PLANET FORMATION

Towards Estimating Galactic Habitability

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Abstract. The present census of the galactic planetary population shows that planets exist outside the Solar System. But the empirical evidence is still insufficient to estimate the overall preconditions for the diversity and abundance of habitats that planets may provide in our galaxy. Detecting planets is still centered around giant planets in orbits with periods comparable and less than Jupiter's around nearby solar like stars. For a global picture, a general understanding of the planet formation process is needed to extrapolate what is known from the Solar System and about extrasolar planets to other stellar types and environments in the galaxy. A predictive theory of planet formation may contribute to this task.

1. Introduction: Planet Formation and Star Formation

Planet formation is closely interrelated with star formation and early stellar evolution (e.g. Mannings et al. 2000). The star formation process leads to the formation of a central body, incorporating most of the mass, and of a circumstellar disk, which retains most of the initial angular momentum and will be the environment where planets will form. The circumstellar disks separate mass and angular momentum and allow the gas to accumulate in a central condensation — the young star. The gas density in the disk is enhanced by a factor of $\sim 10^{10}$ relative to the densest pre-stellar cloud, and reaches typically 10^{12} hydrogen molecules per cm^{-3} from an initial 10^4. Dust particles, which represent about 2% in mass, naturally grow by accretion in this denser environment from submicron sizes to much larger sizes. Most of the present theoretical work on planet formation relies on the planetesimal hypothesis which assumes that the dusty disks produce km-sized, mutually gravitationally interacting bodies called planetesimals, made of elements that are condensible under nebula conditions and constitute the planetary building blocks. Such planetesimals grow by mutual collisions up to terrestrial planet masses and beyond, if sufficient material is available. If sufficiently massive large planetary embryos form before the nebula or remnants of it are dissipated, they attract and permanently bind nebula gas.

Models of the interiors and evolution of giant planets in our Solar System point to a bulk enrichment of heavy elements by more than a factor of two above solar composition and imply heavy element cores ranging from greater than one Earth mass to a considerable fraction of the total mass. That is evidence for the importance of condensible elements in giant planet formation and hence in planet formation in general. The key role of planetesimal accretion is even more visible when looking at the cratered surfaces of terrestrial planets and moons as well as small objects in the Solar System. Indeed many of the comets and asteroids may be leftover planetesimals or are closely related to them.

Detailed models of planet formation explain the diversity of solar system and extrasolar giant planets by varying the assumptions about the protoplanetary nebulae. Variations of nebula properties result in variations of the core growth rates caused be a coupling of the dynamics of planetesimals and the contraction of the massive planetary envelopes they dive into, as well as changes in the hydrodynamical accretion behavior of the envelopes caused by differences in nebula density, temperature and orbital distance.

The key question is how great a diversity of protoplanetary nebulae will provide the preconditions needed for the planetesimal hypothesis to be true and which pathways of planetary growth are working and which are dominating. The diversity of galactic habitats will reflect the diversity of protoplanetary nebulae and the richness of the planet formation process. The question to be answered in the next years is to what extent planet formation is a well-defined self-organizing structure formation process or whether 'anything goes'[1], as might be concluded from the literature following the discovery in 1995 of 51 Peg b, the first extrasolar giant planet in orbit around an ordinary star.

The pioneering study of planet formation around a diversity of stars has been performed by Nakano (1987, 1988a,b). The Kyoto model of Solar System planet formation is applied to stars of 0.5 to 10 solar masses[2]. Planet forming regions are identified by requiring conditions for appropriate

[1] I.e. many qualitatively different pathways lead to planets with planet formation being due to a collection of mechanisms leading to a loosely common outcome with great variety.

[2] That approximately corresponds to effective temperatures of 4000 to 30000 K and luminosities of 0.04 to 4000 solar luminosities on the stellar main sequence.

condensed material to be present and formation within the respective stellar life-time and the age of the universe. While being careful to note that given numbers are likely to change, Nakano concluded that there must be an upper limit for the masses of stars that can be accompanied by planets and one for stars accompanied by planets with surface temperatures nearly equal to that of Earth.

Presently the general theoretical understanding of planet formation is limited by (1) the fact that it is unclear if and how planetesimals must form, given the presently available assumptions, approximations and knowledge about the protoplanetary nebula conditions, (2) the fact that the nebula that forms the planetary building blocks and embryos might lead to their loss via various planet-nebula interactions and (3) uncertainties relating to the duration of final stages of planetary growth and the nebula lifetimes.

1.1. SOLAR SYSTEM FORMATION

Our four giant planets contain 99.5% of the angular momentum of the Solar System, but only 0.13% of its mass. On the other hand, more than 99.5% of the mass of the planetary system is in those four largest bodies. The angular momentum distribution can be understood on the basis of the nebula hypothesis (Kant 1755). The nebula hypothesis assumes concurrent formation of a planetary system and a star from a centrifugally supported flattened disk of gas and dust with a pressure supported, central condensation (Laplace 1796, Safronov 1969, Lissauer 1993, Wuchterl et al. 2000, Markwick and Charnley 2004). Observationally inferred disk sizes and masses are overlapping theoretical expectations and confirm the nebula hypothesis. High resolution observations at millimeter-wavelengths are sensitive to disk conditions at orbital distances $> 50\,\mathrm{AU}$ (see Markwick and Charnley 2004). However, observations thus far provide little information about the physical conditions in the respective nebulae on scales of 1 to 40 AU, where planet formation is expected to occur. Planet formation studies therefore obtain plausible values for disk conditions from nebulae that are reconstructed from the present planetary system and disk physics.

2. Stellar properties during planet formation

The properties of a young star, that result from a given pre-stellar cloud can be evaluated assuming that the cloud collapse is not drastically delayed by the formation and evolution of the disk. Fluid-dynamical calculations can reach the ages of observed young stars — a few to a hundred Ma — from initial conditions that correspond closely to observed cloud fragments (Wuchterl and Klessen 2001, Wuchterl and Tscharnuter 2003). These calculations assume basic physical principles and a calibration of the convection prescription to the Sun. They provide self-consistent quantitative histories of protostars and predict global properties (ages, masses, luminosities, effective temperatures) for young stars during their early evolution, from embedded stages (Class 0) to the T-Tauri-star phenomena for Larson-Penston-type collapse (cf. Markwick and Charnley 2004). They presently theoretically constrain the effects of a forming star on the protoplanetary nebula during the early phases of planet formation (first few Ma). According to these collapse studies, the young Sun had a luminosity of 4 ± 0.4 times its present luminosity, $L_\odot$ with a temperature of $4950 \pm 20\,\mathrm{K}$, hence was twice as bright and $500\,\mathrm{K}$ hotter at an age of 1 Ma than according to the classical calculations of early stellar evolution. Classically stellar evolution studies start by assuming initially fully convective structures without considering the protostellar collapse in detail.

3. Giant Planet Formation

3.1. BASIC PRINCIPLES

Pre-planetary disks are rotating structures in (quasi)equilibrium. The gravitational force is balanced in the radial direction by the centrifugal force augmented by gas pressure, and in the vertical direction by gas pressure alone. This gravitational force is mostly that of the central star; the gravity due to the disk itself (self-gravity) remains weak in comparison.

The key problem in planet formation is that, in addition to this stable situation, any isolated, orbiting object below a critical density (the Roche density) is pulled apart by the stellar tides. Typical nebula densities are more than two orders of magnitude below the Roche density, so compression is needed to confine a condensation of mass M inside its tidal or Hill-radius at orbital distance a:

$$R_T = a \left(\frac{M}{3\mathrm{M}_\odot} \right)^{1/3} . \tag{3}$$

A local enhancement of self-gravity is needed to overcome the counteracting gas pressure.

