THE OUTER PLANETS AND THEIR MOONS

Cover illustration:

A mosaic of nine processed images recently acquired during Cassini's first very close flyby of Saturn's moon Titan on 26 October, 2004, constitutes the most detailed full-disc view of the mysterious moon prior to December 2004. Courtesy of NASA/JPL/Space Science Institute.

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THE OUTER PLANETS AND THEIR MOONS

Comparative Studies of the Outer Planets prior to the Exploration of the Saturn System by Cassini-Huygens

Volume Resulting from an ISSI Workshop
12–16 January 2004, Bern, Switzerland

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ISSI Workshop, 12–16 January 2004, Bern, Switzerland

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PREFACE

The workshop organized by ISSI on the study of the outer planets came exactly one year after it was decided by a group of scientists and by its Science Committee meeting in Beatenberg near Bern in January 2003, that ISSI should broaden its range of subjects, in particular through introducing comparative planetology in its program of workshops and teams. This is a remarkable performance that reflects ISSI's rapid reaction to the advice of its users, i.e. the scientific community. Therefore the book is the first of the ISSI series to address the topic of comparing the planets and their satellites in the Solar System beyond the orbit of Jupiter. The book comes also at a very crucial moment, while the NASA-ESA Cassini-Huygens mission starts the exploration of Saturn and of its system of rings and satellites, including the biggest of them, Titan, with the European Huygens probe.

From the very beginning, ISSI has emphasized the importance of its role in offering to the scientific community a service in the organization of interdisciplinary and truly international meetings, providing a strongly needed cross-fertilization approach between various scientific disciplines. It will be easily recognized through the various chapters of the book that, indeed, the workshop responded exactly to this requirement. The objects that are present in the outer Solar System are so varied, that only can they be properly analyzed, and their properties properly understood, by assembling the best experts in the world in as divers disciplines as the formation of planetary systems, atmospheric and magnetospheric physics and ... biology!

Certainly, the topic addressed here is progressing very fast as the new data from the Galileo and the Cassini-Huygens missions are arriving. The field is therefore moving and the book has no other ambition than to provide a reference of the state of knowledge acquired as of now by these space missions and from their interpretation by an international group of experts. It is offering a tool that the scientists involved in these missions might find useful for the continuation of their work. I am pleased that it comes at such a critical time and that it should remain such a reference, until the work it will inspire opens new avenues in the field which will probably require another workshop in a few years from nowĚ

Preparing a workshop like this one, publishing its proceedings in less than a year, relies on the dedication and on the work of many people, from the scientists involved in establishing the program to those who have written their contributions and those who have taken a substantial portion of their scientific time to read and referee them. Acknowledgements are warmly addressed to all of them on behalf of R. Kallenbach and me. The experts who have reviewed the articles of the book have agreed to be identified:

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Certainly, it is also a pleasure to acknowledge the support and the continuous assistance of the ISSI staff without which no such achievement would be possible.

I am particularly pleased to congratulate one of the authors of this volume, Michel Blanc of the Observatoire Midi Pyrénées, for having received the Jean Dominique Cassini Medal and the 2004 Honorary Membership of the European Geosciences Union. Since the early 1990's, Michel Blanc has obtained important new results on planetary magnetospheres, in particular on plasma transport and radiation belts in the highly axisymetric environment of Saturn. He has played an outstanding role in the preparation of the Cassini/Huygens mission as an Interdisciplinary Scientist. The topic of his medal lecture carried the title 'A Journey to Saturn through Solar System Magnetospheres.'

As this is the second edition of the volume, we meanwhile know that with Margaret Kivelson we also have the holder of the 2005 Hannes Alfvén medal of the European Geosciences Union among the authors. The reprint of this book gives me the chance to direct my cordial congratulations to Margaret Kivelson.

November 2004 and July 2005

Roger-Maurice Bonnet, ISSI Executive Director

A COMPARATIVE STUDY OF THE OUTER PLANETS BEFORE THE EXPLORATION OF SATURN BY CASSINI/HUYGENS: INTRODUCTION

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This volume, number 19 in the "Space Sciences Series of ISSI," presents the proceedings of the workshop on "A comparative study of the outer planets before the exploration of Saturn by Cassini-Huygens" which was held at ISSI in Bern on January 12–16, 2004. The purpose of this workshop was to bring together representatives of several scientific communities, such as planetary scientists, astronomers, space physicists, chemists and astrobiologists, to review our knowledge on four major themes: (1) the study of the formation and evolution processes of the outer planets and their satellites, beginning with the formation of compounds and planetesimals in the solar nebula, and the subsequent evolution of the interiors of the outer planets, (2) a comparative study of the atmospheres of the outer planets and Titan, (3) the study of the planetary magnetospheres and their interactions with the solar wind, and (4) the formation and properties of satellites and rings, including their interiors, surfaces, and their interaction with the solar wind and the magnetospheres of the outer planets.

At present, the study of the outer planets is particularly motivated by the fact that the Saturn system is being investigated by the Cassini-Huygens mission which will last until 2008 and possibly beyond. Ground-based and space observations of the giant planets over the past decade give evidence that each system has unique characteristics. Jupiter has been extensively studied over the past ten years by the Galileo mission, which, for instance, has measured a global enrichment of heavy elements as compared to hydrogen, with respect to the solar values, showing evidence for a solar composition of the icy planetesimals which formed Jupiter; Galileo has also revealed the unexpected internal dynamics of the Jovian satellites. Comparisons among the giant planets' satellites have provided clues to our understanding of the major processes driving the evolution of Earth-like planets. Jupiter has also been explored at the time of the Cassini flyby, while all four giant planets have been studied by HST, ISO and ground-based observations.

The following key questions were addressed at the workshop: What will we explore on Saturn and Titan with Cassini-Huygens, and what do we expect to find? Which coordinated ground-based observations should be made to complement and

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extend those observations? What can we expect from future large ground-based and Earth-orbit observatories? What are the concepts of future space missions, orbiters or probes exploring the outer planets?

The program of the workshop was set up by four conveners, Thérèse Encrenaz (Observatoire de Paris, Meudon, France), Reinald Kallenbach (ISSI, Bern, Switzerland), Tobias Owen (University of Hawaii, USA) and Christophe Sotin (Université de Nantes, France), who invited experts to give reviews in four areas: (1) formation of the outer planets, (2) neutral atmospheres of the giant planets and their satellites, (3) aurorae and magnetospheres, and (4) satellites and rings. In addition, a keynote lecture on the Cassini-Huygens mission was given by J.-P. Lebreton as an introduction. Most of these reviews, with the addition of a few others, have been collected in the present book. The following introduction to the four workshop themes have benefitted from the input of the authors of these reviews.

1. Formation and Evolution of the Giant Planets

In the first section, “Formation and evolution of the giant planets,” J. Lissauer gives an overview of the giant planets’ formation, while S. Weidenschilling studies more specifically the accretion mechanism of planetary cores. I. Baraffe presents theoretical models of the giant planets’ internal structure, with special emphasis to the extrasolar giant planets. W. Benz and Y. Alibert review the models of exo-giant planets’ formation and, in particular, the constraints related to the timescale of the mechanisms involved. D. Gautier and F. Hersant present a model in which volatiles are trapped by clathration.

