Workshop of the International Space Science Institute (ISSI)

Planetary Systems and Planets in Systems

held in Saas Fee, Switzerland, on 2–6 September 2002
in honor of the 60th birthday of Michel Mayor

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with the staff of Hotel Schweizerhof, Saas Fee
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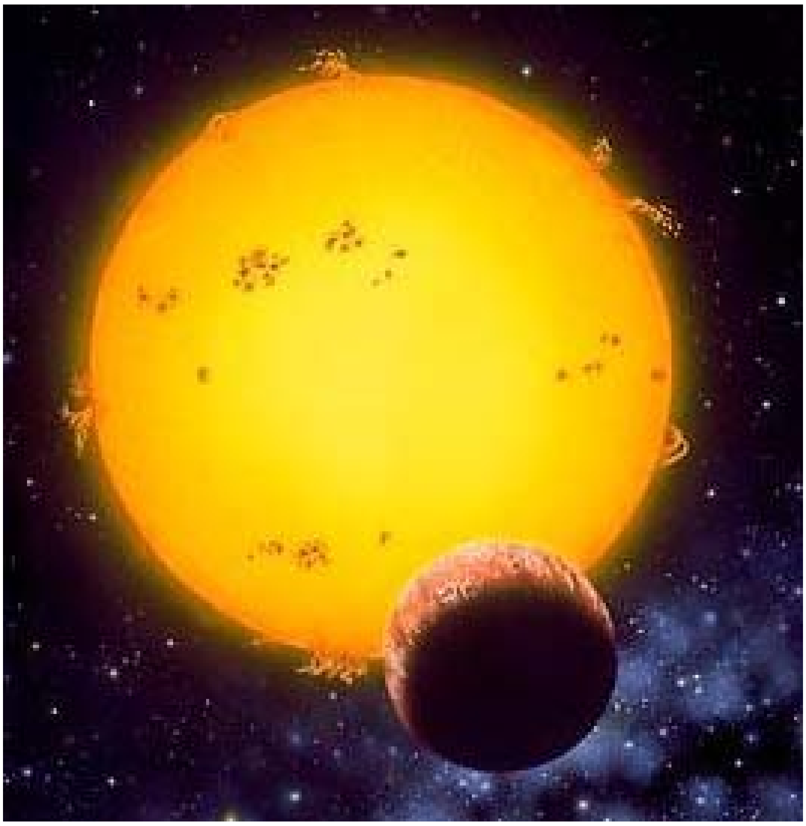

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Programme

	Monday	Tuesday	Wednesday	Thursday	Friday
themes	Giant planets: general view	Multi–planetary systems: obs.	Multi–planetary systems: theory	Planets in systems	Future and conclusions
9:00–9:45	Radial velocity results M. Mayor	Solar nebula D. Gautier	Formation S. Ida In situ formation G. Wuchterl	Planets in binaries S. Udry	Theory J. Lissauer
9:45–10:15	Char. of stars with planets N. Santos	Times scales in solar system A. Halliday	Chaotic interactions E. Ford	Formation in mult. sys. R. Nelson e pumping in binaries T. Mazeh	Astrometry A. Quirrenbach Imaging D. Rouan
10:45–11:15	Transit searches: Results D. Charbonneau	Pulsar planets A. Wolszczan	Long term evolution J. Laskar	Dynamics in multiple sys. I. Bonnel	Planets and life T. Owen
11:15–12:00	Formation scenarii W. Ward	Radial velocity results G. Marcy	Dynamics of planetary systems J. Papaloizou	Is migration inevitable? C. Terquem TBD	Conclusions & outlook A. Boss
15:30–15:50	Multiple planet systems W. Kley	Planetary parameters T. Guillot	Excursion	Kepler W. Borucki	
15:50–16:10		Colors of planets F. Allard		Corot C. Moutou	
16:10–16:30	TBD	Disks, debris A.–M. Lagrange		Report WG 1 (30 min.) T. Brown	
17:00–18:30	WG 1: Detection methods WG 2: Migration in SS WG 3: Viewing formation WG 4: Interactions	Working groups		Report WG 2 (30 min.) W. Benz Report WG 3 (30 min.) M. McCaughean Report WG 4 (30 min.) G. Laughlin	

