Outlook: Testing Planet Formation Theories

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Abstract. 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 (∼0.1 Myr to ∼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 than 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.

1. Introduction

Given the wealth of knowledge about our own Solar System, nearly all work on the theory of planetary system formation has been focused on our own system. Little attention was paid to how the planet formation process might operate under other circumstances, with the noteworthy exception of Wetherill (1996), who studied the formation of terrestrial planets in the case of central stars and protoplanetary disks with varied masses, and with widely varying assumptions about the location of any gas giant planets in the system. This single-mindedness has led to a fairly mature, widely-accepted theory of terrestrial planet formation by the collisional accumulation of progressively larger solid bodies (Wetherill, 1990). Even after decades of research, however, there are two very different hypotheses about how the gas giant (Jupiter and Saturn) and ice giant (Uranus and Neptune) planets formed.

Beginning with the first discovery of an uncontested extrasolar gas giant planet by Mayor and Queloz (1995), the attention of many planetary formation theorists...
have shifted toward trying to understand the origin of the often unexpected properties of extrasolar planetary systems. As a direct result of entering this new era, theories of planetary system formation and evolution are beginning to evolve in order to encompass these new planetary systems. The desire to create a unified theory of planetary system formation, applicable both to extrasolar systems and to our Solar System, will undoubtedly lead to creative tensions that will test our most basic ideas of how these processes occurred.

In this workshop summary, we will review the current status of theoretical work on gas and ice giant planet formation by core accretion and disk instability, the two competing mechanisms. Given the difficulty of deciding between these two competing mechanisms purely on the basis of theoretical arguments, we note that observations of extrasolar planets and star-forming regions must play the central role in deciding between these two mechanisms. We thus conclude by pointing out a number of observational tests that should be applied to help settle the issue of planetary origins. This summary is based in part on a recent review paper (Boss, 2002b).

2. First Census of Neighboring Planetary Systems

The first confirmed discovery of an extrasolar planet orbiting a solar-type star was that of 51 Pegasi’s ≈ 0.5$M_J$ ($M_J$ = Jupiter’s mass) companion (Mayor and Queloz, 1995). Subsequent discoveries have come so rapidly that review articles are quickly outdated – Marcy and Butler’s (1998) review listed only 8 extrasolar planet candidates, whereas roughly 100 planet candidates exist as of September, 2002 (Figure 1). Most of the latest discoveries are either comparable to or greater than Jupiter in mass, or have semi-major axes greater than several AU, implying that most of the higher mass, shorter period planets have already been found, at least for those stars which have been studied for several years or more.

Prior to 1995, the only example of a planetary system was our own, and so it was natural for theorists to concentrate on forming the Solar System’s planets. As is evident from Figure 1, there exist a number of planetary systems which do not even remotely resemble our own. The very first Jupiter-mass planet discovered, 51 Pegasi’s planet (Mayor and Queloz, 1995), has a semimajor axis of ≈ 0.05 AU, 100 times smaller than that of Jupiter, and a surface temperature ∼ 10 times higher, because of its proximity to its star. Several more such “hot Jupiters”, and even “hot Saturns”, have now been found. Extrasolar planets seem to be more or less evenly distributed throughout the range of semimajor axes from about 0.04 AU to 3 AU (at least when viewed in terms of the log of the separation), with many of those orbiting outside 0.1 AU having orbits which are significantly more eccentric than that of Jupiter. Assuming a random distribution of planetary orbital inclinations, the median true masses of these objects are likely to be about 30% greater than the
Figure 1. Discovery space for extrasolar planets and brown dwarfs as of September, 2002. The oblique dashed line illustrates the current sensitivity limit for spectroscopic detections, showing that current limits are sufficient to detect true Jupiter-analogues. Filled circles represent roughly circular orbits, while open circles represent eccentric orbits. All of these objects were found by the spectroscopic method (Mayor and Queloz, 1995; Marcy and Butler, 1998) which yields only a lower limit on the companion’s mass. Objects with masses above $\sim 13M_J$ can burn deuterium and hence may be best classified as brown dwarf stars, rather than as gas giant planets. Nearly all of these objects are in orbit around solar-mass main sequence stars.

minimum masses found by Doppler spectroscopy (Figure 1), so that many of these planets are considerably more massive than Jupiter, by up to a factor of 10 or so.