The discussions associated to this first section can be tentatively summarized as follows. The is a general agreement on the following points: (1) the nucleation model seems to be generally accepted for the giant planets of the solar system; this model is supported, in particular, by the enrichment in heavy elements observed in Jupiter, it is also supported by the carbon enrichment observed in the other giant planets, and by the deuterium enrichment observed in Uranus and Neptune; (2) in the case of exo-giant planets, the high-metallicity correlation seems to be also in favor of the nucleation formation scenario; (3) theoretical models show that the giant and the exo-giant planets can migrate over substantial distances during their formation.

There are many remaining open questions, however. What were the timescales of the three different phases of the nucleation model: runaway solid accretion, solid and gas accretion, and (for Jupiter and Saturn only) runaway gas accretion? Did the giant planets migrate, and how? In which form (ices or clathrates) were the volatiles trapped? How can we explain the low temperature trapping of the planetesimals which formed Jupiter? What were the sizes of the central cores of the giant planets, and what can we expect for exo-giant planets?

What would be the key measurements for the future? A crucial parameter is the determination of elemental and isotopic abundance ratios in all giant planets, as was done by the GCMS experiment aboard the Galileo probe in the case of Jupiter. The CIRS infrared spectrometer aboard the Cassini orbiter is expected to better constrain some of these ratios but the ultimate answer will come from descent probes, in Saturn but also in Uranus and Neptune. We note that in the case of Uranus and Neptune whose cloud structure is expected to extend at deep tropospheric levels (down to 100 bars or more), a probe could measure at least the abundance ratios of carbon and the rare gases. To better constrain the internal structure of the giant planets, we need an accurate measurement of their gravitational moments. Here again, Cassini will hopefully provide some measurements on Saturn's gravity field.

2. Neutral Atmospheres of the Giant Planets and their Satellites

Comparative studies of the giant planets' neutral atmospheres are given by T. Encrenaz for the chemical composition, S.K. Atreya and A.S. Wong for the cloud structure, R.F. Beebe for the dynamics and D.F. Strobel for the photochemical processes. An overview on the formation and evolution of Titan's atmosphere is presented by A. Coustenis, while the behavior of Titan's haze is studied by M. Roos-Serote. A comparative analysis of the nature of aerosols in the giant planets and Titan is presented by R. Courtin. Finally, E. Lellouch summarizes our knowledge of Io's atmosphere and surface-atmosphere interactions.

There is a general agreement within the community about the abundance ratios in Jupiter and, in the three other giant planets, about the C/H and D/H ratios. As mentioned above, these results strongly favor the nucleation model of the giant planets. The main cloud composition and structure in the giant planets seems to be globally understood, on the basis of thermochemical models; however, it was measured only in the case of Jupiter, from the Galileo probe in-situ measurements. The wind profiles are well determined (but not so well understood) for all giant planets. The atmospheric composition of Titan and Io is now well known. The stability of Io's atmosphere can be understood as a balance between sources (SO_2 sublimation, volcanic output) and losses (SO_2 condensation, photolysis and escape).

What are the open questions raised by these results? First, as mentioned above, we need to determine the abundance ratios of Saturn, Uranus and Neptune. Were these planets also made of solar composition icy planenesimals, as seems to be Jupiter? In addition, the O/H ratios measured in Jupiter's and Saturn's tropospheres appear to be smaller than the solar value. This anomaly, in the case of Jupiter, was attributed to local meteorological effects. Is it the case of Saturn too, and what are the mechanisms which drive the general circulations of the giant planets? Another challenging question is related to the observed differences between Uranus and Neptune. Why is there no internal energy in Uranus? Why is the eddy dffusion coefficient much smaller on Uranus than on Neptune? Why are CO and HCN much more abundant in Neptune's stratosphere than in Uranus'? What is the origin of HCN in Neptune, and of CO in both planets? More generally, what is the nature of the oxygen source in the four giant planets and Titan? Finally, what are the elemental abundances in Titan's atmosphere? What is the physical and chemical nature of its surface? What is the source of the atmospheric methane?

Many questions related to Saturn and Titan will be addressed by the Cassini mission. Hopefully, the Huygens probe will provide in-situ masurements of Titan's atmospheric and surface composition. The orbiter instruments will give information on Saturn's atmospheric composition, cloud structure, photochemistry and general circulation. The Herschel submillimeter Earth-orbiting observatory, to be launched in 2007, will hopefully allow us to better understand the nature of the external oxygen source in the giant planets and Titan. Their atmospheric composition will be studied with further detail by HST, NGST, the ground-based submillimeter array Alma and large ground-based optical telescopes. The JIMO space mission, in orbit around Jupiter, will hopefully provide constraints on the composition of Jupiter's deep troposphere and on Io's atmosphere. The next step of space exploration will have to be, as mentioned above, a multiprobe mission toward the giant planets. Concerning theoretical work, future modelling will be necessary to understand the general circulations of the giant planets (Uranus in particular) and Titan. Phochemical models will have to be developed to model the stratospheric composition and evolution of the giant planets in the presence of an external oxygen source.

3. Aurorae and Magnetospheres

The exploration of the Saturn system by Cassini/Huygens offers the opportunity to study many types of interactions between planetary bodies and space plasma. Saturn itself has an intrinsic magnetic field and forms a corotation-dominated magnetosphere inside the solar wind. Unmagnetized Titan with its dense atmosphere forms an induced magnetosphere inside the plasma of the Kronian magnetosphere or at times inside the solar wind. The surfaces and exospheres of the icy satellites such as Dione or Rhea interact directly by microscopic processes with the plasma of the Kronian magnetosphere. M. Blanc, R. Kallenbach, and N.V. Erkaev classify the various types of solar system magnetospheres in order to motivate comparative studies based on Cassini/Huygens results. M. Kivelson describes in detail the large-scale current systems of the terrestrial and Jovian magnetospheres in order to make predictions for Saturn. S. Miller, A. Aylward, and M. Millward review the physics of giant planet ionospheres and thermospheres. N. Krupp summarizes the results from previous space missions to Saturn with emphasis on energetic particle measurements. P. Zarka and W.S. Kurth explain the various processes of radio emission from the giant planets.

Any intrinsic magnetosphere is almost naturally compared to the two best studied magnetospheres, namely those of Earth and Jupiter. As pointed out by M. Kivelson, the surface current of the terrestrial magnetopause (Chapman-Ferraro current) and that of the terrestrial magnetotail, closing through a current sheet in the center of the tail region, have analogues at Jupiter and presumably also at Saturn. However, the large-scale current systems driving the aurorae are very different for Jupiter and Earth. At Jupiter they are mainly driven by the fast planetary rotation, while at Earth they are mainly driven by solar wind energy released through reconnection of the interplanetary with the terrestrial magnetic field. Saturn is intermediate between Earth and Jupiter. It is a fast rotator but the aurorae are driven by the solar wind. The latter prediction by M. Kivelson in this volume has already been confirmed by tracing a CME-driven interplanetary shock from the Sun to Saturn by planetary auroral storms. These coordinated observations involved data of the space missions Cassini, Galileo, HST, POLAR, ACE, WIND, IMAGE, and SOHO (Prangé, R., *et al.*: 2004, ‘A CME-driven interplanetary shock traced from the Sun to Saturn by planetary auroral storms’, *Nature*, in press).