Monday, 2 September 2002

Giant planets: general view

0900–0915		Welcome, logistics
0915–1000	Michel Mayor	Radial velocity results
1000–1030	Nuno Santos	Characteristics of stars with planets
1030–1100		Coffee
1100–1130	David Charbonneau	Transit searches: results
1130–1215	William Ward	Formation scenarii
1200–1530		Lunch
1530–1615	Wilhelm Kley	Multiple planet systems
1615–1645		Tea
1645–1830	Working Groups:	WG 1: Detection methods
		WG 2: Migration in SS
		WG 3: Viewing formation
		WG 4: Interactions

Tuesday, 3 September 2002

Multi-planetary systems: observations

0900–0945	Daniel Gautier (TBC)	Solar nebula
0945–1015	Alex Halliday	Time scales in the solar system
1015–1045		Coffee
1045–1115	Alex Wolszczan	Pulsar planets
1115–1200	Geoff Marcy	Radial velocity results
1200-1530		Lunch
1530-1550	Tristan Guillot	Planetary parameters
1550–1610	Anne-Marie Lagrange	Disks, debris
1610–1640		Tea
1640–1830	Working Groups:	WG 1: Detection methods
		WG 2: Migration in SS
		WG 3: Viewing formation
		WG 4: Interactions

Wednesday, 4 September 2002

Multi-planetary systems: theory

0900–0920	Shigeru Ida	Formation
0920–0940	Guenther Wuchterl	In-situ formation of Pegasi planets
0940–1010	Eric Ford	Chaotic interactions
1010–1045		Coffee
1045–1115	Jacques Laskar	Long-term evolution
1115–1200	John Papaloizou	Dynamics of planetary systems
1200–1900		Lunch, Excursion
1900		Banquet

Thursday, 5 September 2002

Planets in systems

0900–0930	Stephane Udry	Planets in binaries
0930–1000	Richard Nelson	Fomation in multiple systems
1000–1030	Tsevi Mazeh	e pumping in binaries
1030–1100	Coffee	
1100–1120	Ian Bonnell	Dynamics in multiple systems
1120–1140	Caroline Terquem	Is migration inevitable?
1140–1200	TBD	
1200–1530	Lunch	
1530–1550	William Borucki	Kepler
1550–1610	Claire Moutou	Corot
1610–1640	Tim Brown	Report WG1: Detection methods
1640–1710	Tea	
1710–1740	Willy Benz	Report WG2: Migration in SS
1740–1810	Mark McCaughrean	Report WG3: Viewing formation
1810–1840	Greg Laughlin	Report WG4: Interactions

Friday, 6 September 2002

Future and conclusions

0900–0930	Jack Lissauer	Theory
0930–1000	Andreas Quirrenbach	Astrometry
1000–1030	Daniel Rouan	Imaging
1030–1100	Coffee	
1100–1120	Tobias Owen	Planets and life
1120–1205	Alan Boss	Conclusions and outlook
1205–1220	Publication matters	
1220	Adjourn	

Working groups

WG 1: Detection methods

Chair: Tim Brown

Members: Jean-Luc Beuzit, Alain Boss, Xavier Delfosse, Thierry Forveille, Dave Latham, Jose de Medeiros, Christian Perrier, Andreas Quirrenbach, Jean-Pierre Sivan, Alex Wolszczan, …

WG 2: Migration in SS

Chair: Willy Benz

Members: Yann Alibert, William Ward, …

WG 3: Viewing formation

Chair: Mark McCaughrean

Members: Anne-Marie Lagrange, Toby Owen, Didier Queloz, …

WG 4: Interactions

Chair: Greg Laughlin

Members: Ian Bonnell, Anne Eggenberger, Debra Fischer, Eric Ford, Shigeru Ida, Jack Lissauer, Geoff Marcy, Oliver Nyffenegger, John Papaloizou, …

Chemical Properties of Stars with Planets

Nuno C. Santos
Geneva Observatory, Switzerland

Garik Israelian
Instituto de Astrofisica de Canarias, Spain

Michel Mayor
Geneva Observatory, Switzerland

In this talk I will focus on the stellar metallicity - giant planet connection. Current results have shown that stars with planetary mass companions are significantly metal rich when compared with average field dwarfs. Furthermore, they point out towards a "primordial" source for the high abundances. This latter result implies that the chemical composition of the molecular cloud is probably a key parameter to form giant planets. These conclusions may thus impose serious constraints on the planetary systems formation and evolution models.