Giant planet formation theories may be classified by how they provide this enhancement: (i) the *nucleated instability* model relies on the extra gravity field of a sufficiently large solid core (condensed material represents a gain of ten orders of magnitude in density and therefore self-gravity compared to the nebula gas), (ii) a *disk instability* may operate on length scales between short scale pressure support and long scale tidal support, or (iii) an *external perturber* could compress an otherwise stable disk on its local dynamical time-scales, e.g., by accretion of a clump onto the disk or rendezvous with a stellar companion.

If the gravity enhancement is provided by a dynamical process as in the latter two cases, the resulting nebula perturbation, (say of a Jupiter mass of material) is compressionally heated because it is 'optically thick' under nebula conditions and cannot radiate rapidly its internal heat. Giant planet formation would then involve a transient phase of tenuous giant gaseous protoplanets, that would be essentially fully convective and contract on a timescale of typically $\sim 10^6$ yr (Bodenheimer and Pollack 1986).

3.2. NEBULA STABILITY

Preplanetary nebulae with solar composition and a mass that is just sufficient to accommodate the Solar System's inventory of condensible elements — a few percent of a solar mass — are stable. This probably excludes planet formation via disk instability. Substantially more massive disks resulting from the collapse of cloud cores are self-stabilizing due to transfer of disk mass to the stabilizing central protostar (see Bodenheimer et al. 1993). Nevertheless a moderate mass nebula disk might be found that can develop a disk instability leading to a strong density perturbation, especially when forced with a finite external perturbation. Giant gaseous protoplanets (GGPPs) might form when the instability has developed into a clump (DeCampli and Cameron 1979, see Bodenheimer 1985, 1986 for a discussion). These clumps, provided they are stable on a few cooling times, are candidates to become proto-giant planets via an intermediate state as tenuous giant gaseous protoplanet (GGPP).

A key issue, as in any theory involving an instability of the disk gas, is then the a posteriori formation of a core. Only condensates that are present initially would rain out to form a core, while material added later by impacts of small bodies after the GGPP had formed would be soluble in the envelope (Stevenson 1982a). To account for the bulk heavy element compositions of Saturn and certainly Jupiter planetesimal accretion has to occur anyway after the GGPPs have formed their cores. Boss (2003) applied the disk-instability model to the formation of outer giant planets and investigated whether clumps with a few Jupiter masses could result from a disk instability in the outer solar nebula. If the clumps he found indeed later develop into giant planets they would have to subsequently form a core and then loose $\sim 97\%$ of their mass by photo-evaporation driven by assumed massive stars neighboring the early Sun to finally become 'Neptunes'. See Wuchterl et al. (2000) for further discussion.

3.3. NUCLEATED INSTABILITY - CORE-ENVELOPE ACCRETION

Planet formation in the context of the core-nucleated instability hypothesis is the consequence of the formation and growth of the solid building blocks.

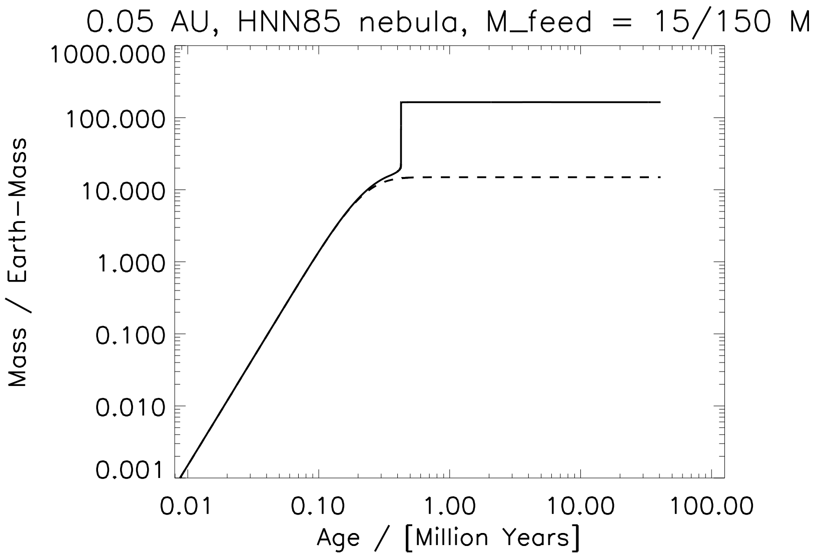

Figure 1. Total mass (full line) and core mass (dashed line) of a Pegasi-planet forming at 0.05 AU from a solar mass star. The accumulation of a gaseous envelope surrounding a condensible element core that grows by planetesimal accretion is shown for the first 100 million years. The structure of the envelope is calculated dynamically including time-dependent theory of convection that is calibrated to the Sun and including detailed equations of state and opacities. Note the gradual build-up of the core by planetesimal accretion and the step-like rapid capture of the gaseous envelope.

According to the 'planetesimal hypothesis' planets grow within circumstellar disks via pairwise accretion of km-sized solid bodies, the so-called planetesimals. Sufficiently massive planetesimals embedded in a gravitationally stable preplanetary nebula can capture large amounts of gas and become the cores of giant planets (e.g. Fig. 1, Wuchterl 1995b, Tajima and Nakagawa 1997, Ikoma et al. 2001). The onset of formation of massive envelopes is characterized by the so-called critical and crossover masses. Typical values for the critical mass (largest static envelope for a growing core) are in the range of 7 to 15 earth masses, for standard (minimum mass) assumptions about the preplanetary nebula.

3.4. THE GASEOUS ENVELOPES

Planetesimals in the solar nebula are small bodies surrounded by gas. A rarefied equilibrium atmosphere forms around such objects. Detailed atmospheric models with radiative and convective energy transfer (Mizuno 1980) showed that cores of typically ten earth masses are needed to gravitationally bind a comparable amount of nebula gas. Such envelopes were found to continue mass-accretion up to a few tens of Earth masses if the contraction of their envelopes was accounted for in quasi-hydrostatic models (Bodenheimer and Pollack 1986). Static and quasi-hydrostatic models rely on the assumption that gas accretion from the nebula onto the core is very subsonic, and the inertia of the gas and dynamical effects as dissipation of kinetic energy do not play a role — in short the motion of gas is neglected. To check whether gas motion remains slow during accretion hydrodynamical investigations are necessary. A linear adiabatic dynamical stability analysis of envelopes evolving quasi-hydrostatically (Tajima and Nakagawa 1997) found that motions would remain slow and hence the gaseous envelopes could relatively slowly grow to giant planet masses. Nonlinear, convective radiation-hydrodynamical calculations of core-envelope proto-giant planets (see Wuchterl et al. 2000 for review) found two pathways for the further evolution. The first one, typical for lower nebula-densities — that lead to mostly radiative envelopes — produces Uranus/Neptune type planets with relatively small hydrogen-helium envelopes around a large core. The second one, for higher nebula-densities — that lead to mostly convective envelopes (Wuchterl 1993, Ikoma et al. 2001) — leads to massive giant planets as Jupiter and Saturn (Wuchterl 1995b).

