**Introduction:** Nominally anhydrous minerals (NAMs) in the S-type asteroids are hydrated with 698–988 ppm weight water (39–55 ppm of equivalent hydrogen) [1]. However, the mechanism(s) by which water can get into the structure of early-formed silicate minerals, while condensing from the gas phase in the nebula is still controversial.

In a terrestrial setting, water can dissolve in hot silicate melts during the crystallization of NAMs under high-pressure, e.g., under a pressure of 10 GPa, pure enstatite can store ~1200 ppm water. However, at low pressures of ~2 GPa, the water in the enstatite structure is only up to 200 ppm [2]. NAMs condensed in the nebula, where the pressure is even lower (likely <10^7 GPa). Thus, the direct dissolving of water in silicate melts cannot account for the incorporation of water into NAMs. An alternate mechanism for the hydration of NAMs is chemi-adsorption, where water molecules in the nebular gas can get adsorbed on the surface of NAMs and involved in the subsequent subsurface hydroxylation [3]. However, the efficiency of this process is likely low because the presence of abundant hydrogen gas in the solar nebula would decrease the coverage of water molecules on the silicate surface. Besides, adsorption preferably occurs at specific planes of silicates, e.g., {100} for olivine [3], and requires additional investigation.

In this study, we propose a new mechanism that explains how hydrogen can be efficiently incorporated into NAMs in a low-pressure nebular setting.

**Methods:** In our model, implantation of H⁺ ions in the hot and rarified environment in the early sun’s history is responsible for introducing hydrogen into the freshly formed minerals. As indicated in Fig. 1, ionized H⁺ ions in the solar nebular gas get implanted into the top surface area of the early-formed silicate grain (Process 1). A concentration gradient in the implanted area of the silicate grain drives the recombination of the implanted H with other hydrogen atoms and leads to their outward diffusion (Process 2). Additionally, the inward diffusion of the projectile hydrogen occurs efficiently and causes a redistribution of hydrogen in the silicate grain (Process 3). The essential details of each process is described below:

**Process 1: Implantation.** In the early solar system, the most abundant solar gases, i.e., H₂ and He, had not dispersed until ~3.8 Ma after the formation of the calcium-aluminum-rich inclusions (CAIs) [4], which overlaps with the formation period of chondrites (1–4 Ma after CAIs) [5]. The stellar and interstellar ultraviolet let protons and X-rays, and galactic cosmic rays ionized the nebular H₂ gas and resulted in a “dusty” plasma [6]. The precursor materials of chondrites, the NAMs were likely surrounded by this plasma, and were constantly bombarded by high-energy H⁺ ions. In terms of the atomic density of H atoms (~2.23 × 10^16 cm⁻³), ionization fraction (10^11) and average flow speed (10 km·s⁻¹) [7, 8], we estimate that the flux of the ionized H⁺ in the solar nebula (f_sv) is ~2.23 × 10^11 cm²·s⁻¹. In addition to the H⁺ ions characterized by the random flow velocities in the nebula, unidirectional H⁺ ions in the solar wind (SW) and high-energy H⁺ ions of galactic cosmic rays (GCR) can also get implanted into the silicate. The flux of protons in SW and GCR protons were estimated as ~3.0 × 10⁶ cm⁻²·s⁻¹ and ~4 cm⁻²·s⁻¹ [9] respectively, which are negligible compared to the H⁺ flux in the ionized solar nebula.

![Fig. 1. A schematic showing the proton implantation-diffusion processes occurring in silicate minerals.](image-url)

Only a portion of the H⁺ ion flux can be implanted in the silicates because H⁺ has the lightest mass and can undergo elastic collisions with atoms of the target and eventually get reflected [10]. We thus estimated the effective flux (f_eff) as f_eff ≈ f_{SW} · N_{H} where N_H is the retention coefficient and denotes the fraction of the ions that get implanted in the target. The retention coefficient is related to the mineral type, energy and dose of the projectile ions, and has been measured by irradiation experiments [11].
**Process 2: Outward diffusion**. The implanted H\(^+\) ions in the top surface layer of the silicate react with other atoms and get physically trapped in lattice defects. On the silicate surface, the formation of H\(_2\) molecule via recombination, and the subsequent desorption of these H\(_2\) generally result in the concentration gradient of the hydrogen within the implanted area and can lead to the outward release of implanted hydrogen [12]. However, in the nebular environment, abundant H\(_2\) gas surrounding the silicate grain would suppress the recombination of hydrogen atoms. As implantation of H\(^+\) ions continues, the amount of H atoms in the implanted area increases until they occupy all vacancies and reach saturation. We calculated the flux of the outward-diffused hydrogen using the Polanyi-Wigner rate equation [13].

**Process 3: Inward diffusion**. Coupled with the outward diffusion, the inward diffusion can evenly redistribute the implanted H\(^+\) ions in the interior of the silicate grain. The calculated inward diffusion rate is >10 times slower than that of the outward diffusion, because the concentration gradient present between the deep interior and the H-implanted area near the surface is smaller than that between the surface and the implanted area. The inward-diffused H\(^+\) ions occupy the vacancies and form the O-H bonds in the crystal lattices, which act as the analog for “water”. The concentration profiles of the inward-diffused hydrogen were calculated using an approximate solution to Fick’s second law of diffusion [14].

**Results and Discussion**: Using the equations of implantation and diffusion defined by processes 1–3, we quantified the water concentration in the NAMs immersed in the ionized nebular gas. Silicate minerals with radii of 50 μm (Fig. 2A and B) and 500 μm (Fig. 2C and D) are assumed to experience the H-implantation in durations of 1 day, 1 month, 1 year, and 10 years. For both grain sizes, the simulations were run with retention coefficients (N\(_R\)) of 0.01 and 0.1. Assuming a low-retention coefficient N\(_R\) = 0.01, the 50 μm grain can obtain >100 ppm water in 10 years, (Fig. 2A), while the 500 μm grain only acquires ~10s ppm water in the same time frame (Fig. 2C). Thus, larger silicates require a longer time for the implanted H\(^+\) ions to be evenly distributed. Second, the retention coefficient of the projectile ions is critical to the implantation-diffusion process. For instance, with low retention coefficients (e.g., N\(_R\) = 0.01), the production of water is less than 200 ppm for both silicates in 10 years (Fig. 2A and C), whereas high-N\(_R\) implantation (e.g., N\(_R\) = 0.1) can produce more than 1000 ppm water within a year (Fig. 4B and D). Therefore, a high retention coefficient is essential to efficiently store hydrogen during the implantation-diffusion process. The recently measured pyroxene minerals in Chelyabinsk and Benenitra contain up to 900 ppm water [15], which can be easily achieved by a N\(_R\)=0.1 implantation in 1 year.

![Simulated concentration profiles of water into the interior of the silicates.](image)

**Conclusions and Implications**: Our calculations prove that implantation of H\(^+\) ions in the early solar nebula can account for the incorporation of water in the early formed NAMs, and can transform the water contents in early-formed solids. The dissipation of the solar nebula plasma can then result in the lower effective flux of protons and significantly limit nebular proton implantation. As a result of the ubiquitous H implantation process, silicate minerals are bound to be D-poor in nature.

Various objects immersed in the solar nebula plasma, including chondrules, regolith of planetesimals, and free-floating particles produced by impacts can be efficiently hydrated by the implantation-diffusion process, described here, in the first few million years of solar system evolution. A study of NAMs from the pristine regolith of asteroid Bennu can show evidence of the implantation-diffusion process, which will enhance our understanding about this process.