Giant Planet Formation and Survival

Wm. R. Ward
Southwest Research Institute

The core accretion model of giant planet formation is reviewed with particular emphasis on three pivotal issues: (i) core accretion time scales, (ii) core survival against type I orbital decay, and (iii) giant planet survival against type II migration. A new explanation for the curiously dissimilar obliquities of Jupiter and Saturn will also be presented.

Multiple Planet Systems

Wilhelm Kley
University of Tuebingen, Germany

The orbital properties of the newly discovered extrasolar planets require a reanalysis of the formation properties of planetary systems. The talks concentrates on the orbital evolution of multiple planetary system.

We investigate the early evolution of planets still embedded in their protoplanetary discs. Gravitational torques acting between the disc and the planet determine their joint evolution. This is modeled through fully hydrodynamic disc simulations coupled to an N-body code.

The mass growth, migration, evolution of orbital elements, resonances and instabilities are discussed.

Time-scales for the Accretion of the Terrestrial Planets

Alex N. Halliday
Department of Earth Sciences, ETH Zentrum, NO, Sonneggstrasse 5, CH-8092, Zürich, Switzerland

The most widely accepted approach for determining the time-scales for the accretion of the terrestrial planets has been dynamic modelling using Monte Carlo simulations. These have provided evidence that each of the terrestrial planets grew to their current size over tens of millions of years, as a result of collisions between planetesimals and smaller planets. These models can be tested using isotopic variations produced by radioactive decay of early solar system nuclides now long extinct. The most effective method has been hafnium-tungsten chronometry. Hafnium and tungsten are both present in trace amounts in the planets, with concentrations of less that one part per million. At the start of the solar system there was a tiny amount ($<$0.01%) of an additional isotope of hafnium, ^{182}Hf. This decays with a half-life of 9 million years to a common isotope of tungsten, ^{182}W. Because the Earth is over 4.5 billion (10^9) years old all of the ^{182}Hf is now extinct – converted to ^{182}W in the first 50 million years of solar system history. By comparing W isotopic compositions of inner solar system metals and rocks that had different proportions of hafnium to tungsten (Hf/W) during accretion and core formation we can determine the early history of the reservoir being studied and constrain the time-scales over which early solar system objects formed. We cannot yet compare the rates of growth at comparable sizes for objects at different heliocentric distances. We find that asteroid-sized objects formed in the first few million years of the solar system. Mars formed in the first 15 million years. The Earth took longer – at least 30 million years. The Moon formed in the final stages of Earth formation. These data provide strong support for the protracted time-scales implied by some dynamic simulations. How such protracted accretionary processes relate to other solar systems is unclear.

Multi-Planetary Systems Observations Using Radial Velocity

Geoff Marcy
University of California, Berkeley

With 96 extrasolar planets discovered (as of 2002 Aug 25), their properties are emerging. About 6% of nearby stars have Jupiter and Saturn-sized planets within 3 AU, with measured masses ranging from 0.3–8 Jupiter masses. Smaller planets remain difficult to detect. The mass distribution rises steeply, with $\mathrm{d}N/\mathrm{d}M$ proportional to $1/M$. Lower mass planets of Neptune mass may be common. There is an obvious absence of massive planets (above $4M_{\mathrm{jup}}$) orbiting near (within 0.3 AU) the host star. The orbital eccentricities are spread between 0.0–0.7 among single stars and they correlate with semimajor axis. Multiple planets are common, with 9 such systems known. The planets commonly reside in resonances, with two systems exhibiting mean motion and two systems secular resonances. These interactions constrain the planet masses. One such planet mass was confirmed by HST/FGS astrometry (Benedict and McArthur) of Gliese 876. Significantly new parameter space may be explored in the near future with VLT astrometry and the Kepler Mission, with space-born optical coronographs to follow.

Giant planets: what do we know and what can we learn about their compositions?