The two pathways are separated by the transition of the outer protoplanetary envelopes from radiative to convective energy transfer. An approximate condition separates the two pathways depending on the midplane nebula density. The resulting criterion gives a minimum nebula density $\varrho_{\rm neb}^{\rm crit}$ that is necessary for a convective outer envelope (Wuchterl 1993, Ikoma et al. 2001):

$$\begin{aligned}\frac{\varrho_{\rm neb}^{\rm crit}}{[10^{-10}{\rm g\,cm^{-3}}]} \quad = \quad & 2.2\left(\frac{T}{[100{\rm K}]}\right)^{3}\left(\frac{\nabla_{\rm s}}{[2/7]}\right)\left(\frac{\mu}{[2.2]}\right)\left(\frac{\kappa}{[{\rm cm^2\,g^{-1}}]}\right)^{-1} \\ & \left(\frac{\dot{M}_{\rm core}}{[10^{-6}\,{\rm M_\oplus\,yr^{-1}}]}\right)^{-1}\left(\frac{M_{\rm core}}{[10\,{\rm M_\oplus}]}\right)^{\frac{1}{3}}\left(\frac{\varrho_{\rm core}}{[5.5]}\right)^{-\frac{1}{3}}, \quad (1)\end{aligned}$$

for midplane nebula temperature T, logarithmic adiabatic gradient (with respect to pressure), $\nabla_{\rm s}$, mean molecular mass μ, opacity κ, core-mass and -density, $M_{\rm core}$, $\varrho_{\rm core}$, resp. and planetesimal accretion-rate $\dot{M}_{\rm core}$. Protoplanets that grow under nebula conditions above that density have larger envelopes for a given core, a reduced critical mass and accrete envelopes that are more massive than the core.

3.5. EXTRASOLAR PLANETS

More than a hundred extrasolar planet candidates have thus far been discovered to orbit main sequence stars other than the Sun. The extrasolar

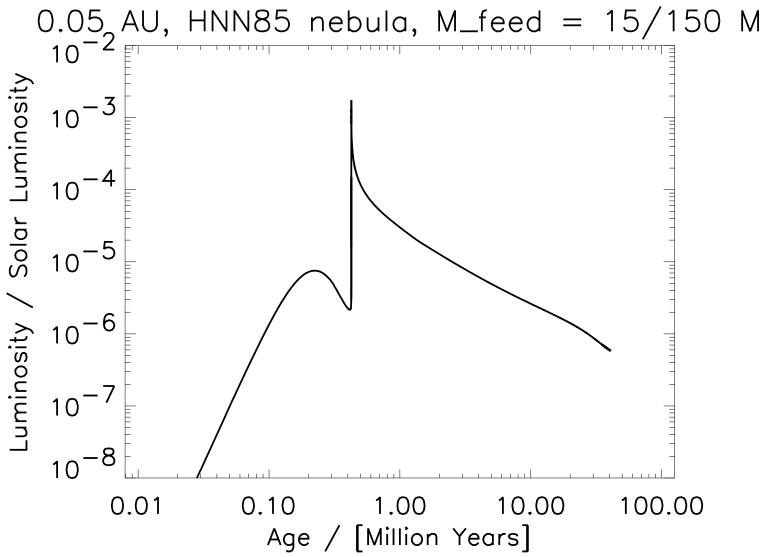

Figure 2. Luminosity of a Pegasi-planet during the first 100 million years according to a fluid-dynamical model. The two maxima correspond to peaks in the accretion of planetesimals and gas respectively (cf. Wuchterl et. al 2000).

planets currently known all orbit nearer to their stars than Jupiter does to the Sun. This is primarily an observational bias because the dominating radial velocity techniques can only safely detect a planet when data are collected for a full orbital period of the planet — about 12 years in the case of Jupiter. Some of these planets orbit on highly eccentric paths, suggesting that after they formed they were subjected to close encounters with other giant planets (Weidenschilling and Marzari 1996, Lin and Ida 1997, Levison et al. 1998) or secular perturbations from companions. Some of the extrasolar planets are separated from their stars by less than one percent of the Jupiter-Sun distance. Guillot et al. (1996) showed that giant planets are stable over the lifetime of a $1\,M_\odot$ star even if they are as close as 0.05 AU. Models involving migration caused by disk-planet interactions are favored by many researchers for the formation of these objects (e.g., Lin et al. 1996; Trilling et al. 1998; Ward and Hahn 2000, and by Lin et al. 2000). However, simulations also show that it may be possible to form giant planets very close to stars.

3.6. HYDRODYNAMICAL MODELS OF PEGASI-PLANETS

Pegasi-planets are massive planets that orbit their star with orbital periods of a few days and distances of a few hundreds of an AU. Applying the above density-criterion immediately leads to the conclusion that they may form by accretion induced by a core of a few Earth masses. Detailed convective radiation hydrodynamical calculations of core-envelope growth at 0.05 AU, indeed show gas accretion beyond $300\,M_{\oplus}$ for core masses around ten earth masses (Figs. 1, 2, Wuchterl 1996, 1997). Hence Pegasi-planets may form in-situ if sufficient mass of gas and dust is available in their feeding zones. That requires surfaces densities that are enhanced above the minimum mass nebula but are plausible if a diversity of nebulae is considered.

3.7. EXTRASOLAR PLANETS AND STELLAR METALLICITY

To show the present state of the discussion and possible problems with biases in the sample of discovered extrasolar planets, I will briefly discuss the planet-metallicity relation (Santos et al. 2003, Fisher et al. 2004). The authors find the frequency of planets to increase with stellar metallicity (i.e. the [Fe/H] stellar metallicity indicator). Because their stellar samples are related to the star-lists that are used in planet searches, I will call them the *planet hunting samples* in the following. Fuhrmann (2002, 2003) studied a volume complete sample of nearby F,G and K stars. Because it correctly represents the galactic stellar population I will call it the *galactic sample* in the following. The complete galactic sample overlaps with the planet hunting samples. That allows to compare the galactic sample to hunting samples allowing a check whether the discovery procedures induce a bias into the hunting samples. We consider the Fisher et al. results — more planets for stars with a larger heavy element abundance, measured by [Fe/H] for their planet hunting sample. Assuming they use the Nidever et al. (2002) *volume limited* hunting sample the following is noticed (Fuhrmann 2003 pers. communication) when comparing their stars to those in the overlapping *volume complete* galactic sample: of the 166 stars in the galactic sample only 90 (54%) are in the hunting sample despite the smaller volume of the volume complete galactic sample. Hence the hunting sample does not contain the stars it should contain, given the overlap — a consequence of incompleteness. In particular it is interesting which stars are absent. Missing in the hunting sample are:

1. a few subgiants,
2. fast rotating stars with $v \sin i > 10$km/s,
3. a few young and chromospherically active stars,
4. stars without a precise luminosity class,
5. binaries and multiple systems.

These are all properties that make planet hunting more difficult. From these findings of Fuhrmann, I can only conclude that stars that are (considered) unfavorable for planet hunting are under-represented. The average [Fe/H]

$= -0.02$, of the 90 stars in the hunting sample, that fall into the intersection with the galactic sample is only 0.01 dex higher than Fuhrmann's respective value for the galactic sample. However, for [Fe/H] ≥ 0.2 only 5 stars are missing but for [Fe/H] ≤ -0.2, 13 stars are missing. Hence there is a slight trend that metal-poor stars are preferentially missing in the hunting sample. Considering the still small numbers that are available for comparison, and the average metallicity of [Fe/H]= 0.00 for thin disk stars derived from the galactic sample, there could be a metallicity effect of +0.10 to +0.15 (contrary to the +0.25 that are favored by Santos et al. 2003 on the basis of their hunting sample).

With the Sun at the thin disk average of [Fe/H] for our distance to the galactic center (Fuhrmann 2003) the role of metallicity may well be a slight increase overall due to a significant increase for the Pegasi-planet's host stars. That would put the Solar System into normality as far as metallicity and planet hosting are concerned. It is such a kind of bias contained in hunting samples, that I think might still be present in the planetary discoveries, and might render the first 100 discovered extrasolar planets somewhat atypical for planetary systems in the galaxy.

