory priorities in the coming decade

Characterizing all molecules of interest to planet formation in all relevant disk regions requires a panchromatic approach ranging from IR to radio observations. Each wavelength addresses a unique aspect of the chemistry of planet formation. The high sensitivity IR observations needed to map out the chemistry in the innermost regions of disks and the ice reservoirs amenable to absorption studies will be addressed by JWST and the next generation ground-based optical/IR telescopes. Below we identify three additional key areas of inquiry, which all require observations at longer wavelengths, and the kind of facilities needed to address them.

2.1 Probing the water reservoir: Need for a cooled far-IR observatory

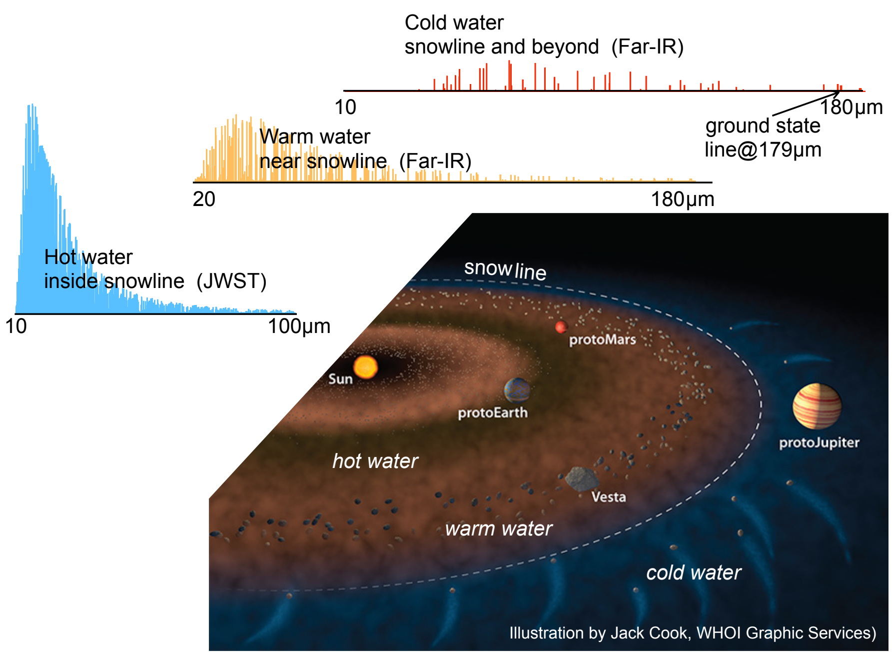

Figure 1: Illustration of the central importance of the water snowline in planet formation. Also shown is the spectral emissions of water *vapor* for hot (600 K), warm (150 K), and cold (50 K) gas. Spectral emissions are taken from Blevins et al. [18].

Water is essential for life as we know it, and its distribution in disks regulates the likelihood of a temperate planet forming wet and/or becoming water-rich through later bombardment of water-rich planetesimals. While some constraints on water in disks can be achieved at IR and millimeter wavelengths, *only the far-IR gives access to the water reservoir across and beyond the water snowline* (Fig. 1). Ground-based millimeter observations are hampered by the Earth's atmosphere and can only detect water vapor under extremely favorable conditions in favorable targets [19]. Near- and mid-IR wavelengths give access to ice absorption features, which will provide valuable information on ice compositions in a small number of disk with the 'right' viewing geometries, and to hot water vapor close to the star (the lowest energy state accessible via the JWST spectrometers is 800 K above the ground).

The water vapor present around and beyond the water snowline, tracing the water reservoir in the main planet and comet forming regions, is best observed at far-IR wavelengths. The far-IR also uniquely enables observations of water ice features in emission, removing the restrictions on disk

