

Heavy element enrichment in protoplanetary disks and gas giants with disk surface accretion

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One of the most fundamental questions in planetary formation theory is where planets formed within their respective protoplanetary disks and how they migrated to their current locations. The atmospheric composition of gas giants provides clues to where they accreted disk gas. Since the atmospheric composition of gas giants can be constrained through astronomical observations, they serve as particularly important targets for unraveling planetary formation and migration. Atmospheric observations of close-in gas giants with the James Webb Space Telescope (JWST) suggest that lower-mass planets tend to have higher heavy-element enrichment in their atmospheres, with the heavy-element concentration reaching nearly 100 times that of their host star (e.g., Kempton & Knutson 2024).

Previous theoretical studies on the formation of gas giant atmospheres have explained the enhancement of heavy elements (elements other than hydrogen and helium) in the inner regions of the disk by assuming that dust, the carrier of heavy elements, has high stickiness. In this scenario, centimeter-sized dust grains rapidly drift inward and sublimate, increasing the heavy-element concentration in the inner disk (e.g., Booth et al. 2017; Schneider & Bitsch 2021). However, recent radio polarization observations of protoplanetary disks (e.g., Stephens et al. 2017, 2023) indicate that large amounts of 0.1–1 mm-sized dust exist in disks, suggesting that the assumption of high dust stickiness in the previous scenario may not be valid.

In this study, we propose a new scenario for the heavy-element enrichment of disk gas that assumes low dust stickiness, which is more consistent with disk observations. Conventional disk models assume that gas accretion flows have a vertically uniform velocity. However, recent magnetohydrodynamic simulations suggest that gas accretion may be concentrated near the ionized surface layers of the disk. In such a surface accretion disk, dust tends to remain in the disk for a longer duration compared to gas (Okuzumi 2025). This implies that in the inner regions of a surface accretion disk, the abundance of heavy-element vapor supplied by dust is expected to increase. To test this hypothesis, we developed a model capable of calculating the transport of both gas and dust in a surface accretion disk. In particular, we focused on oxygen, one of the major heavy elements, and incorporated the processes of coagulation and growth of ice-bearing dust, radial advection, and sublimation-driven water vapor release, along with the transport and diffusion of water vapor. Furthermore, based on recent disk observations, we assumed a low dust stickiness strength (with a critical adhesion velocity of 0.3 m/s).

As a result, in a uniformly accreting disk, the water vapor concentration inside the snow line increased only up to 2 wt%, whereas in a surface accretion disk, it reached up to 20 wt% even with a low dust stickiness. This is because, compared to a uniformly accreting disk, a surface accretion disk has a longer timescale for dust advection, allowing ice-bearing dust to remain in the disk for a longer period. Furthermore, even at a water vapor concentration of 20 wt%, a sufficient amount of gas remains in the disk for the formation of gas giants. Additionally, we found that the water vapor enrichment in the disk gas of a surface accretion disk increases as the total mass of the disk gas decreases. This trend arises because, in the early stages when the disk gas mass is large, water vapor flows away before ice-bearing dust accumulates at the midplane, whereas at later stages, as the disk gas depletes, ice-bearing dust that

has accumulated at the midplane sublimates. This trend qualitatively explains the observed correlation between planetary mass and atmospheric heavy-element enrichment in exoplanets.

Keywords: heavy element, protoplanetary disk, surface accretion, gas giant