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The Origin of Jupiter

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2.1 INTRODUCTION

Giant planets are the *alpha* and the *omega* of planetary formation and evolution. Because they are, by definition, rich in the primary cosmic elements hydrogen and helium, they must form early in the process of planetary formation, within the first few million years when the protoplanetary disk is largely gaseous. Once formed, giant planets by virtue of their large gravitational fields play crucial roles in shaping the dynamical environments of the overall planetary system. They define the regions of long-term orbital stability of the terrestrial planets (Jones *et al.* 2001). By ejecting planetesimals from the realm of the forming planets to distant orbits subject to long-term galactic tidal perturbations, the giant planets set up a regime over eons of impacts on to terrestrial planets that engender global-scale extinctions and resurrections shaping the evolution of complex organisms.

Giant planets may well be common companions to main sequence F-, G-, and K-type dwarf stars, that is, stars similar to the Sun. The Doppler spectroscopic technique has found planets the mass of Saturn or larger around 5% of these types of stars, and when the observational bias toward tight orbits is taken into account, this number corresponds to a 10% occurrence. The distribution of orbital semi-major axes of giant planets detected so far is roughly uniform when plotted logarithmically, while the outer limit on detected orbit periods increases approximately linearly with time since 1995, suggesting indeed that more are to be found particularly in jovian, saturnian and larger orbits around nearby stars. Further, the distribution is consistent with, and perhaps requires, orbital evolution after formation. Interactions with the protoplanetary disk during migration, or mutual interactions among two or more giant planets during and after the gaseous disk phase seem capable of altering orbital semi-major axes and eccentricities toward the distribution observed in the Doppler spectroscopic cohort. These processes, respectively, can also destroy giant planets through merging with the central star or eject giant planets into interstellar space. When such loss mechanisms are considered, the 10% occurrence of giant planets around mature stars implies that roughly 30% of F-, G- and K-type dwarf stars produce giant planets during their formation (Trilling *et al.* 2002).

What mechanisms associated with star formation might create giant planets around 30% of Sun-like stars? What conditions are required, in the context of these formation processes, to permit roughly one third of these objects to survive the pre-main-sequence phase of the evolution of their parent stars? And what circumstances produce systems akin to our own, in which the giant planets are all in loose, nearly circular, co-planar orbits in the cold outer solar system, with the consequence that terrestrial planets in the 1 AU region are dynamically stable over a stellar main sequence lifetime?

To address these questions requires understanding the details of giant planet formation. In this chapter, we focus on the origin of Jupiter. While Jupiter may not turn out to be the "typical" giant planet, either in terms of its internal structure or orbital situation, it is the best studied both from Earth and from spacecraft missions. Only for Jupiter do we have elemental abundances (including noble gases) measured in situ, and it is Jupiter's gravitational field that is the best determined among the solar system's giants (with Saturn a close second). One can hope that formation models constrained by Jupiter's details will generalize to some larger cohort, but it is perhaps too much to expect that all hydrogen–helium objects between the mass of Uranus and that of the deuterium-burning brown dwarfs will have formed in the same way.

Section 2.2 describes a range of physical and chemical constraints on the formation of Jupiter – only some of which can as yet be explicitly included in the formation models themselves. Section 2.3 provides a physical discussion (that is, more descriptive and less mathematical) of the two dichotomous approaches to giant planet formation – disk instability and nucleated instability. The effect of Jupiter in the late stages of its formation on the surrounding nebula, in particular in generating a satellite-forming disk, is discussed in Section 2.4.

2.2 CONSTRAINTS ON THE FORMATION OF JUPITER

2.2.1 Interior Models and Equations of State

Hydrostatic models of the jovian interior that account for the high pressure properties of hydrogen, helium and heavier elements, energy transport through the planet and Jupiter's global properties, require that elements heavier than hydrogen and helium contribute between 10 and 42 Earth masses to the total of 317 (see Chapter 3). This 3–13% by mass is a significant enrichment compared to the Sun's 2%. Uncertainties result primarily from the still incomplete knowledge of the thermodynamical properties of high-pressure hydrogen–helium mixtures. The difference is interesting because both the Sun and Jupiter presumably formed from the same interstellar cloud fragment that collapsed to a central, pressure supported protostellar core and centrifugally supported preplanetary nebula disk. But the process that formed Jupiter led to a much larger fraction of the planet being composed of heavy elements than the collapse that formed the Sun.

In addition, the heavy elements are concentrated in the inner parts of Jupiter, including (but not exclusively) a condensable element core whose size and discreteness remain highly uncertain. The core's outer boundary may not be well defined, and a vanishing core mass is possible if a higher heavy element enrichment is assumed for the molecular and metallic envelope regions. A significant fraction of an initial core may have been eroded after formation by convective penetration of the envelope gas into the core and remixing of the condensable elements into the metallic parts of the hydrogen–helium envelope (see Chapter 3).

The most direct consequence of the distinct equations of state of hydrogen in the molecular and atomic phases lies in the separation of hydrogen and noble gases, including helium, at megabar pressures. The temperature profiles in the interiors of Jupiter, Saturn, and mature extrasolar giant planets up through several tens of Jupiter masses, pass through a region where thermal ionization and dissociation of hydrogen compete with pressure ionization and dissociation. Because this occurs in Jupiter and Saturn at megabar pressures, the separation between hydrogen atoms is comparable to the inter-atomic dimensions, making theoretical treatment difficult (Hubbard *et al.* 2002). Experimental studies at the required pressures, such as with diamond anvil cells, are difficult because hydrogen is so compressible (Nellis 2000). At these pressures hydrogen behaves as a metal, that is, it ionizes but at the same time possesses strong electron degeneracy. Whether this transition occurs abruptly, with the volumetric or entropic discontinuity of a first order phase transition, or continuously, is still not known. For this reason, the existence or magnitude of compositional discontinuities in other species, especially helium, cannot be reliably quantified.

An immiscible helium phase at megabar pressures would be a noble gas liquid that, in the form of droplets, would fall to the center of the planet (Stevenson and Salpeter 1977). The other noble gases may be quite soluble in the helium droplets – at least more soluble in such droplets than in the host metallic hydrogen background phase – and hence phase separation of the helium could carry a portion of the other noble gases into the center. The observable implication is that the relative and absolute abundances of the noble gases measured in the atmosphere of Jupiter might not reflect bulk abundances. Indeed, the *Galileo* mass spectrometer measurements yield a neon abundance well below solar (Mahaffy *et al.* 2000), a result that requires either that the solar nebula gas was subsolar in neon, or that much of the neon has been sequestered in the deep interior. The former makes little sense since neon is difficult to condense out, and no other plausible mechanism exists for scrubbing the neon from the gas phase. The latter explanation is plausible only if neon were highly soluble in a helium liquid phase separating out from hydrogen in the deep interior (but see Fortney and Hubbard (2003) who argue that no such separation is occurring in Jupiter), or immiscible in hydrogen at elevated pressure hence forming its own high-pressure liquid.

If the abundance of neon has been so severely fractionated between the atmosphere and the deep interior by phase separation, what does this imply for the abundances of the other noble gases? Unfortunately, the uncertainties in the metallic and molecular phase diagrams of hydrogen and the noble gases at megabar pressures allows for almost any degree of absolute or relative fractionation (Roulston and Stevenson 1995). Because of their much lower cosmic abundances compared to helium or neon, it is unlikely that argon, krypton and xenon are separately insoluble in metallic hydrogen at megabar pressures, but they may preferentially dissolve into the helium or neon phases at high pressures – and to differing extents. It is conceivable, though unpleasant to contemplate, that the constancy from element to element of the enrichment discussed in the next subsection among S, N, and C as well as the noble gases is the fortuitous result of a fractionation process in the deep interior that has altered the atmospheric values relative to the bulk ratios of the elements in Jupiter.

Until this issue is resolved, interpretation of the noble gas and major element abundances in the atmosphere in terms of various formation models must be done with the caveat that the abundances may not represent bulk values. Much better knowledge of the equations of state of hydrogen and the noble gases will be required to predict with any reliability the extent of fractionation in the deep interior. Further details are given in the Chapter 3.