However, the discoveries to date have also been reassuring in several ways. Evidence for a dozen or so systems containing two or more very low mass companions have been found so far, implying a planetary-like configuration of several smaller bodies orbiting a central star, which is totally unlike the hierarchical configuration of multiple star systems. The discovery of the first (and so far only) transiting planet, around the star HD 209458 (Charbonneau et al., 2000; Henry et al., 2000), has provided the best evidence yet that many if not most of these objects are indeed gas giant planets: the planet’s mass is $\approx 0.7M_J$, with a radius and a density (Mazeh et al., 2000) roughly equal to that expected for a hot Jupiter. In addition, sodium has been detected in the atmosphere of HD 209458’s planet (Charbonneau et al., 2002), exactly as predicted for a hot Jupiter (Seager and Sasselov, 2000). These ongoing discoveries have conclusively shown us that the Solar System is not the
only outcome of the planet formation process. The bulk of these new objects are likely to be gas giant planets, and their formation process and characteristics should be explainable by any general theory of planetary system formation.

3. Gas Giant Planet Formation

There are two logical extremes for forming gas giant planets, namely from the “bottom up” (core accretion), or from the “top down” (disk instability). Historically speaking, by far most of the efforts to understand giant planet formation have been performed in the context of the core accretion mechanism. As a result, the strengths and weaknesses of the core accretion mechanism are much better known than those of the competing disk instability mechanism, the latter of which has only recently been revived and subjected to serious theoretical investigation.

3.1. Core Accretion

The terrestrial planets are nearly universally believed to have formed in the inner solar nebula through the collisional accumulation of successively larger, solid bodies – sub-micron-sized dust grains, kilometer-sized planetesimals, lunar-sized planetary embryos, and finally Earth-size planets (Wetherill, 1990). The core accretion mechanism envisions the same basic process as having occurred in the outer solar nebula as well, leading to the formation of $\sim 10 M_\oplus$ solid cores, on roughly circular orbits initially, which then accrete massive gaseous envelopes from the disk gas (Mizuno, 1980). The $\sim 10 M_\oplus$ solid cores are expected to form through runaway accretion (e.g., Lissauer, 1987), where the largest bodies grow the fastest because their self-gravity increases their collisional cross-sections. An atmosphere forms at an early phase, by accretion of solar nebula gas, and as the protoplanet continues to grow by accreting both gas and planetesimals, this atmosphere eventually can no longer be supported in hydrostatic equilibrium and contracts. This contraction leads to a short period of atmospheric collapse, during which the protoplanet quickly gains the bulk of its final mass (Pollack et al., 1996). At that point, the accretion of solar nebula gas is assumed to be terminated.

The time scale for core accretion to proceed depends strongly on the initial surface density of solids. The surface density in the giant planet region is often assumed to be 5 to 10 times that of the “minimum mass solar nebula” in models of core accretion (Lissauer, 1987). Models which calculate both the accretion of gas as well as of planetesimals (Pollack et al., 1996) show that with a surface density of solids $\sigma_s = 10 \text{ g cm}^{-2}$ at 5.2 AU, core accretion requires $\approx 8 \times 10^6$ years to form Jupiter. When $\sigma_s$ is decreased by just 25%, the time required increases by a factor of 6. Time scales of 8 million years or more exceed current estimates of disk life times for typical solar-type young stars of a few million years in regions of low mass star formation (Briceño et al., 2001), and of less than a million years
in regions of high mass star formation (Bally et al., 1998). Speeding up the core accretion process by increasing the assumed surface density at 5.2 AU does not appear to work for Jupiter: when \( \sigma_s \) is increased to 15 g cm\(^{-2} \), the formation time drops to \( \sim 2 \times 10^6 \) years (Pollack et al., 1996), but produces a central core with a mass exceeding the possible range for Jupiter (Guillot et al., 1997), even given the great uncertainties in models of the Jovian interior. Models of the structure of HD 209458’s hot Jupiter seem to require that this extrasolar planet have no core at all, in order to match its observed radius (Hubbard et al., 2002; Guillot, this volume).