The aurorae are also a central topic of the reviews by S. Miller and co-authors. They study the ion-neutral coupling in the giant planets’ exospheres in regions where H_3^+ ions are a dominant species. The key question is why the exospheric temperatures are several hundred degrees higher than can be produced by the effects of solar EUV heating alone. Solar EUV radiation accounts for an energy input of 2.4 TW at Jupiter and 0.5 TW at Saturn. Energetic particles precipitating in auroral regions of Jupiter could dissipate 10-100 TW by ion-neutral coupling. The amount of energy input from the solar wind through energetic particles into Saturn’s ionosphere remains to be determined by Cassini. For both Jupiter and Saturn, it remains to be explored how the energy is distributed from the auroral regions all over the planet.

A remote diagnostic of aurorae is the detection of radio waves. As reported by P. Zarka and W.S. Kurth, the main auroral radio emissions at Jupiter originate from flux tubes which are magnetically connected to regions where the plasma corotation breaks down, Cassini needs to test the hypothesis that Saturn’s kilometric radiation (SKR) mainly arises from upward currents at the boundaries between open and closed field lines. Temporal and spatial correlations suggest that SKR may also be related to variations in the solar wind pressure, to Kelvin-Helmholtz instabilities at the magnetopause, or to interplanetary shocks as observed at Jupiter during the Cassini flyby.

At Jupiter, correlations of HST ultraviolet images with radio wave emissions, driven by energetic electrons through the cyclotron maser instability, gave evidence for a special class of aurorae. They occur at the ionospheric footpoints of magnetic flux tubes that connect to the wakes of the Jovian satellites Io, Europa, and Ganymede. There may be analogues to these satellite-ionosphere interactions at Saturn. Towards the end of its tour around Saturn, Cassini will explore the high latitudes where the magnetic flux tubes connecting to Dione enter Saturn’s ionosphere. The pick-up, transport, and acceleration processes that generate energetic particles will be studied near the satellites and rings of Saturn, but in particular near Titan.

To date, however, no radio emissions indicating the cyclotron maser instability have been observed in or near Titan's wake. Instead, the radio emissions indicate lightning. Lightning in Titan's atmosphere could be very important for the chemical evolution of organic molecules at low temperatures. Cassini/RPWS measurements will be co-ordinated with Huygens/HASI data and HST observations. In Saturn's atmosphere, the 'imaging' of electric discharge emissions serves to monitor the storm activity which depends on the variation of the ring shadows and the ion-neutral coupling in the thermosphere and ionosphere.

4. Rings and Satellites

T.V. Johnson, D.P. Cruikshank, D.C. Jewitt, and B. Sicardy summarize the knowledge on the satellite and ring systems of the four giant planets and the Kuiper belt and Oort cloud objects. F. Raulin discusses the conditions on Europa and Titan with respect to the possibility of formation of any pre-biotic matter on the satellite surfaces or under-ice oceans.

The properties of the satellites and trans-Neptunian objects give clues on the formation scenario of the solar system: (i) Solar nebula models (Hueso, R. and Guillot, T.: 2003, 'Evolution of the protosolar nebula and formation of the giant planets', *Space Sci. Rev.* **106**, 105–120; Lissauer, J., this volume) seem to be supported by the fact that most satellites and trans-Neptunian objects are formed from a mixture of rock and ice, where water ice dominates out to Uranus' orbit as outlined by T.V. Johnson. (ii) Models on outward migration (Levison, H.F. and Morbidelli, A.: 2003, 'The formation of the Kuiper belt by the outward transport of bodies during Neptune's migration', *Nature* **426**, 419–421) are supported by the fact that Kuiper belt objects must have grown in a denser environment of the protoplanetary disk, i.e. closer to the Sun than their present location, to reach the observed sizes (see D.P. Cruikshank, this volume). (iii) D. Jewitt argues that direct gravitational collapse of the giant planets within about 1000 years seems unlikely because on such a short time scale the solid irregular satellites could not have formed to be available for capture. Core accretion near Jupiter's or Saturn's orbits and outward migration with subsequent collisional capture of irregular satellites is suggested as a possible scenario for the formation of the Uranus and Neptune systems. (iv) Giant planet ring dynamics, composition, size distributions of grains and larger bodies, and the associated formation time scales and lifetimes provide important insights on formation scenarios of proto-planetary disks (see Sicardy, this volume). For instance, spiral density waves are believed to be important collective modes in proto-planetary disks. They are in fact observed in Saturn's rings and can be used to probe the physical propoerties of the disk.

Among the outstanding questions that will be investigated during the Cassini tour around Saturn and the Huygens descent to Titan are:

1. What is the 'relation' between the rings and the satellites? How was the Saturn system including its satellites formed (e.g., Magni, G. and Coradini, A.: 2004, 'Formation of Jupiter by nucleated instability', *Planet. Space Sci.* **52**, 343–360)?
2. What is the internal structure of the satellites of Saturn?
3. Why is Enceladus – although it is rather small and its present orbit's eccentricity suggests insufficient tidal heating – differentiated? Which are the internal heat sources – for instance radioactive decay – of the satellites of Saturn?
4. Which are and were the impactor populations causing the cratering of Saturn's satellites? Is there clear evidence for cryovolcanism?
5. How large is and was the meteoroid flux at Saturn's orbit? How important is this meteoroid flux for the ring erosion and for the source processes of the plasma in the Kronian magnetosphere?
6. Do the rings contain organic material and, if yes, where could it come from?
7. How much of macromolecular carbon-bearing material condensed and accreted in the outer parts of the solar nebula is pre-solar in origin? Most icy bodies in the outer Solar System show colors or low surface albedos that indicate the presence of complex organic material of the kind typically found in comets.
8. And last but not least: Are there liquid layers at the surface and/or in the deep interior of Titan and can this environment offer conditions for the development of life?

The volume is concluded by the article of F. Raulin on exo-astrobiological aspects of Europa and Titan. After Mars, Europa, with its potential subsurface ocean, is usually thought to be better suited for the search of any form of extraterrestrial life than Titan. On the surface of Titan, the emergence of life is not very likely because of the almost certain lack of liquid water and because of the low temperatures. However, it will be interesting to explore how far pre-biotic chemistry can develop under these conditions.

It is our pleasure to thank all those who have contributed to this volume and to the workshop in general. We are grateful to all authors for their contributions, and to the reviewers for their reports. We also want to express our thanks to the directorate and staff of ISSI, for their support in making the workshop happen and in getting the book finalized.

I. FORMATION AND EVOLUTION OF THE GIANT PLANETS

FORMATION OF THE OUTER PLANETS

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Abstract. Models of the origins of gas giant planets and 'ice' giant planets are discussed and related to formation theories of both smaller objects (terrestrial planets) and larger bodies (stars). The most detailed models of planetary formation are based upon observations of our own Solar System, of young stars and their environments, and of extrasolar planets. Stars form from the collapse, and sometimes fragmentation, of molecular cloud cores. Terrestrial planets are formed within disks around young stars via the accumulation of small dust grains into larger and larger bodies until the planetary orbits become well enough separated that the configuration is stable for the lifetime of the system. Uranus and Neptune almost certainly formed via a bottom-up (terrestrial planet-like) mechanism; such a mechanism is also the most likely origin scenario for Saturn and Jupiter.