4. The Growth of Solids in Circumstellar Disks

4.1. GRAIN GROWTH AND PLANETESIMAL FORMATION

Protoplanetary disks have the same elemental composition as the parent cloud and the growing star, that is primarily hydrogen and helium, with $\sim 1-2\%$ heavier elements. Sufficiently far from the central star, it is cool enough for some of this material to be in solid form, either remnant interstellar grains or condensates formed within the disk. Dust agglomerates via inelastic collisions, and gradually settles towards the disk midplane as it grows large enough to be able to drift relative to the surrounding gas (Weidenschilling and Cuzzi 1993). Either by continuing agglomeration and binary accretion or by a gravitational instability (Safronov 1960, Goldreich and Ward 1973) kilometer-sized planetesimals are thought to form. The details of the process, however, are incompletely known and stagnation of growth or loss to the central young star may be common.

Hueso and Guillot (2003) modelled planetesimal formation in a pragmatic approach that includes important processes in planetesimal formation in a balanced way. A simple evolving nebula model is combined with radial transport of gas, condensation and evaporation, and the drift and growth of dust and planetesimals. They show that km-sized planetesimals may form within their approximate but synoptic model and they find an increase in size and number of the planetesimals somewhat interior to the snow-line (cf. Fig. 3).

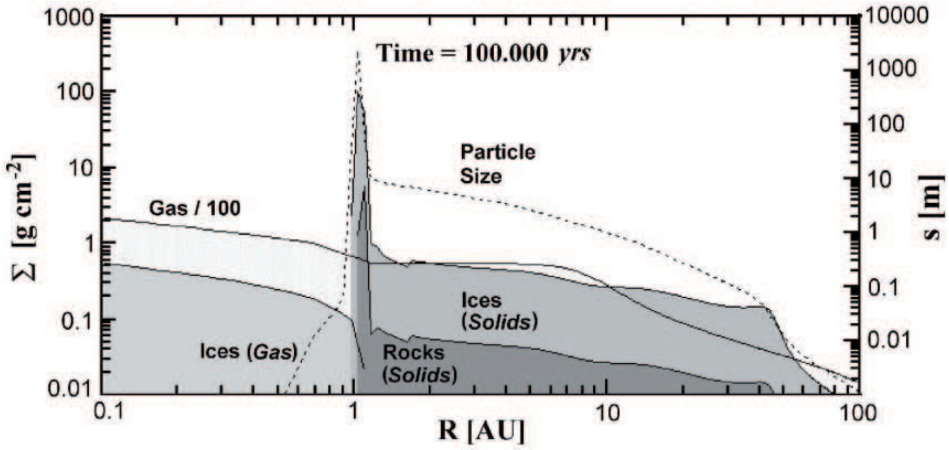

Figure 3. Planetesimal formation in a viscous α-disk model . The surface density of solid material is plotted for a model containing initially 99 % 'gas' and 1% 'ices' (a mixture of water, methane ammonia, etc.), and 0.1 % 'rocks' (silicates and refractory materials). Particle size is shown as a dotted line — right axis (Hueso and Guillot 2003). Note the increased surface-density and size of planetesimals near the snow-line.

4.2. TERRESTRIAL PLANET FORMATION

The primary perturbations on the Keplerian orbits of kilometer-sized and larger bodies in protoplanetary disks are mutual gravitational interactions and physical collisions (Safronov 1969). These interactions lead to accretion (and in some cases erosion and fragmentation) of planetesimals. The most massive planets have the largest gravitationally-enhanced collision cross-sections, and accrete almost everything with which they collide. If the random velocities of most planetesimals remain much smaller than the escape speed from the largest bodies, then these large 'planetary embryos' grow extremely rapidly (Safronov 1969). A few large bodies grow much faster than the rest of the swarm in a process known as runaway accretion (Wetherill and Stewart 1989, Kokubo and Ida 1996). Eventually, planetary embryos accrete most of the solids within their gravitational reach, and the runaway growth phase ends. Planetary embryos can continue to accumulate solids rapidly beyond this limit if they migrate radially relative to planetesimals as a result of interactions with the gaseous component of the disk (Tanaka and Ida 1999). A typical planetary embryo in the terrestrial planet zone of the Solar System would have the size and mass of Mars, i.e.

about half the radius and a tenth of the mass of Earth.

The eccentricities of planetary embryos in the inner Solar System were subsequently pumped up by long-range mutual gravitational perturbations; collisions between these embryos eventually formed the terrestrial planets (Wetherill 1990, Chambers and Wetherill 1998). However, time-scales for this type of growth in the outer Solar System (at least 10^8 years, Safronov 1969) are longer than the lifetime of the gaseous disk (cf., Lissauer et al. 1995). Moreover, unless the eccentricities of the growing embryos are damped substantially, embryos will eject one another from the star's orbit (Levison et al. 1998). Thus, runaway growth, possibly aided by migration (Tanaka and Ida 1999), appears to be the way by which solid planets can become sufficiently massive to accumulate substantial amounts of gas while the gaseous component of the protoplanetary disk is still present (Lissauer 1987).

5. Planet Formation Theory — Critical Summary

The previous discussion focused on detailed models of planet formation that describe the main accumulation processes for solids and gas and are able to cover the entire formation process until the final planetary masses are reached. Known planets, solar and extrasolar, are accounted for by studying a range of plausible nebula properties that allow a consistent overall picture. The detailed models combine two elements of planet formation theory that are most advanced and to some extend capable to obtain quantitative results for a wide range of possible nebula situations. These elements are

1. planetesimal accretion,
2. planetary structure and dynamics.

Modern planetesimal accretion theory includes, both, significant analytical detail and long-range numerical simulations that are able to cover large fractions of the planetary growth process in a single calculation and for a large number of planetesimals, planetary embryos and protoplanets. Using computer-hardware that is specially designed to calculate the gravitational force of a large ensemble of point masses the formation of planetary embryos, and the properties of the planetesimal swarm can be calculated directly. Furthermore the growth of planetary embryos can be followed to the final planetary masses by solving the n-body problem with collisions with symplectic integrators (Chambers and Wetherill 1998). Growth processes in the outer regions of gas-free disks of planetary embryos can be followed to quasi-stable, final configurations, when assumptions are made about the evolution of the gaseous envelopes of the outer planets. Long-term integrations of the solar system planets can explain the sculpturing of the outer Solar System by gravitational erosion of an initial swarm of small bodies and successfully predicted the location of trans-neptunian objects in the Solar System (Malhotra et al. 2000). Hence there are quantitative and predictive elements when the role of gas is minor and the effects of the potentially large number of small bodies (dust and planetesimals) can be neglected for simulations of the final stages of planet formation.

The second, key element, planetary structure and evolution theory, can be confronted with present solar system objects, most prominently Jupiter and Saturn (Guillot 1999). It has many elements in common with stellar structure and evolution theory and hence components, as the convection prescription, can be tested in stars and the Sun before being applied to the planet formation problem. The theory has proven to be of significant predictive power as the possibility of the existence of brown dwarfs and their properties have been quantitatively predicted theoretically (Kumar 1963) more than three decades before the observational capabilities allowed detection of such objects.

But numerous processes in planet formation have not reached a comparable maturity and have been neglected in the previous discussion. That does not mean that they are not needed to arrive at a better overall understanding, but just that they have not been included in models that have sufficient time-span or generality to exclude at least some planetary formation modes in general.