Things get even worse out at Saturn’s orbital radius, as core accretion proceeds more slowly as the orbital radius increases and orbital periods increase. All of these calculations (Pollack et al., 1996) already assume optimum conditions for the growth of cores: infinite reservoirs of accretable solids and gas, maximum possible gravitational cross-sections for collisions, no collisional fragmentation, and the absence of competition from other nearby, runaway protoplanets. Some recent core accretion models have shown that the time scale for envelope growth depends strongly on the assumed core mass and somewhat on the assumed dust grain opacity (Ikoma et al., 2000). Ikoma et al. (2000) claim that a nebula lifetime of more than 100 million years is needed to form Jupiter and Saturn, or else migration of protoplanets may have to be considered. The recent paper by Kokubo and Ida (2002) assumes that disks last for 100 million years, sufficiently long for several Jovian planets to form from massive disks by core accretion. However, the core accretion models by Kornet et al. (2002) have found that the two giant planets in the 47 UMa system might have formed in about 3 million years, assuming that the protoplanetary disk had a mass of 0.164 \( M_\odot \), a local enhancement of the dust-to-gas ratio between 1 AU and 4 AU, no competing protoplanets, no loss of planetesimals by gas drag, and no migration of the protoplanet. While work continues on resolving the time scale problem, core accretion would seem to be competitive only in relatively long-lived protoplanetary disks (Lissauer and Lin, 2000).

Core accretion models of the in situ formation of hot Jupiters have also been attempted. The critical core mass needed for gaseous envelope collapse onto the core could be as low as 2-3 \( M_\oplus \) at 0.1 AU, according to Ikoma et al. (2001). However, other calculations found that core accretion could only proceed very close to the star if solids were transported inward at a high rate in order to feed the growing core (Bodenheimer et al., 2000). The latter models suffer from the same time scale problem that occurs at more traditional distances.

The results of Bodenheimer et al. (2000) suggest that hot Jupiters formed farther out than their current distances, and then experienced inward orbital migration to their present parking orbits (Lin et al., 1996; Bodenheimer et al., 2000). The necessary orbital migration is likely to have resulted from gravitational interactions between the planet and the gas disk, though planet-planet gravitational interactions have also been studied (Ford, this volume). However, prior to the planet becoming large enough to open a gap in the disk, the time scale for inward migration (Type
I migration) is only about $10^4$ years for a $10 M_\oplus$ body. Hence it may be difficult for a growing core to survive long enough to accrete a gaseous envelope and then open a disk gap before the core is lost by inward migration onto the star (Ward, 1997; Papaloizou and Larwood, 2000; Miyoshi et al., 1999). Once a protoplanet grows large enough to remove the gas from its immediate vicinity by opening a disk gap, the protoplanet thereafter migrates (inward, or outward, depending on location in the disk) along with the disk (Type II migration). Opening a disk gap may slow but not stop subsequent growth by accretion of gas (Bryden et al., 1999). The observational fact that extrasolar planets found so far have a wide range of orbital distances from their stars may imply that their Type II orbital migration times were comparable to the life times of their inner disks ($\sim 10^6$ years), a life time that is roughly consistent with estimated disk viscosities based on theoretical estimates of likely sources of turbulent viscosity.

A number of arguments for and against core accretion may be noted. Forming Jupiter by core accretion is consistent with the absence of planets in the asteroid belt (Wetherill, 1996). Core accretion also is consistent with large core masses and non-solar bulk compositions. However, estimated core masses for the gas giant planets have dropped dramatically since 1995, and are now thought to be in the range from 0 to $10 M_\oplus$ for Jupiter, and from 6 to $17 M_\oplus$ for Saturn (Guillot et al., 1997; Guillot, 1999a). Obviously a core mass which is too small to initiate gas accretion would seem to rule out core accretion, unless the core somehow dissolved after the planet formed. HD 209458’s planet appears to be hydrogen-rich (Hubbard et al., 2002) and need not even have a core. The non-solar atmospheric compositions of Jupiter and Saturn (Guillot, 1999b) are likely to be at least in part the result of several billion years of cometary impacts (e.g., Comet Shoemaker-Levy 9’s spectacular demise in Jupiter’s atmosphere). In the core accretion scenario, it is unclear what process could have limited Saturn’s mass to its present value, roughly 1/3 that of Jupiter, given its apparently larger core mass. Considering these concerns about core accretion, it seems worthwhile to examine the prospects of the other possibility for gas giant planet formation.