Keywords: planet formation, giant planets, solar nebula

1. Introduction

There is convincing observational evidence that stars form by gravitationally-induced compression of relatively dense regions within molecular clouds (Lada *et al.*, 1993; André *et al.*, 2000). The nearly planar and almost circular orbits of the planets in our Solar System argue strongly for planetary formation within flattened circumstellar disks. Observations by Goodman *et al.* (1993) indicate that typical star-forming dense cores inside dark molecular clouds have specific angular momentum $> 10^{21}$ cm^2 s^{-1}. When these clouds undergo gravitational collapse, this angular momentum leads to the formation of pressure-supported protostars surrounded by rotationally-supported disks. Such disks are analogous to the primordial solar nebula that was initially conceived by Kant and Laplace to explain the observed properties of our Solar System (e.g., Cassen *et al.*, 1985). Observational evidence for the presence of disks of Solar System dimensions around pre-main sequence stars has increased substantially in recent years (McCaughrean *et al.*, 2000). The existence of disks on scales of a few tens of astronomical units is inferred from the power-law spectral energy distribution in the infrared over more than two orders of magnitude in wavelength (Chiang and Goldreich, 2000). Observations of infrared excesses in the spectra of young stars suggest that the lifetimes of protoplanetary disks span the range of 10^6 – 10^7 years (Strom *et al.*, 1993; Alencar and Batalha, 2002).

Dust within a protoplanetary disk initially agglomerates via sticking/local electromagnetic forces. The later phases of solid body growth are dominated by pair-

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wise collisions of bodies that also influence one another's trajectories gravitationally. Terrestrial planets continue to grow by pairwise accretion of solid bodies until the spacing of planetary orbits becomes large enough that the configuration is stable to gravitational interactions among the planets for the lifetime of the system (Safronov, 1969; Wetherill, 1990; Lissauer, 1993; 1995; Chambers, 2001; Laskar, 2000). The largest uncertainty in our understanding of solid planet formation is the agglomeration from cm-sized pebbles to km-sized bodies that are referred to as planetesimals. Collective gravitational instabilities (Safronov, 1969; Goldreich and Ward, 1973) might be important, although turbulence could prevent protoplanetary dust layers from becoming thin enough to be gravitationally unstable (Weidenschilling and Cuzzi, 1993). Recent calculations suggest that high metallicity disks may form planetesimals via gravitational instabilities, but that dust in disks with lower solids contents may not be able to overcome turbulence and settle into a subdisk that is dense enough to undergo gravitational instability (Youdin and Shu, 2002). Planetesimal formation is a very active research area (Goodman and Pindor, 2000; Ward, 2000), and results may have implications for our estimates of the abundance of both terrestrial and giant planets within our galaxy.

Our understanding, such as it is, of planet formation comes from a widely diverse range of observations, laboratory studies and theoretical models. Detailed observations obtained from the ground and from space are now available for the planets and many smaller bodies (moons, asteroids and comets) within our Solar System. Studies of the composition, minerals and physical structure have been used to deduce conditions within the protoplanetary disk (Hewins, Jones and Scott, 1996). Data on the now more numerous known extrasolar planets are less detailed and more biased, yet still very important. Observations of young stars and their surrounding disks provide clues to planet formation now taking place within our galaxy. Laboratory experiments on the behavior of hydrogen and helium at high pressures have been combined with gravitational measures of the mass distribution within giant planets deduced from the trajectories of passing spacecraft and moons to constrain the internal structure and composition of the largest planets in our Solar System.

Theorists have attempted to assemble all of these pieces of information together into a coherent model of planetary growth. But note that planets and planetary systems are an extremely heterogeneous lot, the 'initial conditions' for star and planet formation vary greatly within our galaxy (Mac Low and Klessen, 2004), and at least some aspects of the process of planet formation are extremely sensitive to small changes in initial conditions (Chambers *et al.*, 2002).

The remainder of this chapter concentrates on the formation of bodies much larger than Earth yet substantially smaller than the Sun. Observations of giant planets in our Solar System and beyond are summarized in Section 2. Formation models are reviewed in Section 3, and conclusions are given in Section 4.

2. Observations

About 90% of Jupiter's mass is H and He, and these two light elements make up $\sim$75% of Saturn. The two largest planets in our Solar System are generally referred to as *gas giants* even though these elements aren't gases at the high pressures that most of the material in Jupiter and Saturn is subjected to. Analogously, Uranus and Neptune are frequently referred to as *ice giants* even though the astrophysical ices such as H_2O, CH_4, H_2S and NH_3 that models suggest make up the majority of their mass (Hubbard *et al.*, 1995) are in fluid rather than solid form. Note that whereas H and He *must* make up the bulk of Jupiter and Saturn because no other elements can have such low densities at plausible temperatures, it is possible that Uranus and Neptune are primarily composed of a mixture of 'rock' and H/He (Hubbard *et al.*, 1995).

The large amounts of H and He contained in Jupiter and Saturn imply that these planets must have formed within $\sim 10^7$ yrs of the collapse of the Solar System's natal cloud, before the gas in the protoplanetary disk was swept away. Any formation theory of the giant planets should account for these time scales. In addition, formation theories should explain the elemental and isotopic composition of these planets and variations therein from planet to planet, the presence and/or absence of internal heat fluxes, axial tilts, etc.

Lithium and heavier elements constitute $< 2\%$ of the mass of a solar composition mixture. The *atmospheric* abundances of volatile gases heavier than helium* are $\sim$3 times solar in Jupiter (Young, 2003), a bit more enriched in Saturn, and substantially more for Uranus and Neptune. The *bulk* enhancements in heavy elements relative to the solar value are roughly 5, 15, and 300 times for Jupiter, Saturn and Uranus/Neptune, respectively. Thus, all four giant planets accreted solid material substantially more effectively than gas from the surrounding nebula. Moreover, the total mass in heavy elements varies by only a factor of a few between the four planets, while the mass of H and He varies by about two orders of magnitude between Jupiter and Uranus/Neptune.

The extrasolar planet discoveries of the past decade have vastly expanded our database by increasing the number of planets known by more than an order of magnitude (Mayor *et al.*, 2004). The distribution of known extrasolar planets is highly biased towards those planets that are most easily detectable using the Doppler radial velocity technique. The extrasolar planetary systems that have been found are quite different from our Solar System; however, it is not yet known whether our planetary system is the norm, quite atypical or somewhere in between.