Tristan Guillot
Observatoire de la Côte d'Azur, France

On the basis of what we know on the giant planets in our solar system, I will discuss the prospects of obtaining useful constraints on the internal structure and compositions of extrasolar giant planets. One particularly promising method consists in the combination of photometric observations of transiting planets and radial velocimetry information. In that case, the statistical information gathered could improve considerably our knowledge of the giant planets which, like HD209458b and 51 Peg b, orbit extremely close to their star. However, this will require improving the modeling of these heavily irradiated atmospheres (including the difficult issue of atmospheric dynamics, cloud formation and disequilibrium chemistry). Theoretical efforts in this direction are currently made, and further observations of photometric variations of the star+planet system (i.e. albedos and phase function) with instruments such as COROT, KEPLER and MOST could provide direct constraints on atmospheric conditions. Last but not least, continued analysis of our giant planets (particularly with space missions aimed at determining the bulk abundance of water in these planets) should be pursued in order to progress in our understanding of planet formation.

Formation of Cores of Giant Planets

Shigeru Ida
Tokyo Institute of Technology, Japan

Solid core accretion from planetesimals is discussed for not only the minimum mass disk model for Solar system but also for disks with different surface density distributions. Our N-body simulation (Kokubo & Ida 2002, ApJ, in press) shows that oligarchic growth model can be applied to wide varieties of disks. Cores are always formed with orbital separations of 10–15 Hill radii, which enables us to evaluate isolation masses of cores.

Using the oligarchic growth model, we also did model calculations of solid core accretion and gas accretion onto the cores. Since the isolated cores do not start orbit crossing and mutual accretion, the isolation masses of cores based on oligarchic growth model predict subsequent gas accretion onto the cores. The results of the calculations predict that in slightly massive disks, intermediate mass (10–50 M_{Earth}) planets around 1 AU, which causes radial velocity variation of 1–10 m/s of the host star, may form, if outer giants formed prior to the inner one shut disk gas inflow to the inner regions. Also, if surface density gradient is very steep in inner regions, 55 Canc type multiple planet system could form. For more realistic arguments, effects of planetary migration must be included in the model.

In Situ Formation of Pegasi Planets

G. Wuchterl
MPE (wuchterl@mpe.mpg.de)

The preplanetary nebula conditions close to a star are characterized by relatively high temperatures and strong stellar tides. Those conditions result in the gravitational stability of the gaseous disk for a wide range of surface densities. The gravity of planetary embryos causes accumulation of nebula gas that becomes significant once a 'core' grows to a critical mass of a few earth masses. Rapid accretion of gas is fluid-dynamically favored after the nucleated instability, at this 'critical' mass, because the outer protoplanetary envelopes tend to be convective in the innermost parts of many nebulae. Provided sufficient reservoirs of gas and solids exist, the subsequent gas-accretion results in the rapid formation of a giant planet.

I will discuss the formation of such 'Pegasi'-planets in a variety of nebula models ranging from the minimum to the maximum mass nebula. The latter being defined as the marginally gravitationally stable nebula for a given class of models.

I propose to use 'hot Neptunes' to distinguish between the alternatives of nucleated-instability/in-situ-formation and gravitational instability/migration for the origin of Pegasi-planets. A hot Neptune is a hypothetical giant planet with core and envelope mass similar to Neptune but in an orbit close to its star (typically less than 1 AU). If migration is important for the formation of Pegasi-planets, they are all expected to have large envelopes because a migrating Neptune would continue to accrete and hence develop a more massive envelope. Therefore no hot Neptunes are expected if migration is an important process in the formation of Pegasi-planets.

Chaotic Interactions in Multiple Planet Systems

Eric B. Ford
Princeton University, Department of Astrophysical Sciences

The detection of ~ 100 extrasolar planets has provided many challenges for theories of planet formation. Numerous mechanisms have been proposed to explain the surprising distributions of semi-major axes and eccentricities. Dynamical instabilities and chaotic interactions in planetary systems with multiple giant planets appear to provide a natural mechanism for producing the highly eccentric orbits frequently observed.

In a protoplanetary disk, the semi-major axis of a protoplanet is determined before the mass of the eventual planet. As nearby protoplanets accrete mass, a dynamical instability may lead to close encounters. Alternatively, a dissipative disk may prevent mutual interactions from exciting significant eccentricities. Once the disk clears, the eccentricities may grow and eventually permit close encounters. In any case, once planets begin to undergo close encounters, the planets may collide or be ejected from the system. These processes can significantly alter the orbits of the remaining planets. Numerous orbital integrations of possible planetary systems can determine the frequencies of the final outcomes for such systems and allow for comparison with observations.

