博士学位论文摘要选登

太阳系外行星系统构型的形成与动力学

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自从 Maryor 和 Queloz 于 1995 年在 51Pegb 周围发现了第 1 颗主序恒星系统内的行星以来，人类已经利用越来越精密的探测方法获得了更多的太阳系外行星系统的信息. 截至 2010 年 3 月，人类已经探测到了 431 颗太阳系外行星，其中包含了 45 个多行星系统. 从统计结果来看，系外行星系统的构型以及行星的特点与太阳系存在很多差异. 研究这些系统的形成过程可以对太阳系的形成有更深刻的理解，并将推进行星系统形成理论的发展.

本文主要研究太阳系外多行星系统形成过程中几个重要因素和阶段对系统构型的影响，包括行星之间的散射过程，轨道收敛迁移过程中的共振俘获以及发散迁移过程中的共振穿越，小质量行星的第 1 类轨道迁移等. 这些过程最终将决定系统中行星的轨道半长径和偏心率的构型，是否存在类地行星和可居住行星等现象.

我们主要研究了 3 种构型的形成过程：(1) 偏心率 – 近点角平面上的近分界线运动构型是目前观测到的系外多行星系统中主要的动力学特点之一，我们发现系统形成过程中行星与行星胚胎或者行星之间的散射机制是该动力学特点的重要触发机制之一. (2) OGLE-06-109L 系统中两行星的构型与太阳系中木星 - 土星的构型相似，尤其是半长径和偏心率，这两个系统在形成中可能经历了相同的过程. 我们研究了形成该系统偏心率构型的 3 种可能机制：行星收敛迁移中的平运动共振俘获、行星之间的散射过程、行星发散迁移中的平运动共振穿越. 揭示了 3 种机制下形成的行星最终构型的不同特征，如：平运动共振俘获最后两行星会处于共振中；散射过程将会导致偏心率的激发，并使行星对的构型处于近分界线运动中，行星偏心率演化周期为系统长期摄动周期；共振穿越后行星的偏心率演化周期与最近穿越过的平运动共振的周期相近. 目前的观测还不能完全确定哪一种机制在该系统中起主导作用，有待后续观测的检验. (3) 以 HD40307 系统为例研究了 3 颗行星处于近 1:2:4 共振 (Laplace 共振) 轨道构型的形成机制. 该系统中 3 颗行星均为短周期的大质量类地行星. 我们提出，它们是在雪线附近形成后通过第 1 类轨道迁移到内部区域的，而为了形成其轨道周期的近 1:2:4 的构型，模拟表明第 1 类轨道迁移比较合理的速度是目前线性分析估计结果的 0.1 倍. 3 颗行星在共振中进一步迁移，到靠近中心天体位置时，行星在与恒星之间的潮汐作用下最终脱离共振后演化到目前观测的位置. 最后，在考虑第 1 类轨道迁移对类地行星形成的影响下，我们对以 OGLE-06-109L 系统为代表的矮星系统中类地行星尤其是可居住行星的分布进行了研究. 结果显示，根据以后观测可能得到类地行星和可居住行星的质量和含水量等信息，就可以推知行星轨道迁移过程中速度的快慢以及是否经历过碰撞合并过程.

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Configuration Formation and Dynamics of Exoplanet Systems

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To date, more than 431 exoplanets have been detected since 1995, among them there are 45 multiple planetary systems. There are lots of differences between the solar system and the extrasolar planetary systems. We study several important factors and phases in the formation process of exoplanet system, including scattering process, mean motion resonance (MMR) capture, resonance crossing and the speed of type I migration for low-mass planets. Those processes will decide the final configurations of semi-major axes and eccentricities in the system and whether there are terrestrial and habitable planets in the system.

We mainly study three configurations: (1) Near-separatrix motion which is one of the properties of the multiple exoplanet systems. According to our research, during the formation process, planet scattering will lead to the near-separatrix motion which is common in exoplanet systems. (2) OGLE-06-109L system is an analog of the solar system especially the Jupiter-Saturn configuration in semi-major axes and eccentricities. So the two systems may undergo the same process. We study three possible reasons that can lead to this configuration: MMR capture during the smooth convergent migration, planetary scattering and MMR crossing during the divergent migration. They will lead to different properties of the final configuration of the system. After the resonance capture, two planets will be in MMR until some processes destroy it. Scattering process will excite the eccentricities of the planets and lead them into near-separatrix motion. Then the evolution period of the eccentricities of planets will be in the period of secular motion. Resonance crossing will also excite the eccentricities of planets. The evolution period of the eccentricities will be in the period of MMR which they just crossed. According to the present observational data, we can not decide which mechanism is the best one, but in the future they will be checked out. (3) We study the configuration of near 1:2:4 resonances (Laplace resonance) using HD40307 as an example. The three planets in the system are all massive terrestrial planets. We suggest that they all formed near the snow-line of the system and migrate to the locations where they are observed through type I migration. In order to form the configuration of near 1:2:4, the speed of type I migration may be one tenth of the linear analysis result. When they migrate to the locations close to the central star, the tidal effect from the star will lead them into the nominal locations. Finally, we study the distributions of the habitable planets and terrestrial planets in dwarf stars under the effect of the speed of type I migration. We use OGLE-06-109L as an example. Through our study on the type I migration and water content in planet, if we know the masses and the water contents of the habitable planets in the system, we will deduce the migration speeds during the formation processes and whether they have gone through merging process during the formation.