JUPITER'S NOBLE GAS ABUNDANCES MAY REQUIRE EXTERNAL UV IRRADIATION OF THE SOLAR NEBULA.
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Background: The Galileo probe measured abundances (relative to H) of many elements in Jupiter's atmosphere. While He and Ne (and perhaps O) appear depleted, other elements appear uniformly enriched relative to H and solar abundances, with $[X/H] \sim 3\,[X/H]_\odot$, where X may be C, N, S, P, Ar, Kr or Xe [1-4], using solar abundances of [5]. Two models of Jupiter's enrichments, especially of the noble gases, are currently debated: the "solar composition icy planetesimal" (SCIP) model, in which Jupiter accreted large masses of ices that trapped all elements uniformly in solar proportions [5]; or the photoevaporated disk model , in which Jupiter accreted gas that was simply depleted in H_2 and possibly He and Ne—but *not* Ar, Kr or Xe [7]. Either model requires Ar, Kr and Xe to be trapped in ices; the photoevaporated disk model posits that UV irradiation by a nearby massive star removed gas that did not contain Ar, because it had been sequestered in ice grains that were dynamically decoupled from the gas as it was lost. Ar (and the less volatile Kr and Xe, too) can be trapped in amorphous ice as it is forming, provided temperatures are $< 35\,\mathrm{K}$ [8]. While temperatures are higher than this, $\approx 50\,\mathrm{K}$, at Jupiter's location at 5 AU, these low temperatures are achieved in protoplanetary disks beyond about 15 AU [9]. We note that while [7] invoked photoevaporation from the top of the disk at about 5 AU, removal of gas is much more physically plausible at 50 AU [10].

Jupiter's physical separation from the region where Ar is sequestered in ice speaks to transport, and distinguishes between these models. In the SCIP model, Jupiter must directly accrete Ar-enriched ice; but Jupiter is most likely to accrete local ice that is not enriched in Ar, posing problems for the SCIP model. But the photoevaporated disk model also demands transport: Ar-bearing gas from 5 AU must be transported outward to 50 AU; Ar must be sequestered in ices; photoevaporation must remove H_2; and the newly H-depleted gas must be mixed back to the 5 AU region to be accreted by Jupiter (see Figure 1). The outward transport of gas from 5 AU to 50 AU is predicted to occur in externally photoevaporated disks [11], but Ar must be sequestered into ice after the material moves beyond the 35 K line at 15 AU, but before the gas is lost at 50 AU.

In this abstract we examine the conditions under which Ar, Kr and Xe can be sequestered into ice in the outer solar nebula. We conclude that trapping of noble gases requires not only cold temperatures but also UV irradiation. UV irradiation enables both the needed transport of ice and the trapping of Ar in it.

The Need to Photodesorb Ice: To be trapped in ice, Ar must be part of the chemical structure, not simply adsorbed as monolayers on ice surfaces. Assuming the standard definition of a monolayer, (10^{15} atoms per cm^2, or $10\mathring{A}^2$ per binding site), and assuming 1% of the gas mass is in the form of ice grains with radii 1 mm, at most 2×10^{-8} grams of Ar can be trapped per gram of gas, far short of the solar At mass ratio $f_{\rm Ar} = 1 \times 10^{-4}$ [5]. Noble gas clathrates like $\mathrm{Ar} \cdot 6\mathrm{H_2O}$ are thermodynamically stable below 48 K [12], perhaps as close to the Sun as 5 AU. Likewise, amorphous ice can stably trap and hold Ar at temperatures below 35 K. But what is not clear is whether water ice and Ar gas transported outward can *transform* to Ar-bearing ices in reasonable timescales; at such cold temperatures (< 50 K) such transformations are likely to be kinetically inhibited. In practice, [8] found that trapping of Ar in amorphous ice was possible at temperatures $< 35\,\mathrm{K}$, but only during *co-deposition* of the Ar and the water vapor. But, as long as water vapor is condensing as amorphous ice, it is likely to trap all noble gases with equal efficiencies. Potentially, water ice can trap as many Ar atoms as water molecules [8].

Trapping of Ar atoms in ice requires not just cold (< 35 K) temperatures, but the presence of water vapor. Cold water vapor is observed in the outer regions of protoplanetary disks such as DG Tau [13]. Because of the cold temperatures, H_2O molecules are removed as soon as they encounter ice, taking a time ~ 300 years to freeze out (assuming again 1% of the mass of the gas, with density $\approx 10^{-13}\,\mathrm{g\,cm^{-3}}$, is in the form ice grains with radius 1 mm). Water vapor therefore must be continually produced, and photodesorption of ice by UV radiation, with an efficiency $\epsilon \approx 7 \times 10^{-3}$ water molecules desorbed per UV photon [14], successfully explains the mass of vapor in disks like DG Tau [13].

