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博士学位论文摘要选登

类地行星的形成、内部结构与大气逃逸

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截止到2014年4月21日, 已发现了1 490多颗系外行星和3 705颗Kepler候选体. 这从观测角度证明了行星在银河系中是普遍存在的. 对系外行星的研究丰富并加深了人们对行星形成与演化的认识. 另外, 新的观测与发现也不断提出新的科学问题. 本论文开展了类地行星的形成演化、内部结构以及大气逃逸的研究.

本文第2章针对行星形成晚期的大规模碰撞阶段开展了数值模拟, 发现类地行星(包括位于系统宜居区内的行星)的形成是普遍现象. 模拟结果表明, 巨行星的较大轨道倾角不利于星子吸积，因为在高倾角巨行星的扰动下, 大量星子会被散射出系统或直接撞向中央恒星, 这使得星子盘内部的物质大幅度减小. 加入轨道迁移的模拟表明，行星的轨道迁移是产生短周期类地行星的主要机制. 除了迁移机制外，我们还发现通过碰撞合并机制形成的短周期类地行星，其动力学形成过程主要体现在行星胚胎间的大规模碰撞.

在第3章，我们建立了一个计算类地行星内部结构的数值模型，并利用这个模型得到了木卫二的3种可能结构. 进一步，我们把这个内部结构模型应用于低质量系外行星, 发现一些系外行星的质量半径关系不符合岩石类行星, 它们只能用具有大气包层或者含有大量水冰成分的结构模型来拟合. 这些结果可以对系外行星的总体物质成分做出限定.

在第4章, 我们用semi-gray模型(Guillot 2010)对现有的计算行星大气结构的程序做了改进，加入了恒星辐射对行星大气上层的加热效应. 这个改进一方面使行星演化程序适用于短周期行星，另一方面可以得到行星大气上层辐射区域的结构，这样程序就可以模拟由恒星的X-ray与EUV辐射驱动的流体动力学大气逃逸. 本章的模拟表明, 低质量行星很容易受到大气逃逸影响, 它们有可能在演化阶段被剥离全部初始大气. 相反, 气态巨行星的演化受大气逃逸的影响较小, 它们只能被剥离很少一部分大气. 本章还在行星内核质量、大气质量比例、轨道半长径的参数空间对大气逃逸做了研究, 发现在行星演化早期的100 Myr内大气逃逸最剧烈. 其后, 大气逃逸对行星演化的影响不明显.

在第5章, 将大气逃逸模型与基于核吸积模型的行星族群综合分析(Planetary population synthesis)结合起来(Mordasini et al. 2012a,b). 我们给出了在行星的半径分布上由大气逃逸产生的统计特征. 研究发现, 在2 $R_\oplus$附近行星半径呈双峰分布(Owen & Wu 2013), 这个双峰分布与行星族群最初的特性相关. 因为在由核吸积模型产生的行星族群中, 所有行星的大气均为原生的H/He大气. 此外，小于4 $R_\oplus$的行星的初始大气质量比例一般小于10%, 它们的大气层容易被全部剥离. 而大质量行星具有较大的初始大气质量比例与引力势能, 它们受大气逃逸的影响很小. 通过与Kepler候选体的半径分布做比较，我们排除了不含大气逃逸的演化模型与加热效率为100%的大气逃逸模型.

本文的第6章介绍了一个计算行星光谱的辐射转移模型. 这是为将来建立一套大气反演程序所做的准备工作.

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Formation and Internal Structure of Terrestrial Planets, and Atmospheric Escape

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As of 2014 April 21, over 1490 confirmed exoplanets and 3705 Kepler candidates have been detected. This implies that exoplanets may be ubiquitous in the universe. In this paper, we focus on the formation, evolution, and internal structure of terrestrial planets, and the atmospheric escape of close-in planets.

In chapter 2, we investigate the dynamical evolution of planetary system after the protoplanetary disk has dissipated. We find that in the final assembly stage, the occurrence of terrestrial planets is quite common, and in 40% of our simulations finally at least one planet is formed in the habitable zone. We also find that if there is a highly-inclined giant planet in the system, a great many bodies will be either driven out of the system, or collide with the giant planet or the central star. This will lead to the difficulty in planetary accretion. Moreover, our results show that planetary migration can lead to the formation of close-in planets. Besides migration, close-in terrestrial planets can also be formed by a collision-merger mechanism, which means that planetary embryos can kick terrestrial planets directly into orbits that are extremely close to their parent stars.

In chapter 3, we construct numerically an internal structure model for terrestrial planets, and provide three kinds of possible internal structures of Europa (Jupiter's moon) based on this model. Then, we calculate the radii of low-mass exoplanets for various mass combinations of core and mantle, and find that some of them are inconsistent with the observed radius of rocky planets. This phenomenon can be explained only if there exists a large amount of water in the core, or they own gaseous envelopes.

In chapter 4, we improve our planetary evolution codes using the semi-gray model of Guillot (2010), which includes the incident flux from the host star as a heating source in planetary atmosphere. The updated codes can solve the structure of the top radiative zone of intensely irradiated planets, and thus can simulate the atmospheric escape of close-in planets driven by strong stellar X-ray or EUV emissions. We find that low-mass planets are sensitive to the atmospheric escape, and they could lose all their initial H/He envelopes during the evolution. On the other hand, gas giant can only lose a small fraction of their initial envelopes. We then carry out a parameter study of atmospheric escape at the planetary core mass, envelope mass fraction, and semi-major axis space. We find that the most intense phase of evaporation occurs within the early 100 Myr. Afterwards, atmospheric escape only has a small impact on the planetary evolution.

In chapter 5, we apply our new planetary evolution model to different synthetic planet populations that are directly produced by the core-accretion paradigm (Mordasini et al. 2012a,b). We show that although the mass distribution of the planet populations is hardly affected by evaporation, the radius distribution clearly shows a break around 2 $R_{\oplus}$. This break leads to a bimodal distribution in planet sizes (Owen & Wu 2013). Furthermore, the bimodal distribution is related to the initial characteristics of the planetary populations.

We find that in two extreme cases, namely without any evaporation or with a 100% heating efficiency in the evaporation model, the final radius distributions show significant differences compared to the radius distribution of Kepler candidates.

In chapter 6, we introduce a radiative transfer model that can calculate the radiation spectrum of close-in exoplanets.

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