Simulations of two equal mass planets initially on nearly circular coplanar orbits result in a bimodal distribution for the final eccentricity. The simulations which result in the two planets colliding end with a more massive planet in a nearly circular orbit, while the simulations which result in one planet being ejected from the system leave one planet on an eccentric orbit with $0.4 \leq e \leq 0.8$. However, if the two planets are assigned different masses, then the eccentricity after an ejection depends on the ratio of the planet masses. The observed distribution of eccentricities can be well reproduced for plausible distributions of the planet mass ratio. While a proper comparison would require careful consideration of observational selection effects and the unknown initial distributions, the two planet scattering model predicts a maximum eccentricity of $\simeq 0.8$ independent of these complications. Simulations of three equal mass planets initially on nearly circular coplanar orbits also result in a broad distribution of final eccentricities which seldom exceeds 0.8. The three planet scattering model distinguishes itself by predicting that an additional planet typically lies on a longer period orbit. Further, the relative inclination between the two planets is typically enhanced, up to $\sim 40°$. Future observations, including long-term radial velocity measurements, long-term precision astrometric measurements, and direct imaging, could test these predictions.

Dynamics of planetary systems

John Papaloizou
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Extrasolar planetary systems contain close orbiters, highly eccentric orbits and resonant pairs. It is likely that both disc-planet and planet-planet interactions have been important in configuring the observed syatems. Some possible processes are discussed and reviewed.

Dynamics in Multiple Systems and Stellar Clusters

Ian Bonnell
University of St. Andrews, U.K.

We explore the role of multiplicity and stellar interactions in affecting the formation and evolution of planetary systems. Observations of star formation show that most stars form in groups and clusters. Numerical simulations of the formation of such groups highlights the importance and frequency of stellar interactions which can limit the lifetime of a protoplanetary disc. Stars that form in dense systems are therefore less likely to have planetary systems than those in less dense systems. Once any planets have formed, stellar interactions in stellar clusters can ionise the planets resulting in free-floating planets. We discuss the properties that these objects should have and their expected lifetime in the cluster.

Is migration inevitable?

Caroline Terquem
Institut d'Astrophysique de Paris, France

According to current theories, tidal interactions between a disc and an embedded planet may lead to the rapid migration of the protoplanet on a timescale shorter than the disc lifetime or estimated planetary formation timescales. Therefore, planets can form only if there is a mechanism to hold at least some of the cores back on their way in. Once a giant planet has assembled, there also has to be a mechanism to prevent it from migrating down to the disc center.

I will review the different mechanisms that have been proposed to stop or slow down migration.

Planet Formation: Questions Ripe For Theoretical Advances

Jack J. Lissauer
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Modern theories of star and planet formation suggest that giant planets are most likely to form several AU from stars, so experts were quite surprised when, in 1995 Michel Mayor and Didier Queloz discovered the star 51 Pegasi to have a Jupiter-mass companion with an orbital period of less than 5 days. The possibility of that planets may migrate towards their star was suggested by Goldreich and Tremaine back in 1980, but researchers believed that virtually all of the planets which migrated inwards substantially would fall into their star and be consumed. Although models have subsequently been proposed to halt inwardly-migrating giant planets, the origin of the orbital distribution of known extrasolar planets remains mysterious. The mass distribution of extrasolar planets and the paucity of brown dwarfs orbiting within a few AU of Sun-like stars also needs to be explained. There doesn't seem to be a firm cut-off in planet masses, simply a gradual decline in number above a Jovian mass – what physical processes yield this distribution? Several major questions in theories of planet formation have remained a concern for over a decade: How do planetesimals form (especially the growth from mm – km size)? What core mass (if any!) is needed for a planet to accumulate substantial quantities of hydrogen and helium? What is the distribution of sizes and orbits of terrestrial planets? How common are habitable planets? Many of these questions are likely to be answered in the next decade, some by purely theoretical advances, others involving additional observations or experiments.

Future and Conclusions: Imaging

Daniel Rouan
Observatoire de Paris Meudon, France

Direct imaging of extrasolar planets is an important goal: beyond the media impact, this capability will:

a) complete the discovery space not covered by radial velocity technique or astrometry;

b) bring new pieces of information on the physical parameters of extrasolar planets: albedo, orbital elements, combined information on temperature and composition, seasonal variations;

c) provide statistics on many systems.