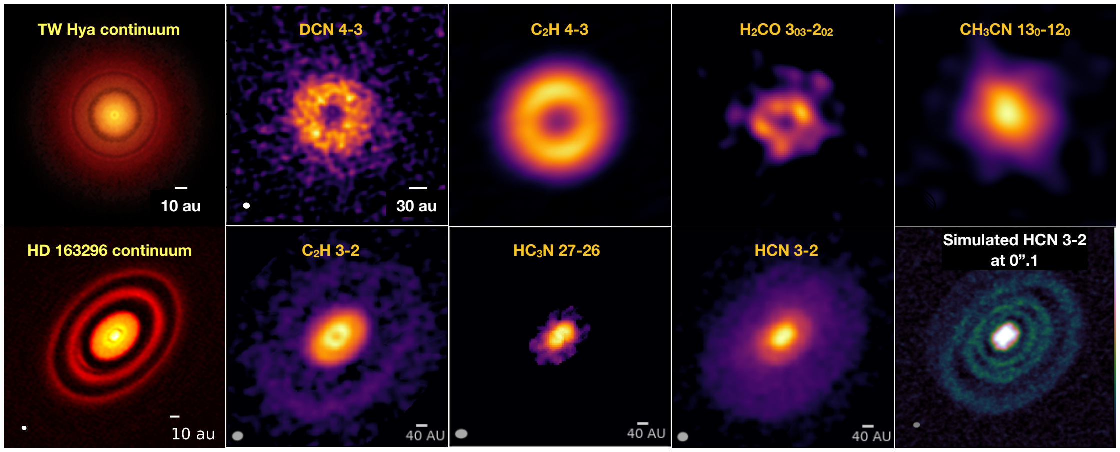

Figure 2: Examples of dust and chemical substructures in planet forming disks with ALMA [22, 23, 17, 24, 25, 26, Öberg et al. in prep., Bergner et al. subm.]. The bottom right panel is from a simulation, illustrating the kind of results we expect from an ongoing large program aimed at high-resolution chemical studies with a beam of ∼12-15 au.

geometry accompanying ice absorption studies [20, 21]. A cooled far-IR space observatory provides the only means to mapping out the water reservoir in a large sample of 'normal' disks and thus to develop a probabilistic framework for water incorporation into forming planets and water delivery to nascent planets.

Recommendation: Characterization of water vapor and ice across statistical samples of disks at different evolutionary stages and across the HR diagram requires a cooled (4 K), large aperture (> 5m) far-infrared ($\sim$ 20 μm – 179 μm) observatory with a sensitivity below 10^{-20} W/m^2 at 179 μm and high-resolution spectroscopy capabilities (R $> 3 \times 10^4$ at 179 μm). The latter is required to use line kinematic profiles to map out the water vapor across the disk, and to achieve sufficient line-to-continuum contrast; gas-rich disks have high thermal dust continuum emission near 179 μm, and high spectral resolution is required to increase the contrast between weak line emission superposed on the strong continuum and therefore enable detection of water emission in sources with lower water content. In summary we recommend an observatory with the capabilities of the proposed Origins Space Telescope.

2.2 Elemental ratios and organic reservoirs in the proto-Habitable Zone: Need for a more sensitive ALMA

During the past decade ALMA has revolutionized our view of dust and chemical structures and sub-structures in planet forming disks (Fig. 2). CO snowlines have been localized using both chemical tracers and direct observations of rare CO isotopologues [27, 28, 29]. C/N/O ratios in intermediate disk layers have been constrained through simultaneous observations of molecular O, C, and N-carriers [23, 30]. Deuterium and nitrogen fractionation, a key tool to determine the origins of volatiles including Earth's water and atmosphere, has been found to be active on all disk scales between 10s and 100s of AU [31, 32]. Finally, disks have been found to be rich in nitriles [33, 26, 24], a key ingredient of the most promising origins of life scenario here on Earth [34], and active promoters of O-rich ice chemistry [35, 17], the starting point of complex molecule formation in circumstellar environments[36, 37]. All observations so far have, however, probed scales of 10s of au at best. Upcoming programs are taking these studies into the main comets and Gas and Ice Giant planet forming regions at scales of $\sim$7 au, as well as exploring the relationship between dust and chemistry sub-structure. These observations will push ALMA to its utmost (e.g. in an ongoing large program 130h is used to observe 5 disks).

Observations of C/N/O ratios, S and P molecular carriers of interest to prebiotic chemistry, and organic compositions on smaller scales, e.g. around the water snowline and in the terrestrial planet forming region, are not possible with ALMA in its current state. Nor are observations with $<$10 au resolution in large samples of disks, or detections of large complex organic molecules. Such observations require a more sensitive millimeter and submillimeter interferometer coupled with a more efficient set of backends than is currently available at ALMA.

