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New framework for dust diffusion in partially ionized plasma with high dust-to-gas ratio: an application to a gap created by a protoplanet in a protoplanetary disk

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The transport and distribution of dust particles in partially ionized plasmas are fundamental to a wide range of astrophysical environments, including interstellar clouds, cometary comae, and protoplanetary disks. Among these, planet-forming systems such as protoplanetary disks offer a particularly rich setting in which dust dynamics significantly influence both microscopic plasma behavior and large-scale structure formation. For instance, gravitational perturbations from massive embedded protoplanets can carve out gap structures in which the disk gas is highly depleted, strongly affecting dust migration and accumulation. While many dusty plasma systems are characterized by low dust content, protoplanetary disks often exhibit regions with unusually high local dust-to-gas mass ratios. In such dust-enriched environments, the dust component can no longer be treated as a passive tracer but instead exerts strong dynamical feedback on the gas. This backreaction modifies turbulent cascades, alters angular momentum transport, and necessitates a theoretical treatment beyond conventional background-field approximations.

In numerical models of protoplanetary disks, turbulent diffusion of dust has traditionally been implemented under the assumption that gas turbulence acts as a fixed background field. Two common approaches are used to incorporate turbulent diffusion into dust–gas systems: (1) introducing a diffusive flux directly into the dust continuity equation[1], and (2) including an effective turbulent diffusion velocity in the dust momentum equation[2]. However, both approaches inherently assume that the gas responds negligibly to the presence of dust, neglecting the backreaction arising from dust-induced momentum and energy exchange in the microscopic scale. This assumption breaks down in regions with high dust-to-gas ratios, leading to physically inconsistent models that violate fundamental conservation laws.

In this study, we propose a new theoretical framework for dust diffusion under isotropic turbulence, which rigorously enforces momentum and energy conservation between gas and dust. Specifically, we introduce a momentum exchange term based on a microscopic phenomenological picture and explicitly derive the energy source required to sustain the microscopic motion of dust particles. This approach eliminates the need for ad hoc external diffusion coefficients and ensures dynamical consistency throughout the model. The resulting formulation satisfies the physical requirement that turbulent dust diffusion necessarily induces a response in the gas, and is expected to be particularly valid in environments with high dust-to-gas mass ratios.

We apply this model to the environment surrounding a planet-induced gap in a protoplanetary disk and demonstrate that the resulting dust distribution exhibits qualitatively distinct features compared to those predicted by conventional models. In particular, our framework reveals novel behaviors in dust accumulation, radial migration, and transport into the inner gap region, which in turn modify both the inferred solid accretion rate onto the planet and the predicted brightness profile of dust rings. These findings suggest that a dynamically consistent treatment of turbulent diffusion is crucial not only for understanding the solid delivery process in theoretical models of gas giant planet formation, but also for interpreting high-resolution observations of disk substructures.

In this talk, we present the formulation of our momentum- and energy-conserving dust diffusion model, along with its application to planet–disk interaction problems. We further discuss its broader implications for turbulent transport theory in partially ionized dusty plasmas and explore its potential applicability to diverse systems beyond planet formation, within the wider scope of Solar and Astrophysical Plasma Physics.

References

[1] Weber et al., 2019, The Astrophysical Journal, 884:178 (15pp)
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