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DUST-GAS DYNAMICS AND PLANETESIMAL FORMATION IN PROTOPLANETARY DISKS

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RESUMEN

Aunque se han detectado miles de sistemas planetarios extrasolares, aún queda por trazar un panorama completo de cómo se forman los planetas a partir de sus discos protoplanetarios natales. Una de las etapas más desafiantes es la formación de planetesimales a escala kilométrica a partir de partículas de polvo de tamaño centimétrico o milimétrico en el disco. Estas partículas sufren de derivas internas problemáticamente rápidas y de una baja eficiencia de adherencia debido a la fragmentación y el rebote en las colisiones. Este artículo revisa brevemente nuestro conocimiento actual de la dinámica del polvo y el gas en los discos protoplanetarios y sus consecuencias en la formación de planetesimales. Específicamente, se examina cómo y bajo qué condiciones las partículas de polvo pueden concentrarse activamente a una alta densidad para que se formen planetesimales, la función de masa inicial de los planetesimales y los efectos de la turbulencia.

ABSTRACT

Even though thousands of extrasolar planetary systems have been detected, a comprehensive picture of how planets are formed from their natal protoplanetary disks remains to be drawn. One of the most challenging stages is the formation of kilometer-scale planetesimals from centi-/milli-meter-sized dust particles in the disk. These particles suffer from problematically rapid inward drifts and poor sticking efficiencies due to fragmentation and bouncing at collisions. This article briefly reviews our current understanding of the dust-gas dynamics in protoplanetary disks and its consequences on planetesimal formation. Specifically, how and under what conditions dust particles can actively concentrate themselves to high density for planetesimals to form, the initial mass function of planetesimals, and the effects of turbulence are examined.

Key Words: Hydrodynamics — Instabilities — Magnetohydrodynamics (MHD) — Planets and Satellites: Formation — Protoplanetary Disks — Turbulence

1. INTRODUCTION

As of this writing, more than 5,600 extrasolar planets have been detected outside of our own Solar System.[2] Statistically speaking, for about every ten and two Sun-like stars, one should find one giant planet and one Earth-sized planet, respectively (Winn & Fabrycky 2015). This ubiquity of extrasolar planets implies that planet formation should readily proceed around young stellar objects. However, a comprehensive theoretical picture of how planets are formed from their natal protoplanetary disks (a.k.a. circumstellar disks) remains to be drawn. From interstellar dust grains to newborn planets, planet formation spans 30 orders of magnitude in mass and 13 orders of magnitude in size. It involves intricate interactions between the solid materials, the gaseous medium, the stellar irradiation, and the magnetic field, resulting in complicated dynamics in protoplanetary disks (see, e.g., Lesur et al. 2023, and references therein).

In the core accretion scenario of planet formation, dust coagulation proceeds via mutual collisions and electrostatic forces, but the maximum size this process can reach is limited by two physical barriers. First, a natural negative radial pressure gradient in the gaseous disk exists, so the gas moves around the central star at a slightly slower speed than Keplerian. On the other hand, the dust particles move at the Keplerian speed and hence experience constant headwind from the gas drag. As the dust particles grow, this results in their radial drift towards the central star in a significantly short timescale compared with the disk lifetime (Adachi, Hayashi, & Nakazawa 1976; Weidenschilling 1977; Youdin 2010). Second, dust particles may not necessarily stick at collisions; they may fragment each other at high collision speeds or just bounce off each other at moderate speeds (e.g., Zsom et al. 2010). In general, dust growth is limited by fragmentation or bouncing bar-

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[2]For the latest census, see, e.g., `https://science.nasa.gov/exoplanets/discoveries-dashboard/`.

rier in the inner region ($\lesssim$10 au) of the disk and by radial-drift barrier in the outer region ($\gtrsim$10 au) (e.g., Birnstiel, Fang, & Johansen 2016).

These barriers pose a stringent obstacle to the formation of kilometer-sized planetesimals. Numerous mechanisms have been proposed to overcome these barriers, and most of which center around the potential to drive local concentration of solid materials to high density such that planetesimals can form via direct gravitational collapse. In this concise review, we focus on one such mechanism, the so-called "streaming instability", which became popular as it is the only mechanism that the dust particles can actively assist themselves to concentrate, instead of passively relying on the gas dynamics.

2. THE STREAMING INSTABILITY

The streaming instability was originally discovered as a linear instability (Youdin & Goodman 2005). The essential ingredient for this instability is the back reaction of the dust particles to the gas drag, albeit the solid abundance is small at the percentage level. As a linear instability, small perturbations exponentially amplify with time, and these perturbations must saturate nonlinearly into some kind of turbulent or stochastic flow (Johansen & Youdin 2007). The local dust density concentration in this saturation state does not appear to be sufficiently high to trigger gravitational collapse. Instead, this state induces turbulent diffusion which should balance vertical sedimentation of the dust particles to maintain a finite thickness of the dust layer (Yang & Zhu 2021; Baronett, Yang, & Zhu 2024).

