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Accretion of supersolar gas by the growing proto-Jupiter in the vicinity of the amorphous ice snowline

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Abstract

Argon, krypton, xenon, carbon, nitrogen, sulfur, and phosphorus have all been measured enriched by a quasi-uniform factor in the 2-4 range, compared to their protosolar values, in the atmosphere of Jupiter. To elucidate the origin of these volatile enrichments, we investigate the possibility of inward drift of particles made of amorphous ice and adsorbed volatiles, and their ability to enrich in heavy elements the gas phase of the protosolar nebula once they cross the amorphous-to-crystalline ice transition zone. To do so, we use a simple accretion disk model coupled to modules depicting the radial evolution of icy particles and vapors, assuming growth, fragmentation and crystallization of amorphous grains. We show that it is possible to accrete supersolar gas from the nebula onto proto-Jupiter's core to form its envelope, and allowing it to match the observed volatile enrichments. We also discuss the possible oxygen bulk abundances that could result in Jupiter, based on our scenario.

1. Context

To explain Jupiter's properties, a category of models advocate that the giant planet's envelope was fed from protosolar nebula (PSN) gas already enriched in heavy elements. For instance, it has been proposed that Jupiter's metallicity was acquired prior accretion in the PSN gas phase as a result of the desorption of the volatiles trapped together in amorphous water [1]. Because volatiles trapped by amorphous water are likely to be released together at a similar temperature, this study points out that the trapped volatiles would have the same evaporation radii in the PSN, thus potentially leading to homogeneous enrichments in volatiles in the disk gas phase that would be similar to those observed in Jupiter. Here, we consider this idea and investigate the possibility of inward drift of particles made of amorphous ice and adsorbed volatiles and their ability to enrich in Ar, Kr, X, C, N, S, and P the gas phase of the PSN located around the snowline corresponding to the amorphous-to-crystalline ice transition zone (ACTZ). To do so, we use a simple accretion disk model coupled to modules that track the radial evolutions of icy particles and vapors, assuming growth, fragmentation and crystallization of amorphous grains. We refer the reader to [2] for a full description of the employed model.

2. Results

Figure 1 represents the evolution of the volatile abundances normalized to protosolar in the PSN and supplied as vapors to the gas phase for two different values of the viscosity parameter α, namely 10^{-3} and 10^{-2}. Volatiles are released to the gas phase of the PSN by the drifting grains once they cross the ACTZ and diffuse radially. With time, the ACTZ moves inward and evolves from 9 AU ($\alpha = 10^{-3}$) and ~5.5 AU ($\alpha = 10^{-2}$) at t = 0 down to close 1 AU after 2 Myr of PSN evolution. Because of the initially high surface density of dust in the PSN (1% that of the gas), its gas phase around the location of the ACTZ is quickly enriched in volatiles released by the crystallization of drifting amorphous particles. The volatile enrichments factors (relatives to their protosolar values) reach maximums of {~40 and 25 at t = 0.5 Myr in the 2-3 AU region of the PSN, which corresponds to the location of the ACTZ at this epoch, assuming α values of 10^{-3} and 10^{-2}, respectively. The enrichments profiles decrease with time because of the diminishing number of particles crossing the ACTZ and releasing their volatiles. This trend is faster when using a higher a value, as diffusion is more efficient.

4. Conclusions

We built a numerical model allowing us to quantitatively test this hypothesis and we find that it is indeed possible to accrete supersolar gas from the PSN onto proto-Jupiter's core to form its envelope, and allowing it to match the observed volatile enrichments. This implies that there is no need to invoke the accretion of solids or the core erosion to provide the required amounts of Ar, Kr, Xe, C, N, S, and P in Jupiter's envelope.

Interestingly, while the Ar, Kr, Xe, C, N, S, and P enrichments in Jupiter can be explained via its formation over a large range of heliocentric distances in the PSN, it appears that the O abundance in the envelope strongly depends on its formation location. Two extreme scenarios of O abundance can be envisaged in Jupiter's envelope: (1) formation around the ice line where Jupiter's oxygen abundance is supersolar due to the redistributive diffusion of water vapor around its vaporization location, and (2) formation around the ACTZ where Jupiter's oxygen abundance is smaller, and eventually subsolar, because of the limited amount of extra water supplied by the outward diffusion of vapor. For further detail about our study, we refer the reader to [2].

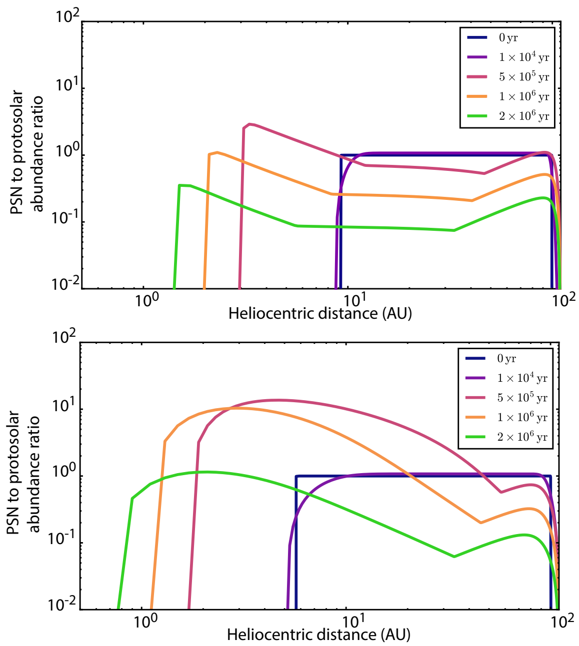

Fig. 1. Time and radial evolution of the abundances of volatiles released to the PSN gas phase by the icy grains subsequent to their drift through the ACTZ. Calculations have been performed for $\alpha = 10^{-3}$ (top panel)} and $\alpha = 10^{-2}$ (bottom panel). The brown horizontal bar represents the range of volatile enrichments (nominal values) measured in Jupiter. At a given epoch, the metallicity of the PSN gas phase matches Jupiter's value at heliocentric distances at which the abundance profile of volatiles intercepts the horizontal bar. The black dots designate the location of the ACTZ during the evolution of the PSN.

References

[1] Monga, N., & Desch, S. 2015, ApJ, 798, 9

[2] Mousis, O., Ronnet, T., Lunine, J.I. 2019, ApJ, 875, 9.