2.2.2 Chemical Constraints – Tropospheric Composition

After decades of ground-based observations, the best available data on the composition of the upper troposphere of Jupiter came from the *Galileo* probe that entered Jupiter's atmosphere on December 7, 1995. The mixing ratio of helium to hydrogen was measured by a dedicated experiment (van Zahn *et al.* 1998), and the mass spectrometer (Niemann *et al.* 1998) yielding an identical value of 0.157 ± 0.0036 for He/H_2. The mass spectrometer also measured the isotope abundances of these two gases (Mahaffy *et al.* 1998) as well as abundances and isotope ratios of other constituents (Niemann *et al.* 1998, Mahaffy *et al.* 1999). A comprehensive review of all of this work has been published by Atreya *et al.* (1999) and has just been updated (Atreya *et al.* 2003). Tables 1 and 2 in this last publication are the best summary of atmospheric abundances at the time this chapter was written. Measurements of isotopic ratios have been summarized and discussed by Owen and Encrenaz (2003).

All of the heavy elements whose abundances could be measured (except helium and neon) reveal an enrichment relative to solar values (as tabulated by Anders and Grevesse 1989) by a factor of 3 ± 1, when expressed as a ratio relative to H (Owen *et al.* 1999). The probe did not survive to levels sufficiently deep in the jovian atmosphere to permit a measurement of the global value of O/H. The dominant carrier of oxygen is H_2O, and the entry point of the probe was a desiccated region of the atmosphere (a "hot spot"). All condensable species were depleted relative to expected values in the upper part of the probe trajectory. As the probe descended, it reached levels where H_2S and NH_3 were well mixed, but the H_2O mixing ratio was still increasing at the last data transmission at 19.8 bar. Hence, the determination of O/H on Jupiter remains a critical measurement.

The factor of three enrichment in all measured elements regardless of the volatility of their presumed primordial carriers was unexpected. Comets have generally been considered to have been the delivery agent causing any enrichment of heavy elements on the giant planets. Yet comets are notoriously deficient in nitrogen (Gloeckler and Geiss 1998, Krankowsky 1991, Wyckoff *et al.* 1991). New upper limits of 1/10 and 1/13 solar for Ar/O in comets C/2001 A2 (LINEAR) and C/2000 WM1 (LINEAR) (Weaver *et al.* 2002) severely challenge the reported detection of a solar value of Ar/O in Comet C/1995 01 by Stern *et al.* (2000), indicating that comets are deficient in Ar as well. Yet both N and Ar exhibit the same factor of 3:1 enrichment on Jupiter as S and C.

If Jupiter's atmosphere is indeed representative of the bulk composition of the planet, this three-fold enrichment implies the addition of at least 12 Earth masses of these solar composition icy planetesimals (SCIPs) to the complement of heavy elements contributed by the nebular gas itself. If this material has also enriched the other giant planets, it must have been the most abundant solid in the early solar system (Owen and Encrenaz 2003). The resulting total of 18 Earth masses of heavy elements is well within the range of 10–43 Earth masses derived from interior models.

The origin of these unusual planetesimals is difficult to understand. If they formed originally by the trapping of volatiles in amorphous ice, low gas densities and temperatures less than 30 K are required, suggesting formation at the outer fringes of the solar system or in the presolar interstellar cloud (Owen *et al.* 1999). The problem, as yet unsolved, is to understand how the gas-laden ice was transported to Jupiter's orbit where it could participate in the formation of the planet without alteration in the composition of the trapped volatiles. If instead crystalline ice condensed to form clathrate hydrates in grains at Jupiter's orbit, the ice must have remained in contact with the gas supplying volatiles during a long cooling period in the nebula exceeding of order a million years (Gautier *et al.* 2001). It is unclear whether this requirement is in conflict with models proposing growth of large planetesimals in less than a million years (Weidenschilling 1997) or a 10 Earth mass core in ~0.5 My (Pollack *et al.* 1996a, Hersant *et al.* 2001). Longer timescales for core formation have been proposed by others (Section 2.3.3).

Given the importance of solid planetesimals for building giant planets it is obviously critical to understand how these constraints on the formation of SCIPs can be satisfied. Measurement of the global water abundance on Jupiter would provide a clear test of the clathration hypothesis. If clathration was 100% efficient, O/H on Jupiter would be nine times the solar value, while amorphous trapping would predict the same enrichment factor of 3:1 exhibited by the other elements.

Nitrogen is a key volatile element whose enrichment must be explained. Initial difficulties in measuring the NH_3 abundance on Jupiter with the *Galileo* Probe Mass Spectrometer (GPMS) (Niemann *et al.* 1998) have been overcome by additional laboratory calibrations (Wong and Mahaffy 2002), so that the value of N/H on Jupiter now reflects both the mass spectrometer result and the indirect determination by attenuation of the probe's radio signal (Folkner *et al.* 1998). Thus, it is clear that N is enriched by the same factor as the other elements that were measured, viz., C, S, Ar, Kr, and Xe.

However, it is important to note that whereas $^{38}Ar/^{36}Ar$ and $^{13}C/^{12}C$ are the same in Jupiter and the Earth, $^{15}N/^{14}N$ is distinctly lower (Owen *et al.* 2001). This can be understood if the nitrogen on Jupiter originally reached the planet in the form of N_2 rather than NH_3 or other nitrogen compounds (Owen and Bar-Nun 1995, Owen *et al.* 2001). The reason is the same one that distinguishes the D/H in H_2 from that in H_2O: ion–molecule reactions in the interstellar medium have enriched the heavy isotope compared with its relative abundance in the much larger reservoir consisting of the pure element. In the interstellar medium, the dominant form of nitrogen is N or N_2, with a fractional abundance of 70 to 90% (Van Dishoeck *et al.* 1993). Calculations by Terzieva and Herbst (2000) demonstrate that under interstellar conditions, $^{15}N/^{14}N$ in compounds can have 1.3 times the value in N_2. On Jupiter, $^{15}N/^{14}N = 2.3 \pm 0.3 \times 10^{-3}$, compared with 3.1 $(+0.5, -0.4) \times 10^{-3}$ in HCN measured in Comet Hale–Bopp (Jewitt *et al.* 1997). Both the cometary and jovian isotope ratios were presumably established in the ISM and preserved against re-equilibration in the solar nebula; the difference then results from the different molecular carriers, in good agreement with the calculations. The terrestrial value of $^{15}N/^{14}N = 3.66 \times 10^{-3}$ may ultimately allow us to identify the compound(s) that brought nitrogen to the Earth. N_2 was evidently not a major player in this delivery, whereas it was apparently a dominant carrier of nitrogen to Jupiter and presumably to the Sun as well (Owen *et al.* 2001).

The results from the *Galileo* probe Mass Spectrometer (GPMS) are very robust. As summarized by Gautier and Owen (1989), the value of He/H determined by this instrument agrees exactly with the measurement by the probe's helium abundance detector, and the enrichment of carbon by a factor of three compared to solar C/H agrees with earlier remote sensing measurements including those by the *Voyager* spacecraft (Gautier *et al.* 1982). Thus the measurements of additional abundances and isotopes made by the GPMS are on a sound footing.

This is important because these measurements provide a useful constraint on models for the formation of Jupiter (Owen 2004): Gravitational instabilities in the solar nebula will produce planets with solar composition (Boss 1998, 2000, 2001, Mayer *et al.* 2002). The proposal to enrich the atmospheres through impacts by small bodies (Boss 1998) is no longer viable, as there are no small bodies we know of that exhibit solar ratios of noble gases, nitrogen, carbon and sulfur. The deduction that nitrogen was delivered to Jupiter in the form of N_2 adds considerable force to this conclusion. Where it has been measured, N_2 in comets is a minor fraction of the nitrogen inventory (Iro *et al.* 2002), which is already depleted relative to solar abundances, as mentioned above. Cochran *et al.* (2002) have been unable to detect N_2^+ (which is well-correlated to the N_2 abundance) in three comets. Hence the comets we know could not have delivered the nitrogen we now find on Jupiter. *Thus the GPMS results effectively rule out the gravitational disk instability models for forming Jupiter.* This obviously does not exclude the possibility that this process formed the giant planets found around other stars.

Core accretion models are still viable if SCIPs were available to build the cores and if mixing from the cores into the envelopes was efficient. (Mixing from the outside inward is attested by the depletion of He and Ne in the sensible part of the atmosphere.) The same mission that measures the deep water abundance on Jupiter can measure ammonia as well, thereby providing a good determination of the abundances of heavy elements in the envelope. Accurate tracking of a close flyby or orbiter will constrain the mass of the core. Comparable information about the other giant planets (including results from atmospheric probes) will determine just how uniform the giant planet formation process was in our own solar system.