Nonetheless, the following unbiased statistical information can be distilled from available exoplanet data: Approximately 1% of sunlike stars (chromospherically-

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* One notable exception to this trend is neon, which is substantially depleted relative to solar abundance. However, the paucity of neon in Jupiter's atmosphere is believed to be the result of gravitationally-induced settling of neon (together with some of the helium) towards the center of Jupiter within the past 1 – 2 Gyr, and thus is not taken to be a clue to the planet's formation.

quiet late F, G and early K dwarf stars without close binary star companions that are located in our region of the Milky Way galaxy) have planets more massive than Saturn within 0.1 AU. Roughly 7% of sunlike stars have planets more massive than Jupiter within 2 AU. Some of these planets have very eccentric orbits. Within about 5 AU of sunlike stars, Jupiter-mass planets are more common than planets of several Jupiter masses, and substellar companions that are more than ten times as massive as Jupiter are rare (Mayor *et al.*, 2004; Marcy *et al.*, 2004). Stars with higher metallicity are more likely to host detectable planets than are metal-poor stars (Santos *et al.*, 2003; Fischer and Valenti, 2003). The distribution of planets is more clustered than it would be if detectable planets were randomly assigned to stars, i.e., stars with one detectable planet are more likely to host more detectable planets. At least a few percent of sunlike stars have very Jupiter-like companions (0.5 – 2 M_J, 4 AU $< a <$ 10 AU, but $>$ 20% lack such companions (Marcy *et al.*, 2004). The one extrasolar giant planet with a well-measured mass and radius, HD 209458b (which was discovered using the Doppler technique and subsequently observed to transit across the disk of its star), is predominantly hydrogen (Charbonneau *et al.*, 2000; Burrows *et al.*, 2003), as are Jupiter and Saturn.

Transit observations have also yielded an important negative result: Hubble Space Telescope photometry of a large number of stars in the globular cluster 47 Tucanae failed to detect any transiting inner giant planets, even though ∼17 such transiting objects would be expected if the frequency of such planets in this low metallicity cluster was the same as that for sunlike stars in the solar neighborhood (Gilliland *et al.*, 2000). However, it appears likely that a ∼3 M_J planet is orbiting ∼20 AU from the pulsar PSR B1620-26 – white dwarf binary system, which is located in the globular cluster Messier 4. This system has been taken to be evidence for ancient planet formation in a low metallicity (5% solar) protoplanetary disk within the globular cluster by Sigurdsson (1993) and Sigurdsson *et al.* (2003). Sigurdsson's formation scenario requires a fairly complex stellar exchange to account for the planet in its current orbit. There is a much more likely explanation for the planet orbiting PSR B1620-26, which requires neither planetary formation in a low metallicity disk nor stellar exchange. This system has two post-main sequence stars sufficiently close to have undergone disk-producing mass transfer during the white dwarf's distended red giant phase, which occurred within the past 10^9 years (Sigurdsson *et al.*, 2003). Such a metals-enriched disk could have been an excellent location for the giant planet to form, and growth within such a disk (whether near its observed location or closer to the stars) would fit well with both planet formation theories and the observed strong correlation of planetary detections with stellar (and presumably protostellar disk) metallicity. Sigurdsson (1993) noted the possibility that the planet formed in a post-main sequence disk, but he discounted this scenario because he relied on the planetary growth timescales given by Nakano (1987), whose model requires an implausibly long 4×10^9 years to form Neptune.

3. Formation Models

The observation that the mass function of young objects in star-forming regions extends down through the brown dwarf mass range to below the deuterium burning limit (Zapatero *et al.*, 2000), together with the lack of any convincing theoretical reason to believe that the collapse process that leads to stars cannot also produce substellar objects (Wuchterl and Tscharnuter, 2003), strongly implies that most isolated (or distant companion) brown dwarfs* and isolated high planetary mass objects formed via the same collapse process as do stars.

By similar reasoning, the 'brown dwarf desert', a profound dip in the mass function of companions orbiting within several AU of sunlike stars (Mayor *et al.*, 2004; Marcy *et al.*, 2004), strongly suggests that the vast majority of extrasolar giant planets formed via a mechanism different from that of stars. Moreover, the relationship between bulk composition and mass within our Solar System, wherein bodies up to the mass of Earth consist almost entirely of condensable (under reasonable protoplanetary disk conditions) material, and the fraction of highly volatile gas increases with mass through Uranus/Neptune, to Saturn and finally Jupiter (which is still enriched in condensables at least threefold compared to the Sun), argues for a unified formation scenario for all of the planets and smaller bodies within our Solar System. The continuum of observed extrasolar planetary properties, which stretches to systems not very dissimilar to our own, suggests that extrasolar planets formed as did the planets within our Solar System.

Models for the formation of gas giant planets were reviewed by Wuchterl *et al.* (2000). Star-like direct quasi-spherical collapse is not considered viable, both because of the observed brown dwarf desert mentioned above and theoretical arguments against the formation of Jupiter-mass objects via fragmentation (Bodenheimer *et al.*, 2000a). The theory of giant planet formation that is favored by most researchers is the *core instability model*, in which the planet's initial growth resembles that of a terrestrial planet, but it becomes sufficiently massive (several $M_\oplus$) that it is able to accumulate substantial amounts of gas from the surrounding protoplanetary disk. The only other hypothesis receiving significant attention is the *gas instability model*, in which the giant planet forms directly from the contraction of a clump that was produced via a gravitational instability in the protoplanetary disk.

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* Following Lissauer (2004), the following definitions are used throughout this chapter:

- *Planet*: negligible fusion ($< 13\ M_J$) + orbits star(s) or stellar remnant(s).
- *Star*: self-sustaining fusion is sufficient for thermal pressure to balance gravity.
- *Stellar remnant*: dead star - 'no' more fusion (i.e., thermal pressure sustained against radiative losses by energy produced from fusion is no longer sufficient to balance gravitational contraction).
- *Brown dwarf*: substellar object with substantial deuterium fusion (more than half of the object's original inventory of deuterium is ultimately destroyed by fusion).

Numerical calculations on gravitationally unstable disks by Adams and Benz (1992) and recent work by Boss (2000) and Mayer *et al.* (2002) have revived interest in the gas instability model. Although there are uncertainties in the processes of gaseous giant protoplanet formation, the disk instabilities are a dynamical effect and the planets would form very rapidly on time scales of at most a few tens of orbits. Boss (1998) suggested that ice and rock cores *should* be able to form inside Jupiter after the occurrence of gravitational instability, but more detailed calculations, including realistic (fractal) models of grain growth and the affects of fluid motions within the planet are needed to test this claim. Furthermore, the masses of the condensations in most calculations of this process tend to be 5–10 M_J, although Boss (2001) finds condensations of mass $\sim$1 M_J. Nevertheless these models suggest that under appropriate conditions in the disk, fragmentation into objects of $\sim$10 M_J is likely to occur on a time scale short compared with the disk dispersal time of a few million years (Haisch *et al.*, 2001; Lada, 2003; Chen and Kamp, 2004; Metchev *et al.*, 2004), thus avoiding one of the main problems with the core accretion mechanism. Numerical simulations show that sufficiently unstable disks can, indeed, produce clumps comparable in mass to giant planets (Mayer *et al.*, 2002). In contrast, simulations performed with the same code, but different initial conditions, demonstrate that mildly unstable disks can redistribute mass via spiral density waves. Moreover, Laughlin and Bodenheimer (1994) showed that the unstable disk develops spiral arms that saturate at low amplitude and result in angular momentum transport and accretion of disk material onto the star, rather than fragmentation into subcondensations. Computational limitations to date have precluded simulations that begin with stable disks and allow the disk to become unstable via cooling or growth by accretion on astrophysically realistic timescales. Whether disks which are prone to fragmentation are a likely result of gravitational collapse of a molecular cloud core has still to be determined. An even more serious difficulty is that the gas instability hypothesis only accounts for massive stellar-composition planets, requiring a separate process to account for the smaller bodies in our Solar System and the heavy element enhancements in Jupiter and Saturn. The existence of intermediate objects like Uranus and Neptune is particularly difficult to account for in such a scenario.