3.2. DISK INSTABILITY

The only known alternative to core accretion is disk instability, where gas giant protoplanets form rapidly through a gravitational instability of the gaseous portion of the disk (Cameron, 1978; Boss, 1997). The disk instability mechanism had been neglected for years largely because it could not easily account for the initial estimates of the core masses of Jupiter and Saturn (in the range of 20 to 30 Earth masses), or for their non-solar bulk abundances. However, it seems likely that a significant solid core could form in a giant gaseous protoplanet by the process of sedimentation of dust grains to the center of the protoplanet, prior to contraction of the protoplanet to planetary densities and temperatures high enough to dissolve or melt the solids (Boss, 1997, 1998a). This is the same process that is thought to
lead to the formation of solid planetesimals in the core accretion mechanism, as dust grains sediment downward toward the midplane of the disk, only now in the spherical geometry of a gaseous protoplanet. A disk instability leading to gaseous protoplanet formation and the process of core formation by sedimentation of dust grains would occur essentially simultaneously, within $\sim 10^3$ years. Contraction of the protoplanet to planetary densities requires another $\sim 10^6$ years or so. For a Jupiter-mass protoplanet with a solar abundance of metals, sedimentation of all of the metals could lead to the formation of at most a $\sim 6M_\oplus$ core, a core mass more or less in the middle of the currently estimated range (Guillot, 1999a). The impacts of the fragments of Comet Shoemaker-Levy 9 with Jupiter, combined with recent gas giant interior models (Guillot, 1999b), suggest that the present atmospheres of the gas giant planets reflect their accretion history more than their primordial compositions. A Jupiter formed by disk instability may then have experienced much the same accretion history as a Jupiter formed by core accretion, leading to similar envelope enrichments.

The standard core accretion model (Pollack et al., 1996) seems to require a surface density at 5.2 AU which implies at least a marginally gravitationally unstable nebula, because midplane temperatures in the solar nebula drop quickly beyond the asteroid belt (Boss, 1998c) and are constrained to values below about 50 K in the outer nebula by the presence of low temperature molecular species seen in comets. Detailed three dimensional hydrodynamical models have shown that such a marginally unstable disk will become strongly non-axisymmetric and form trailing spiral arms within just a few rotation periods (Boss, 1998a). When followed with a sufficiently high spatial resolution calculation, these spiral arms break-up into high-density clumps containing enough mass to be self-gravitating and tidally stable (Boss, 2000). Hydrodynamical models with a full thermodynamical treatment, including three dimensional radiative transfer in the diffusion approximation (Boss, 2001), have shown that a disk instability proceeds in a similar manner as in the previous calculations (Boss, 2000), which employed thermodynamical assumptions which were more favorable for the growth of self-gravitating clumps. This similarity results because the time scale for cooling from the disk surface is comparable to the dynamical (orbital) time scale, so that clump formation is slowed, but not prevented, by compressional heating. The energy produced by compressional heating at the disk midplane is transported to the disk surface by convective cells, with convective velocities at 10 AU being large enough to transport heat to the disk surface on the orbital time scale (Boss, 2002c).

Disk instability can produce self-gravitating protoplanets with cores in $\sim 10^3$ years, so there is no problem with forming gas giant planets in even the shortest-lived protoplanetary disks. Even if core accretion can form gas giant planets in about 3 million years (Kornet et al., 2002), disk instability evidently will outrace core accretion, if it can occur in the first place. Disk instability is enhanced in increasingly massive disks, and so it should be able to form planets at least as massive as Jupiter, given that Jupiter-mass clumps form even in disks with masses
of $\sim 0.1 M_\odot$. Disk instability sidesteps any problem with Type I orbital migration, and with gap-limited mass accretion, because the clumps form directly from the gas without requiring the prior existence of a solid core subject to Type I drift that can disappear before opening a gap. Once they are formed, the clumps quickly open a disk gap, preventing Type I motion with respect to the gas, but only after most of the protoplanet’s mass has already been captured. Thereafter the protoplanet migrates with the disk; in the case of the Solar System, little orbital migration appears to be necessary, implying a short life time for the solar nebula (see below). Rapid Jupiter formation by disk instability appears to be compatible with terrestrial planet formation by collisional accumulation and may help limit the growth of bodies in the asteroid belt (Kortenkamp and Wetherill, 2000; Kortenkamp et al., 2001; Thébault and Brahic, 1999). In fact, disk instability could even help to speed the growth of the Earth and other terrestrial planets (Kortenkamp et al., 2001). As in the core accretion mechanism, the ongoing accretion of comets is needed to explain the non-solar compositions of the envelopes of the gas giant planets.