2.2.3 Constraints from the Deuterium and Helium Abundances

Helium in Jupiter and Saturn

Since the H_2 and He present in Jupiter today originated from the protoplanetary disk that formed our solar system (hereafter, the solar nebula), a naive approach would suggest that the He/H ratio measured in the outer envelope of the planet is equal to the value in the primitive solar nebula; namely to its value in the early Sun. This is not the case however. The per mass protosolar abundance Y(He) is estimated from evolutionary models constrained to fit the present age, radius and luminosity of the Sun, and is found equal to 0.275 $\pm$ 0.01 (Bahcall and Ulrich 1988, Proffitt 1994). (The relationships between Y, the helium mole fraction $q_{\rm He}$ and the H_2/He mixing ratio are given in Appendix I.) On the other hand, the in situ measurements made by the mass spectrometer aboard the *Galileo* probe yield Y = 0.234 $\pm$ 0.005 (Von Zahn *et al.* 1998, Niemann *et al.* 1988) while the value inferred from the combination of radio occultation (RSS) and infrared data (IRIS) of *Voyager* was 0.18 $\pm$ 0.04 (Gautier *et al.* 1981, Conrath *et al.* 1984). The cause of the discrepancy between the *Voyager* and the *Galileo* determinations appears to be a systematic error affecting the original retrieval of the radio occultation profile (Conrath and Gautier 2000), so that we take the *Galileo* result. Although much closer to the solar value for helium, the *Galileo* determination implies a modest helium depletion, presumably associated with the immiscibility of helium in the metallic phase of hydrogen at multi-megabar pressures. However, the most recent interior model of Jupiter (Fortney and Hubbard 2003), finds no predicted unmixing of helium from hydrogen, so the origin of the modestly subsolar helium abundance found by *Galileo* remains unresolved.

Deuterium in Jupiter and Saturn

The major reservoir of deuterium in Jupiter and Saturn is hydrogen in the form of HD. Since HD is not expected to fractionate when hydrogen undergoes a transition from molecular to metallic form, the D/H ratio in both Jupiter and Saturn is expected, in a first approach, to be equal to the so-called protosolar value, namely the value in the primitive solar nebula.

Since D was converted into ^{3}He in the Sun, the protosolar D/H value can be derived from measurements of the ^{3}He/^{4}He ratio in the solar wind from which is subtracted the ^{3}He/^{4}He ratio in the early Sun. This last value is assumed equal to that measured in the "planetary gas component" found in meteorites, namely $(1.5 \pm 0.2) \times 10^{-4}$ (Gloeckler and Geiss 1998) which is consistent with the value $(1.66 \pm 0.05) \times 10^{-4}$ measured in Jupiter by the *Galileo* mass spectrometer (Mahaffy *et al.* 1998). The radial distribution of ^{3}He/^{4}He throughout the Sun has been modeled and shows an increase of a few percent only from its early value up to the Outer Convective Zone (OCZ) today (Gautier and Morel 1997). Gloeckler and Geiss (1998) have estimated the fractionation between the solar wind and the OCZ. All uncertainties taken into account, this results in a protosolar D/H ratio equal to $(2.1 \pm 0.5) \times 10^{-5}$ (Gloeckler and Geiss 1998).

The D/H ratio in the hydrogen of Jupiter measured in situ by the *Galileo* probe has been found equal to $(2.6 \pm 0.7) \times 10^{-5}$ (Mahaffy *et al.* 1998), which is consistent with the remote sensing determination of $(2.4 \pm 0.4) \times 10^{-5}$ made by ISO (Lellouch *et al.* 2001). Considering the difficulty in properly evaluating the fractionation factor between methane and hydrogen in the deep atmosphere of Jupiter and Saturn (Smith *et al.* 1996), the inference of D/H in H_2 from CH_3D/CH_4 should be considered as only approximate. Within error bars, the determinations of Gloeckler and Geiss (1998), Mahaffy *et al.* (1998) and Lellouch *et al.* (2001) agree rather well, although the central value of Gloeckler and Geiss (1998) is somewhat lower than the values of the other authors. In fact, the D/H ratio measured in the hydrogen of Jupiter today results from the mixing of D/H in the hydrogen of the nebula with D/H in water ices, which may be substantially enhanced in deuterium with respect to the protosolar deuterium abundance. The weighted mean of the D/H ratios in the two reservoirs depends upon the deuterium enrichment in ices in the region of formation of Jupiter and upon the mass of ices in the planet. The first parameter may be estimated from the calculations of

Hersant *et al.* (2001), which suggest an enrichment of 10 at 5 AU, namely a value of about 2×10^{-4}, if we adopt the protosolar ratio of Gloeckler and Geiss (1998). The second one is difficult to estimate because models of interiors that fit the external gravitational moments provide an estimate of the mass of heavy elements but not the ice-to-rock ratio I/R per mass in these elements. Modelers frequently take I/(I+R) between 1/2 and 2/3 because they assume a solar composition. Assuming the above-mentioned range for I/(I+R), and a maximum D/H ratio in ices of 3×10^{-4}, Guillot (1999) concluded that the deuterium enrichment due to ices is too small to be detected, given the observational error bars. However, the assumption of a solar I/R ratio in Jupiter is arbitrary because I/R depends in fact upon the history of planetesimals in the feeding zone of Jupiter and upon the manner in which these bodies are incorporated in the envelope of the planet. The water measurements made aboard the *Galileo* atmospheric probe reflect atmospheric dynamical processes and do not constrain the deep oxygen abundance. Therefore, we do not know if I/R is oversolar in the envelope of Jupiter. This uncertainty precludes us from evaluating the contribution of deuterium-enriched ices to the value of D/H directly measured in Jupiter. At this point, we consider that the safest determination of the protosolar deuterium abundance is that of Gloeckler and Geiss (1998) because it does not depend on the amount of ices in Jupiter.

2.2.4 Constraints from the Natural Satellites

The system of the Galilean satellites constrains the formation of Jupiter because the regular orbits of the satellites and their well-defined compositional gradient with separation suggest a process of assembly tied closely to the growth of Jupiter itself. In other words, it is clear that these are not captured objects.

Schubert *et al.* (1986) inferred a silicate composition for Io, a hydrated silicate composition for Europa, and a Ganymede and Callisto that are roughly 50% rock and 50% ice based on *Voyager*-determined densities. The gravitational fields of the Galilean satellites measured by the *Galileo* orbiter (Kuskov and Kronsov 2001, Sohl *et al.* 2002), confirmed this, and provided additional detail: Europa is mainly silicate with a water ice–liquid outer shell of about 120–140 km (7–8% of the total mass) and Ganymede could have an Fe and eutectic Fe–S core of 820–900 km size surrounded by a solid ice shell of 890 920 km (46–48% of the total mass). In addition, they concluded that Callisto should be differentiated, albeit incompletely.

From the total mass of the Galilean satellites it is possible to derive a minimum mass subnebula out of which the satellites formed by assuming an originally solar composition gas between 5 and 30 jovian radii, which then must be accounted for in the context of models of the assembly of Jupiter. This concept must be used cautiously because the mass of the gas in a presumably turbulent subnebula (Mousis and Gautier 2003) decreased with time, leading to a time-dependent increase in the relative abundance of condensables.

2.2.5 Solar Nebula Models

Overall Constraints on the Disk

A considerable number of models of the primitive solar nebula have been published, and reviewing each of them in detail is impossible within the space constraints of this chapter. Reviews that are more detailed are available in the two recent *Protostars and Planets* books (Levy and Lunine 1993, Mannings *et al.* 2000). We follow instead what might be called the pragmatic approach of Cassen (1994), who notes that the main difficulty is not the elaboration of models but the discrimination among models – a consequence of the relative scarcity of observational data. Models of the primitive solar nebula should be consistent with the following constraints, at least:

(i) conservation of angular momentum throughout the nebula
(ii) mass of the disk within a range 0.03–0.3 solar masses
(iii) general properties of disks around young stars
(iv) the existence of Jupiter and Saturn
(v) compatibility with the isotopic composition of primitive objects such as meteorites, comets and giant planets.

Constraint (i) implies transport of angular momentum and mass throughout the gaseous nebula, because dissipative processes are present. Transport of angular momentum is accomplished through gravitational torques (e.g., via spiral density waves), magnetic torques, and turbulence which increase the dissipation in the disk to a high value. This in turn decreases, in principle, the disk dynamical lifetime. The relative importance of each of these processes is a function of position and time in the disk, and observations are only now becoming sufficient to constrain them.