5.1. PROBLEMS OF THE STANDARD PLANET FORMATION MODELS

The models of planet formation that have been worked out in detail are still closely related to models of Solar System formation (Wuchterl et al. 2000). That is mostly due to the fact that the Solar System provides by far most of the constraints that are needed to determine the many unknowns in theoretical planetary formation models. For the astrobiological application, i.e. the formulation of an expectation of what planetary systems may look like in general and what were the conditions in their early evolution, the predictive power will be dominated by the problems of planet formation theory. Hence the uncertainties and unsolved problems will determine how successfully we can extrapolate from the present solar system state to the planet formation time here and elsewhere. I will therefore discuss the weaknesses of our understanding to provide a guide for what we might encounter in other systems. Where we know the least, other systems are most likely to differ significantly.

There are three mayor problems in planet formation theory. The qualitative problem of planetesimal formation, the qualitative problem of migration that might be turned into a quantitative one when migration-rate estimates decrease further, and finally the purely quantitative formation time-scale issue.

5.2. FORMATION OF THE PROTOPLANETARY DISK

There is presently no way, to infer even the most basic properties of protoplanetary disks with a precision that constrains planet formation theories (Markwick and Charnley 2004). Observationally the disks are very likely observed at relatively evolved stages, when critical processes like planetesimal formation and growth to the planetary embryos are already over. Furthermore the spatial resolution is presently insufficient to infer properties at orbital positions that are comparable to any known planet. Theoretically the formation of protoplanetary disks is technically elusive, because investigations that are able to model a fragmenting collapsing cloud with significant geometrical detail (in 3D) are based on explicit numerical fluid-dynamics schemes and hence unable to cover the disk-evolution time-scales to a steady or quasi-steady state, that could be considered a starting point for planet formation. Furthermore all non-spherical calculations of star formation in general and protostellar cloud collapse in particular, that might be able in principle to determine the mass and angular momentum of circumstellar disks have to make highly idealized assumptions about the thermal budget so that they rather prescribe temperatures one way or the other than to determine it. But it seems to be exactly the thermal evolution once clouds become optically thick and heat up that is responsible for the final outcome of the fragmentation process and hence how much mass ends up with what angular momentum in orbit around what kind of stellar system. Even the formation of binary stars, requiring ‘only’ the determination of the distributions of much larger fractions of cloud fragment mass then the few percent that go into protoplanetary disks is still far from a prediction of the masses and angular momentum of stellar companions. Hence it is essentially unknown how the protoplanetary disks look like in general. Information is available from reconstructions for the Solar System and it is known from observations that disks around young stars have masses that are consistent with the masses theoretically expected for gravitationally stable disks.

5.3. EVOLUTION OF THE PROTOPLANETARY DISKS

It is clear that with an unknown initial state the evolution is difficult to access. Viscous accretion disks models provide important information about the mass and angular momentum evolution during stellar accretion. They also have the property that they forget about their initial state on their evolutionary time-scale of typically a few Ma. But planet formation, especially planetesimal formation occurs on the same time-scale and there is no consensus yet about what disk models are realistic in the sense that they are corroborated by observations. There is also no consensus about the mechanism that provides the assumed viscosity. There is even the possibility, that there is no such anomalous viscosity of a magnitude that is of relevance to the star formation process, and angular momentum redistribution was essentially completed by gravitational torques early in the stellar accretion history.

5.4. STRUCTURE OF PROTOPLANETARY DISKS

Given a distribution of mass and angular momentum, momentary or initial, the structure and appearance of disks can be calculated in great detail and with some reliability. Assumptions about their overall properties and physical structure can be made that are consistent with observations of material in orbit around young stars and brown dwarfs. But the overall agreement can hardly be exploited for inversions that would serve quantitative planet formation theory. The result is that there are two basic categories of idealized disks used for planetary formation models: (1) 'passive', quiet, non-accreting disks, as the Kyoto nebula (Hayashi et al. 1985) with a thermal structure determined by the (proto-) stellar energy input or (2) 'active', viscous α-accretion discs with a net mass accretion rate onto the star and the thermal structure governed by the dissipative process that allows accretion and angular momentum redistribution.

5.5. STABILITY OF PROTOPLANETARY DISKS

Classical protoplanetary disks models, similar to the minimum reconstitutive nebulae and α-accretion disks are gravitationally stable. But alternative protoplanetary nebulae can be imagined that might be gravitationally unstable (see section on disk instability, above). Actually in early stages of star formation it seems likely, for plausible assumptions about the rotation of the cloud fragment before it starts to finally collapse, that significant amounts of mass do not fall onto the central star directly but first onto the disk. Subsequently the mass is accreted through the disk onto the star (resulting in an active nebula as described above). Depending on the efficiency of the angular momentum transfer processes in the disk — that is essentially unknown and only weakly constrained — the mass flow either (1) proceeds in a quasi-steady manner, with the flow onto the star balancing the rate of material that drops onto the disk from the ambient cloud (standard accretion disk models) or, if the angular momentum transfer efficiency is insufficient (2) the gas piles up in the disk, increasing its mass. The third case with disk accretion being faster than disk mass loading is likely to act stabilizing in any case. The second case will likely result in a gravitational instability. The development of the instability is controversial, not only because it depends on the assumptions that are made about the initial disk and the mass-influx, from the cloud, but also because different investigators found different results for the same problem. In any case such stability calculations essentially answer the question whether there is an instability of the nebula and how it will develop. Present studies are essentially non-linear stability analysis and can only address the early phases of planet formation, both in terms of compression and evolutionary phase. All stability investigations presently published are performed with explicit hydrodynamical techniques, that are limited by basic numerical stability requirements, to a few dynamical time-scales. In our problem that is a few orbital time-scales of the respective disk, or to be more precise those of the innermost parts of the disk that are in the domain of calculation. The overall time covered is typically a few to a few hundred orbits, with planet formation requiring a few million to a few hundred million orbits. The limitations in nebula gas compression are even more severe. Due to resolution limitations the maximum compression typically reached in such calculations is less then 1000, while planet formation requires a robust factor of 10^{10}.

A synoptic interpretation of the present literature is that, mass loaded disks are driven towards an instability, that develops into restabilizing the situation by accretion of mass onto the central object and outward transfer of angular momentum. If that holds, the cloud collapse onto a disk would self-produce the very efficient angular momentum transfer process, that is needed, and disks would be limited to the gravitationally stable regime. The instabilities that might develop would stabilize the nebulae and ultimately lead to a relatively quiet protoplanetary nebula situation. I refer to Wuchterl et al. (2000), for a more detailed discussion relating disk-stability and planet formation.

5.6. PROBLEMS OF DUST-GROWTH AND -DYNAMICS

When considering dust growth in the nebula from a global perspective we encounter the uncertainties in the nebula structure again. For the two extreme regimes — quiet or viscous-turbulent — dust growth proceeds in different macroscopic gas-flows, and under different temperatures and vertical nebula structures, for given orbital radius, say. The midplane temperature, e.g. in turn depends on the opacities, that are governed by dust throughout the planet formation zone. The optical properties of dust depend on the chemistry, mineralogy, and size-distribution of the grains. Progress is made for assumed nebulae and consistent determinations of local nebula structure, chemistry, dust growth and mineralogy are presently developed.

The enormous advantage for the dust growth problem considered locally, is that laboratory experiments have confirmed theoretical considerations and can be used for calibrating the models (Blum and Wurm 2000). Together with a consistent determination of the mineralogy that will provide the opportunity to predict the production of ‘sand’ an ‘ice’-properties for given global nebula structure. So there are good perspectives to determine the general properties of planetesimal raw-material in the near future (cf. Markwick and Charnley 2004, Hueso and Guillot 2003).