Recommendation: We recommend adding more sensitivity to ALMA as well as to upgrade the receivers and correlators to enable more line detections per observation. To resolve gas-phase emission lines within a few AU requires a (sub)millimeter interferometer that is at least 5$\times$ more sensitive than ALMA. This effectively means adding more antennas, since most of its receivers already operate close to the theoretical sensitivity limit.

2.3 Chemistry in the deepest disk layers: Need for a sensitive radio array

The recent realization that disks are ripe with dust sub-structure [1, 22, 25] presents a problem for disk chemistry studies, since this implies that there are disk regions that are optically thick even at millimeter wavelengths [38, 39]. Longer wavelengths are needed to probe line emission from disk midplanes inside of dust sub-structures. Radio lines of CH_3OH, CH_3CN, carbon chains and the major N-carrier NH_3 are promising targets for such studies. Compared to millimeter wavelengths, radio molecular lines are intrinsically weak, however, and at least an order of magnitude increase in sensitivity is required compared to existing radio facilities, including the JVLA.

Recommendation: Constraining the chemical compositions in the deepest and most obscure disk layers require sensitive radio observations. We therefore recommend an expansion of the JVLA to increase its sensitivity by more than an order of magnitude. The current plans for the ngVLA would accomplish these goals and also readily provide the resolution of a fraction of an arc second required to map out the otherwise obscured organic content across nearby protoplanetary disks.

3 Laboratory and theory priorities

Even the best observatories can only provide a partial snapshot of the chemistry in planet forming disks. A complete view of the chemistry of planet formation requires model development to interpret observed chemical patterns, and to predict the evolution of this chemistry as planets are assembling. Models in their turn need to be anchored by laboratory experiments.

3.1 Funding for laboratory astrochemistry

Many key disk chemical structures are regulated by chemical reactions that are difficult or impossible to calculate from first principles and therefore require experiments to characterize. Examples of data that can only be obtained through experiments are sublimation kinetics of disk volatiles[40, 41], grain coagulation and shattering properties [42], ice chemistry reaction rates governing the growth of chemical complexity during planet formation [43, 44, 37], and many gas-phase reactions [45].

Recommendation: Laboratory astrochemistry experiments often fit an awkward funding category that is difficult to support within the existing NSF astronomy grant system; they are generally too expensive for the typical PI grant, but too small for larger instrumentation grants. Developing a grant program for small-sized, 1-2 M$ instrumentation and laboratory equipment is key for the health of the laboratory astrochemistry field.

3.2 Working Across Disciplines

The major challenge for modeling the chemistry active during planet formation is that in many disk regimes it is strongly coupled to the dynamical evolution of disks, including accretion flows, grain growth and drift, vertical and radial mixing of material through diffusive flows and turbulence. All of these processes work in concert to the incorporation of the ingredients of habitable worlds into planetesimals. This chemical-dynamical coupling affects our interpretation of water vapor/ice observations, snowline locations, and the main carriers of life's elements (C, H, O, N, S, P). Further chemical-dynamical couplings are likely at the heart of some of the key mysteries of planetary science/cosmochemistry such as the puzzling oxygen isotopic anomalies seen in primitive meteorites [46], and the meaning of the D/H fingerprint and its relation to the origin of Earth's water [12, 47, 48, 49]. Theoretical work on these processes is inherently interdisciplinary cutting across the boundaries of cosmochemistry, planetary science, earth science, astrochemistry, exoplanet science, and research into life's origins.

A fully integrated chemical-dynamical model has so far been computationally prohibitive. To date these issues have only been addressed via simple chemical approximations (such as ice condensation/sublimation) with grain growth [50] or detailed gas turbulence with chemistry and no dust evolution [51, 52]. Developing such a model should be a key priority of the field. Taking these models into the realm of planet formation further requires the ability to connect to models of the physical/chemical evolution within planetesimals, bombardment of young differentiating Earth's, atmospheric loss, and giant planets perhaps influencing redistribution of material from beyond the ice-line. The complexity of these efforts represents a challenge, but if we wish to understand the birth of a habitable planet it must be done. A current obstacle to achieving this goal is that, beyond the large scale efforts of the Astrobiology Institute, funding for cross-disciplinary work is scarce with limited options within traditional funding avenues from the NSF or NASA.

Recommendation: There is an urgent need for more funding and recognition of the value of cross-disciplinary work. We recommend that NASA and NSF create more individual programs at the grant program level that enable such efforts.

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