# Formation and Evolution of Exoplanets

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**Chapter 1 – Exoplanet Observations**

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The discovery and characterization of planets around other stars has revolutionized our view of planetary system formation and evolution. In this chapter, we summarize the main results from the observational study of exoplanetary systems in the context of how they constrain theory. We focus on the robust findings that have emerged from examining the orbital, physical, and host star properties of large samples of detected exoplanets. We also describe the limitations and biases of current observational methods and potential overinterpretations of the data that should be avoided. In addition, we discuss compelling individual results that offer views beyond the well explored parameter spaces.

**Chapter 2 – Pinpointing Planets in Circumstellar Disks**

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Recent observations of circumstellar disks have revealed a variety of interesting morphology: clearings, puffed up disk edges, gaps, spiral-like features, warps, clumps, and lopsidedness. Models proposed to account for circumstellar disk morphology can involve unseen massive objects, such as planets or planetary embryos. Here we review recently explored scenarios and dynamical processes relating circumstellar disk morphology to underlying planetary system architecture. The directly detected outer planet in the Fomalhaut system confirms a prediction for its orbit and mass made prior to discovery based on its interaction with the Fomalhaut's circumstellar disk. Interpretations of circumstellar disks will increasingly depend on dynamical scenarios linked to planetary system evolution.

**Chapter 3 – Planet-Planet Interactions**

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Planetary orbits in multiple planet systems change with time due to gravitational perturbations between planets. These interactions often produce periodic variations in the orbital properties, but in some cases incite chaotic motion, culminating in the ejection of one or more planets from the system. This chapter introduces how planets may interact gravitationally, describes techniques that model the perturbations, and presents the current range of observed interactions. Many observed systems lie close to the boundaries between dynamical stability and different types of apsidal motion, placing tight constraints on origins scenarios.

**Chapter 4 – Formation Via Disk Instability**

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We review the disk instability mechanism for giant planet formation. We begin with describing the physics of gravitational instability in gaseous protoplanetary disks and its modeling by means of numerical simulations. We present the predictions of current simulations for the masses, orbits and dynamical evolution of clumps formed by disk fragmentation. We compare the predicted properties with those of the known population of extrasolar planets. Disk instability appears to produce planets with masses ranging from that of Saturn to $10-15$ Jupiter masses, and with eccentricities $e = 0.1 - 0.3$, close to the mean orbital eccentricity of extrasolar gas giants. Lower mass planets with masses comparable to ice giants and super-Earths may also form as result of photoevaporation of the envelopes of clumps formed by disk instability. Subsequently, we discuss scenarios that could explain the observed correlation between the frequency of planets and the metallicity of host stars in the context of disk instability. In addition, recent results on the interior structure and composition of giant planets formed via fragmentation are presented. We discuss how formation of a solid core and envelope enrichment could take place in the gas clumps later during their evolution. We conclude with a critical scrutiny of how the initial conditions of protostellar disks, their dynamical evolution, and the presence of a binary companion might affect the fragmentation process.

**Chapter 5 – Core Accretion Model**

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The discovery of planets around stars other than the Sun has provided planetary scientists with a challenge to extend their knowledge that is based on our planets in the Solar System. With the ever increasing number comes the realization that the nature of these planets is diverse thereby adding complexities to an already complicated problem. Scientists and philosophers have been proposing models for planetary formation for centuries, however, contemporary models are sophisticated enough now to explain the various observations associated with the gas giants in the solar and extrasolar systems.

One scenario for the formation of the gas giant planets is the core nucleated gas capture model, known widely as the core accretion model. According to this model, planets begin their evolution by accreting planetesimals into a solid core that is eventually large enough to gravitationally accrete gas from the solar nebula. This chapter describes the basic information that is needed to acquire a robust understanding of the model in its theoretical and computational form.

This chapter begins with a brief historical review of the core accretion model and the results and progress by the early investigators will be presented. This is followed by a description of the observational constraints that any theoretical model should address. An overview of the core accretion model will follow that describes the protoplant's growth from an embryo to a present day gas giant planet and the introduction of the the mathematical structure of the model, the boundary conditions, and the assumptions applied in the simulation will be included. After a discussion of the results of computer simulations based on the core accretion model, the chapter will end with a summary of topics related to the core accretion model (*e.g.* migration, metallicity, etc.) and final remarks for future studies.

**Chapter 6 – Formation of Terrestrial Planets**

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Terrestrial planets are thought to form in a series of dynamical steps, starting from micron-sized dust grains in protoplanetary disks. Km-sized planetesimals form via a combination of collisional growth, concentration of small particles via gasdynamic effects, and gravitational collapse. Roughly Moon-sized planetary embryos are thought to form via runaway and oligarchic growth from planetesimals while still embedded in the gaseous disk, although recent results suggest that the runaway stage may be skipped if 100-1000 km planetesimals are quickly assembled from cm- to m-sized rocks in turbulent structures. Finally, full-sized terrestrial planets accrete from embryos and planetesimals on a 10-100 Myr timescale. This final stage is strongly affected by gravitational perturbations from any giant planets, which are constrained to have formed in the few Myr lifetime of the gaseous component of the disk. Mixing between radial zones occurs during the last stages of growth, and determines the bulk planetary compositions. The primary factors that govern terrestrial planet formation are the properties of the protoplanetary disk, and perturbations from giant planets and binary companions if they exist. A simple model is derived to apply the results of accretion simulations to the known extra-solar planet population.