We focus here on the turbulent transport of angular momentum. In principle, solving equations for a turbulent accretion disk requires the exact calculation of the turbulence (namely, at all scales). This would require an unrealistically large amount of computer time for an object the scale of the protoplanetary nebula, and modelers simplify the problem by discarding small scale features via the introduction of a turbulent viscosity which relaminarizes the mean flow and wipes out small scale features. Following Shakura and Sunyaev (1973), the turbulent viscosity can be set equal to

$$\nu_s = \alpha c_s H \tag{2.1}$$

where α is a dimensionless coefficient of turbulent viscosity, which is usually taken equal to 10^{-3}–10^{-2}. The sound speed is labeled c_s, and H is the half-height of the disk that increases with distance from the proto-Sun.

It is well known that the above relation is arbitrary, and hence that the physical significance of α is dubious. However, particularly for chemical models in which large amounts of computer time are taken up with calculating reactions and equilibrium species abundances, the α model is used in place of explicit modeling of the turbulence. Other important parameters are the mass of the disk M, the accretion rate of the mass, dM/dt, and the radius of the nebula R_D. Once the parameters are given, the radial distributions of temperature, pressure, surface density, and height of the disk are fully determined (Dubrulle 1993, Huré 2000). Constraint (ii) on the mass of the nebula is straightforwardly defined. The minimum mass of the disk is the mass of the planets of the solar system augmented with the solar hydrogen and helium abundance, which leads to a value of 0.03 solar masses. This is almost certainly a lower limit, and the maximum mass of the disk is that compatible with its stability, estimated to be 0.3 solar masses (Shu *et al.* 1990). Of course, more than this amount of gas is processed through the disk over its lifetime in order to generate a star at the center of one solar mass in the case of our system.

Observations of circumstellar disks, that is, constraint (iii), provide information on dM/dt as a function of time. Overall, the accretion rate declines as a function of the age of the disk (Hartmann 2000, Calvet *et al.* 2000). Although there is a large spread in the mass accretion rate at a given age, the temporal decrease of dM/dt can be represented by a law of the form $(1 + t/t_o)^{-\eta}$, where η is roughly 1.5. This decay law is readily adapted to time-dependent models of the nebula, in which the disk radius expands under the effect of the redistribution of the angular momentum (Ruden and Pollack 1991). In order to consider the effects on chemistry, a simpler approach is to approximate the disk evolution by a series of steady state solutions with accretion rates changing according to the relation

$$dM/dt = (dM/dt)_{t=0}(1 + t/t_o)^{-1.5} \qquad (2.2)$$

Here t_o is taken equal to the accretion time $R_{D0}^2/3\nu_D$, where ν_D is the turbulent viscosity at the initial radius of the nebula R_{D0}. The temporal and radial evolution of the physical parameters of the nebula are then fully defined once $(dM/dt)_{t=0}$, R_{D0}, and α have been given (Dubrulle 1993, Huré 2000). The fact that the temperature and pressure distributions with radial distance in the nebula decrease with time has dramatic effects on the chemical and physical properties of the protoplanetary disk, which play into the formation processes and final compositions of solar system bodies, including Jupiter and its natural satellites. Various data on circumstellar disks suggest that the lifetime of the gaseous phase of the protoplanetary disk should not have exceeded roughly 10 million years (Hollenbach *et al.* 2000).

With regard to constraint (iv), the amount of hydrogen in Jupiter today (see subsection 2.2.1) must have been present in the feeding zone of the planet during its formation, and the implied surface density then requires that the size of the feeding zone and the accretion rate (relative to the rate of in-fall of new material into the disk) be specified. Models of the interactions between giant planets within gaseous disks, including their migration, suggest that the planets remain well spaced and their feeding zones do not overlap. Timescales for the accretion of gas on to the giant planets are short in current models, of order 10^4 years, implying that during formation of the gaseous envelopes of the giant planets the protoplanetary disk must exhibit a surface density consistent with the mass of hydrogen required for such envelopes (Hersant *et al.* 2001).

Most of the isotopic fractionations (constraint (v)) observed or predicted to occur in the interstellar medium because of ion–molecule reactions should not obtain in a medium as dense as the protoplanetary disk, where reactions are largely between neutrals and hence are facile only at temperatures so high that resulting fractionations are negligible (Richet *et al.* 1977), with the exception of deuterated species. While the fractionations among these molecules are much less than in the interstellar medium, they are still significant – an order of magnitude or more above the protosolar value in the hydrogen gas. The major reservoir of deuterium in the nebula is deuterated molecular hydrogen, HD. Then the elemental ratio of D to H ("D/H") in the protoplanetary disk is nearly

$$D/H \approx (D/H)_{\text{molecular hydrogen}} = 1/2[HD]/[H_2] \qquad (2.3)$$

where [HD] indicates the abundance of molecular species HD, etc.

Minor reservoirs of deuterium, that is in the carbon-, oxygen- and nitrogen-bearing species, are generated by isotopic exchange between molecular hydrogen and the other species. For example, the reversible equation of isotopic exchange for water is

$$HD + H_2O \leftrightarrow HDO + H_2 \qquad (2.4)$$

resulting in a D/H value in water equal to

$$(D/H)_{\text{water}} = 1/2[HDO]/[H_2O] \qquad (2.5)$$

At high temperatures ($T > 1000$ K), the D/H values are the same in hydrogen and the heavier molecule under consideration, but as the temperature decreases, the deuterium tends to move into the heavier molecule where the bonding energy is more negative. However, equilibrium is never reached in the nebula, except at high temperatures, because of the temperature dependence of the reaction rates. This dependence can be described as roughly following an Arrhenius exponential curve such that the exchange is fully inhibited below 225 K for a timescale corresponding to the lifetime of the nebula, and at higher temperatures for typical dynamical mixing times in the nebula. Hence, only modest fractionations can be obtained in deuterium, and the large enrichments in deuterated water seen in comets (for example) must have been initially acquired in the presolar molecular cloud. The low deuterium enrichment measured in clays of LL3 meteorites (Robert 2001) implies a substantial reprocessing of water in the protoplanetary disk. These and other observations constrain the spatial distribution and temporal evolution of the temperature gradient in the protoplanetary disk.

Drouart *et al.* (1999) and Hersant *et al.* (2001) have integrated the differential equation that describes the evolution of the enrichment of deuterium in the nebula with respect to the protosolar value, under the assumption that the initial enrichment in water was that acquired in the presolar molecular cloud. They showed that fitting the D/H value in both comets and LL3 meteorites requires that interstellar ices vaporized in the early outer solar nebula and remained in the vapor phase on dynamical mixing timescales. This, in turn, constrains the radial temperature gradient in the disk midplane, since vaporization associated with gas dynamical heating during in-fall of grains to the disk is followed quickly by recondensation of the water (Lunine *et al.* 1991, Chick and Cassen 1997).

Composition of the Early Solar Nebula

Modern scenarios for the formation of Jupiter are based on the assumption that the planet was embedded in a disk of gas and planetesimals, and the latter did not – for the most part – migrate into or out of planetary feeding zones. This is an oversimplification, since solid bodies encounter drag in the gas and do migrate radially inward in the disk. Planets grow, of course, and gravitational scattering leads to further radial migration. The model of Pollack *et al.* (1996b) does not exclude the possibility that microscopic grains mixed with gas entered the jovian feeding zone throughout the formation of the planet.

The early feeding zone contained three major species – molecular hydrogen, helium and neon – which did not condense at any time in the disk. Other elements were partly or completely trapped in the condensed phase. Silicates infalling from the presolar cloud on to the nebular disk were presumably all amorphous. Accretion processes transported these silicates towards the inner hot nebula where they crystallized, in agreement with the fact that silicates observed in meteorites are entirely crystalline. Turbulent motions in turn may have transported crystalline silicates outward to the zone of formation of Jupiter, and beyond into the region of formation of comets. There they would have mixed with amorphous silicates, resulting in the mixed composition seen in Oort Cloud comets (Bockelée-Morvan *et al.* 2002, Wehrsted and Gail, 2002). The primary condensation of water occurred at 150 K, roughly; the corresponding distance in the disk is a function of time as the nebula cooled (Hersant *et al.* 2001). Water also was incorporated in silicate grains by hydration and adsorption, though condensation was by far the most important process for putting water in the solid phase at Jupiter's distance from the proto-Sun. The radial transport of icy grains, once formed, is a complex problem. Stevenson and Lunine (1988) modeled water vapor transport by eddy diffusion across the ice condensation front, leading to an enhanced population of water ice at and just beyond the condensation front ("snowline"). Cyr *et al.* (1998) updated this work by incorporating inward radial drift of water ice grains, which gradually decoupled from the gaseous disk as they grew. Supulver and Lin (2000) incorporated global turbulence, condensation, growth by coagulation, and sublimation of water in their numerical simulation. The models of Cyr *et al.* (1998) and Supulver and Lin (2000) suggest a local zone of enhancement of water vapor with respect to the solar abundance around the snowline, and hence a zone of enriched water ice abundance that moved with the snowline as the nebula cooled.

