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Search for water and life's building blocks in the universe: A summary

Edwin A. Bergin

Department of Astronomy, University of Michigan, 1085 S. University Ave., Ann Arbor MI, 48109, USA
email: `ebergin@umich.edu`

Abstract. Water and organics need to be supplied to terrestrial worlds like our own to provide the essential compounds required for the origin of life. These molecules form initially during the earliest stages of stellar birth, are supplied by collapse to the planet-forming disk predominantly as ice, and may undergo significant processing during this collapse and within large planetesimals that are heated via radioactive decay. Water and organic carriers can be quite volatile, thus their survival as ices within rocks is not preordained. In this focus meeting our goal is to bring together astronomers, cosmochemists, planetary scientists, chemical physicists, and spectroscopists who each explore individual aspects of this problem. In this summary we discuss some of the main themes that appeared in the meeting. Ultimately, cross-field collaboration is needed to provide greater understanding of the likelihood that terrestrial worlds form with these key compounds readily available on their surfaces – and are hence habitable if present at the right distance from the star.

Keywords. Water, Organics, Solar System, Exoplanets, Earth

1. Introduction

The goal of this focus meeting was to bring together experts in the study of organics and water in space. In a sense the motivation for this seems obvious - as the origin of life on our planet required water and the presence of organics. However, the disparate aspects of the problem make the this sort of "big picture" aspect somewhat difficult to approach. What we mean here is that the study of the birth of our planet has an astronomical focus from the starting materials (both solids and gas) towards exoplanetary systems. Similarly the origin of the Earth has a distinct focus in the respective fields of geophysics/geochemistry, cosmochemistry, and planetary science. Within each of these areas there are also interesting cross-currents, as the study of the birth of our solar system requires knowledge of the dynamical interactions of the forming solid bodies with the gas and on the timescales/locations of gas giant formation. Even more broadly, the field of astrochemistry is grounded by information from chemistry regarding gaseous and solid state interactions at low temperatures and also requires fundamental knowledge, such as, e.g., the frequencies and spectroscopic constants of emission lines of complex molecular species. Thus, putting together all the pieces of understanding the origin and evolution of water and organics starting in interstellar space, and as seen in our solar system, necessitates the synthesis of a significant amount of research that also has its own unique and intrinsic merit.

In this summary we will not duplicate the excellent individual (and collective) scholarship that went into the contributions provided for this focus meeting. Rather, we will summarize some key theme's of the meeting that highlight important areas of current

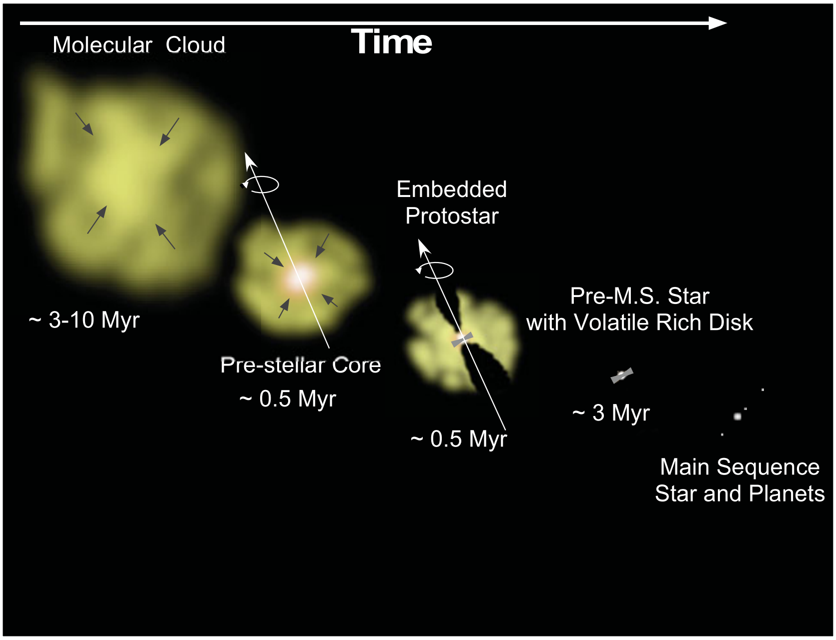

Figure 1. Schematic of the various phases of star and disk formation, and their estimated time-scales. Taken from (Bergin 2014, Bergin (2014)).

scientific interest. Before we do we will provide a broad overview of the physical perspective that sets the stage for understanding how aspects of the chemistry might evolve.