The core-instability model relies on a combination of planetesimal accretion and gravitational accumulation of gas. In this theory, the core of the giant planet forms first by accretion of planetesimals, while only a small amount of gas is accreted. Core accretion rates depend upon the surface mass density of solids in the disk and physical assumptions regarding gas drag, etc. (Lissauer, 1987; Inaba *et al.*, 2003). The escape velocity from a planetary embryo with $M > 0.1\ M_\oplus$ is larger than the sound speed in the gaseous protoplanetary disk. Such a growing planetary core first attains a quasi-static atmosphere that undergoes Kelvin-Helmholtz contraction as the energy released by the planetesimal and gas accretion is radiated away at the photosphere. The contraction timescale is determined by the efficiency of radiative transfer, which is relatively low in some regions of the envelope. Spherically symmetric (1-D) quasi-hydrostatic models show that the minimum contraction timescale is a rapidly decreasing function of the core's mass. The gas accretion rate, which is initially very slow, accelerates with time and becomes comparable to the planetesimal bombardment rate after the core has grown to $\sim$10 $M_\oplus$. Once the gaseous component of the growing planet exceeds the solid component, gas accretion becomes very rapid, and leads to a runaway accretion of gas.

The composition of the atmospheres of a giant planet is largely determined by how much heavy material was mixed with the lightweight material in the planet's envelopes. Once the core mass exceeds $\sim$0.01 $M_\oplus$, the temperature becomes high enough for water to evaporate into the protoplanet's envelope. As the envelope becomes more massive, late-accreting planetesimals sublimate before they can reach the core, thereby enhancing the heavy element content of the envelopes considerably.

The fact that Uranus and Neptune contain much less H_2 and He than Jupiter and Saturn suggests that Uranus and Neptune never quite reached runaway gas accretion conditions, possibly due to a slower accretion of planetesimals (Pollack *et al.*, 1996). The rate at which accretion of solids takes place depends upon the surface density of condensates and the orbital frequency, both of which decrease with heliocentric distance. Alternatively/additionally, Uranus and Neptune may have avoided gas runaway as a result of the removal of gas from the outer regions of the disk via photoevaporation (Hollenbach *et al.*, 2000). Additional theoretical difficulties for forming planets at Uranus/Neptune distances have been addressed by Lissauer *et al.* (1995) and Thommes *et al.* (2003). New models are being proposed to address these problems by considering the possibility of rapid runaway accretion of a very small number of planetary embryos beyond 10 AU. In the model presented by Weidenschilling *et al.* (2004), an embryo is scattered from the Jupiter-Saturn region into a massive disk of small planetesimals. In the model presented by Goldreich *et al.* (2004), planetesimals between growing embryos are ground down to very small sizes and are forced into low inclination, nearly circular orbits by frequent mutual collisions. Planetary embryos can accrete rapidly in such a dynamically cold disks as those in the models of Weidenschilling et al. and Goldreich et al. Alternatively, Thommes *et al.* (2003) propose that Uranus and Neptune formed closer to the Sun, and were subsequently scattered out to their current distances by gravitational perturbations of Jupiter and Saturn.

During the runaway planetesimal accretion epoch, the protoplanet's mass increases rapidly. The internal temperature and thermal pressure increase as well, preventing substantial amounts of nebular gas from falling onto the protoplanet. When the planetesimal accretion rate decreases, gas falls onto the protoplanet more rapidly. The protoplanet accumulates gas at a gradually increasing rate until its gas mass is comparable to its heavy element mass. The key factor limiting gas accumulation during this phase of growth is the protoplanet's ability to radiate away energy and contract (Figure 1). The rate of gas accretion then accelerates more rapidly,

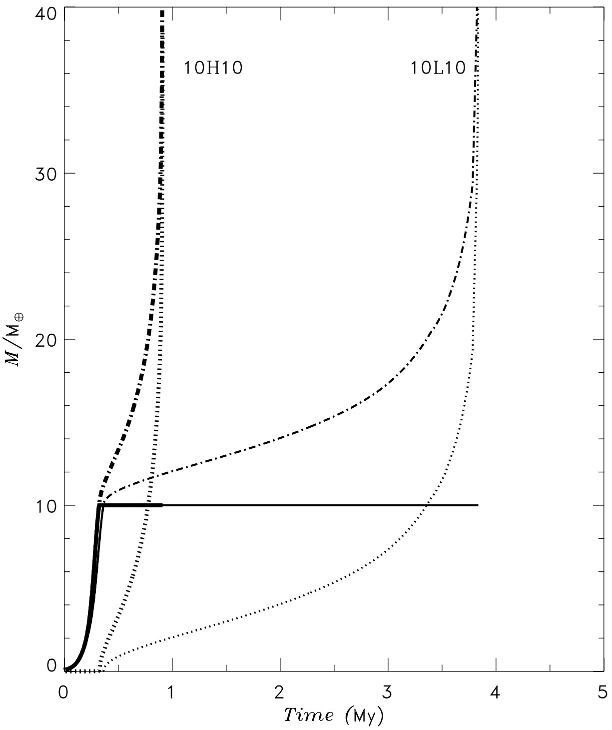

Figure 1. Evolution of a giant protoplanet for two values of the atmospheric opacity. The planet's mass is plotted as a function of time. The solid line denotes the mass of the core (which for these models has been limited to 10 $M_\oplus$), the dotted line denotes the mass of the envelope, and the dash-dotted line denotes the total mass. Both models are computed at 5.2 AU from a 1 $M_\odot$ star in a disk with planetesimal surface density = 10 g/cm^2. The thick curves, labeled 10L10, denote models using opacity values that correspond to an atmospheric abundance of grains equal to 2% that of typical interstellar matter. The thin curves, labeled 10H10, denote models computed with full interstellar grain opacity. Calculations by Podolak (2003) suggest that the grain abundance in a giant protoplanet's atmosphere is likely to be lower than that in interstellar matter. (Courtesy: O. Hubickyj; details will be presented in Hubickyj, Bodenheimer, and Lissauer, 2005.)

and a gas runaway occurs. The gas runaway continues as long as there is gas in the vicinity of the protoplanet's orbit. The protoplanet may cut off its own supply of gas by gravitationally clearing a gap within the disk (Lin and Papaloizou, 1979), as the moonlet Pan does within Saturn's rings (Showalter, 1991). D'Angelo *et al.* (2002, 2003) are using a 3-D adaptive mesh refinement code to follow the flow of gas onto an accreting giant planet. Models such as this will eventually allow the determination of final planetary mass as a function of the time-varying properties (density, temperature, viscosity, longevity, etc.) of the surrounding disk. Such a self-regulated growth limit provides a possible explanation to the observed mass distribution of extrasolar giant planets. Alternatively, the planet may accumulate all of the gas that remains in its region of the protoplanetary disk.