Trapping of volatiles in the solid phases occurred by formation of clathrate hydrate, during slow cooling (Gautier *et al.* 2001), cold-trapping in amorphous ice at large radial distances (low temperatures) with subsequent inward migration of material (Owen *et al.* 1999), or direct preservation of interstellar grains (Owen and Encrenaz 2003).

2.3 THE FORMATION OF JUPITER

2.3.1 Nucleated Instability *vs.* Direct Collapse

Since the 1970s two hypotheses have been discussed that try to overcome the difficulties of collapse in a disk. The *gravitational disk instability* seeks an analog of the gravitational "Jeans-instability" of star formation, while the *nucleated instability hypothesis* explains giant planet formation as the consequence of the formation of planetary embryos composed of rock- and ice-forming elements that act as gravitational seeds for nebula gas capture/condensation. Disk instability requires protoplanetary disks that undergo self-compression in a dynamically unstable situation and lead to a transition from a smooth regular disk to an ensemble of clumps in orbit around the Sun. Such clumps may be regarded as candidate precursors of protoplanets. Nucleated instability relies on the additional gravity field of a planetary embryo, a "core" to trigger gas compression and "envelope" growth in otherwise stable nebulae.

Disk models based on the minimum mass solar nebula, that is, models which add hydrogen and helium to the known planetary masses to bring the mix to solar composition, are gravitationally stable and more massive pre-planetary disks are self-stabilizing (Wuchterl *et al.* 2000). To form long-lasting Jupiter mass condensations under such conditions requires either the extra gravitational field of a condensed element planetesimal that dominates its feeding zone – a planetary embryo, or "core" – or a specific trigger that results in the formation of gaseous clumps in a generally stable overall nebular situation.

2.3.2 Mechanisms of, and Requirements for, Direct Collapse

Early work on the disk instability hypothesis essentially assumed the existence of an instability (DeCampli and Cameron 1979, Bodenheimer *et al.* 1980, Bodenheimer 1985). Recent work focuses on the identification of a nebula structure and the demonstration of a working instability that produces planetary mass clumps in a circumstellar nebula. Simple instabilities like the (one-dimensional) pressure *vs.* gravity Jeans-instability, or the axially symmetric two-dimensional gravity *vs.* pressure and Keplerian shear "Toomre-instability" are stable or produce rings instead of planets. A more complicated, three-dimensional instability is needed to produce a clump in a sheared Keplerian disk that is under the influence of considerable solar tides. Results depend on assumptions regarding the radial temperature profile in the disk (isothermal or otherwise) and the particulars of the numerical technique and resolution used (Boss 2000, Pickett *et al.* 2000).

The general numerical approach is that of a nonlinear instability calculation that introduces a finite perturbation, usually a density enhancement in a specific nebular model, to determine the response of the disk flows. The calculations test whether the inserted density enhancement amplifies and retains its identity. If such a clump survives for a number of revolutions (e.g., a few hundred) around the central star, then the calculation is considered to demonstrate instability successfully and to be indicative of the formation of a protoplanet (Boss 2001). Recent 3-D simulations have produced persistent clumps of mass one to several times that of Jupiter, and central densities 10^5 times the background disk density, on timescales of hundreds of years (Mayor *et al.* 2002).

Once the candidate instability is proven, it has to be shown that the resulting clump is stable with respect to the ongoing evolution in the dynamically active disk. Disruptive forces include tides, shear and pressure perturbations such as those produced by the clump itself. The gaseous clumps of planetary mass have to persist long enough to contract subsequently to form a long-lived protoplanet. That is a non-trivial issue because the calculations that consider the structure inside the clump show that post-disk-instability collapse is not imminent because the clumps are optically thick; the clumps will settle into a quasi-hydrostatic equilibrium after a brief phase of contraction (see, e.g., Bodenheimer, 1985). The subsequent contraction and the approach to a collapse or rapid contraction to "planetary densities" proceeds on the thermal timescale of the clump, expected to be a few million years (though this has not been explicitly calculated).

The evolution from a clump to a long-lived condensation may involve giant gaseous protoplanets that have masses much larger than the final planetary masses, and therefore are more likely to become gravitationally unstable. The large gas envelopes may be subsequently removed by UV radiation from the young Sun, or extrasolar evaporation mechanisms (Boss *et al.* 2002).

None of these processes directly enrich heavy elements. Therefore, the proto-giant planets formed by disk gravitational instability have to be enriched by an additional mechanism. The heavy element composition of Jupiter, specifically the nitrogen abundance and the enrichments in argon, krypton and xenon with respect to the solar abundance discussed in Section 2.2, seem to rule out this model for Jupiter. While the same detailed compositional data are not available for Saturn, its large heavy element abundance and existence "close" to Jupiter from a dynamical standpoint would argue in favor of a common formation mechanism for the two. However, absent detailed compositional data on any extrasolar giant planets (including HD209458b, which we know is to first order hydrogen, but for which no specific data on heavy element abundance is available), disk instability cannot be ruled out for those objects. The efficiency of planetesimal capture by a giant planet also decreases after it has reached its final mass because ejection of planetesimals becomes an important process (Guillot and Gladman 1999).

2.3.3 Mechanisms of, and Requirements for, Nucleated Instability

The nucleated instability hypothesis posits giant planet formation as the consequence of the formation of "terrestrial planet embryos" in the giant planet region of the solar nebula, followed by accretion of large amounts of gas on to the resulting cores. To trap large amounts of nebula gas the planetary embryo has to grow to a certain minimum size while enough mass of gas is present. Whether that is possible depends on the lifetime of the nebula gas, the minimum core size to permanently capture nebula gas, and the time needed to grow an embryo to the required minimum mass. The lifetime of the gaseous disk, as noted above, is likely no more than 10 million years. In this section, we consider the general physical properties of the core and surrounding environment over the enormous range of mass from lunar to that of Jupiter itself. We then proceed to a more detailed examination of the critical mass, defined below, and consequent accretion timescales.

From Lunar-Mass Planetesimals to Jupiter

At very low masses, 0.01 Earth masses ($M_{\rm E}$) or below, a planetesimal embedded in the nebula gas creates a density enhancement of less than a factor of ten within a region defined by the accretion radius, $r_{\rm acc} = GM/c^2$, where M is the body mass and c is the speed of sound. For a lunar-mass object at Jupiter's position in a Hayashi-type nebula, (Hayashi *et al.* 1985), $r_{\rm acc}$ would be more than three times the body's physical radius, but nebular gas at the body's surface would only stay there if confined by the pressure of an existing nebula.

At 0.1 $M_{\rm E}$, close to a Mars mass, a significant envelope can develop, with a gas density at the core surface that is enhanced by a factor 100 above nebular values (Mizuno 1980, see Wuchterl *et al.* 2000 for review). Between 0.1–1 $M_{\rm E}$, the density enhancement starts to increase more rapidly with the embryo-mass and may reach 10^6 at an Earth mass. But the process can still be regarded as gravity-assisted compression under the ambient nebula pressure; gas is bound *to* the core but by the nebula, not the core itself. Nebula decompression results in envelope decompression and loss.

It is useful to consider the structure of the envelope in this phase. An envelope is formed by the combination of nebula pressure and core-gravity. But there is no accretion flow from the nebula on to the core. Rather the envelope gas is essentially at rest. In the inner parts of the envelope, the gravity of the core is much larger and balanced by an increased pressure (and density) resulting in a stable hydrostatic equilibrium. It is important even in this mass range to consider the detailed thermal structure of the envelope. Even pure hydrogen–helium envelopes with the most favorable conditions for energy loss due to their lack of dust and many molecular opacity sources begin to heat up and depart from an isothermal behavior for core masses of order 0.1 $M_{\rm E}$. Above this threshold, the compression proceeds further but now the core-to-envelope ratio decreases toward unity as the core mass increases, and the envelope starts to control the evolution of the energy budget. The evolution and especially the mass of the envelope are determined by the thermal behavior of the envelope and how it self-regulates its contraction (Mizuno 1980, Safronov and Ruskol 1982, Bodenheimer and Pollack 1986).

