Sublimating Ices Feeding Forming Planets

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Overview

With over 5000 exoplanets detected[¶] around nearby stars it is necessary to take a step back and study their birth environments - protoplanetary disks. The wide array of planet sizes, planet compositions and orbital architectures are the outcome of the planet formation process which, is set by the physical and chemical conditions in the disk. An important tool to trace the formation location of a planet is its elemental composition. The relative abundances of the primary volatiles, carbon and oxygen, in the gas and ice in disks vary as a function of radius [1]. Therefore, a planet's composition should reflect its formation location in the disk relative to the key snowlines.

Tracing disk composition with ALMA

Disks are made up of dust, gas and ice and with the Atacama Large Millimeter Array (ALMA) we can probe the distribution of the millimeter-sized dust and molecular gas on 10-100 au scales, e.g., [2, 3]. Observations of the dust show clearly that disks most often have rings of dust and less frequently asymmetries (see Figure 1 for examples of the continuum emission from the HD 100546 and IRS 48 disks [4, 5]). ALMA observations of gas in disks probe the composition of the warm molecular layer and the primary gas tracer in disks is carbon monoxide (CO). Initial observations revealed a depletion of CO in disks relative to the value in the interstellar medium. In addition to this, the complementary gas tracers, e.g., C_2H, CS and SO show that in most disks the gas at $>$10 au is depleted in both carbon and oxygen with an overall elevated C/O$>$1, e.g., [7]. The depletion of volatiles can be partly explained by the chemical conversion of CO to CO_2 and more complex ices [8], but another mechanism is required to fully match the observations.

Volatile redistribution in disks

The impact of the dust evolution on disk chemistry is becoming increasingly more pertinent to understand. As disks evolve the smaller micron-sized dust grains will grow to at least millimetre sizes. During this process, the grains will decouple from the gas, settle in the midplane and drift inwards. This process also removes simple molecules from the gas as they will freeze out onto the surfaces of these dust grains. The inward transport of these ices leaves the outer disk volatile poor but will enrich the inner planet-forming zone ($<$ 10 au) [9]. But, if this inward drift is stopped then these volatiles will remain trapped in ices in the outer disk. The dust traps (like those seen in Figure 1) are indeed common and are likely caused by the presence of giant planets or low mass companions located on orbits within the disk cavities. These dust traps are also ice traps sequestering volatiles in the outer disk and preventing them from reaching the inner (terrestrial) planet-forming zone of the disk < 10 au.

[¶]https://exoplanetarchive.ipac.caltech.edu/

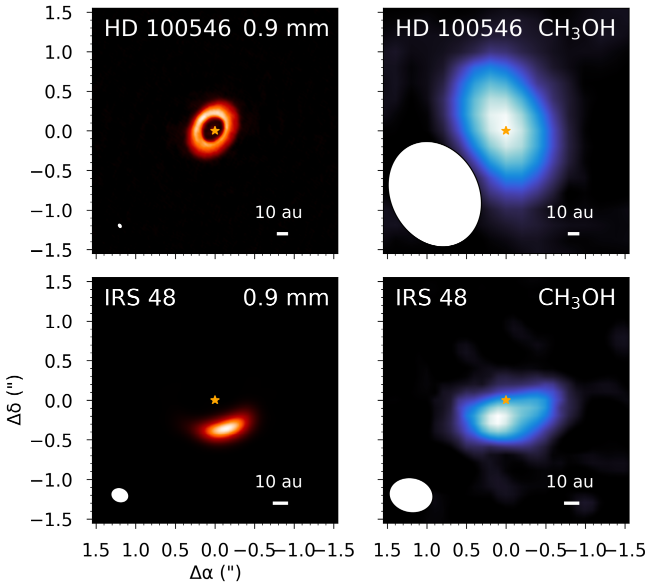

Figure 1: Intensity maps of the 0.9 mm continuum and CH_3OH emission which indicates dust temperatures $>$100 K at the cavity edge in the HD 100546 and IRS 48 disks [4, 5, 6, 12]. Angular resolution of the observations are shown via ellipses in the bottom left corner of each panel.

Sublimating ice traps

The clearest evidence for these ice traps was seen via the detections of methanol (CH_3OH) in the warm Herbig transition disks HD 100546 and IRS 48 [6, 10]. Here, although the dust is trapped at 10's of au, the dust at the cavity edge is heated by irradiation from the star allowing for the thermal sublimation of CH_3OH and likely H_2O (100-150 K). An array of simple oxygen-bearing molecules have also been detected in these disks including SO, SO_2 and/or NO [11, 12, 13]. These species all have a common gas-phase formation path via the OH radical, a product of the photodissociation of H_2O. In this region of the disk, we expect the full volatile content to be in the gas phase and is thus observable to us with ALMA. This results in a C/O $\leq$0.5: the opposite of most other disks. The observations of IRS 48 are the most striking since this disk has an asymmetric dust-trap where all of the larger grains and ice reservoir are located on one side of the disk (see Figure 1).

