Searching For the t=0 of Planetary System Formation

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Abstract. The composition of bodies in the solar system points to strong gradients in the volatile content within solid bodies hinting at the presence of gas-ice transitions across sublimation fronts in the young formative stages when the gas-rich disk was present. Terrestrial worlds are constructed out of the disk solids which are primarily silicate and water, but might also contain a significant fraction of organic material. These refractory organics are the source of carbon to Earth-like worlds, but have the potential to be destroyed if temperatures exceed 300-500 K (depending on pressure). These temperatures are most readily prevalent during the early stages of planetary system formation where the seeds of terrestrial worlds are potentially assembled. Here we present an ongoing observational search for refractory carbon grain destruction. We also discuss the implications on the overall gas phase chemistry within sublimation zones and on the ultimate composition of planetary bodies forming from available materials.

1 Hot Gas and Terrestrial Planet Formation

One of the most important tasks for astronomy during the coming decade(s) will be to characterize potentially habitable planets. A central facet of habitability is whether the elements needed to foster life: C, H, O, N, S, P, are present or absent. For the Earth it is believed that water and carbon (with other elements) were provided by impacts of asteroid-like materials (i.e. C I chondrites and other meteorite classes), perhaps with some cometary contribution [1]. However, when viewed from the interstellar context there is a more fundamental problem with the disposition of carbon in terrestrial worlds and even primitive (unaltered) meteorites in that, for example, the Earth is four orders of magnitude depleted in carbon when compared to the carbon content of interstellar grains. Fig. 1 demonstrates this graphically, comparing the C/Si ratios within in the solar system to the Sun and the interstellar medium (ISM).

In the ISM about 50% of the carbon is present in refractory form [3]. These ISM carbon grains are seen in the refractory organic material within both comet Halley and 67P. Heading towards the inner solar system, carbonaceous chondrites are a class of primitive meteorites. The C I chondrites are the most pristine material delivered from the asteroid belt as they are largely thermally unaltered and generally reflect solar abundances [4]. One glaring exception to this is that the C/Si ratio in C I chondrites is lower than that carried by ISM grains by a factor of 10! Even in this context, relative to chondrites, we stress that the Earth is even more significantly depleted in carbon.

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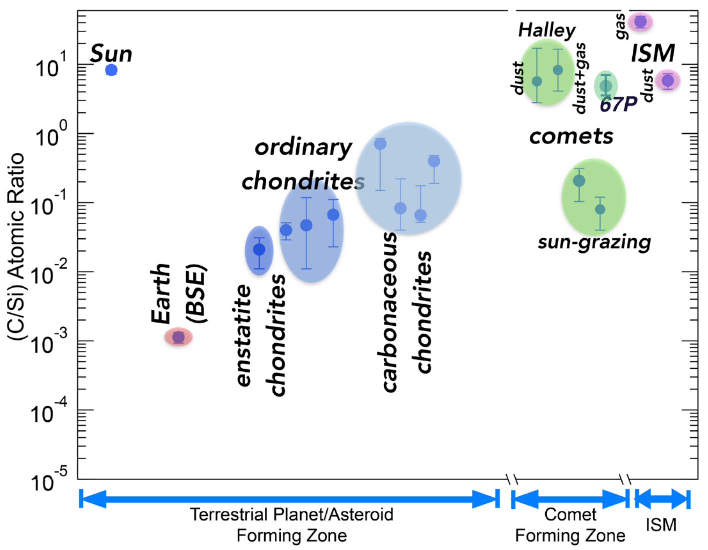

Figure 1. Atomic ratios of bulk carbon relative to silicon in various solar system bodies and the ISM. The shaded ovals represent the range/errors in the measured data for each class. For chondrites the errors represent the range of determined values, while for other bodies the errors are 1σ measurement uncertainties. Adapted from [2].

A central facet in the *cosmochemical and geophysical* understanding of the composition of solids in the inner solar system is the process of equilibrium condensation [5]. In this model, the primary theory for the origin of Earth's composition, all elements are initially assumed to be in chemical equilibrium within hot (>2000 K) gas. As the gas cools various minerals form in a sequence dictated by their condensation temperature and precipitate [6]. At minimum, two pieces of evidence support this picture. First, according to chemical equilibrium, the first solids to condense will be minerals containing calcium and aluminum [7] and calcium-aluminum rich inclusions (CAI) in meteorites represent the oldest solids in these bodies, thereby setting t=0 for the evolution of the Solar System [8]. Second, when normalized to Magnesium (Mg) and solar composition there is a trend in relative abundances for lithophile elements (rock loving elements found in the mantle and not in the metal dominated core) with their half-mass condensation temperature, the temperature at which 50% of the mass in an element is condensed from the gas into solids. This is shown graphically via the blue-shaded band in Fig. 2.