Planetesimal formation obviously then results as the key unsolved problem because its precursor steps are incompletely understood. However, a theory of planetesimal formation is needed to predict the size distribution, chemical composition, mineralogy and orbital properties of this planetary building blocks everywhere in the protoplanetary disk.

5.7. DYNAMICAL PLANET-DISK INTERACTION

A key problem, starting already at the embryo size is the gravitational interaction of the growing planet with the ambient nebula gas. It determines if and how much nebula gas can flow from the nebula into the planet’s gravitational sphere and whether the planet gains or looses mass and angular momentum to the nebula. Furthermore it determines how the planet modifies the disk in its neighborhood. Detailed structure and dynamical models of planetary growth cannot self-consistently account for that interaction because its geometry is necessarily non-spherical and hence beyond the capabilities of present planetary structure models based on implicit numerical techniques. Two alternative approximate approaches have been followed:

The first one is to approximate the growing planet by a smoothed gravitational potential of point mass that acts as a hole to account for accretion. Nebula gas that approaches an inner region that cannot be resolved by the numerical grid is assumed to proceed to the hydrostatic parts of the planet. These are not calculated as part of the flow-model. It is assumed that the mass is accreted by the planet and removed from the flow and added to the point-mass. With this procedure it is possible to calculate the protoplanets’ effect on the quasi-keplerian nebula flow in 2D and 3D (Kley 1999, D’Angelo et al. 2002, 2003 for recent models). Calculations show the effect of approximate point-mass planets on initially unperturbed nebula disks. They are twofold: (1) the point-mass planet reduces the nebula density in a region of the order of a tidal radius around the planet, a situation, referred to as *gap-opening*. (2) outside the gap, the potential of the point mass induces density waves that are found to produce a net torque of the disk on the planet. The magnitude and even the sign of this torque somewhat depends on the physical assumptions and properties of the calculations (how the planetary potential is smoothed on small, subgrid scales, the spatial resolution and the method). Disk-planet interactions of growing planets are also attractive mechanisms to self-limit planetary masses. In particular gaps induced in the protoplanetary disk by grown-up giant planets have been proposed to cut off gas-accretion. High-resolution calculations have shown however, that the gas finds a way onto the planet even through well developed gaps and hence the process is unable to stop accretion. If the torques found in these 'disk-response to a point mass calculations' cumulate on secular time-scale, so called type II planetary migration will result — i.e. a protoplanet in a gap moving with the nebula towards the star. That may ultimately determine the planet's survival.

The second approach is to parameterize the results of planetesimal accretion, planetary structure and use simplified, usually analytical formulae for the planet-nebula interaction (Trilling et al. 1998, Bryden et al. 2000) and look at the combined outcome. It assumes that the results obtained for the component processes are not changed by the mutual interaction. That allows to look at the combined problem of protoplanetary mass evolution, interaction with the nebula and orbital evolution. Planets are introduced into an assumed nebula and their masses and orbits are evolved according to the parameterized prescriptions of the various processes, e.g. simple envelope structure and growth models for the protoplanet, subject to roche-lobe constraints for mass overflow and combined with a viscous α-accretion nebula disk and an analytical formula for the torque of the disk onto the planet due to disk planet interaction (e.g. Papaloizou and Terquem 1999). The results provide overall histories for simplified physics and a choice of parameters. Generally severe compromises have to be made to connect the different model parts and it is doubtful whether possible artifacts, due to the inconsistencies that are likely to be introduced, can be reliably excluded. The uniqueness of the choice of parameters is unlikely even if it is possible to sufficiently constrain all the parameters in the first place. With the obvious lack of calibrations, the parameterizations introduce new uncertainties into the calculations. That is in addition to the uncertainties about the nebula and hence the predictive power may be low, even if the procedures turn out to capture the most important physical processes in a qualitatively correct way. What is obtained is mostly a balance between the time-scales of the competing component processes.

Both approaches address two questions of disk-planet interaction:

1. Mass budget: During the final stages of gas-accumulation of massive giant planets, fluid-dynamical effects govern the accretion process. Control of the further evolution then passes from the ability of the inner hydrostatic parts of the planet to contract to the supply of nebula gas. With gas from the feeding zone already accumulated onto the planet,

nebula gas accretion into the planetary feeding zone becomes the process limiting further growth. That relates to the key problem of how the final masses of gaseous envelopes and hence giant planets are determined. The detailed models of planetary growth (all with spherical symmetry) presently explicitly or implicitly assume a given reservoir of mass, from which the planet may accrete. In general it is unknown at what values the final masses of giant planets would arrive if that reservoir is not prescribed.
Studies calculating the flow of gas from the ambient nebula into the feeding zone of the planet (Kley 1999, D'Angelo et al. 2002, 2003) generally find that gas supply from the nebula to the planet occurs on a time-scale that is very small compared to both the nebula life-time and the contraction and cooling times of the planets found in the detailed planetary structure models. That is due to the fact, that the nebula densities are relatively high and dynamical time-scales in protoplanetary envelopes and the transition regions into the nebula are short (10000a) compared to the overall planet formation time of Ma. Hence even a very inefficient dynamical process is capable of transferring mass from the nebula into the feeding zone from which the proto-giant can capture gas. As a consequence stopping giant planet growth requires a very efficient cut-off mechanism or a very complete removal of nebula residues to shut off gas accretion and determine the planetary masses. To demonstrate a complete shut-off is a great challenge to present computational techniques.

2. Angular momentum budget and orbital evolution: Generally it is found that violent migration has to be expected, if the nebulae are viscous. Planets migrate significant distances after they are formed and a potentially very large number of planets moves into the host star. Additional processes that stop migration at orbital distances that are consistent with those observed for extrasolar planets are invoked. Since parameters are adjusted to account for what is known, the predictive power as far as the general population of planets is concerned is small, especially for planetary systems like the Solar System where migration-effects apparently were small and there seems to be no evidence for violent migration.

5.8. NEBULA DISPERSAL

Many effects, as the fade-out of violent migration and mass-limitation of giant planets, in particular of Uranus/Neptune type relate to how the nebula gas dissipates during or after the final stages of planet formation. Hollenbach et al. (2000) discuss four candidate processes, (1) viscous accretion,

(2) close encounters, (3) stellar winds (considered unlikely) and (4) photoevaporation. But it is still unclear how nebulae disappear after the end of the planet formation era especially close to the stars where the escape speeds are largest. An obvious possibility is that the nebulae disappear because they condense into planets. Photo-evaporation typically operates efficiently in the outer parts of proto-planetary disk, accretion of the residual material onto the star is most efficient for close-in parts of the disk. If violent migration dominates planet formation, the details of nebula dispersal will control the planetary outcome, in terms of survival and mass limitation. Planet formation may then be mostly a competition between planetary and nebula loss processes — of course assuming efficient formation in the first place — with an outcome that will be theoretically very hard to predict.

5.9. LATE ACCRETION AND PLANET-PLANET INTERACTIONS

This regime starts when the disk mass has been significantly reduced and the disk stops to be dynamically important for the planets' orbital evolution on the secular time-scales. What remains is the accretion of the residual gaseous nebula material, the interactions with other planets, the remaining planetary embryos and planetesimals (Levison et al. 1998, Thommes and Lissauer 2003, Levison and Agnor 2003). The relevant overall masses in all components may or may not be comparable to the mass of the largest planet. There is probably still a large and locally dominant number of bodies around, that in case of the Solar System are responsible, e.g. for the formation of the Moon and the late heavy bombardment. Late accretion affects are apparently important in the asteroidal region of the Solar System where it is possible that Jupiter‘s perturbations precluded the accretion of embryos into a planet. The important remaining dynamical process is then the orbital evolution of planets and embryos due to secular mutual perturbations. Eccentricity excitation is possibly damped by a remaining small-size planetesimal population via dynamical friction. The time-scale is larger than 10^5 orbital periods leading to the completion of the planetary system formation process on time-scales of tens to hundreds of Ma.