An inherited organic reservoir

Disks inherit their dust, gas and ice from the earlier stages of star formation. But, it is not clear how pristine this material is, i.e. do all the ices sublimated during the formation of the disks or if some of the interstellar ices are preserved. The detection of CH_3OH in the warm Herbig disk HD 100546 was the first clear evidence that some ices in disks are preserved from earlier times. CH_3OH can only form efficiently on the surfaces of cold (20 K) dust grains and not via gas-phase processes [14]. But, the dust in these disks is too warm to make CH_3OH locally. Further work has detected the more complex molecules dimetheyl ether (CH_3OCH_3) and tentatively methyl formate (CH_3OCHO) in Class II disks for the first time [13]. These detections are in the IRs 48 system where again, the ices are sublimating at the dust cavity edge. The ratio of CH_3OCH_3 to CH_3OCHO is consistent with what has been measured in other environments [16]. This again strongly supports the ice inheritance of ices from the cold dark cloud stage.

Impact on forming planets

The composition of a planet is set by the local disk material it accretes. In disks like HD 100546 and IRS 48 where the dust trap is located close enough to the star to allow for thermal ice sublimating, the gas in the cavity will have a low C/O ratio $\approx$0.5 (or even lower if O abundances are enhanced due to pebble drift). This means that the gas making its way into the inner ($\lesssim$1 au) planet-forming zone of the disk will be oxygen-rich and the small grains bare. The dust traps are located at $\approx$20-50 au from the central stars, so the ice sublimation is at a much further radius than the expected H_2O snowline in a full disk. This shows clearly that the dust evolution has profoundly affected the thermal structure of the disk and thus the chemistry. But, this all depends on where the dust trap is located and the temperature of the host star. Since, other transition disks, e.g., PDS 70, do not show these chemical signatures of ice sublimation [15]. Therefore, in the PDS 70 disk, the planets in the cavity are likely accreting gas with a C/O$>$1. The detections of complex organic molecules (COMs) in HD 100546 and IRS 48 have shown that disks can inherit ices from the earlier stages in star formation. This result sets the precedent that all disks, and as a consequence all exoplanet systems, should all have the ingredients necessary for prebiotic chemistry.

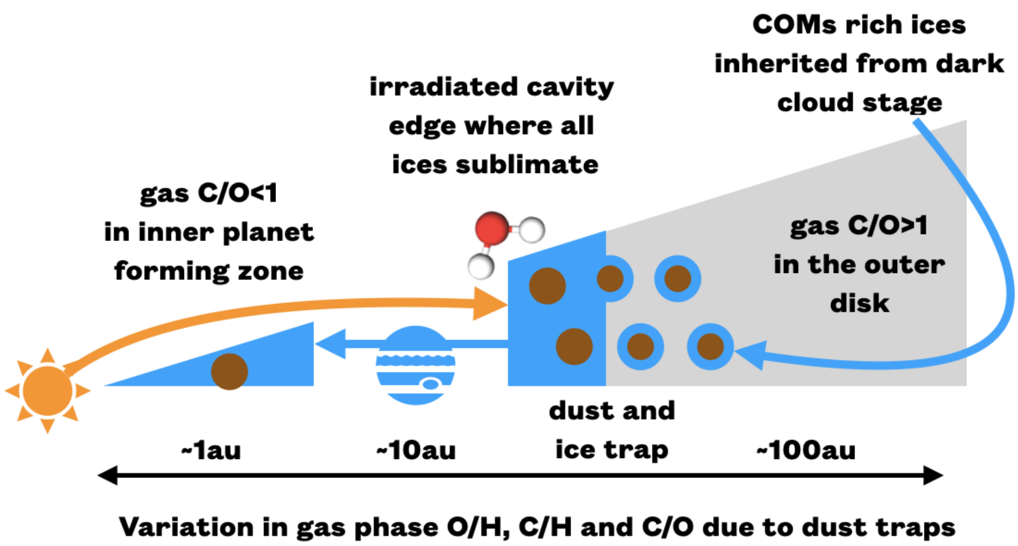

Figure 2: Cartoon showing the impact of a sublimating ice trap on the gas-phase C/O in a disk.

References

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Short CV

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