A major uncertainty associated with the emergence of planets is their orbital migration as a consequence of the same type of gravitational torque between the disk and the planet that may allow planets to clear gaps around themselves (Goldreich and Tremaine, 2000; Ward, 1986; Bate *et al.*, 2003). Planetary orbits can migrate towards (or in some circumstances away from) their star as a consequence of angular momentum exchange between the protoplanetary disk and the planet. Calculations indicate that the torque exerted by the planet on the outer disk is usually stronger than that on the inner disk. Planets that are more massive than Mars may be able to migrate substantial distances prior to the dispersal of the gaseous disk. Thus, it is quite possible that giant planets may form several AU from their star and then migrate inwards to the locations at which most extrasolar planets have been observed. Disk-induced migration is considered to be the most likely explanation for the 'giant vulcan' planets with periods of less than a week, because *in situ* formation of such objects is quite unlikely (Bodenheimer *et al.*, 2000b). Livio and Pringle (2003) find no basis to suggest that planetary migration is sensitive to disk metallicity, and conclude that higher metallicity probably results in a higher likelihood of planet formation. The difficulty with the migration models is that they predict that planets should migrate *too rapidly*, especially in the Earth to Neptune mass range that planetary cores grow through in the core accretion scenario. Moreover, as migration rates should increase as a planet approaches a star, most planets that migrate significant distances should be swallowed up by their star. However, a planet may end up in very close 51 Peg-like orbits if stellar tides can counteract the migration or if the disk has a large inner hole (Lin *et al.*, 1996; Lin *et al.*, 2000). Resolution of this rapid migration dilemma may require the complete and nonlinear analysis of the disk response to the protoplanet in the corotation regions. See Ward and Hahn (2000), Masset and Papaloizou (2003), and Thommes and Lissauer (2003) for more detailed discussions of planetary migration.

Many of the known extrasolar giant planets move on quite eccentric ($0.2 < e < 0.7$) orbits. These eccentric orbits may be the result of stochastic gravitational scatterings among massive planets (which have subsequently merged or been ejected to interstellar space, Rasio and Ford, 1996; Weidenschilling and Marzari, 1996; Levison *et al.*, 1998; Ford *et al.*, 2001), by perturbations of a binary companion (Holman *et al.*, 1997), or by past stellar companions if the now single stars were once members of unstable multiple star systems (Laughlin and Adams, 1998). However, as neither scattering nor migration offer a simple explanation for those planets with nearly circular orbits and periods from a few weeks to a few years, the possibility of giant planet formation quite close to stars should not be dismissed (Bodenheimer *et al.*, 2000b).

4. Conclusions: Summary of Giant Planet Formation Models

The smoothness of the distribution of masses of young M stars, free-floating brown dwarfs, and even free-floating objects somewhat below the deuterium burning limit, argues strongly that these bodies formed in the same manner, via collapse, in some cases augmented by fragmentation. In contrast, the mass gap in nearby companions to sunlike stars (the brown dwarf desert) is convincing evidence that at least most known giant planets formed in a different manner.

Various models for giant planet formation have been proposed. According to the prevailing core instability model, giant planets begin their growth by the accumulation of small solid bodies, as do terrestrial planets. However, unlike terrestrial planets, the growing giant planet cores become massive enough that they are able to accumulate substantial amounts of gas before the protoplanetary disk dissipates. The primary questions regarding the core instability model is whether planets with small cores can accrete very massive gaseous envelopes within the lifetimes of gaseous protoplanetary disks.

The main alternative giant planet formation model is the disk instability model, in which gaseous planets form directly via gravitational instabilities within protoplanetary disks. Formation of giant planets via gas instability has never been demonstrated for realistic disk conditions. Moreover, this model has difficulty explaining the supersolar abundances of heavy elements in Jupiter and Saturn, and it does not explain the origin of planets like Uranus and Neptune. Nonetheless, it is possible that some giant planets form via disk instability.

Most models for extrasolar giant planets suggest that they formed as Jupiter and Saturn are believed to have (in nearly circular orbits, far enough from the star that ice could condense), and subsequently migrated to their current positions, although some models suggest *in situ* formation. Issues involving the ultimate sizes and spacings of gas giant planets are complex and poorly understood (Lissauer, 1995), and provide a major source of uncertainty for modeling the potential diversity of planetary systems. Gas giant planet formation may or may not be common, because the majority of protoplanetary disks could be depleted before solid planetary cores can grow large enough to gravitationally trap substantial quantities of gas. Additionally, an unknown fraction of giant planets migrate into their star and are consumed, or are ejected into interstellar space via perturbations of neighboring giant planets, so even if giant planet formation is common, these planets may be scarce.

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References

Adams, F.C. and Benz, W.: 1992, 'Gravitational instabilties in circumstellar disks and the formation of binary companions', in H.A. McAlister and W.I. Hartkopf (eds.), *Complementary approaches to double and multiple star research*, ASP Conf. Ser. **32**, IAU Colloquium 135, pp. 185–194.

Alencar, S.H.P. and Batalha, C.: 2002, 'Variability of Southern T Tauri Stars. II. The Spectral Variability of the Classical T Tauri Star TW Hydrae', *Astrophys. J.* **571**, 378–393.

André, P., Ward-Thompson, D., and Barsony, M.: 2000, 'From Prestellar Cores to Protostars: the Initial Conditions of Star Formation', in V. Mannings, A. P. Boss, and S. Russells (eds.), *Protostars and Planets IV*, Univ. Arizona Press, Tucson, pp. 59–96.

Bate, M.R., Lubow, S.H., Ogilvie, G.I., and Miller, K.A.: 2003, 'Three-dimensional calculations of high- and low-mass planets embedded in protoplanetary discs', *Mon. Not. Roy. Astron. Soc.* **341**, 213–229.

Bodenheimer, P., Burkert, A., Klein, R.I., Boss, A.P.: 2000a, 'Multiple Fragmentation of Protostars', in V. Mannings, A.P. Boss, and S. Russells (eds.), *Protostars and Planets IV*, Univ. Arizona Press, Tucson, pp. 675–701.

Bodenheimer, P., Hubickyj, O., and Lissauer, J.J.: 2000b, 'Models of the in Situ Formation of Detected Extrasolar Giant Planets', *Icarus* **143**, 2–14.

Boss, A.P.: 1998, 'Evolution of the solar nebula. IV. Giant gaseous protoplanet formation', *Astrophys. J.* **503**, 923–937.

Boss, A.P.: 2000, 'Possible rapid gas giant planet formation in the solar nebula and other protoplanetary disks', *Astrophys. J.* **536**, L101–L104.

Boss, A.P.: 2001, 'Gas Giant Protoplanet Formation: Disk Instability Models with Thermodynamics and Radiative Transfer', *Astrophys. J.* **563**, 367–373.

Burrows, A., Sudarsky, D., Hubbard, W.B.: 2003, 'A Theory for the Radius of the Transiting Giant Planet HD 209458b', *Astrophys. J.* **594**, 545–551.