2. Physical Perspective

In Fig. 1 we provide a schematic of the various phases and timescales in star and planet formation, which are briefly described below. Stars are born within concentrations of molecular gas within individual giant molecular clouds. Molecular clouds are quire large with sizes of many parsecs (1 pc = 3 $\times 10^{18}$ cm) with densities on the order of 500-3000$\times$ the average density of the ISM ($< n >_{\rm ISM} \sim 1$ cm^{-3}). The initial stages of collapse, the pre-stellar phase, encompasses the gradual central concentration of molecular gas with central densities of $\sim 10^5$ to 10^6 cm^{-3} within "cores" that have typical sizes of $\sim$ 0.1 pc. This initial evolution takes place at quite cold temperatures of $\sim 10 - 20$ K for both the gas and dust. When the core reaches a point where gravity can overcome opposing forces, it will collapse to form a star and surrounding disk system.

The star grows in mass via accretion from the disk, while the gas-rich protoplanetary disk continues to accrete matter from the natal envelope. The energy from this accretion represents the bulk of the observed astronomical emission during this stage. The process of accretion may not be steady in the sense that it is believed that there are bursts of accretion onto the star. This will periodically and rapidly heat the forming disk. In all, this phase has significant energy release and the young disk likely undergoes significant physical evolution, with strong temperature variations vertically and radially with time. The scale of the temperature range is $\sim$ 20 K (more distant bulk gas and dust) to $>$ 1500 K in some regions of the disk.

Eventually stellar winds and outflows disperse the surrounding envelope and gas-rich disk becomes exposed to the interstellar radiation field. Theory and observations show that the disk is flared, intercepting more energy than the case for a flat configuration. This again leads to sharp vertical and radial thermal gradients. There is also significant surface exposure to high energy (ultraviolet and X-ray) radiation originating from the star due to continuing accretion and an active chromosphere. During this phase, and perhaps even early, solids coagulate, settle to the dust-rich midplane, and, via a series of dynamical effects (streaming instabilities, vortices, dust traps), grow to planetesimal (∼km) sizes in the midplane. According to cosmochemical studies much of the solid content of the inner (and perhaps outer) nebula was exposed to high temperatures. Collisional evolution of bodies then leads to the growth of planetary embryos (Mar-sizes bodies). During the gas rich phase, many Earth size cores form beyond the water snow-line and grow to sizes large enough to gravitationally capture gas from the nebula forming gas giant planets. Due to heating from ^{26}Al, the interiors of planetesimals can be exposed to a variety of geophysical mechanisms that depend on the size (thermal metamorphism, aqueous alteration, differentiation). After the dissipation of the gaseous disk, dynamical interactions between the resulting bodies redistribute material leading to the formation of terrestrial worlds. The effects of impacts on the forming terrestrial bodies can be profound in terms of both the supply of volatile material, such as water and carbon/nitrogen bearing compounds, but also can lead to potential atmospheric loss.

The above is a just a short – incomplete – snapshot of the overall evolution. However, it captures some of the details in the gas/solid physics that influence the chemistry of organics and water. A series of references for the above material, with greater detail and content can be found in (Audard *et al.* 2014; Chiang and Youdin 2010; Morbidelli *et al.* 2012; Elkins-Tanton 2012; Caselli and Ceccarelli 2012; Testi *et al.* 2014; Johansen *et al.* 2014; Bergin *et al.* 2015, Audard *et al.* (2014), Chiang & Youdin(2010), Morbidelli *et al.* (2012), Elkins-Tanton (2012), Caselli & Ceccarelli (2012), Testi *et al.* (2014), Johansen *et al.* (2014), Bergin *et al.* (2015)).

3. Themes of the Meeting

- One aspect that is important is the recognition of the presence of significant processing of materials throughout all stages. Astronomical observations suggest that the initial composition of ices is set via kinetic chemical interactions within and between the gas and solid state pools. However, the strong thermal gradients that are put in place after stellar birth can lead to ice sublimation and potential reprocessing in the gas phase. Within meteorites the internal heat due to ^{26}Al decay can liquify the water. This can actively alter the in situ chemistry via aqueous alteration, thereby adding more chemical complexity. Thermal metamorphism can also play a role. Thus much of the evolution described in § 2 can be a strong contributor towards activating a variety of paths toward chemical complexity - and perhaps the components needed for reproductive chemistry. Various aspects this evolution are highlighted in the contributions of Aikawa, Öberg, Fraser, Caselli, Meech, d'Hendecourt, Martins, Dartois, Coustenis, Pasek, and Messenger.

