論文の内容の要旨

Polarized view on protoplanetary disks: grain dynamics and alignment

（偏波観測を用いた原始惑星系円盤ダストの運動と整列過程の研究）

氏名　　森　智宏

The study of planet/planetesimal formation has been attracted special interest for half a century to investigate how the solar system and exoplanets with various properties do form in our galaxy. The birthplace of planets or planetesimals is believed to be protoplanetary disks, which are inevitably formed as a consequence of the angular momentum conservation. To establish the formation scenario, a number of theoretical and observational works regarding the disk structure, dynamics, and grain properties have been conducted.

Theoretically, a plausible pathway of terrestrial planets or planetesimals is the collisional growth of dust grains in protoplanetary disks. However, there are several barriers, which prevents dust grains from growing into planetesimals: Dust grains that have nonzero electrical charge rarely stick to each other due to the repulsive force (charge barrier). Grain collisions do not lead to only grain growth but also rebounds or fragmentation (bouncing barrier and fragmentation barrier). Rapid inward drifting due to gas aerodynamic drag quickly removes the dust grains from the disks (Radial drift barrier). These barriers make the planetesimal formation scenario terrifically complicated.

Recent enhancements of observational quality in sensitivity and spatial resolution have provided us a wealth of information for disk structures and grain properties. One of the most crucial insights obtained on the observations is that disks commonly have substructures such as ring, gap, spiral and so on. These various structures possibly capture the critical step of planet formation and provide solutions to tackle the proposed barriers above. However, the formation mechanisms for such substructures are also highly uncertain. It is because they are thought to invoke complex and various physics regarding gas-grain interactions, which are tightly dependent on grain sizes. Thus, observational constraints on grain sizes and moreover grain dynamics are essential for better understandings of planetesimal formation.

To tackle the difficulties, we conduct continuum polarization observations at millimeter wavelengths of disks. The polarized emission is believed to originate from a combination of grain alignment and scattering. Previously proposed sources that can align grains in disks are magnetic fields, radiative gradients, and gas flow directed on grains. The thermal emission from elongated dust grains aligned with the sources can be observed as polarized emissions. The other mechanism, self-scattering, is scattering-induced polarization where dust grains of sizes comparable to the wavelengths scatter the thermal dust emissions. The relative importance of these processes is sensitive to grain sizes, shape and response to above external forces acting on grains. This is invaluable information to explore the planetesimal formation. Nevertheless, it is largely unclear (1) which origin dominates, (2) whether just one or multiple origins contribute to the polarization and (3) how large and elongated the grains are. To address the questions, we investigate the origins of polarized emission detected on two disks around HL Tau and AS 209.

First, we conduct detailed modeling for the polarized emission of the HL Tau disk. Polarization features obtained on the HL Tau disk in Band 3 are as follows. (1) Elliptical polarization pattern and (2) uniform polarization fraction in the azimuthal directions. In previous studies, the origin of the polarization was concluded to originate from thermal emission of grains aligned by a radiative gradient in the disk (Kataoka et al., 2017; Stephens et al., 2017). However, Yang et al. (2019) pointed out that the radiative alignment predicts the circular pattern and strong polarization variations in the azimuthal directions, both of which are incompatible with (1) and (2). Alternatively, gas-flow alignment, where aspherical grains aligned by gas-flow with their long axes parallel to the flow, can produce the elliptical pattern. However, it also predicts strong azimuthal polarization variations, which is incompatible with (2). To solve the problem, we perform semi-analytical and radiative transfer modeling that includes the contributions from scattered emission as well as thermal emission of the aligned grains. As a result, we find that the combination of the gas-flow alignment and scattering can reproduce the features (1) and (2), whereas the radiative alignment + scattering cannot reproduce both the features. This result is surprising because the gas-flow alignment has been believed to occur when the velocity of the gas-flow on grains is supersonic while that in disks is subsonic. This raises a question regarding our understanding of alignment processes.

Next, we present 870 μm ALMA polarization observation toward the Class II protoplanetary disk around AS 209. We successfully detect the polarized emission and find that the polarization orientations and fractions have distinct characteristics between the inner and outer regions. In the inner region, the polarization orientations are parallel to the minor axis of the disk, which is consistent with the self-scattering model. This indicates the presence of an order of 100 micron-sized grains in the region. In the outer region, we detect $\sim$1.0% polarization and find that the polarization orientations are almost in the azimuthal directions. Moreover, the polarization orientations have systematic angular deviations from the azimuthal directions with $\Delta\theta \sim 4.^\circ5 \pm 1.^\circ6$. The pattern is consistent with a model that radially drifting dust grains are aligned by the gas flow against the dust grains. We consider possible scenarios of the grain dynamics at the AS 209 ring which can reproduce the polarization pattern. However, the directions of the observed angular deviations are opposite to what is predicted under the fact that the disk rotates clockwise. This poses a question in our understandings of the alignment processes and/or grain dynamics in protoplanetary disks.