論文の内容の要旨

Observational characterization of protoplanetary disks, exo-rings, and Earth-twins in exoplanetary systems

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Since the discovery of the first exoplanet around a Sun-like star in 1995, our understanding of planetary formation has drastically advanced, and, currently, there have been over 4000 discovered exoplanets. Most of the discovered planetary systems are significantly different from the planets in the Solar System implying the diversity of the extrasolar world as well as current observational limitations.

In this thesis, we attempt to tackle three specific themes related to the planetary formation and evolution; systematic search for exorings, observational quest for alignment among proto-planetary disks, and global mapping of an Earth analog.

In the first theme, we perform a systematic search for exoplanetary rings using the Kepler data. Signatures of transiting ringed planets are slightly different from ringless planets, and the difference between them can be exploited to search for planetary rings. Using a fast and precise algorithm for a transiting ringed planet, we search for exoplanetary rings among 168 Kepler planets, whose light curves possibly allow the detection of Saturn-like rings with the size of twice the planetary radius. We apply ringed and ringless models to phase folded light curves and compare the fitting outcomes to identify the signatures of rings. Firstly, we find 29 tentative systems, where fitting by ringed models is statistically favored compared with the ringless models. Although we examine these possible signatures in detail, we are not able to find convincing evidence of rings. In turn, we put constraints on possible planetary rings using the null results. Most of our targets have close-in orbits, so the planes of planetary rings are likely to be on the orbital planes of planets due to the tidal alignment. Based on this assumption, we conclude that the occurrence rate of rings larger than twice the planetary radius is less than 15%. Although the majority of targets in this study are short-period planets, the null detection puts the quantitative constraint on origins, formation and evolution of planetary rings.

The second theme is to search for alignment among proto-planetary disks in nearby five star-forming regions using interferometric observations by ALMA. We analyze the directions of disks in five star-forming regions, and we find that the disk orientations projected in the sky are likely to be random in four regions out of five, which is consistent with a theory that angular momentum is generated by turbulent motions in molecular clouds. At the same time, we find the possible alignment in the Lupus III at the statistical significance of 2σ, and it might imply other mechanisms beyond turbulent motions for generating angular momentum. For the robust discussion in the Lupus region, we compare different observations and methods including sparse modeling for estimating disk's axes, and we find that all of them show consistent estimations of disk orientations. On the other hand, we find the alignment in Orion Nebula Cluster, but it turns out to be more likely a false positive, which is produced by systematic noises during an observation.

Finally, we present a new methodology for global mapping of an Earth analog in future direct imaging missions. In the study, we introduce new regularization terms of L1-norm and Total Squared Variation to recover the two dimensional map from scattered light curves of directly imaged planets. For quantifying the potential improvement by the new method, we compare the recovered maps with the ground truth map of the Earth by varying regularization parameters. Using both simulated and real data of scattered light of the Earth for 1 or 2 years, we find that particular sets of the regularization parameters in the new method give more correct 2d map than the conventional method. In addition, we also explore the feasibility of global mapping by considering limited observational duration and noise associated with directly imaging observations for an Earth analog at distance of 10 pc. We find that observations for only the first day of the month in 2 years can roughly recover the surface distribution of the Earth. Our study shows the importance of choices of regularization terms in global mapping, and demonstrates the feasibility of recovering the surface inhomogeneity of an Earth analog in future direct imaging missions such as HabEx and LUVOIR.

In this thesis, we present methods for characterizing exoplanetary counterparts of objects in the Solar System, Saturn and Earth analogs. We also explore the applicability of sparse modeling by exploiting interferometric data and light curves of directly imaged planets. These studies open new possibility of the sparse method in astronomy, and the further investigation is rewarding. In addition, we also attempt to provide unconventional ways to unveil the architecture of planetary systems; we present the potential methods for constraining planetary spins, and explore global alignment among proto-planetary disks beyond one particular planetary system.

These works would contribute to understanding the origins and formation of planetary systems including the Solar System, and the methodologies presented in this thesis can be naturally applied to the current and future observations.