論文の内容の要旨

論文題目
Study of Exoplanet Migration Mechanisms with the Direct Imaging Method
（太陽系外惑星の惑星軌道移動に関する直接撮像法を用いた研究）

氏名　髙橋　安大

Since the first discovery of an extrasolar planet (or an exoplanet) in 1995, an increasing number of observations have already discovered about one thousand exoplanets. The first planet was detected in radial velocity (RV), and most of the planets have been also detected with the RV method or the transit method. Using the RV method, a minimum mass and an eccentricity, e, of a planet can be determined with analyzing RV curves. The transit method, on the other side, can lead to a planetary radius but not a planetary mass. However, a true mass of a transiting planet can be practically decided by combining with the RV method. Moreover, an apparent RV anomaly arises when a planet transits a star and partially occults its photosphere. The event is called as the Rossiter-McLaughlin effect in general. Investigating a shape of the RV anomaly allows us to know how a planet goes across a photosphere, in other words; the parameter λ, which indicates the projected angle between a stellar spin axis and a planetary orbital axis. According to observational results obtained with the indirect methods, a lot of Jovian-mass planets but orbiting in periods of a few days (hot Jupiters) have been discovered, as well as planets in highly eccentric orbits (eccentric planets), and planets on orbital planes inclined against stellar equatorial planes (tilted planets; $|\lambda| > 0$ deg). Recently, advancing techniques of the direct imaging method, which aims to directly image a faint object hardly separated from a bright star, enable us to detect planets with large semi-major axes of several tens AU (wide-orbit planets).

Meanwhile, planet formation theories have been constructed to duplicate the Solar system before the discovery of the exoplanets. Planet formation is currently believed to occur in a disk or protoplanetary disk, which rotates around a star in a circular orbit and in the same direction as the stellar spin (so-called prograde) due to its viscosity. Planet formation scenarios are divided mainly in two; the gravitational instability and the core accretion. The gravitational instability model describes that planets directly develop from segments which result from a gravitationally unstable disk. The theory can form a gaseous giant planet in a wide orbit. According to the core accretion model, dust in a disk collides to grow up into planetesimals, and they sequentially accrete to be protoplanets. Rocky planets are expected to be survivors of the protoplanets or consequences of giant impacts. Gaseous planets and icy planets are regarded as those with or without gathered gas by their gravity within the formation time limits, respectively. Therefore, planetary systems including the Solar system are currently believed to be formed via the core accretion model, except that wide-orbit planets which are directly imaged may be explained by the gravitational instability.

However, these planet formation models are not able to explain eccentric planets or tilted planets. This is because a planet formed in a circular-rotating and prograde protoplanetary disk consequently has a circular and prograde orbit. In order to explain the close-in planets as well as these eccentric or tilted planets, planet migration mechanisms have been newly initiated. Based on the models, current planets are not formed *in situ* but migrate from their birthplaces. To explain the eccentric or tilted planets, mainly two models, planet-planet scattering and Kozai mechanism, have been proposed. Planet-planet scattering predicts that more than two giant planets in a system results in two remaining planets and one planet ejected from the system or fallen onto the central star as consequences of their gravitational interactions and orbital intersections. The planets left in the system have eccentricities and orbital inclinations with wide distributions. Kozai mechanism expects an oscillation of a planetary orbit due to a secular perturbation if an outer object (e.g. a stellar companion) is present around the planetary system. This oscillation can explain a high eccentricity and an obliquity of its orbital axis. And yet, it is observationally unclear how effective each migration model is.

In this thesis, we describe the results of our high-contrast observations aiming to constrain the migration mechanisms. We focus on a binary rate in the stars hosting eccentric planets or tilted planets. In single planetary systems, it is unlikely that planet-planet scattering works, which needs counterparts of the scattering; therefore only Kozai mechanism can theoretically work. Therefore, if the binary rates are significantly different in these eccentric or tilted planetary systems, Kozai mechanism can be responsible. If not, the rates suggest that Kozai mechanism is likely ineffective and unknown counterparts of the scattering may be exist. We employed a high-contrast imaging instrument HiCIAO and an adaptive optics system AO188 onboard the Subaru telescope to conduct direct imaging observations at near-infrared wavelengths, targeting planetary systems hosting eccentric ($e \geqq 0.7$) planets or tilted ($|\lambda|>0$ deg) planets. Contrasts for our observations were high enough to practically detect faint objects around the target stars typically with masses of red dwarfs. This is the first high-contrast direct imaging survey with the intension of approaching the planet migration mechanisms and will be important basis for future discussions, though therefore sample sizes are limited. As a result, we detected companions in two out of eight eccentric planet host star systems and in four at least or twelve at most out of fifteen tilted planet host star systems. Of the eccentric planetary systems, the common proper motion test confirmed that two systems really host a physical companion each and one has a background star. Including a known binary system, a binary rate for the eccentric planet host stars resulted in 3/8. Meanwhile, only a few titled planet host stars were adaptable to the test, because of a small proper motion. The final binary rate is unchanged. All companion candidates are effective in causing Kozai effects for a hypothetical planet beyond the snow line of each system.

Although the binary rates are statistically identical with a rate for Solar-type stars in the Solar neighborhood (46%), the rate for the tilted planet host stars except for the least case are significantly higher than the rate for global planet host stars (11.95%) and the rate for the eccentric planet host stars shows statistical indistinguishability but a possible sign of the difference due to the small sample size. The differences possibly indicate that tilted planets (and perhaps eccentric planets as well) have been formed by Kozai mechanism. Though precise theoretical calculations are necessary, our simple estimates could show that more than zero out of eight eccentric ($e \geqq 0.7$) planets and more than one out of fifteen tilted ($|\lambda|>0$ deg) planets have been formed via Kozai mechanism. Our results likely suggest that the influence of Kozai mechanism is statistically negligible. In addition, discussions based on the Bayes factor demonstrate that our sample selections sufficiently eliminate an influence of an aligning model, like type II migration. Moreover, some specific cases significantly favor the rate for the Solar neighbors compared to the rate for global planet host stars. Therefore a possibility that tilted planet host stars more frequently have companion stars than the rate for global planet host stars remains. However, the Bayes factor also indicates that both e and λ distribution of our samples can be explained by planet-planet scattering alone, especially conflicting with the high binary rate for the tilted samples. The inconsistency between the high binary rate and the λ distribution will be solved by future observations and theories. In the future, a larger number of targets are necessary to verify robustness of our results. Furthermore, a rate for circular (e~0) or aligned ($|\lambda|$~0 deg) planets will be surely needed to precisely estimate the influence of Kozai mechanism.