Disk instability is not without its own problems, however, though potential solutions may exist in some cases. It is unclear how massive a core formed by sedimentation of dust grains would be, particularly if the interior temperature should become too high for water ice to remain solid. Whether or not a marginally gravitationally-unstable disk will evolve in such a way as to produce self-gravitating clumps is also unclear, as gravitational torques may simply redistribute mass and angular momentum instead. The pioneering work on this question had insufficient numerical resolution (25,000 particles, versus over 1 million grid cells in current disk instability models, e.g., Boss, 2003) to allow self-gravitating clumps to form (Laughlin and Bodenheimer, 1994). As a result, disk instabilities may require some sort of trigger to produce clumps, such as the accumulation of gas in a magnetically-dead zone of the disk, episodic accretion of infalling gas onto the disk (Boss, 1997), or perhaps a close encounter with another star. The conditions under which newly-formed clumps survive to become gas giant planets also remain to be understood, though calculations by Mayer et al. (2002) suggest that the clumps can survive as they orbit in the disk. Disk instability would also have trouble forming sub-Jupiter-mass planets, unless one invokes tidal stripping of the protoplanet’s envelope during a phase of rapid inward orbital migration, or photoevaporation of the protoplanet’s envelope (see below).

4. Ice Giant Planet Formation

The same two mechanisms that have been advanced for explaining the formation of the gas giant planets are also possibilities for explaining the formation of the ice giant planets.
4.1. CORE ACCRETION

Because of their relatively modest gaseous envelopes, the ice giant planets are somewhat less constrained than the gas giant planets by the observed life times of protoplanetary disks; e.g., it has been suggested that they formed as recently as 3.9 billion years ago (Levison et al., 2001). Nevertheless, there remains a severe time scale problem for forming ice giants by core accretion. Time scales for collisions to occur increase with increasing orbital period. As a result, collisional accumulation is even slower in the outer solar nebula than in the gas giant planet region. Furthermore, lower surface densities of solids at greater heliocentric distances slow collisional growth even more. Perhaps most importantly, because the escape velocity from the Solar System at 20 AU to 30 AU is \( \sim 8 \text{ km s}^{-1} \), comparable to orbital velocities and to the relative velocities between growing planetary embryos, the effect of mutual encounters of embryos is to excite orbital eccentricities so much that the embryos soon cross the orbits of Saturn or Jupiter. As a direct result, embryos can be ejected on hyperbolic orbits, lost by impact with the gas giant planets, or perturbed onto comet-like orbits (Lissauer et al., 1995). In fact, it has been asserted that ice giant planets cannot form in the standard core accretion model (Levison and Stewart, 2001). Theorists have artificially increased collisional cross sections of the growing planetary embryos by several orders of magnitude in order to try to gain some understanding of what might have happened in the outer Solar System (Levison et al., 1998). Even in this unphysical case, the bodies that do grow have eccentric orbits that inhibit further growth and do not resemble the more nearly circular orbits of the outer planets.

One approach to solving the problem of the ice giant planets has been to invoke a hypothetical drag force that would damp orbital eccentricities in the outer Solar System (Levison and Stewart, 2001), due perhaps to extended planetary envelopes, or to interactions with the remaining gas and planetesimals in the nebula. One could also imagine the runaway accretion of a single embryo all the way to Uranus-size (Bryden et al., 2000), instead of assuming the oligarchic growth of multiple embryos (Kokubo and Ida, 1998). Perhaps the leading suggestion for forming the ice giant planets by core accretion is the idea (Thommes et al., 1999) that the ice giants were formed between Jupiter and Saturn (i.e., that core accretion was able to form four cores between 5 and 10 AU), and then were gravitationally scattered outward to their current orbits, following the rapid growth of the gaseous envelopes (and masses) of one or two of the other cores that were destined to become Jupiter or Saturn. This scenario might then be only a little more difficult than that of forming just the gas giant planets by core accretion.