- A second intriguing aspect is that water-poor worlds also bear information on the history of our solar system (contributions by Elkins-Tanton, Pendelton). Thus the water embedded within Lunar rocks contains information on the history of our own planet. While the presence of cosmochemical volatiles (atoms such as K) within Mercury suggests that impacts do not completely de-volatilize a planet (see contribution by Quintana for greater discussion of impacts).

- Heritage or reset: how much of the solar system record is inherited before the birth of the Sun. The contribution by Aikawa highlights that the D/H ratio in water ice presents the strongest evidence for some sort of inheritance. In this regard the other isotopic systems (O, N) need to be considered, as discussed in this volume by Meech.

- There are strong links between laboratory studies of water and astronomical observations as outlined in the contributions by Caselli, Aikawa, Öberg, Najita, Neufeld, van der Tak, and Pontoppidan. It is clear that water predominantly forms via a series of reactions on the surfaces of interstellar dust grains. Many of these reactions have been characterized in the lab within the context of O and H reactions. However, the larger chemical system is more complex, for example C and N atomic and molecular carriers are also present. More characterization is needed to place the formation of species such as water in a context where channels involving other species (e.g. C or N) are included. In this regard, we have traced water emission from the beginnings of stellar birth to the central regions of protoplanetary disks as shown in Fig. 1. In the latter stage we are now finding evidence for the long sought after water snow-line (the ice/vapor sublimation front). These snow-lines may be important as factories of dust evolution. The water snow-line is constrained via combinations of unresolved Spitzer and Herschel data, while the CO snow-line is resolved by ALMA ((Qi *et al.* 2013, Qi *et al.* 2013)). This is an exciting time as protoplanetary disks are the key phase to connect extra-solar forming planetary systems to the broad knowledge base that exists regarding our own solar system.

- The study of organics in space is an area of intense focus. Key aspects to highlight are the need for high resolution spectroscopy to resolve often complex spectrum and a close link to critical laboratory measurements of basic quantities such as frequencies and line strengths. Contributions explored the detections of organics with potential astrobiological import (Ohashi, Jorgensen, Garcia-Lario, Liu, d'Hendecourt, Mendoza). Here one aspect seems clear. Most models still suggest that the majority of organic molecules from via complex reaction pathways on grain surfaces. The laboratory and theoretical chemical physical underpinning for many of these processes is gradually increasing and we can hope for improved understanding in the coming years.

- More broadly organics are seen in a variety of solar system materials as outlined in the contributions by Martins, Dartois, Bradley, Bockelee-Morvan, Coustenis, Lopes, and Messenger. One statement was made by Martins: "all key components of terrestrial biochemistry are present in extra-terrestrial materials". This clearly drives home the import of understanding the origins of these organic compounds. Here we must note the difference between the organics seen in interstellar space, which are much simpler, as opposed to the vast array of complexity seen in, e.g., meteoritic materials. One issue is that astronomical observations are subject to bias as our instruments have fundamental sensitivity limits. As molecules get larger the number of potential modes for excitation increases (i.e. a larger partition function), which makes the individual emission lines weaker and harder to detect. Thus, at present we do not know whether all the species detected in meteorites are present in interstellar space; this requires more sensitive instruments (see contribution by Goldsmith). However, when implanted in rocks it is also clear that organics can be exposed to a variety of processes (aqueous alteration, thermal metamorphism) that can either lead to greater complexity or degradation of the compounds. In this light, one path to search for broad links between ISM, protoplanetary disk chemistry, and solar system organic material would be the isotopic enrichment and total carbon content (relative to silicon as one example).

- To put all these pieces together and form planets like the Earth, the forming body must be provided with both water and organic material. Another piece of the connective tissue explored by the meeting was the formation of terrestrial worlds, the delivery of volatiles to the Earth, and expectations for other planetary systems. This was outlined by the contributions by Mulders, Zsom, Walsh, Matsumura, and Quintana. Here key questions like the formation location and movement of giant planets have strong influence on the dynamical excitation of the overall system. In this regard, we also must pay attention to the timing of volatile delivery. Volatiles delivered late, after core formation, will remain on the surface and, hence, be available for the genesis of life. Linking our understanding to the growing field of exoplanets will also require greater understanding but some limits can be explored today (see contribution by Zeng).

4. Overview

In general from my perspective the true import of this meeting was to bring all the practitioners together who are looking at different pieces of this puzzle. Going into the future we must continue to extend our hand to incorporate the knowledge gained from our growing understanding of exoplanets. The origin of our solar system, planet, and life from the gaseous and solid state progenitors in space remains a difficult problem. Each investigation has its own intrinsic merit, but there is strong and continued need for cross-field collaboration/communication to try to solve pieces of the big picture.

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