**Chapter 7 – Brown Dwarfs**

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This chapter explores the relationship between brown dwarfs and planets. It begins by examining definitions of brown dwarfs and giant planets and possible observational diagnostics for distinguishing between these two classes of substellar objects. The prospects for planet formation around brown dwarfs are then investigated through a review of the observed properties of circumstellar disks around brown dwarfs, including their frequencies, lifetimes, compositions, inner holes, radii, and masses. Finally, results from searches for planets around brown dwarfs are summarized.

**Chapter 8 – Exoplanet Chemistry**

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The terrestrial and gas-giant planets in our solar system may represent some prototypes for planets around other stars; the exoplanets because most stars have similar overall elemental abundances as our sun. The solar system planets represent at least four chemical planet types, depending on the phases that make them: Terrestrial-like planets made of rock (metal plus silicates), Plutonian planets made of rock and ice, Neptunian giant planets of rocky, icy with low H and He contents, and Jovian gas-giant planets of rocky,

icy planets with near-solar H and He contents. The planetary compositions are linked to the chemical fractionation in the planetary accretion disks. Chemical tracers of these fractionations are described. Many known exoplanets are gas-giant planets with up to several Jupiter-masses and their atmospheric chemistry is compared to that of brown dwarfs. Exoplanets in close orbits around their host stars may resemble hot brown dwarfs (L-dwarfs). Planets receiving less radiation form their host may compare more to the methane-rich T dwarfs. The cloud layers resulting from condensation of oxides, metal, sulfides, and salts in these hot and cool gas giant planets and their chemical tracers are described.

## Chapter 9 – Migration and Multiplicity Effects During Giant Planet Formation

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Protostellar disks convert themselves into planetary systems in complex interplay of different physical processes . The imprint of this is recorded in the diverse masses, orbits and dynamics of the detected exoplanets, and in the Solar System. Here, we begin by summarizing the current understanding of planet-disk interactions, and how these drive orbital migration of young planets. Then, we look at how migration combines with the other major concurrent processes— planet-planet interactions, competitive accretion and disk evolution— over the 1-10 Myr lifetime of a protostellar disk. By considering all these effects together, we gain a much clearer understanding of how planet formation produces such a rich variety of outcomes.

## Chapter 10 – Planets in Mean Motion Resonance

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At the time of writing (October 2008) about 30 extrasolar planetary systems containing multiple planets have been detected. Among those a high fraction (about 30%) seems to be located in a mean-motion resonance (MMR). In a MMR the orbital periods of the involved planets are commensurable and their ratio can be described by two small integers. The most frequent commensurability found in the extrasolar planetary systems is the 2:1 MMR while others such as 3:1, 4:1 or 3:2 may also exist. Current scenarios of planet formation allow for the creation of planets at arbitrary radii. Hence, it is strongly believed that the special resonant configurations did not form in situ but are a result of evolution of the whole planetary system. Thus, the mere existence of resonant configurations may provide us with additional information about the evolutionary history of planetary systems.

In the Solar System the 3:2 mean-motion resonance between Neptune and Pluto was caused by an outward migrating Neptune. Similarly, extrasolar planets can be driven into a resonant configuration through the operation of a dissipative mechanism that is able to change the energy of the orbits, *i.e.* the corresponding semi-major axis of the objects. In the context of planet formation of massive planets, the interaction of the protoplanets with the ambient gaseous protoplanetary disk is able to provide a differential migration between two planets, and upon reaching commensurability resonant capture may occur. In this chapter we briefly summarize the current observational evidence for mean-motion resonances in extrasolar planetary systems, and then outline in more detail possible formation scenarios and the particular conditions that may have led to the presently observed states.

**Chapter 11 – Planet–Planet Gravitational Scattering**

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In planetary systems populated by two or more giant planets, planet–planet scattering can lead to collisions and ejections of one or more bodies. The original planetary configuration can be significantly altered by this kind of dynamical evolution and the presently observed system would be very different from the original outcome of the planet formation process. For scattering to occur, either the planets formed in an unstable configuration or migrated into it because of tidal interactions with the protostellar disk. The strong gravitational interactions typical of the chaotic phase of planet–planet scattering cause large changes in the orbital elements of the planetary bodies. The distribution of orbital eccentricities for the known extrasolar planets, with values even exceeding 0.9, may easily arise through planet-planet interactions. In addition, the combination of planet–planet scattering and tidal circularization can explain some of the orbits of the so called "Hot Jupiters", giant planets with very short period orbits. In this context, the efficiency of close–in planets production is significantly increased by Kozai oscillations induced by the outer planet(s) on the inner one. The chaotic evolution of the system dominated by close encounters between the planets depends on the presence of a residual gas disk which may affect the interactions between the planetary bodies. In binary star systems this evolution is even more complex and the gravitational perturbations of the companion star may influence the outcome of the planet–planet scattering phase.

**Chapter 12 – Tides and Exoplanets**

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Tides have influenced the orbital and physical properties of exoplanets with orbits close ($\leq 0.2$ AU) to their host stars. Recent studies have shown that gaseous exoplanets have experienced orbital circularization and migration, merging with the host star, and that undetected planets may be present in some systems. Furthermore, dissipation of tidal energy inside gaseous exoplanets can inflate their radii. These same tidal processes may also occur on rocky exoplanets, potentially impacting habitability. This chapter describes tidal theory and summarizes recent investigations examining tides and exoplanets.