4.2. DISK INSTABILITY

Recently it has been proposed that disk instability might be capable of forming the ice giant planets, provided that the Solar System formed in a region of high mass star formation, similar to the Orion nebula cluster (Boss et al., 2002). The
conventional view of Solar System formation is that the presolar cloud collapsed in a region of low-mass star formation, similar to Taurus-Auriga. In such a quiescent setting, the background UV flux is likely to be low and limited largely to the flux from the protosun, once it forms.

However, in regions similar to the Orion Trapezium environment, extreme ultraviolet radiation (EUV) from the massive stars would photoevaporate the disk gas outside a radius of about 10 AU in about $\sim 10^5$ years (Bally et al., 1998). Recent observations of young stars in the Eta Carina nebula have revealed the presence of protoplanetary disks being exposed to a level of EUV radiation roughly 100 times higher than that in Orion (Smith et al., 2002), leading to proportionately shorter outer disk life times. Once the disk gas is removed, the outermost protoplanets would then be exposed to EUV radiation, and provided that they do not contract to planetary densities in a time much less than $\sim 10^4$ to $\sim 10^6$ years (DeCampli and Cameron, 1979), their gaseous envelopes will also be photoevaporated by the
incoming EUV flux, leaving behind the cores previously formed by sedimentation and coagulation of their dust grains. Given the formation by disk instability of four gas giant protoplanets with masses of order 1 to 2 $M_J$, close to the orbits of Jupiter, Saturn, Uranus, and Neptune (Boss, 2003; Figure 2), EUV photoevaporation of the gaseous envelopes of the outermost three protoplanets would leave behind cores with partial gaseous envelopes, producing planets similar in composition to Saturn, Uranus, and Neptune (Boss et al., 2002). The innermost gas giant, destined to become Jupiter, is inside the critical radius where the disk gas cannot be removed by EUV radiation because of the protosun’s gravitational attraction, and so does not lose any envelope gas.

Much remains to be studied in this unconventional mechanism for ice giant planet formation, but this mechanism does have the major advantage of being applicable in general, as most stars are believed to form in regions similar to Orion. If correct, this would mean that the Solar System need not have formed under somewhat special circumstances, and so need not be the exception, but could instead be the rule among planetary systems. While roughly 5% of nearby sun-like stars are circled by planetary systems quite unlike our own (Figure 1), the remaining sun-like stars might still shelter planetary systems similar to the Solar System.

5. Conclusions

Thanks to the pathbreaking work of Michel Mayor, Didier Queloz, and their colleagues, we are now embarked on a grand journey to explore the possibilities for other habitable planets in our corner of the Milky Way galaxy. As we proceed on this journey, we are likely to learn enough about the characteristics of planetary systems to be able to differentiate between the two competing theories of the origin of gas and ice giant planets. We conclude by highlighting a few key observational tests that should aid in this process.

5.1. Observational Tests for Gas Giant Planet Formation

If core accretion requires an exceptionally long-lived disk in order to have sufficient time for the accretion of a massive gaseous envelope, then gas giant planets might be no more frequent than long-lived disks. If disk instability is able to occur, on the other hand, it should lead to the formation of gas giants in even the shortest-lived protoplanetary disk. Hence, one basic test is to determine the frequency of gas giant planets: are they rare or commonplace? The results to date (Figure 1) would suggest that gas giants are abundant, but only continued efforts by the ground-based radial velocity surveys will reveal the true gas giant planetary census, particularly for the longer period planets more closely resembling Jupiter.

Because core accretion is slow with respect to disk instability, if core accretion dominates, young stars should not show evidence of gas giant companions until
they reach ages of several million years or more. If disk instability dominates, however, even the youngest stellar objects may have gas giant planets. Dating the epoch of gas giant planet formation is thus another means to differentiate between the two contenders (Boss, 1998b). Several techniques could be employed. NASA’s Space Interferometry Mission (SIM) will search for the astrometric wobbles of young stars caused by gas giant companions, beginning perhaps as early as 2009. Nearby low-mass star-forming regions such as Taurus and Ophiuchus will be the primary hunting grounds. The Atacama Large Millimeter Array (ALMA) will be able to form mm-wave images of protoplanetary disks with \( \sim 1 \) AU resolution and search for disk gaps created by massive protoplanets. The radial velocity technique is hampered in dating the epoch of gas giant planet formation because of the rapid rotation rates (and hence broad spectral lines), chromospheric activity, and variability of young stars.