More rapid energy loss and more rapid envelope contraction result in an increased growth rate for the envelope mass. Time-dependent calculations of the envelope contraction (Bodenheimer and Pollack 1986, Tajima and Nakagawa 1997, Wuchterl 1994) and hydrodynamic calculations (Wuchterl 1993, Wuchterl 1994) find the first small but noticeable departures from *strictly static* non-contracting envelopes in this phase. Up to this phase, the envelopes are static to within 10% in global quantities. Simplified static analytical envelope models can reproduce essentially all properties to very good approximation (Stevenson 1982), but they also show that there must be a qualitative change in the properties of gaseous envelopes for core masses that are a few times larger still.

At core masses somewhere in the range of 10 $M_{\rm E}$, the static sequence of proto-giant planets ends (Wuchterl 1991a, Wuchterl 1991b). Beyond that "critical mass", a core embedded in the nebula cannot form static envelopes. Originally, it was conjectured that the critical mass would indicate a Jeans-like instability and the onset of collapse (Perri and Cameron 1974), but the precise physical significance of the critical mass remains uncertain. The critical mass is certainly not a sufficient condition for an envelope collapse.

Studies that looked at the envelope's response to small adiabatic perturbations found dynamical stability at the critical mass (Mizuno 1980, Hayashi *et al.* 1985, Wuchterl 1991a, Tajima and Nakagawa 1997). Quasi-hydrostatic studies that allow slow changes on thermal timescales always find slow contraction and an increasing rate of envelope mass growth beyond the static critical core mass (Bodenheimer and Pollack 1986, Pollack *et al.* 1996a, Tajima and Nakagawa 1997). Radiation fluid-dynamic studies (nonlinear calculations of the gas motion and thermal budget of the protoplanetary envelope including energy transfer by radiation and convection) found ejection of large fractions of the envelopes under some circumstances (Wuchterl 1991b, 1994).

In general, accretion of gas is relatively slow up to and beyond the critical mass and is controlled mainly by the thermally regulated contraction of the gaseous envelope. The pacemaker of the evolution switches from the core to the envelope typically shortly beyond the critical mass. Once the energetics of the envelope dominate that of the core, usually when the masses and hence the potential energies of the envelope become larger than the core's, the protoplanetary evolution becomes independent of core properties, including the planetesimal accretion of the core. Hydrodynamic effects alter the envelope contraction beyond 50 M_{E}, but the situation is still far from a large-scale collapse.

Rapid accretion on a dynamical timescale will not set in until masses larger than 100 M_{E} are reached. In that regime, the interaction of the hydrostatic envelope with the nebula and the structure of the nebular flow around the planet (gaps, circumplanetary disk, accretion streamers) become important. The growing envelopes of giant planets will be close to hydrostatic almost to their final masses – but not their final radii. During their growth they are large objects that fill their Hill spheres and have gas-enhanced cross-sections for the capture of planetesimals. The overlapping timescales (orbital, dynamic, thermal, core-evolution) make it a computationally difficult problem that requires multiple timescale methods that can correctly describe a slow transition from thermal viscous evolution on million-year timescales, via a regime of slow but finite Mach-numbers, to possible supersonic collapse. Presently only 1-dimensional methods fulfill the necessary requirements and all models of planet formation that include at least a plausible description of the protoplanetary envelope structure have spherical symmetry.

The evolution between 100–300 M_{E} depends on the interaction with the ambient protoplanetary nebula. Depending on how the gas from the nebula is transported to the Hill sphere of the planet, the proto-Jupiter may or may not collapse to its present size, and depending on the angular momentum transfer it may or may not produce a significant circumplanetary disk (Korycansky *et al.* 1991). This final phase involves 2/3 of the final mass of Jupiter and may be crucial to determining the bulk composition of the envelope. If that growth phase is slow, on the timescale of millions of years, then envelopes have a large cross section for capture of planetesimals on a timescale significant compared to that of the nebula itself. But at present, quasi-hydrostatic models of Jupiter stop before 300 M_{E} are reached (Pollack *et al.* 1996a) and fluid-dynamical models (Wuchterl 1994, Wuchterl *et al.* 2000) are of unknown accuracy above 100 M_{E} due to the expected departures from spherical symmetry. Very recently, Magni and Coradini (2003) have modeled the gas accretion in a 3-dimensional scheme, in order to take into account the combined gravitational effects of the Sun and protoplanet and to treat in detail the boundary between the growing planet and surrounding disk. The present mass and angular momentum of Jupiter are well-reproduced at the end of this simulation.

Specific Values of the Critical Core Mass

The simplest way to determine the critical mass is to embed a planetary core into the nebula gas and assume that energy produced during planetesimal accretion and envelope contraction can be radiated out of the envelope as it is produced. This is equivalent to an isothermal envelope. Critical masses for idealized isothermal envelopes are of order 0.01 M_{E} (Sasaki 1989). But if the energy budget of the envelope is accounted for, it is found that the protoplanets are non-isothermal with an adiabatic (convective) interior and a radiative outer envelope that remains close to isothermal only in the outermost parts of the Hill sphere (e.g., Mizuno 1980). Hence, the critical mass must be evaluated in the context of a more detailed numerical model.

More detailed models take typical values of planetesimal accretion rates chosen according to numerical models of planetesimal accretion (Mizuno 1980, Wuchterl 1991a,b, 1993, Bodenheimer and Pollack 1986), or solve for the coupled problem of planetesimal accretion in the presence of a gaseous envelope (Pollack *et al.* 1996a, Bodenheimer *et al.* 2000), and then determine the gaseous envelope accretion rate corresponding to the growing cores under specific nebula conditions. The results are the core masses and growth times needed for massive envelopes. The various calculations are reviewed in Wuchterl *et al.* (2000). They depend somewhat on assumptions made about the dust opacities that might be reduced by the formation of planetesimals and on the details of the core accretion rates. A limiting case is provided by pure hydrogen–helium protoplanets (without dust and most molecular opacities); these have critical core masses of 1.5 M_{E} and 3 M_{E} for planetesimal accretion rates between 10^{-8}–10^{-6} $M_{\mathrm{E}}\,\mathrm{yr}^{-1}$, respectively (Wuchterl 1994, Wuchterl *et al.* 2000).

A recent model for a solar composition nebula, with grains, yields a critical core mass between 7–27 M_{E} for accretion rates between 10^{-7}–10^{-5} $M_{\mathrm{E}}\,\mathrm{yr}^{-1}$ (Ikoma *et al.* 2000). For the Pollack *et al.* (1996a) determination of an almost constant core accretion rate of 10^{-6} $M_{\mathrm{E}}\,\mathrm{yr}^{-1}$ during the relevant accretion phase in their nominal Jupiter case, the Ikoma *et al.* (2000) value would be about 12.4 M_{E} – close to the value in Mizuno (1982). Ikoma *et al.* (2001) determined a critical core-mass of 19 M_{E} using the Saumon *et al.* (1996) equation of state and Alexander and Ferguson (1994) opacity data for a Jupiter formed at 5 AU in a minimum mass nebula.

In summary, at 5 AU in a standard minimum mass nebula, values for the critical core mass range from 1.5 M_{E} (for the extreme case of protoplanets made only of hydrogen and helium) to 20 M_{E} (for full interstellar dust opacities) depending on the model assumptions for the protoplanet. While the critical mass is almost essentially independent of the location in the solar nebula (Mizuno 1980, Stevenson 1982) and only weakly dependent on dust opacities (for depletion to ~0.01 of the solar-composition value) and core accretion rate (Ikoma *et al.* 2000), it is sensitive to the total nebular mass.

Wuchterl (1993) analyzed the conditions for the formation of massive Jupiter-like envelopes after a dynamical instability at the critical mass resulted in the widespread formation of Uranus/Neptune type objects (low envelope-to-core mass ratio) under minimum mass nebula conditions. He found that the critical mass starts to depend on the nebula pressure and temperature once the outer envelopes become sufficiently convective (Wuchterl 1993, Wuchterl *et al.* 2000, Ikoma *et al.* 2001). An interesting property of these "convective-critical" protoplanets is that, for sufficiently large nebular mass, they can grow to 60 M_E quickly and without exhibiting the critical core mass behavior described above (Wuchterl 1993). Further studies of largely convective protoplanets are needed. They may offer a way to form giant planets on timescales short compared to the 10^6–10^7 year disk lifetime, over a range of semi-major axes, and hence have applicability to some extra solar giant planets (Ruzmaikina 1998, Ikoma *et al.* 2001, Bodenheimer *et al.* 2001, Mayer *et al.* 2002).