However, refractory organics are not a product of equilibrium condensation [4, 9]. The only solution to this conundrum is that the carbon carried by ISM grains in the inner few au is returned to the gas. When the star is born these materials are released into the gas within a volatility trend linked to the sublimation temperature of the primary elemental carbon carriers from volatile ices to more refractory carriers. This sequence is provided as the grey thick line in Fig. 2. In order to account for the bulk Earth's carbon upper limit [9], ISM refractory carbon must be destroyed [e.g. 10] prior to the formation of the Earth's initial materials.

The unifying theme for both condensation and sublimation is that the largest effects *must* be found in phases where temperatures are elevated above ~300–500 K in the inner disk, with even higher temperatures required for heavier elements. This project seeks to merge astro-

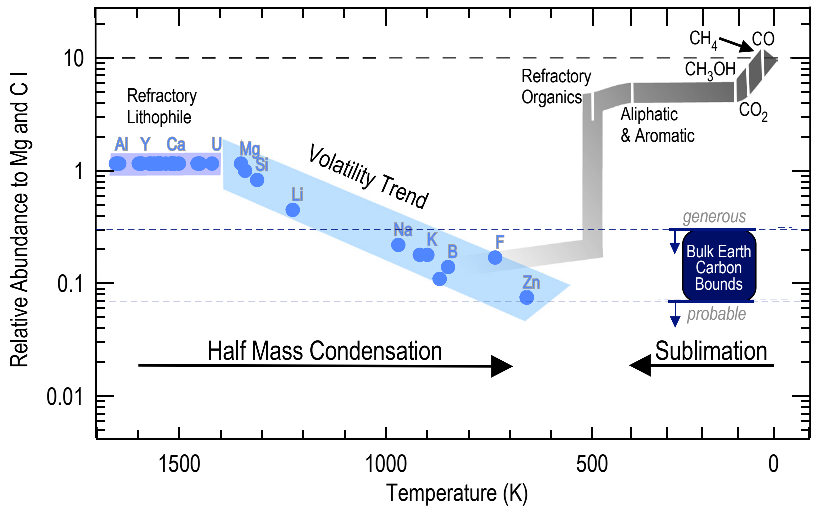

Figure 2. *Elemental relative abundances on Earth compared to measurements in CI chondrites (representing solar abundances) in both cases measured relative to Mg. The* **volatility trend associated with condensation (blue-shaded band)** *describes the relative abundances of lithophile ("rock loving") elements in the "bulk silicate Earth" (its mantle and crust) as a function of their half-mass condensation temperatures. On the low-temperature side,* **the sublimation sequence of carbon (gray thick line)** *traces the falling relative abundance of condensed carbon in the solar nebula as the disk warms up with refractory and icy carbon carriers released into the gas. Adapted from [9].*

physics and geophysics to find this gas and set new and unique constraints on the formation of solids in the inner parts of the Solar System and *exo-planetary systems*.

2 The t=0 Project

Sublimation readily operates in the midplane and can destroy carbonaceous mm/cm-sized pebbles that constitute the first steps toward planetesimals at temperatures between 300-500 K (pressure dependent) [9, 11]. This location is called the soot-line [12] analogous to the water ice-line which lies at greater distances from the star. Class II disks are generally dominated by stellar irradiation and the soot-line resides interior to the meteorite formation zone near a few au [13–15]. A soot line that lies inside of the meteorite formation zone would produce bodies with substantial amounts of carbon, comparable to that of 67P or Halley (C/Si ∼ 5). This is well above the carbon content of even the most primitive meteorites (∼0.2; Fig. 1). Thus, the pre-cursors to meteoritic material (and the Earth) must have formed primarily during earlier protostellar stage [9]. In this case, the soot-line lies at greater distances due to the higher amount of energy released from the active accretion. This gas might be more detectable and is the focus of our work.

We have begun a systematic search for carbon grain destruction in the hopes of constraining its presence or absence. Our first goal is to locate high temperature (>300 K) gas in close proximity to protostars (presumably in a young disk) via spatially unresolved NOEMA observations. Once this gas is isolated we aim to search for whether it is chemically distinct in comparison to gas above the water sublimation temperature (>100 K). For example, van 't Hoff[11] proposed N released from C-rich grains could be a signature as it would produce abundant nitriles in hot gas, but see also [16]. A final, longer-term, step would be to resolve the emission.

