論文の内容の要旨

The Statistical Properties of the Detailed Structures of the Protoplanetary Disks in the Taurus Star-forming Region with ALMA Super-resolution Imaging Technique

(ALMA 超解像度画像で探るおうし座星形成領域における原始惑星系円盤の詳細構造)

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Planets are thought to originate from protoplanetary disks composed of cold gas and solid particles (dust) surrounding young stars. Such disks are a natural consequence of star formation, and several hundred have been confirmed with (sub)millimeter observation, such as the Submillimeter Array (SMA), in the low-mass star-forming regions at a distance of ~ 140 pc from the solar system. Owing to the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), substructures, such as annular gaps and rings, of the disks have been discovered at a high spatial resolution. Several theories have attempted to explain the observational result, and some theories have proposed the planet origin of these substructures, that is, an idea that the interaction between the planet and disk is thought to have created these gaps in the disk. To investigate how and where planetary formation occurs in the disks or how the relationship between young planets in the disk and its stellar mass plays a role, high spatial resolution is one of the keys. However, a spatial resolution of $0''.02 - 0''.03$ (or $3 - 4$ au at $d = 140$ pc) is an ideal case, even for ALMA, which needs the observations using the longest baselines. Generally, ALMA observations have a spatial resolution of $0''.1$ due to the limited use of such longest baselines, becoming difficult to simultaneously image dozens of disks with a resolution on the scale of a few au. The application of so-called "super-resolution imaging techniques" has a potential to increase the number of spatially resolved disks on this scale even with originally $0''.1$ resolution data, and to achieve higher spatial resolution than ever. Here, I have focused on a new data science approach to image reconstruction in ALMA data, known as sparse modeling (SpM). This image reconstruction fits the observation data of both short and long baseline lengths by utilizing non-parametric imaging, which consists of the chi-square and penalty terms, and relying on the sparsity of the true solution. It thus has the potential to significantly improve the effective resolution of ALMA. Given this background, I study the following topics with a wealth of available ALMA observation data.

As the first step of the present work, SpM is applied for the first time to the observational data sets taken by ALMA. I chose two independent data sets observed with different array configurations at Band 7 (0.9 mm), targeting the protoplanetary disk around HD 142527; one in the shorter-baseline array configuration ($\sim$ 430 m), and the other in the longer-baseline array configuration ($\sim$ 1570 m). The image resolutions reconstructed from the two data sets are different by a factor of $\sim$ 3. I confirm that the previously known disk structures appear on the images produced by both SpM and the conventional method, CLEAN, at the standard beam size. The image reconstructed from the shorter-baseline data using the SpM matches that obtained with the longer-baseline data using CLEAN, achieving a super-resolution image from which a structure finer than the beam size can be reproduced. The results demonstrate that SpM can recover high-quality images even at the super-resolution regime.

Following the successful demonstration of SpM imaging of HD 142527, I focus on the case study targeting the T Tau system (T Tau N, Sa & Sb) located in the Taurus region. The previous ALMA observations have not revealed the detailed structure in the disk around T Tau due to insufficient spatial resolution: T T Tau N has a small disk with a radius of about 20 au, and the T Tau S system has a dwarf disk compared to T Tau N. To elucidate the detailed structure in the disks around T Tau, I carried out super-resolution imaging with SpM. I use the ALMA Band 6 (1.3 mm) continuum data and achieve an effective spatial resolution of $\sim$ 30% (5 au) compared with the conventional CLEAN beam size of 17 au. The reconstructed image reveals a new annular gap structure at $r = 12$ au in the T Tau N compact disk with a disk radius of 24 au and resolves the T Tau Sa and Sb binary into two sources. If the observed gap structure in the T Tau N disk is caused by an embedded planet, we estimate a Saturn-mass planet when the viscous parameter of the disk is 10^{-3}.

I next present Taurus disk survey with the super-resolution imaging. I utilize ALMA 1.3 mm images for 40 Class II protoplanetary disks in the Taurus star-forming region. The target is selected from ALMA archival Band 6 (1.3 mm) data, which are observed with a nominal resolution less than $0''.1 - 0''.2$ and a relatively high signal-to-noise ratio (SNR > 30). The SpM imaging is applied to explore several au-scale substructures in compact and large disks with gaps and rings, which may evidence forming planets. The dust disk radius $r_{\rm d}$ is found to have a wide span ranging from 8 up to 200 au with a median of 45 au. Using the SpM images of 40 disk sources, such as achievable effective spatial resolution and limitation of its applicability has been investigated, As a result, SpM achieves better spatial resolution than CLEAN, i.e., $\sim 30-50\%$ of the CLEAN beam for half of the disk sample with more compact size and higher SNR. SpM images reveal 23 gaps, 29 rings, and 30 inflections (suggesting unresolved gaps or other features), and four disks with a ring alone. The gap locations $r_{\rm gap}$ of the target disks are located at $r_{\rm gap} = 5.5$ to 131 au; $r_{\rm gap}/r_{\rm d}$, the gap location normalized by their disk radius, is found to be around 0.1 or 0.4-0.7. Including several disks of the Disk Substructures at High Angular Resolution Project (DSHARP), I find the stellar mass dependence of the gap size and then estimate planetary masses assuming the gaps are due to forming planets and by applying the theoretical method of gap-formation, which connects the planetary mass and gap properties. If viscous parameters are taken over a wide range of $10^{-2} - 10^{-4}$, the stellar mass dependence of planetary mass in the outer disk regions ($r > 20$ au) can be observed for large disks. The majority of the inferred planets with a low-mass star (M–K type) is found to be Neptune-mass planets.

This thesis concludes that the new imaging technique using SpM is an attractive choice to provide a high-fidelity super-resolution image with ALMA, substructures such as gap and ring are found to be common for Class II disks in the low mass star-forming regions, and host stellar masses depend on gap size of their disks, suggesting that planetary masses inferred from the gap properties are related to the host stellar mass.