Core Formation Timescales

In the original Safronov (1969) version of the planetesimal theory the late stages of "oligarchic growth" resulted in formation times for the giant planet cores comparable to the age of the solar system. Lissauer (1987) gave a possible accretion scenario for the rapid formation of the giant planets by combining early "runaway" and late "oligarchic" growth and considering nebulae that are enhanced with respect to the minimum mass solar nebula. Based on many-body simulations to simultaneously determine the distribution of orbital elements of planetesimals and the growth of protoplanetary embryos, Tanaka and Ida (1999) estimate accretion times for protoplanets of mass M_p and distance a to be t_{grow} (years) $= 8 \times 10^5 (M_p/M_E)^{1/3} (a/5\text{AU})^{12/13}$.

Runaway accretion stops at the so-called isolation mass, which is typically an Earth mass in the outer solar system and a Mars mass at 1 AU. Protoplanets with masses larger than an Earth mass enter the "oligarchic" growth stage, and in the absence of gaseous accretion have much longer growth times. Kokubu and Ida (2000) estimated the total accretion times of planetary cores through runaway accretion and the late phases of oligarchic growth in the jovian planet region, using a slightly more sophisticated approach. They estimate that at 5 AU the final mass of a protoplanet accreting within 40 million years would be 5 M_E. A 9-M_E core at Saturn's position would require 300 million years. Tanaka and Ida (1999) investigated the accretion of migrating protoplanets. The "type I" migration rate due to the tidal torque associated with the disk (Ward 1986) can enhance accretion rates once the core is larger than 0.06 M_E. In a minimum mass nebula a core can grow to a few M_E on a timescale shorter than the type I migration rate into the Sun. To reach a critical core mass of 10 M_E in the presence of type I migration, Tanaka and Ida had to assume a surface density enhancement of a factor of five over the minimum mass nebula; the total growth time to 10 M_E was about six million years. Since such timescales are comparable to, but perhaps less than, the lifetime of the gas, they suggest that the nucleated instability model is marginally plausible from the point of view of timescale.

2.4 PRODUCTION AND PROPERTIES OF A SATELLITE-FORMING DISK DURING JUPITER FORMATION

The mechanism of gas inflow on to the forming Jupiter should have determined not only the timing of its own formation, but also the structure of a disk of gas and dust swirling around it. The presence of a disk is strongly suggested by the existence of regular satellite systems. In turn, the formation of the regular satellite systems cannot be understood without attention to the formation and evolution of Jupiter and particularly to its final phases. Recent numerical simulations of the formation of the satellite systems in the context of giant planet accretion point to the occurrence of a circumplanetary disk as a natural consequence of giant planet accretion, after the hydrodynamic collapse of the gas (Lubow *et al.* 1999, D'Angelo *et al.* 2002, Magni and Coradini 2003).

2.4.1 Models of Satellite Disks

Four conceptually distinct models for the formation of satellites from a disk have been enumerated (Pollack *et al.* 1991). In the *accretion disk* model, the satellite-forming disk is derived directly from solar nebula gas entering the region around the planet. Under the assumption of solar composition for the gas, the mass of the disk must have been initially equal to 0.1–0.2 M_J , where M_J is the mass of Jupiter today. This may not be true at the time of formation of satellites when most of the gas may have vanished from the subnebula. The *co-accretion* model forms a disk as solar nebula planetesimals collide within the planet's gravitational sphere of influence. This disk would have been dominated by solids rather than gases, and the composition of planetesimals embedded in the subnebula must have obviously been similar to that of planetesimals present in the nebula around 5 AU and at the end of the formation of Jupiter. In the *spin out disk,* the disk was formed from the outer parts of the planet's envelope being left behind as the planet contracted. This model has been proposed by Korycansky *et al.* (1991). The authors obtained a disk that exhibits a mass and angular momentum comparable with observed values. However, the angular momentum of Jupiter is different from that observed today, and further, it is difficult to understand how silicates could be delivered to the forming satellites in the context of this model. The *blow out disk* model invokes an impact by a large planetesimal ejecting material to form a disk. This model has been successful in explaining the presence and bulk properties of a satellite system around Uranus coplanar with the planet's equator (and which has a very large obliquity relative to the solar system's invariable plane)(Stevenson 1986). However, it does not appear to lead to the kind of compositional gradient in satellite-building material consistent with the Galilean satellite system (see below), and has not been presented in the literature as a mechanism for forming Jupiter's largest moons.

2.4.2 Accretion Disk Models

The progressive enrichment of water in the Galilean moons moving outward from Io to Callisto has long prompted modelers to assume a temperature gradient in the subnebula surrounding Jupiter. Lunine and Stevenson (1982) then elaborated a detailed model of the jovian subnebula in which the temperature decreases adiabatically from the planet outwards at least to Callisto. In their model, water does not condense at planetocentric distances of Io and Europa but condenses at the distances of Ganymede and Callisto. This is a static disk, with no mass inflow or viscous radial transport. Prinn and Fegley (1981) also proposed an adiabatic temperature density model for the nebulae of Jupiter and Saturn, especially with the goal of interpreting the composition of the atmosphere of Titan, which was found by *Voyager* to be mainly made of molecular nitrogen and methane. The weakest point of the models of Prinn and Fegley (1981) and of Lunine and Stevenson (1982) is that their temperature density profiles are not valid for a subnebula in which the angular momentum would be transported outwards by turbulent viscosity (Wood 2000). In other words, these models are not consistent with those derived from the solution of the standard equations for a turbulent accretion disk.

The cause of the turbulent instability in accretion disks is controversial, and a detailed discussion of the question is out of the scope of the paper. A simple argument however has been proposed by Mousis *et al.* (2002) who argued that Reynolds number Re is much higher than the critical value Re^* above which the flow is no longer laminar in laboratory experiments. Assuming that the radius of the subnebula of Saturn (or of Jupiter) is equal to the Hill's radius, then Re – calculated as the ratio of the angular momentum at the Hill's radius to the mean molecular viscosity – is found equal to 10^{12}. The laboratory experiments on the Couette-Taylor flow, which seem the most appropriate for astrophysical applications, suggest a Re^* value between 2×10^5 and 6×10^5 (Richard and Zahn 1999).

Makalkin *et al.* (1999) and Shakura and Sunyaev (1973) modeled a two-dimensional circum-jovian turbulent accretion disk. This is a stationary model, in which the turbulent viscosity is calculated with the so-called "α-parameterization" of Shakura and Sunyaev (1973) (see Section 2.3.1). The turbulence redistributes gas and microscopic grains in the subnebula in such a way that much of the material moves toward Jupiter while a smaller part moves outwards and increases the disk radius. Other input parameters for constructing the model are the radial accretion rate, the luminosity , and the radius of the early Jupiter. The temperature, pressure and surface density radial distribution of the models are expected to reproduce the mass of the Galilean satellites, the absence of water ice in Io, the low water content in Europa, and the high water content in Ganymede and Callisto (see Section 2.2.4). However, Makalkin *et al.* (1999) were not able to find a model satisfying simultaneously the water content distribution in Galilean satellites and the minimum disk mass derived from the total mass of these satellites. Disks that are more massive would not have permitted the condensation of water at the present location of the Galilean satellites.

Coradini *et al.* (1995), Coradini and Magni (1997), Magni and Coradini (2003) have elaborated a 3-dimensional code in order to study the accretion of Jupiter from the gas instability around the core up to the end of accretion when the final mass of the planet is achieved (see Section 2.3). The formation of the satellites through an accretion disk is then, in their model, a natural consequence of the formation of the planet. This approach provides a large-scale description, in which regions comparable in size to the Hill radius are considered. Angular momentum considerations suggest that the gas flowing into the Hill sphere forms a high optical depth disk around the protoplanet, in agreement with the conclusions of Lubow *et al.* (1999), and of D'Angelo *et al.* (2002). The disk is partitioned into an inner and outer disk. The transition region between the inner disk and the outer one can be characterized by the presence of shock waves, when the gas velocity overcomes the local sound velocity. The position of the transition region depends on the mass of the planet.