Disk instability appears to be relatively insensitive to the opacity of the disk, which is dominated by dust grains, and thus to the metallicity of the host star and disk (Boss, 2002a). It is unclear if core accretion is helped or hindered by higher metallicity, but the overall effect should be to raise the surface density of solids and thus to speed the growth of cores. Another test is thus to see if a high primordial metallicity is necessary for gas giant planet formation. This will require either spectroscopic or astrometric ground-based searches for gas giants around metal-poor stars, the latter using the Keck Interferometer (KI) or the Very Large Telescope Interferometer (VLTI).

Finally, the mass of Jupiter’s core remains as an important clue to its origin. If Jupiter’s core is much more massive than \( \sim 6M_\oplus \), then it probably could not have formed by disk instability, unless it had lost part of its gaseous envelope by EUV stripping and then migrated inward to 5.2 AU. A large Jupiter core would seem to support formation by core accretion. A Jupiter polar orbiter mission to probe the planet’s gravitational field might be needed to better constrain the Jovian interior.

5.2. OBSERVATIONAL TESTS FOR ICE GIANT PLANET FORMATION

If core accretion can occur, but seldom occurs in a disk long-lived enough for a gas giant planet to form, then the typical result may be a system of failed cores, i.e., a system of ice giant planets, unaccompanied by gas giants. If disk instability dominates, inner gas giants should be the rule, accompanied by outer ice giant planets in systems which formed in Orion-like regions and experienced EUV envelope stripping. In Taurus-like regions, disk instability should produce only gas giants, unaccompanied by outer ice giants. Ground-based radial velocity surveys for “hot Neptunes” will shed light on the frequency of short period ice giants. The Corot, Kepler, and Eddington space missions will use photometry to detect “hot” and “warm Neptunes” by the transit method. “Cold Neptunes” could be detected astrometrically by the KI, VLTI, or SIM.
The question of planetary system architectures is another potential factor: where are the ice giants orbiting with respect to the gas giants? If extrasolar planetary systems are typically as well-ordered as the Solar System (inner terrestrial planets, intermediate gas giants, outer ice giants), such an architecture would imply formation *in situ*, or else an orderly, disk-driven inward orbital migration from more distant regions. However, if extrasolar planetary systems are more often disordered, this would imply that gravitational interactions between the protoplanets led to a phase of chaotic evolution where information about the primordial planetary orbits has been lost. In the latter case, it may be hard to place constraints on the formation mechanisms involved.

5.3. DETECTION OF EXTRASOLAR EARTHS

The ultimate goal of the search for extrasolar planetary systems is to find terrestrial-like planets orbiting in the habitable zones of their stars, planets that might well be analogous to the Earth, though perhaps at a much different phase of planetary evolution. While this goal still seems distant, it is much closer than it was in 1995, before Mayor and Queloz (1995) made their epochal discovery. Both NASA and ESA are planning to fly space missions that will first estimate the frequency of Earth-like planets by transit photometry (Kepler and Eddington, respectively), and then detect and characterize Earth-like planets by direct imaging, either with an optical coronagraph or with an infrared interferometer (Terrestrial Planet Finder and Darwin, respectively). The detection of extrasolar Earths will tell us much about the outcome of the collisional accumulation process in different stellar environments, and will begin to answer the question of the existence of life elsewhere in the universe. History will record that this journey began in 1995 with the work of two Swiss astronomers.

Acknowledgements

I thank the meeting organizers for their support of my attendance at this grand celebration of Michel Mayor's life and achievements. This work has also been partially supported by the U.S. National Aeronautics and Space Administration through grant NAG 5-10201.

References


Briceño, C., A. K. Vivas, N. Calvet, L. Hartmann, R. Pacheco, D. Herrera, L. Romero, P. Berlind, 

Gap Formation in Protoplanetary Disks: Gap Clearing and Suppression of Protoplanetary Growth’. 

544, 481–495.


DeCampli, W. M., and A. G. W. Cameron: 1979, ‘Structure and Evolution of Isolated Giant Gaseous 


from Galileo Measurements and Interior Models’. Icarus 130, 534–539.