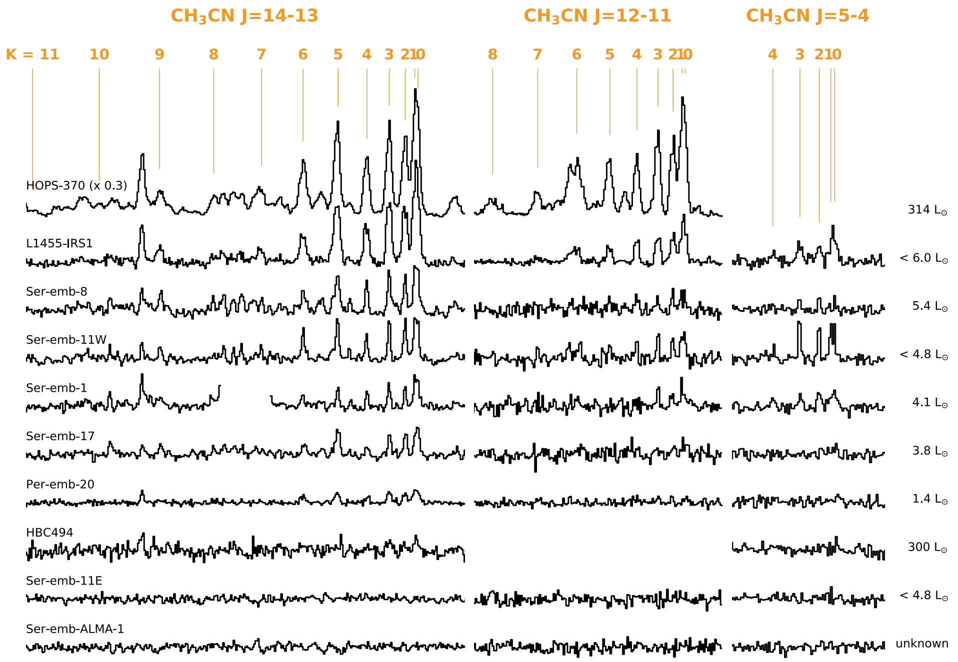

Figure 3. *Results from the NOEMA pilot suvey of CH_3CN towards young protostars. All spectra are shown at a uniform velocity resolution of 2 km/s. For a given J transition the K components have the same flux scaling, but the flux scale is different between J transitions. The 5-4 and 12-11 data are obtained with ~1.0″ resolution, while the 14-13 transitions are observed with ~0.4″ resolution. Data will be published by van 't Hoff et al. (in prep.).*

2.1 NOEMA Pilot Survey

Over the past 3 years, our team has been compiling an extensive dataset of high resolution (~0.4″ at 1mm, ~1.0″ at 2mm, ~1.0″ at 3mm) NOEMA observations of 10 protostars. Eight of these have luminosities commensurate with low mass (solar mass or below) star formation, one is a FU Ori type object (HBC494) and one is likely an intermediate-mass star (HOPS-370). These sources have been pre-selected to be rich in organic emission based on detection of CH_3OH [17, 18], or their outbursting nature. Our 1mm data are taken at 0.4″ (~hundred au at source distances) and do not spatially resolve the soot line. So we will use the central pixel to isolate the central regions and then detect the hot gas via emission lines that arise from high energy states ($E_u > 300$ K). This does not guarantee the presence of hot gas, as these lines would still be emissive at 100–200 K; but, multiple lines can be used to derive the gas temperature as described below. Because of concerns about high dust optical depth in the innermost regions of protostellar envelopes or in the young disk we also obtained observations at 3mm with NOEMA (image cubes) and single point observations at 4mm with the GBT.

To find, and characterize hot gas we use CH_3CN, a symmetric top [19] that is a well known probe of temperature in hot gas and has been used to explore temperature more recently in disk sources [20]. In Fig. 3 we show an example of why CH_3CN is a fantastic thermal probe. Symmetric tops allow for observation of multiple emission lines arising from different energy states (labelled with J_K) over a small window. Further, lines with different K for a given J state are only connected via collisions and have relative populations that trace the gas kinetic temperature [see, e.g., 21]. Multiple lines of CH_3CN are detected in nearly every system. Amazingly, for many systems, we detect emission from the 14_9–13_9 transition with an upper state energy level of 670 K. This line requires hot gas (> 200 K) for excitation.

In sum, hot gas appears to be present in these systems. We are in the process of compiling and understanding the rotation diagrams for each source and all transitions. It is complicated by the fact that the emission appears optically thick for lower-J lines. Intriguingly, the column density required for lower-J lines (at 3mm) is higher than inferred for the transitions detected at 1mm. This may hint that dust optical depth is obscuring a complete sampling of the CH_3CN column at shorter wavelengths [22], but thermal gradients might contribute as well. This work will be published by van't Hoff et al. (in prep.).

3 Implications

Models of planet formation suggest two modes of planetary construction: one dominated by accretion of planetesimals (∼10–100 km-sized bodies) and another proceeding through accretion of mm to cm-sized pebbles [23, 24]. Depending on many factors, in particular the presence or absence of a cold gas giant in the system (i.e., Jupiter-analog) and on the inwards drift of volatile-rich pebbles[24] a range of outcomes, including terrestrial worlds with more bulk carbon content, is possible. Whether these worlds are habitable will be an interesting question for future exploration; but the presence/absence of refractory carbon material is central.

In our initial analyses for several systems, temperatures appear to be well above that expected for carbon grain sublimation. Formally speaking, if all carbon grains sublimate in the inner disk, it is just a factor of two extra carbon. This factor of two is, of course, bulk and the speciation of carbon can lead to order of magnitude enhancements in specific molecules [16]; understanding this issue is a key goal of this effort. We stress that a null result (i.e., no evidence for carbon grain destruction) in a sense has the most far-reaching implications as it implies that carbon-rich pebbles are available for planet formation.

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