To trigger gravitational collapse to form planetesimals within a sedimented layer of dust particles, sufficiently high solid loading is required. When the dust layer has a solid abundance Z—defined as the dust-to-gas *column* density ratio $\Sigma_\mathrm{d}/\Sigma_\mathrm{g}$—above a certain threshold Z_c, strong radial concentration of dust particles appear in the mid-plane of the disk (Johansen, Youdin, & Mac Low 2009), forming roughly axisymmetric, dense dusty filaments (Yang & Johansen 2014). The process could be interpreted as traffic jams, as a local clump of dust particles drifts radially at a slower rate than isolated particles, secularly accretes these particles from upstream, and hence the drift speed of the clump is further reduced. Depending on the size of the particles, Z_c appears to be on the order of 1% (Yang, Johansen, & Carrera 2017; Li & Youdin 2021). Moreover, the higher the solid abundance Z above Z_c, the smaller the radial separations between adjacent dusty filaments are (Yang & Johansen 2014; Yang, Johansen, & Carrera 2017; Yang, Mac Low, & Johansen 2018).

Naively, hydrodynamical or MHD turbulence already operating in the gaseous disk should inhibit dust particles from concentrating and hence forming planetesimals. However, this effect does not appear to be as strong as one expects. Yang et al. (2018) conducted the first non-ideal MHD simulations of this kind, focusing on a layered accretion disk model dominated by Ohmic diffusion, and found that $Z \sim 2\%$ is sufficient to trigger strong concentrations of solids. Similar results were found by Xu & Bai (2022) with a non-ideal MHD disk model regulated by ambipolar diffusion. The hydrodynamical turbulence driven by vertical shear instability (VSI) could even trigger more concentrations of solids than without VSI (Schäfer, Johansen, & Banerjee 2020; Schäfer & Johansen 2022). In all these models, the dust layers are significantly thicker than those supported by pure streaming turbulence, while the critical solid abundance Z_c does not appear to be proportionately increased. This indicates that the conventional criterion of the local dust-to-gas *volume* density ratio $\rho_\mathrm{d}/\rho_\mathrm{g} \gtrsim 1$ for planetesimal formation may not be an accurate one (see also Li & Youdin 2021).

3. PLANETESIMAL FORMATION

As described above, the back reaction of the dust particles in the mid-plane of the disk creates traffic jams to concentrate the particles to high density. As soon as the density reaches above the Hill density, numerous local clumps of particles in the dense dusty filaments should gravitationally collapse into planetesimals (Johansen et al. 2015; Simon et al. 2016). With high-resolution computer simulations, the number of collapsed clumps is large enough such that the resulting mass function of planetesimals has become statistically meaningful. It is generally observed that the mass function is top-heavy to the extent the majority of the total mass is shared by a few large planetesimals, while the less massive the planetesimals, the more numerous they are.

Continuing the simulation model of the largest local shearing box at the time by Yang & Johansen (2014), Schäfer, Yang, & Johansen (2017) conducted simulations of planetesimal formation and analyzed the mass distribution of the newborn planetesimals. It appears that the high-mass end of the cumulative distribution is not a sharp cutoff, but a shallower exponential taper (see also Li, Youdin, & Simon 2019). The mass where this taper occurs determines the characteristic mass of planetesimals, which was found to be correlated with the mass reservoir in the dusty filaments. This shallow exponential taper was nicely reproduced by Kavelaars et al. (2021) using a meta-analysis of the observed cold classical Kuiper Belt objects—which are believed to be the least disturbed left-over planetesimals from the formation of the Solar System.

Moreover, it appears that the characteristic mass of the collapsed products could reach sub-earth masses in the outer regions ($\gtrsim$20 au) of some systems. One is in a turbulent disk driven by gravitational instability when the disk is still young and massive (Baehr, Zhu, & Yang 2022). Another is in a large-scale gaseous vortex, which naturally traps and concentrates dust particles (Lyra et al. 2024). If any of these processes proves to be robust, the theoretical timescale for planet formation could be significantly shortened and better meet the constraint of a typical disk lifetime of a few million years inferred from observations (see, e.g., Williams & Cieza 2011).

As a final remark, how a distribution of dust particles of different sizes participate in the formation of planetesimals has generated quite some interests in recent years. Below the radial-drift barrier, the smaller a dust particle, the more tightly coupled to the gas it is (see, e.g., Weidenschilling 1977). This results in increasing mobility of dust particles of increasing sizes in streaming turbulence and hence the largest particles tend to be found in regions with high total dust density while being depleted in regions with low total dust density (Yang & Zhu 2021). Therefore, it is implied that the composition of a newborn planetesimal should be significantly more contributed by the largest dust particles. Indeed, this implication has been recently found in computer simulations by Cañas et al. (2024).

4. SUMMARY

In summary, planetesimal formation suffers from radial-drift and fragmentation/bouncing barriers. To overcome these barriers, dust particles can actively help themselves concentrate to high densities via the back reaction of the drag force to the gas. The criterion for planetesimal formation depends on the solid abundance ($> O(1\%)$), the particle size, the radial pressure gradient, and perhaps the gas turbulence. The initial mass function of planetesimals is top-heavy and shows a characteristic exponential cut-off at high-mass end. The composition of planetesimals may be predominantly contributed by those of the largest dust particles.

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