5.10. GRAVITATIONAL EROSION

Secular orbit-dynamical instabilities seem to shape orbital structures including the planets after the early formation period with its strong chaos. The distribution and evolution of orbital elements in the Solar System can presently be understood if the major masses, i.e. the major planets are set up at the backward integrated orbits, that they occupied at the time of Solar System formation. Although *the Solar System is not stable, just old*, the stabilization process of *gravitational erosion* leads to well separated orbits that satisfy radial exclusion principles (Lecar et al. 2001). They are based on non-overlapping of the gravitational spheres of influence around the orbits. Their half widths are estimated to be of the order of 10 Hill-radii for stability over the age of the Solar System. These structuring processes are expected to operate in general planetary systems and provide relatively quiet conditions in terms of impact history as an ‘aging effect’. But presently it is unknown for how large a class of planetary systems they are important. The key challenge here is to transform the understanding that has been developed by very long range time integrations of the Solar System to planetary systems in general. A task that is just beginning.

This enumeration of incompletely studied processes that are relevant for the overall outcome of planet formation reflects the piecewise approach that is necessary. Solving the overall problem in particular for arbitrary nebulae is presently beyond reach. Only after the various stages in a step-wise approach are heuristically joined together, overall statements about the final outcome, the planetary yield, can be made. An alternative approach is to statistically analyze the final outcome, i.e. the possible and probable end-states of the process, the planetary equilibria, as the basis of the structure of planets (Pečnik and Wuchterl 2004).

5.11. PROBLEMS OF PLANETESIMAL FORMATION

Planetesimal formation by coagulation and agglomeration may stall at dm to m size where loss processes by radial drift may halt the planet formation process. Planetesimal formation by a gravitational instability of a dust-subdisk may require special nebula conditions that are incompletely explored to decide under how wide a range the instability will operate and whether the non-linear outcome are the consolidated condensible element bodies that are envisaged and assumed in the planetesimal hypothesis. The related key question is how wide a diversity of nebulae will lead to instabilities that produce appropriate planetesimals. Being appropriate mostly means a size large enough to decouple from the head-wind of the nebula gas, an event that typically occurs at km size. Other, yet unknown planetesimal production processes do not automatically imply that planet formation will not proceed as presently imagined but new pathways in a theoretically essentially unexplored regime have to be worked out in that case.

5.12. PLANETARY MIGRATION

This second problem becomes severe at larger sizes because it is proportional to the planetesimal mass. It is expected by many investigators to become important in the mass range resulting from the early fast *runaway* mode of planetesimal growth. The runaway phase ends when all planetesimals that are within the gravitational range of the locally largest body have been accreted and hence its feeding zone has been emptied. Grown-up planetesimals in that mass range of order 0.1 to 1 earth masses are referred to as *planetary embryos*. Planetary embryos gravitationally interact with the ambient gas disk, planetesimal disk and other planetary embryos or planets. As a result *planetary migration* can come about (see Thommes and Lissauer (2004), for a review).

Planetary migration had been noticed by Fernandez and Ip (1984) and has been considered by Hayashi et al. (1985) as a process that shortens the growth times of Uranus and Neptune. In the late stages of outer Solar System formation these planets would move outward as a consequence of angular momentum exchange when passing comets down to Jupiter for subsequent ejection to the Oort cloud. After the discovery of 51 Peg b it has become a custom in planet formation theory to denote many kinds of change in the planetary semi-major axis or orbital distance as planetary migration. That is usually independent of the physical process underlying the orbital change. With many proposed processes and a suggested terminology of types I to III, that only covers certain regimes in particular described by Ward (1997), we distinguish between migration processes that modify the orbit by less than a factor of e^2 (or 10) and those that may lead to larger changes up to orders of magnitude in the orbital radius, and may ultimately result in the loss of the planet. The latter processes we will call *violent migration* in the following. They may dominate the planet formation processes if they operate in many and diverse nebulae.

Violent migration is a back-reaction of the planetary embryo's 'bow wave' in the nebula onto the embryo itself. As the embryo orbits the star, its gravitational potential adds a bump to the stellar one. At the embryo's orbit — at the corotation resonance, in the linear terminology of migration theory — the embryo and its potential move almost at the same velocity as the nebula gas. That is co-orbital motion as in the case of Jupiter and the Trojan asteroids. Inside the embryo's orbit, the gas in a quasi-keplerian disk orbits faster and hence the embryos potential and gravitational acceleration travel at a different speed. This accelerates the disk gas and excites a pressure- and density-wave that travels with the embryo. Because matter deeper in the primaries potential must orbit faster, the waves are dragged forward inside, and backwards relative to the embryo, outside the embryos orbit. These rather particular protoplanetary bow-waves include density enhancements that gravitationally back-react onto the planet. Due to the inherently asymmetric nature of the situation (Keplerian orbital velocities changing $\propto r^{-1/2}$) and the particular wave-pattern the forces (and in particular the torques) on the planet may not cancel out, leading to a net exchange of angular momentum between the planetary embryo and the gaseous disk if the waves dissipate or break in the disk neighboring the planet's gravitational sphere of influence. The result is the familiar reaction of orbiting matter if angular momentum exchange is allowed: most matter (the embryo) moves in and a small amount (some gas) moves out carrying away the angular momentum. Hence, the very growing of the embryo would lead to orbital decay and gradual movement towards the star on time-scales of disk evolution or much smaller. Many studies are presently devoted to determine the strength of the effect and evaluate the rates of orbital decay and hence the possible survival times for planets of given mass in a given disk. If migration dominates it has the potential to wipe out any and many generations of planets. In that case and because it originates in a delicate torque balance, it seems unlikely that we will be able to reliably predict much about planet formation in the galaxy any time soon.

5.13. PLANET FORMATION TIMES

The standard model is centered around the planetesimal hypothesis that has been successful to understand a wide range of solar system bodies, to a large extent in a quantitative way. But observational results obtained for nearby star-forming and young star regions quantitatively challenge the standard model because indicators of the presence of circumstellar disks (Haisch et al. 2001) suggest disk depletion time-scales that are comparable or shorter than some calculated formation times for solar system giant planets. Modern theories of planetesimal accretion (Kokubo and Ida 2002) could account for rapid growth if increased solid-surface densities are allowed. In addition, the theoretical estimates for planet formation times have been known to be idealized because of the many approximations that are necessary to reliable calculate at least an idealized situation to allow a quantitative discussion and theoretical progress. Recently, the collisional cross-sections of planetesimals with gaseous envelopes have been studied (Inaba and Ikoma 2003, Inaba et al. 2003). Accretion-rates were found to increase significantly, reducing the planet-growth times considerably. This is especially important for the giant planet regime where the envelopes may become comparable to the condensible element cores during the runaway phase. Hence growth times decrease when the nebula gas is not neglected in determining the collision cross sections.

6. Astrobiological Goals of Planet Formation Theory

Theoretically characterizing the galactic habitat can be coined into two questions: What can be deduced in terms of astrobiological relevance from planet formation theory as sketched above? What is the expectation value of potentially habitable planets per star or stellar system? To address the questions we may distinguish three items:

1. the number of planet forming star systems,
2. critical events that may potentially quench the planet formation process,
3. efficiency issues, that determine how many planets form per star system.

The second issue relates to the question of whether there is only one star with terrestrial planets, i.e. the question how unique the Solar System is.

