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系外行星系统中潮汐和共振的动力学研究

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近年来, 行星形成理论与行星系统动力学已经成为天文学研究的一个重要领域. 随着系外行星探测的不断深入, 各种与太阳系相比特征迥异的系外行星系统被发现. 大批离恒星极近的行星被发现, 它们的周期只有几天, 从而会受到强烈的潮汐耗散作用. 很多多行星系统中相邻行星的周期比都接近简单整数比, 这预示着它们很可能处在平运动共振. 行星的轨道面与恒星的赤道面夹角的范围也从太阳系内的行星的$\lesssim 7^\circ$ 扩展到$0^\circ \sim 180^\circ$的整个有效范围, 出现了不少逆行的热木星. 这些新现象在挑战传统的行星形成理论与行星系统动力学的同时, 也为其进一步的完善和发展提供了前所未有的机遇. 本文将基于最新的观测数据和统计特征, 从行星系统动力学角度出发, 将潮汐作用与诸共振相结合, 研究行星演化过程中的不同构型.

本文首先回顾了与潮汐力和共振相关的系外行星方面的主要应用和最新进展. 然后分别给出了最经典的和当前最常用的潮汐模型的推导和各根数的平均变化率, 近距离接触了平衡潮模型的简化假设和建模过程. 之后从动力学角度出发, 利用数值模拟和理论分析相结合的方法, 研究了以下3个问题: 行星的自转-轨道共振对其轨道偏心率的影响; 潮汐作用下近$2:1$平运动共振和Laplace共振的演化特点; 外气体盘引力对空洞内行星轨道激发的促进作用. 同时考虑潮汐耗散和行星形变产生的引力, 本文第3章得出结论, 处于非同步自转-轨道共振比处于半平衡状态下的行星轨道耗散速率更大, 从而偏心率也被圆化得更快. 为解释HD40307系统中三行星近$2:1$的两个周期比的形成, 本文第4章分不同情况模拟它们的演化路径. 如果行星在气体盘消散后的演化很稳定, 由行星间相互作用产生的偏心率很小($\sim 10^{-4}$), 导致周期比的变化时标远大于系统的年龄. 而如果行星经历过不稳定阶段, 在期间产生的自由偏心率便可以有效地加速周期比的演化. 在这种情况下, 存在3条路径可以达到当前构型, 3条路径的半长径初值分别对应周期比平面上的3个不同区域. 由此可推断, 气体盘耗散后的不稳定阶段是系统在潮汐作用下从$2:1$共振演化到当前构型的必要条件.

本文第5章针对最新观测到的逆行热木星, 提出一种可以减小轨道激发的临界倾角的机制. 考虑外气体盘的引力, 空洞内的行星在合适位置上会发生长期共振, 长期共振激发的轨道倾角又有可能引发行星之间的Kozai共振, 从而激发内行星的偏心率和倾角. 我们发展了长期摄动下三体问题的根数变化率方程(从相对于不变平面的形式扩展到相对于任意平面的形式), 并给出了二维盘引力下各根数的变化率, 把这两部分线性叠加而得到的演化方程可以很好地近似N体模拟的结果. 利用演化方程对参数空间的扫描, 我们初步给出了可以形成逆行热木星的临界条件, 并较完整地讨论了各个相关参数的影响.

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The Dynamics of Tide and Resonances in Exoplanetary Systems

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In recent years, the planet formation theory and planetary system dynamics have become an important area of astronomy. With more details of exoplanets being found, many characteristics quite different from the solar system have been found in the exoplanetary systems. A large number of planets are found to be very close to their host star, and their periods are only a few days, which brings strong tidal dissipation with the star. Many period ratios of adjacent planets in multi-planetary systems are close to the simple integer ratios, which indicates that the planets are likely in the mean motion resonances (MMRs). The range of the angles between the orbital plane of the planets and the equatorial plane of their hosts expands from $\lesssim 7^\circ$ for the planets in the solar system to $0^\circ \sim 180^\circ$, and some retrograde hot Jupiters exist. These new phenomena are testing out the traditional planetary formation theory and planetary system dynamics, but also provide an unprecedented opportunity for their further improvement and development. Based on these latest observational data and statistical features, the thesis investigates some special configurations combining the resonances and tidal dissipation by the way of planetary system dynamics.

The thesis first reviews the primary applications and the latest progress in the tide as well as various resonances of exoplanets. Then it gives some tidal model derivations, including the classic one and most popular one, in order to understand the assumptions of the equilibrium tide. Meanwhile, the average rates of change of orbital elements under tidal dissipation are exhibited. By both numerical simulation and theoretical analysis, the following three questions are investigated: the evolution of the eccentricity of planets in the non-synchronous spin-orbit resonances, the characteristics of nearly 2 : 1 MMR and Laplace resonance under tidal dissipation, and the promoting role of the gravity of outer gas disk for exciting the planets in its inner cavity. Chapter 3 takes into account the tidal dissipation and the gravity from planet deformation, and concludes that, the tidal dissipation rates in all the non-synchronous spin-orbit resonances are greater than that in the quasi-stationary state of the spin of the planet, so the eccentricity is also damped within a shorter duration. In order to explain the formation of two period ratios nearly 2 : 1 in the three planet HD40307 system, Chapter 4 simulates the evolution paths of planets in two different situations. If the planets are always stable during and after the dissipation of gas disk, their eccentricities directly from the interaction among planets are very small ($\sim 10^{-4}$). So the changing timescale of period ratios is much larger than the age of the system. On the contrary, if the planets have experienced unstable phases, their eccentricities would be excited, which can accelerate the evolution of the period ratios effectively. In this situation, three paths exist to achieve the current configuration, whose initial semi-major axes respectively correspond to three different regions on the plane of two period ratios. It can be inferred that the instability stage after the dissipation of the gas disk is a necessary condition for the system to achieve the evolution from 2 : 1 MMRs to the current configuration under tidal dissipation with the

star.

Chapter 5 proposes a mechanism to reduce the critical inclination of orbital pumping, in order to explain the retrograde hot Jupiters in latest observations. Considering the gravity of the outer gas disk, a secular resonance would occur between the planets in the inner cavity if they are in appropriate positions, which pumps the mutual inclination of the planets and induces the Kozai resonance between them in some situations. Then the eccentricity and inclination of the inner planet will be excited eventually. We develop the equation of the rates of change of orbital elements under the secular perturbation in hierarchical three-body system (with respect to an arbitrary plane rather than the invariant plane of the two orbits), as well as give the rates of change of orbital elements under a 2-D disk gravity equations. Combining the two parts, the results by integrating the evolution equations are good approximation of the N-body simulations. By scanning the parameter spaces using the evolution equations, we get the preliminary critical condition for the retrograde hot Jupiters formed, and give a complete discussion of the impact of relevant parameters.