Gas Trapping by Amorphous Ice in the Solar Nebula

Fred J. Ciesla and Sebastiaan Krijt

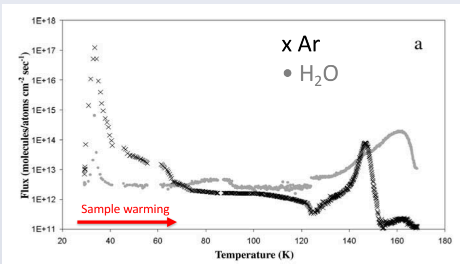
Department of the Geophysical Sciences
The University of Chicago
fciesla@uchicago.edu

Introduction

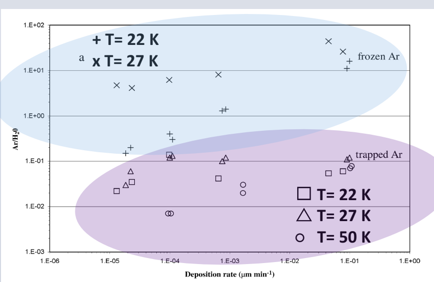
The manner by which noble gases were incorporated into primitive solids prior to the formation of the planets remains unclear, though identifying this process will help us understand the origin of comets, Jupiter's bulk atmosphere, and, perhaps, the mysterious Q phase found in chondritic meteorites. Experiments have shown that amorphous water ice formed at low temperatures is able to trap noble gases within its structure [e.g. 1-4]. As a result of this trapping, the noble gases are thus locked up within the water ice, being released only when the water ice itself is vaporized at higher temperatures. To date, trapping experiments were performed at conditions which differ significantly from those expected in the solar nebula or molecular clouds. Thus, it remains unclear what the trapping efficiency would be in actual astrophysical environments. Here we describe a numerical model we have developed and applied to reproduce the experimental trapping results. We then apply this model to determine the efficiency with which noble gases could be trapped in protoplanetary disk environments.

Review of Experiments

- A mix of water-vapor and a guest species (here we'll focus on Ar) flowed over a cold plate, depositing ice layers measuring ~0.1 μm thick on timescales of minutes to days (deposition rates of ice of ~10^{-5}-10^{-1} μm/min) [e.g. 1-3].
- The experimental chamber was then pumped to low pressure, and the deposited ice heated at rates of ~1 K/min.
- During heating, gas was continuously pumped away and its composition measured; the composition reflected what was sublimated from the ice at that time.



The above figure shows the flux of species from the ice in one of the experiments carried out by [2]. In this case a 1:1 H_2O:Ar gas was deposited on the cold plate at 27 K. During warm up, a large amount of Ar was released at T< 45 K, which was interpreted to be Ar that was directly frozen onto the water ice. A second peak in the Ar flux is seen at T>135 K. This is interpreted as "trapped Ar" as it only is released once the water molecules begin to sublimate at the same temperature.

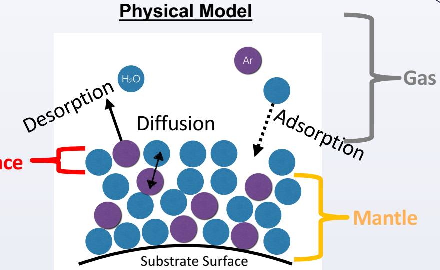


Here, the results of the various runs done by [2] at different temperatures and various deposition rates. General observations include:

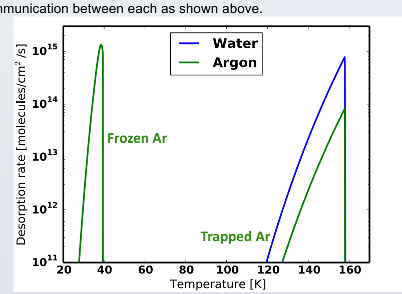
- There is no frozen Ar at T=50 K
- At 50 K, the amount of trapped Ar decreases with decreasing deposition rate
- Lower temperatures allow for more efficient trapping than higher temperatures

Experimental deposition rates correspond to water fluxes onto the cold plate of ~10^{11}-10^{15} molecules/cm^2/s. These fluxes are up to 15 orders of magnitude higher than expected in solar nebula or molecular cloud environments.

Physical Model



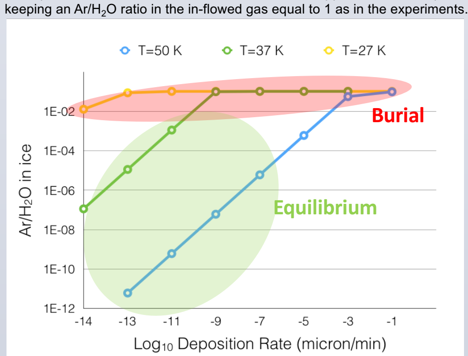
We developed a kinetic model for ice deposition and trapping following a 3-phase model [5,6] which treats each species as being in the gas, ice surface, or ice mantle, with communication between each as shown above.