Model for Trapping Ar in Ice We calculate the flux of UV needed to continuously create water vapor sufficient to trap all of the gas-phase Ar moving outward in a disk through an annulus between 15 to 50 AU, with area $A \sim 1.6 \times 10^{30}\,\mathrm{cm}^2$. Disks that are externally photoevaporated are predicted to have net outward transport of gas, with mass flow perhaps $\dot{M} \sim 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ [11]. The number of Ar atoms flowing into this annulus per time is $f_{\mathrm{Ar}}\dot{M}/m_{\mathrm{Ar}}$, where m_{Ar} is the mass of an argon atom. The number of H_2O molecules produced in the annulus per time is $(F_{\mathrm{ISRF}}G_0 e^{-\tau}/h\nu)\epsilon A$, where the UV flux is G_0 times the interstellar radiation field $F_{\mathrm{ISRF}} = 1.6 \times 10{-}3\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, the mean energy per photon is $h\nu \approx 10\,\mathrm{eV}$, the UV optical depth between the disk midplane and the surface is τ, and it is assumed that essentially every UV photon is absorbed by an ice grain. Equating these, we estimate a minimum UV flux $G_0 > 1e^{+\tau}\,(\dot{M}/10^{-8}\,\mathrm{M_\odot\,yr^{-1}})$ is required. It is also necessary that the water molecules be desorbed in a region deep enough in the disk so that they are not immediately part of warm gas that is lost in a photoevaporative flow. According to [10], at optical depths $\tau > 5$, the gas ceases to be heated by the UV flux. Setting $\tau = 5$, we find a minimum UV flux $G_0 > 150(\dot{M}/10^{-8}\,\mathrm{M_\odot\,yr^{-1}})$. This is to be compared to the UV flux leading to mass loss at 50 AU, roughly $G_0 \approx 3000\,(\dot{M}/10^{-8}\,\mathrm{M_\odot\,yr^{-1}})$. We conclude that the UV fluxes required to photoevaporate protoplanetary disks also produce enough UV photodesorption of ice to produce water vapor sufficient to trap Ar and other noble gases in amorphous ice, before the gas is removed from the disk.

Given that Ar can be sequestered in amorphous ice, generated by the constant photodesorption and refreezing of water in the outer disk, it will not be removed from the disk, provided dust grains grow quickly enough to dynamically decouple from the gas. The formulas of [15] can be used to estimate this timescale. Assume small (radii $r_0 \sim 1\,\mu\mathrm{m}$) icy grains initially mixed with the gas with scale height H. These coagulate and grow in radius an amount $\Delta r = f_{\mathrm{ice}}\rho_{\mathrm{gas}}H/(4\rho_{\mathrm{s}})$ and then settle out of the gas to a new scale height H_{f}. Assuming an ice-to-gas mass ratio $f_{\mathrm{ice}} = 0.01$, gas density $\rho_{\mathrm{g}} = 10^{-13}\,\mathrm{g\,cm^{-3}}$, and ice density $\rho_{\mathrm{s}} = 1\,\mathrm{g\,cm^{-3}}$, we find $\Delta r \approx 0.2$ mm. The growth timescale is $t_{\mathrm{grow}} \sim t_{\mathrm{K}}/(f_{\mathrm{ice}}S)\,\ln\left[S(\Delta r/r_0)(H/H_{\mathrm{f}})\right]$, where $t_{\mathrm{K}} \approx 140\,\mathrm{yr}$ is the local orbital period and $S \approx 1$ the sticking coefficient, With these parameters, we estimate the time taken for ice grains to grow to sizes sufficient to decouple from the gas is ~ 75000 years.

This is to be compared with the time for gas to cross the annulus, $(35\,\mathrm{AU})/V_r$, where $2\pi r\,\Sigma\,V_r = \dot{M}$. Assuming $\Sigma \sim 30\,\mathrm{g\,cm^{-2}}$ [11] and $\dot{M} = 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$, we find an outward velocity $V_r = 17\,\mathrm{AU\,Myr^{-1}}$, and a crossing time $\sim 2\,\mathrm{Myr}$. Dust grains therefore can grow and decouple from the gas before crossing the annulus. Photoevaporation will therefore remove only H_2, He and Ne from the disk, not Ar, Kr or Xe. The gas will be uniformly enriched relative to H in all the noble gases, and this gas will diffusively mix on a similar timescale ~ 2 Myr.

Conclusions: The same UV that photoevaporates a disk will also photodesorb ice, producing abundant water vapor that can recondense as amorphous ice, trapping Ar, Kr and Xe as it does so. This presents the loss of these noble gases as the disk is photoevaporated. Subsequent mixing brings this H-depleted gas to where Jupiter forms, thereby explaining Jupiter's uniform enrichments.

References: [1] HB Niemann et al. 1998 JGR 103, 22831. [2] PR Mahaffy et al. 2000 JGR 105, 15061. [3] MH Wong et al. 2004 Icarus 171, 153. [4] PGJ Irwin et al. 1998, JGR 1031, 23001. [5] M Asplund et al. 2009 ARA&A 47, 481. [6] T Owen et al. 1999 Nature 402, 269. [7] T Guillot & R Hueso 2006 ApJL 367, L47. [8] A Bar-Nun et al. 1988 Phys Rev B 38, 7749. [9] MV Lesniak & SJ Desch 2011 ApJ 740, 118. [10] FC Adams et al. 2004 ApJ 611, 360. [11] SJ Desch 2007 ApJ 671, 878. [12] K Lodders 2003, ApJ 591, 1220. [13] L Podio et al. 2013 ApJ 766, L5. [14] MS Westley et al. 1995 P&SS 43, 1311. [15] Y Nakagawa et al. 1981 Icarus 45, 517.

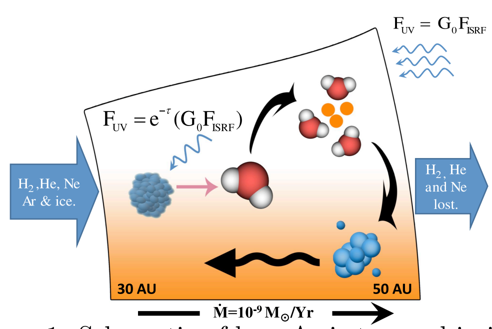

Figure 1: Schematic of how Ar is trapped in ices.