Cassen, P., Shu, F.H., and Terebey, S.: 1985, 'Protostellar disks and star formation', in D.C. Black and M.S. Matthews (eds.), *Protostars and Planets II*, Univ. Arizona Press, Tucson, pp. 448–483.

Chambers, J.E.: 2001, 'Making More Terrestrial Planets', *Icarus* **152**, 205–224.

Chambers, J.E., Quintana, E.V., Duncan, M.J., and Lissauer, J.J.: 2002, 'Symplectic Integrator Algorithms for Modeling Planetary Accretion in Binary Star Systems', *Astron. J.* **123**, 2884–2894.

Charbonneau, D., Brown, T.M., Latham, D.W., and Mayor, M.: 2000, *Astrophys. J.* **529**, L45–L48.

Chen, C.H. and Kamp, I.: 2004, 'Are giant planets forming around HR 4796A?', *Astrophys. J.* **602**, 985–992.

Chiang, E. and Goldreich, P.: 1997, 'Spectral Energy Distributions of T Tauri Stars with Passive Circumstellar Disks', *Astrophys. J.* **490**, 368–376.

D'Angelo, G., Henning, T., and Kley, W.: 2002, 'Nested-grid calculations of disk-planet interaction', *Astron. Astrophys.* **385**, 647–670.

D'Angelo, G., Kley, W., and Henning, T.: 2003, 'Orbital Migration and Mass Accretion of Protoplanets in Three-dimensional Global Computations with Nested Grids' *Astrophys. J.* **586**, 540–561.

Fischer, D.A. and Valenti, J.A.: 2003, 'Metallicities of stars with extrasolar planets', in D. Deming and S. Seager (eds.), *Scientific Frontiers in Research on Extrasolar Planets*, ASP Conference Series **294**, ASP, San Francisco, ISBN: 1-58381-141-9, pp. 117–128.

Ford, E.B., Havlickova, M., and Rasio, F.A.: 2001, 'Dynamical instabilities in extrasolar planetary systems containing two giant planets', *Icarus* **150**, 303–313.

Gilliland, R.L., *et al.*: 2000, 'A lack of planets in 47 Tucanae from a Hubble Space Telescope search', *Astrophys. J.* **545**, L47–L51.

Goldreich, P., Lithwick, Y., and Sari, R.: 2004, 'Planet Formation by Coagulation: A Focus on Uranus and Neptune', *Ann. Rev. Astron. Astrophys.* **42**, in press.

Goldreich, P. and Tremaine, S.: 1980, 'Disk-satellite interactions', *Astrophys. J.* **241**, 425–441.

Goldreich, P. and Ward, W.R.: 1973, 'The Formation of Planetesimals', *Astrophys. J.* **183**, 1051–1062.

Goodman, A.A., Benson, P.J., Fuller, G.A., and Myers, P.C.: 1993, 'Dense cores in dark clouds. VIII - Velocity gradients', *Astrophys. J.* **406**, 528–547.

Goodman, J. and Pindor, B.: 2000, 'Secular instability and planetesimal formation in the dust layer', *Icarus* **148**, 537–549.

Haisch, K.E., Jr., Lada, E.A., and Lada, C.J.: 2001, 'Disk frequencies and lifetimes in young clusters', *Astrophys. J.* **553**, L153–L156.

Inaba, S., Wetherill, G.W., and Ikoma, M.: 2003, 'Formation of gas giant planets: core accretion models with fragmentation and planetary envelope', *Icarus* **166**, 46–62.

Hewins, R., Jones, R., and Scott, E. (eds.): 1996, *Chondrules and the Protoplanetary Disk*, Cambridge Univ. Press.

Hollenbach, D., Yorke, H.W., and Johnstone, D.: 2000, 'Disk dispersal around young stars', in V. Mannings, A.P. Boss, and S. Russell (eds.), *Protostars and Planets IV*, Univ. Arizona Press, Tucson, pp. 401–428.

Holman, M.J., Touma, J., and Tremaine, S.: 1997, 'Chaotic variations in the eccentricity of the planet orbiting 16 CYG B.', *Nature* **386**, 254–256.

Hubbard, W.B., Podolak, M., and Stevenson, D.J.: 1995, 'The interior of Neptune', in D.P. Cruikshank (ed.), *Neptune and Triton*, Univ. Arizona Press, Tucson, pp. 109–138.

Hubickyj, O., Bodenheimer, P., and Lissauer, J.J.: 2005, in preparation.

Lada, E.A., Strom, K.M., and Myers, P.C.: 1993, 'Environments of star formation – Relationship between molecular clouds, dense cores and young stars', in E.H. Levy and J.I. Lunine (ed.), *Protostars and Planets III*, Univ. Arizona Press, Tucson, pp. 245–277.

Lada, E.A.: 2003, 'Evolution of circumstellar disks in young stellar clusters', Am. Astron. Soc. Meeting 202, abstract # 24.06.

Laskar, J.: 2000, 'On the spacing of planetary systems', *Phys. Rev. Lett.* **84**, 3240–3243.

Laughlin, G., and Bodenheimer, P.: 1994, 'Nonaxisymmetric evolution in protostellar disks', *Astrophys. J.* **436**, 335–354.

Laughlin, G. and Adams, F.C.: 1998, 'The modification of planetary orbits in dense open clusters', *Astrophys. J.* **508**, L171–L174.

Levison, H.F., Lissauer, J.J., and Duncan, M.J.: 1998, 'Modeling the diversity of outer planetary systems', *Astron. J.* **116**, 1998–2014.

Lin, D.N.C., Bodenheimer, P., and Richardson, D.C.: 1996, 'Orbital migration of the planetary companion of 51 Pegasi to its present location', *Nature* **380**, 606–607.

Lin, D.N.C. and Papaloizou, J.C.B.: 1979, 'Tidal torques on accretion discs in binary systems with extreme mass ratios', *Mon. Not. Royal Astron. Soc.* **186**, 799–812.

Lin, D.N.C., Papaloizou, J.C.B., Terquem, C., Bryden, G., and Ida, S.: 2000, 'Orbital evolution and planet-star tidal interaction', in V. Mannings, A. P. Boss, and S. Russell (eds.), *Protostars and Planets IV*, Univ. Arizona Press, Tucosn, pp. 1111–1134.

Lissauer, J.J.: 1987, 'Timescales for planetary accretion and the structure of the protoplanetary disk', *Icarus* **69**, 249–265.

Lissauer, J.J.: 1993, 'Planet formation', *Ann. Rev. Astron. Astrophys.* **31**, 129–174.

Lissauer, J.J.: 1995, 'Urey prize lecture: On the diversity of plausible planetary systems', *Icarus* **114**, 217–236.

Lissauer, J.J.: 2004, 'Formation of giant planets and brown dwarfs', in J.-P. Beaulieu, A. Lecavelier des Etangs, and C. Terquem (eds.), *Extrasolar Planets, Today and Tomorrow*, ASP Conf. Ser. 3xx, Astron. Soc. of the Pacific, San Francisco, in press.

Lissauer, J.J., Pollack, J.B., Wetherill, G.W., and Stevenson, D.J.: 1995, 'Formation of the Neptune System', in D. Cruikshank (ed.), *Neptune and Triton*, Univ. Arizona Press, Tucson, pp. 37–108.