Example of model run reproducing the T=27 K and 0.1 μm/min deposition experiment of [2] for a Ar:H_2O gas of 1:1 (experimental result shown to left). Frozen Ar is desorbed as the sample warms until T~40 K; this comes from Ar on the surface ice and untrapped Ar that diffused to the surface from the mantle. Ar is not released again until H_2O begins to desorb at T>120 K as water begins to be desorb, indicating it was trapped. Parameters were found that reproduce the trapped Ar/H_2O reported in [2] for all experiments.

Extrapolations Down to Lower Deposition Rates

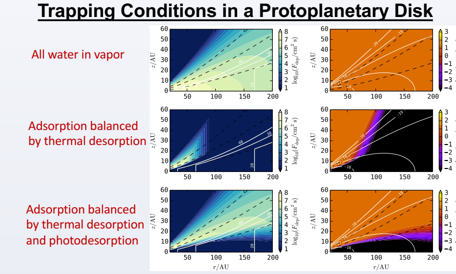
The best fit parameters determined from our model were applied to lower deposition rates, keeping an Ar/H_2O ratio in the in-flowed gas equal to 1 as in the experiments.



Two regimes of trapping are found:

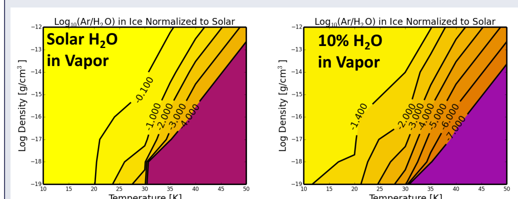
- ***Equilibrium trapping*** occurs when the rate of adsorption and desorption of the Ar achieves kinetic equilibrium on timescales that are short compared to the timescale for the surface layer to be buried under another layer of ice.
- ***Burial trapping*** occurs at high deposition rates when an ice layer forms before equilibrium is achieved. Any Ar present on the surface is thus buried. This is line with the predictions of [4] who found Ar would be trapped in amorphous ice even at T~77 K, though at very low abundances.

Trapping Conditions in a Protoplanetary Disk



Water deposition rates in astrophysical environments will vary with P, T of the system, as well as the amount of H_2O in the gas phase. Above we show deposition fluxes for different environments in a disk modeled after TW Hya where cold water vapor that may yield amorphous ice upon freeze-out has been detected [7]. We also show density and temperature contours for this disk. We take $H_2O/H_2=2\times10^{-4}$ and $Ar/H_2=2.5\times10^{-6}$ [8]. Fluxes are much less than in the trapping experiments, and Ar/H_2O ratios are highly variable, with Ar being more abundant than H_2O in the gas in most locations where amorphous ice would form.

Model Extrapolation to Disk Conditions



The above figures show the amount of Ar trapped in H_2O ice (relative to solar) as a function of ambient conditions. In the left panel it is assumed all water is present in the gas at the beginning of the calculation, while the right panel assumes only 10% of the water is present as a vapor. Trapping efficiency decreases with increasing T and decreasing gas density as expected and is not simply a function of T as often assumed [e.g. 3]. Trapping is also less efficient when water vapor concentrations are low as a barrier locking away Ar is unable to develop at the ice surface. A similar feature was found in CO and CO_2 trapping experiments of [6].

Conclusions and Implications

- **We developed a kinetic model for ice deposition and trapping following a 3-phase model which reproduces the collective results of experiments where noble gases were trapped within amorphous ice.**
- **Experiments were generally conducted at deposition rates that were much higher than expected in astrophysical environments.**
- **The amount of noble gas trapped in water ice is a function not only of temperature, but also deposition rate of the ice.**
- **Low abundances of water in the gas phase would reduce or limit the efficiency of trapping. A thick enough lid at the surface is needed to keep Ar trapped.**
- **While trapping of noble gases may occur in the solar nebula, it is unlikely to produce solids with solar ratios of Ar/H_2O for the conditions considered here. Low temperatures and high water vapor abundances are needed.**

References

[1] Bar-Nun et al. (1985) *Icarus* 63, 317-332. [2] Notesco et al. (2003) *Icarus* 162, 183-189. [3] Notesco and Bar-Nun (2005) *Icarus* 175, 546-550. [4] Yokochi et al. (2012) *Icarus* 218, 760-770. [5] Hasegawa and Herbst (1993) *Monthly Notices of the Royal Astronomical Society* 263,589-606. [6] Fayolle et al. (2011) *Astronomy & Astrophysics* 592, A74. [7] Hogerheijde et al. (2011) *Science* 334, 338-340. [8] Asplund et al. (2009) *Annual Review of Astronomy & Astrophysics* 47, 481-522.

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