Theoretical error bars are worth to be mentioned here. They are a result of technical limitations in approximations and computational techniques as well as lack of knowledge about contingencies (as nebula conditions) and entire processes (as planetesimal formation).

It is very hard to estimate the accuracy of planet formation theories because there is not yet a test to assess the real errors. Detailed theories in planet formation have an intrinsic precision, obtained by inter-comparison of results between different investigations of about 10% for global planetary properties as mass and luminosity for standard cases as Jupiter-formation and in regimes where the assumptions overlap (Wuchterl 1995b). The differences are much larger for non-standard issues like the formation of Pegasi-planets (see Wuchterl et al. 2000). If we take the optimistic view that the precision above is representing contemporary theoretical accuracy, we have a ten percent domain of uncertainty that essentially makes it impossible to make a relevant statement about the galactic issue of quenching planet formation. A prediction of $0 \pm 10\%$ of star-systems that contain terrestrial planets would allow a lot of planets in the galaxy overall. It may, however lead to significant limitations of observationally accessible planets in the galactic neighborhood, and in particular concerning the about few hundred stars of similar type as the Sun within a distance of 25 pc, say. If the empirical estimates extrapolated from planet searches of about 20% of stars hosting detectable planets hold in general, a theoretical result that excludes terrestrial planets in 90% of the detected systems could easily leave us with a zero to a handful for the expectation value for the number of neighboring extrasolar terrestrial planets.

6.1. THE NUMBER OF APPROPRIATE STAR SYSTEMS IN TIME

Planet formation theories require evidence for star formation with some heavy elements to allow planetesimal formation as a side effect. A large fraction of stars in the milky way formed early in the history of the galaxy, with Arcturus being the most prominent member of this so called thick disk population. Together with the presently more conspicuous thin disk population, a galactic population of about 10^{12} star systems has been around for almost 14 Ga, with little indication of an age-metallicity relation, and hence an early enrichment in heavy elements (50% in the first Ga), at least in some parts of the galaxy. There is evidence for a star formation gap (12-8 Ga) after the 'starburst' of the milky way (Fuhrmann 2004). Hence there are 10^{12} potentially planet hosting systems possibly producing planets in the galaxy for 10^{10} years with a 4 Ga gap.

6.2. QUENCHING PLANET FORMATION

There are two processes that might inhibit planet formation:

1. the failure to form planetesimals,
2. violent migration of planetary embryos.

Planetesimals may fail to form because dust growth stalls and/or gravitational instability of the dust subdisk does not occur. That is halting in a size range (between cm and giant planet size) where all presently available detection techniques are blind for extrasolar systems and hence widespread quenching would be consistent with observations for sufficiently small planets, less then 50 earth masses, say. The indirect evidence of dust-size growth and disappearance of the observational signatures of smaller solids is consistent with the standard view of planet formation but also with an unexpected stalling below the planetesimal size. Replenished disks, like the famous example of β-Pictoris, offer additional evidence for larger bodies via the requirement to resupply the smaller particles, that are observationally accessible, by larger, invisible parent bodies. But their sizes are not sufficiently constrained to conclude about the planetesimal nature of such sources. Possible *falling evaporating bodies* that appear as additional spectral signals of condensible elements and from time to time in high resolution spectra of β-Pictoris and a few other stars provide evidence for extrasolar comets and hence for possible presence of residual extrasolar planetesimals (Lagrange et al. 2000).

At the other end of the size range the detected extrasolar planets and planetary candidates provide evidence for the build up of planetary masses but not (yet) for a growth via planetesimals and condensible element core build-up. Investigations of candidate alternative formation mechanism for those objects, as the disk-instability theories, may succeed to show that they are capable of forming the observed bodies *without* planetesimals. However, detailed models of giant planet formation show that extrasolar planet candidates can be formed in a way consistent with the planetesimal hypothesis, if a wide range of nebulae is assumed to exist (Wuchterl et al. 2000).

The Solar System provides some evidence that the planetesimal formation process operates successfully under a wide range of stellar tides, nebula temperatures and densities, and microphysical and chemical environments. There are icy cometary bodies in the outer Solar System and rocky asteroidal bodies of the sizes assumed in the hypothesis. Hence the process successfully operated widespread, both in heliocentric distance as well as in chemical/mineralogical domains. We may conclude that despite the theoretical uncertainties the pathway to planetesimals does have a finite width but it is still possible that it is very narrow on the scale of the overall galactic stellar population.

Violent migration of *planetary embryos*, if indeed an important process, is more an efficiency issue because repeated planetary embryo generations can be envisaged to balance ongoing losses. If careful timing of nebula removal and planetary migration histories occurs, and that seems plausible at least in a statistical view, at least some embryos — and as a consequence the planets they grow into — will stop migrating with the nebula removed just in time to leave them in a safe orbit (Lin et al. 2000). Violent migration might make terrestrial planets rare but it will not be able to quench the process in the entire galaxy.

7. Towards Estimating Galactic Habitability

With the possibility of quenching planet formation due to the failure to produce planetesimals we finally consider the question of what processes may limit the planetary yield. Hence we assume the planetesimal hypothesis to hold for a large fraction of the galactic stellar population in the following.

Given a large fraction of condensible elements in planetesimals there are two possibilities to arrive at an estimate for the number of potentially habitable planets in the galaxy:

1. calculate the planet-forming and planet-degrading processes and look at the outcome,
2. calculate all possible planetary systems, i.e. all combinations of stable planets in stable orbital configurations.

The first approach is analogous to determining the result of a process from reaction kinetics, the second is analogous to thermodynamics.

In the first approach planetesimals grow into embryos rapidly and continue to grow into terrestrial protoplanets. The processes seem to be limited by the amount of available planetesimals and the fact that massive planets start clearing out the remaining building blocks. Kokubo and Ida (2002) have given an estimate of the diversity of expected planetary systems based on a variation of the assumed surface density of planetesimals in the protoplanetary nebula. Giant planets are then an automatic consequence of a terrestrial planet of a few earth masses and availability of nebula gas.

The second approach seems more appropriate to giant planets because their envelopes rapidly reach equilibrium conditions due to their short dynamical time-scales. A variety of proto-giant planets are constructed to arrive at a general overview over masses and properties of such planets (Wuchterl 1993, Ikoma et al. 2001 and Pečnik and Wuchterl 2004). Giant planet formation is found to occur under very general conditions with some indications that massive, Jupiter like planets and close-in Pegasi planets do require more massive nebulae, or at least higher gas- and solid-surface-densities in their feeding zones.

8. Conclusions

The nucleated instability hypothesis provides a viable model for the formation of the giant planets observed in our Solar System and beyond if the planetesimal hypothesis holds in general. Presently known extrasolar planets may have accreted *in situ* if their preplanetary nebula provided sufficient amounts of gas and solids. Alternatively, according to studies of disk-induced migration, planets may have moved considerably during and after their formation. In that case the orbits of most, if not all, planets known to be bound to main sequence stars *other than the Sun* suffered substantial orbital evolution.

The key question determining how widespread planet formation is in the galaxy, is planetesimal formation. Presently an answer cannot be given, but if it is positive then planet formation should occur in any gravitationally stable circumstellar disk that lives long enough to produce planetary embryos, 10^5a, say.

Planet formation studies are starting to develop predictive elements to determine the properties of planetary systems in general. But the transition from theories to account for the formation of the Solar System, to a general theory of planet formation is far from complete.

Because of that, the completion of the copernican revolution, in the sense that we can safely say that the Earth is not the center of habitability in the galaxy and the Sun not the center of the galactic planet formation process, is still ahead of us.

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