The detection of faint extended sources or point-like companions near a bright star is however not an easy task and requires both a high angular resolution and a high dynamic range, when one considers that a standard Jupiter at 10 pc around a G2V star is 23 magnitudes (i.e., 1.3×10^9 times) fainter than its star in the visible and separated only by $0.5''$. However, there is a large range of conditions that could make the life easier. For instance, a young massive (10 $M_{\rm Jup}$) planet, still on the contraction phase – and thus at a rather high temperature – orbiting a cold M star and observed at 20 microns, is now only 4.8 magnitude fainter than its star. Between those two cases, there is a variety of conditions that could be potentially frequent and represent the right door to enter the era of the direct detection of extrasolar planets. On the instrumentation side, there are two avenues to explore: in the near to mid-IR using ground-based large telescopes equipped with adaptive optics and from space, in the thermal IR, using cold telescopes. In both cases, however, a coronagraph blocking most of the light from the bright source is mandatory. A variety of coronagraph has been proposed in the past few years, from nulling interferometer to distant occulting screens. A short review of space missions and ground-based experiment that are currently studied will be done and an example of capabilities detailed in the case of one instrument.

Planets with Detectable Life

Tobias Owen
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Our ideas about the conditions required for the origin and evolution of life are still entirely dependent on the single example we know. Attempting to generalize, we look for rocky planets with abundant supplies of carbon and nitrogen that can maintain open bodies of liquid water on their surfaces for at least 5 billion years post surface cooling. Less favorable conditions may still be generative but are less likely to lead to life that produces copious amounts of gases out of equilibrium with the global environment. This is detectable life. Giant planets in the habitable zones of their stars may harbor potential life-bearing planets as giant satellites or Lagrangian hostages. Our primary targets, however, are independently orbiting Earth-size planets. In our own solar system, adequate reservoirs of H_2O, C, and N, are common but not ubiquitous. The sources of these vital volatiles should be equally active in other planetary systems. Candidate disequilibrium species indicative of life include O_2, CH_4, H_2S, and NH_3. To assess the probability that such gases are truly biomarkers, we will need to know the sizes and orbits of the potential life-bearing planets, as well as the approximate ages of their stars.

Outlook: Testing Planet Formation Theories

Alan P. Boss
Carnegie Institution, 5241 Broad Branch Road, NW, Washington, DC 20015-1305, USA

The discovery of the first planetary companion to a solar-type star by Mayor and Queloz (1995) launched the extrasolar planetary systems era. Observational and theoretical progress in this area has been made at a breathtaking pace since 1995, as evidenced by this workshop. We now have a large and growing sample of extrasolar gas giant planets with which to test our theories of their formation and evolution. The two competing theories for the formation of gas giant planets, core accretion and disk instability, appear to have testable predictions: (i) Core accretion seems to require exceptionally long-lived disks, implying that gas giants should be somewhat rare, while disk instability can occur in even the shortest-lived disk, implying that gas giants should be abundant. The ongoing census of gas giants by the spectroscopic search programs will determine the frequency of gas giants on Jupiter-like orbits within the next decade. (ii) Core accretion takes millions of years to form gas giants, while disk instability forms gaseous protoplanets in thousands of years. Determining the epoch of gas giant planet formation by searching for astrometric wobbles indicative of gas giant companions around young stars with a range of ages ($\sim$ 0.1 Myr to $\sim$ 10 Myr) should be possible with the Space Interferometry Mission (SIM). (iii) Core accretion would seem to be bolstered by a higher ratio of dust to gas, whereas disk instability occurs equally well for a range of dust opacities. Determining whether a high primordial metallicity is necessary for gas giant planet formation can be accomplished by spectroscopic and astrometric searches for gas giants around metal-poor stars. Eventually, ice giant planets will be detectable as well. If ice giants are found to be much more frequent that gas giants, this may imply that core accretion occurs, but usually fails to form a gas giant. Terrestrial planets will be detected through photometry by Kepler and Eddington, astrometry by SIM, and imaging by Terrestrial Planet Finder and Darwin. Ultimately these detections will clarify the process of Earth formation by collisional accumulation, the only contending theory.