論文の内容の要旨

Formation of hot Jupiters and their spin-orbit evolution

(ホットジュピターの形成とその主星自転・軌道公転角の進化)

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Ever since the first discovery of an exoplanet, 51 Pegasi b, hundreds of hot Jupiters (HJs) with Jupiter-size and semi-major axis less than 0.1 AU have been observed around main- sequence stars. Nevertheless, their origin remains one of the important unsolved puzzles in this field.

The first question addressed in this thesis is the formation of HJs. We investigate the formation of HJs in near-coplanar eccentric hierarchical triple systems via the secular interaction between an inner planet and an outer perturber (Coplanar High-eccentricity Migration; CHEM). This mechanism was originally proposed as a unique formation model of counter-orbiting HJs (the spin-orbit angle, the angle between the stellar spin and the planetary orbit axis, $\psi > 160^{\circ}$). We examine this mechanism in detail by performing a series of systematic numerical simulations, and consider the possibility of forming HJs, especially a counter-orbiting one under this mechanism. We incorporate quadrupole and octupole secular gravitational interaction between the two orbits, and also short-range forces (correction for general relativity, star and inner planetary tide and rotational distortion) simultaneously. We find that most of systems are tidally disrupted and that a small fraction of survived planets turns out to be prograde. The formation of counter- orbiting HJs in this scenario is possible only in a very restricted parameter region, and thus very unlikely in practice. We generalize the previous work on the analytical condition for successful CHEM for point masses interacting only through the gravity by taking into account the finite mass effect of the inner planet. We find that efficient CHEM requires that the systems should have $m_1 \ll m_0$ and $m_1 \ll m_2$. In addition to the gravity for point masses, we examine the importance of the short-range forces, and provide an analytical estimate of the migration timescale. In addition, we extend CHEM to super-Earth mass range, and show that the formation of close-in super-Earths in prograde orbits is also possible. Finally, we carry out CHEM simulation for the observed hierarchical triple and counter-orbiting HJ systems. We find that CHEM can explain a part of the former systems, but it is generally very difficult to reproduce counter-orbiting HJ systems.

The other question addressed in this thesis is the long term spin-orbit angle evolution at the realignment stage. Indeed current observations of the Rossiter-McLaughlin effect have revealed a wide range of spin-orbit misalignments for transiting HJs. We

examine in detail the tidal evolution of a simple system comprising a Sun-like star and a hot Jupiter adopting the equilibrium tide and the inertial wave dissipation effects simultaneously (the Lai model). We find that the combined tidal model works as a very efficient realignment mechanism; it predicts three distinct states of the spin-orbit angle (i.e., aligned, polar, and anti-aligned orbits) for a while, but the latter two states eventually approach the aligned spin-orbit configuration. The intermediate spin-orbit angles as measured in recent observations are difficult to be achieved. Therefore the Lai model cannot reproduce the observed broad distribution of the spin-orbit angles, at least in its simple form. This indicates that the observed diversity of the spin-orbit angles may emerge from more complicated interactions with outer planets and/or may be the consequence of the primordial misalignment between the proto-planetary disk and the stellar spin, which requires future detailed studies.

keywords: planetary migration; dynamical process; tides; numerical simulation