The outer region of the Jupiter subnebula, a kind of flattened cloud surrounding the planet and gravitationally bound to it, feeds the inner region, and hence determines the overall characteristics of the inner disk through the mass input on to the disk's external boundary. In the outer zone, it is assumed that a polytropic gas law approximates the gas equation of state. The inner zone of the circumplanetary nebula is where regular satellites were formed. Here, the equilibrium between mass in-fall to the planet and mass motions in the disk can be assumed, and mass in-fall rate depends on the gas viscosity. The model of subnebula is a 2-D stationary α-disk, as described by Coradini and Magni (1984), derived from the solar nebula model of Lynden-Bell and Pringle (1974).

The main characteristics of the subnebula have been published by Coradini and Magni (1997) and by Magni and Coradini (2003). These authors demonstrated that the core of Jupiter could not accrete the mass directly but that a disk should be formed beyond a certain distance that depends upon the mass assumed for the feeding zone. The process of formation resulting from their calculations is as follows: at first rapid accretion and consequent thermal effects cause the planet to expand, extending its atmosphere far beyond the present orbits of the Galilean moons; subsequently, accretion diminishes, the planet cools and undergoes a slow contraction until it reaches its present radius; at the end of the slow accretion, the planet attains its present radius and angular momentum while a disk of material, gravitationally bound to the planet, is left. It is possible, although not certain, that this is the disk within which the Galilean satellites formed. The model generates a specific angular momentum of the disk comparable to the present angular momentum of the satellites. Coradini and Magni (1997) calculated that the radial temperature in the subnebula out to 30–40 jovian radii is higher than that of vaporization of water ice. Moreover, it clearly appears that most of the mass of the disk resides far beyond the present position of the Galilean satellites. This suggests, as initially proposed by Coradini *et al.* (1989), that planetesimals which formed the satellites migrated inwards from the outer region of the subnebula.

Mousis *et al.* (2002) derived a turbulent evolutionary model of the subnebula of Saturn, derived from the 1-D analytical model described in Dubrulle (1993) and in Drouart *et al.* (1999), and which can be applied to the study of the evolution of the subnebula of Jupiter. The simulation begins toward the end of accretion, when the mass of Jupiter was close to its value today. The model is calculated for an initial accretion rate of 8×10^{-8} jovian masses per year, for a radius of the nebula equal to the Hill's radius of Jupiter, namely $R_D = 704\, R_{Jup}$, where R_{Jup} is for Jupiter radius, and for $\alpha = 4 \times 10^{-4}$. The initial mass of the disk is then equal to $10^{-3} R_{Jup}$. The accretion rate is assumed to decrease following the power law of Makalkin and Dorofeeva (1991), a questionable assumption at this point. Under these conditions, the accretion timescale of the disk is equal to 21 000 yr.

The radial profiles of temperature, pressure and surface density of this model decrease with time. The water ice never vaporized at distances greater than $170\, R_{Jup}$, and the snowline front reached Ganymede (at $15.1\, R_{Jup}$) and Callisto (at $26.6\, R_{Jup}$), at $t = 1.55 \times 10^6$ yr and $t = 3 \times 10^6$ yr, respectively, after Jupiter reached its present mass. So, late in the history of the subnebula, the mass within 15 or 25 R_{Jup} was obviously much smaller than the total mass of the Galilean satellites. Mousis and Gautier (2003) pointed out that this result requires that the planetesimals which formed Ganymede and Callisto, at least, were produced in the outer, much more massive part of the subnebula and migrated inward. However, they did not model this migration, and thus were not able to quantitatively reproduce the present pattern of the Galilean satellites (Section 2.2.4).

2.4.3 Co-accretion Models

Canup and Ward (2002a) proposed a model in which gas accretion on to Jupiter proceeded on a timescale that is long compared to dynamic timescales in a circum-jovian disk. The growth of satellites then occurred in the presence of the final gas inflow, at an epoch when the circumplanetary disk would then have been much less massive than the disks considered above. Canup and Ward (2002a) argued that an accretion disk produced by a low inflow of gas and solids, namely of order of 10^{-7} jovian masses per year, is most consistent with conditions needed to form the Galilean satellites. The thermodynamical properties of the "gas starved" disk were calculated as in Lynden-Bell and Pringle (1974). The model exhibits subnebula temperatures low enough to avoid vaporization of ices beyond the present location of Callisto. Satellite accretion rates are calculated to be longer than 10^5 yr. This disk has orders-of-magnitude lower gas density than that of a minimum satellite mass subnebula, and thus a low gas-to-solids ratio. In fact, the final stages of growth occur in a relatively gas-free and low-pressure environment.

The radial temperature profile of the "gas starved" model becomes isothermal (with $T = 150\,$K) at distances beyond 40 R_{Jup}. This is a consequence of the assumption that the model is stationary. In fact, the solar nebula continuously cooled, and at some epoch, the temperature of the outer nebula at 5 AU must become substantially lower than 150 K (Hersant *et al.* 2001). In the end stage of the subnebula, when the accretion rate becomes negligible, temperature and pressure at the subnebula edge must be equal to the local temperature and pressure of the solar nebula. At 10 to 15 millions of years (see Section 2.3.1), gas disappeared from both the nebula and the subnebula.

2.4.4 Comparison of the Models of Jovian Satellite Formation

From a dynamical point of view, the "gas starved" disk of Canup and Ward (2002a) is the most detailed and appears to be the most plausible. (See also the recent work of Mosqueira and Estrada 2003a,b.) However, the study of the chemistry of the subnebula of Jupiter requires the elaboration of an evolutionary model, presumably turbulent. Note that the chemistry of the system of Saturn is much more constraining than that of the Jupiter system, because models must explain the composition of the atmosphere of Titan, mainly made of N_2 and of CH_4, as attempted by Mousis *et al.* (2002) from an evolutionary turbulent model. The *Cassini-Huygens* mission is expected to provide tests for the origin of Titan (Mousis *et al.* 2002). Canup and Ward (2002b) have also applied the "gas starved" model to the case of Saturn, which is challenging from the point of view of dynamics, because Titan overwhelmingly dominates the total system mass.

The approach and the conclusions of Magni and Coradini (2003) and of Mousis and Gautier (2002) are not in conflict with the "gas starved" model of Canup and Ward (2002a), when the temporal evolution is taken into account. All models are consistent provided it is assumed that Galilean satellites were formed late in the history of the subnebula, when the accretion rate and the surface density of gas were low. All of the models seem most compatible with the nucleated instability model of the formation of Jupiter; the rapid collapse and disruption of the surrounding nebula inherent in the gravitational disk instability model would seem to mitigate against the formation of a regular system such as the Galilean satellites.

Perhaps the most important result of the analysis of Canup and Ward (2002a) is that grains that finally led to the formation of Galilean satellites appear to have originated from the local solar nebula around 5 AU. This suggests that landers deposited at the surface of Ganymede and Callisto could provide information on the nature of grains or planetesimals embedded in the solar nebula.

2.5 CONCLUSIONS

A cursory reading of this chapter might suggest to some that little progress has been made in our understanding of the origin of Jupiter, and in particular, that two rather different models are still viable candidates as formation mechanisms. In fact, both the interior modeling and compositional data have proceeded to the point where we can probably rule out the gravitational disk instability mechanism in favor of the nucleated instability mechanism for Jupiter, and by reasonable extension, for Saturn. And advanced numerical techniques coupled with fast computers have made it possible to more quantitatively model the details of formation, as well as the coupled process of the assembly of satellites. But in parallel with these advances, the detection of over 100 extrasolar giant planets has created a new conundrum. Are these bodies the result of the same formation process that created Jupiter and Saturn, an essentially "planetary formation" that involved the accretion of solids prior to and throughout the relatively slow capture of gas? Or are these bodies the low-mass end of a stellar formation mechanism in which direct disk collapse rapidly produces dense self-gravitating clumps throughout the disk, some destined for ejection, others to survive the resulting disruption of the massive disk?

In part the answer depends on the significance one attaches to the semi-major axis and eccentricity distributions of the orbits of extrasolar giant planets: are these a reflection of post-formation migration or are they the fossil record of where instabilities occurred in the disk itself? The answer may have to await compositional studies of these still-mysterious extrasolar jovian mass bodies, and it may be that both formation mechanisms are in play around other stars.

Though the basic formation mechanism for Jupiter may not be in doubt, important ambiguities remain. The timescales for planetesimal growth and the formation of heavy element cores remain poorly understood. The source region(s) for the solid material that contributed the heavy element enrichment in Jupiter is unclear. The two endmember candidates – cold, distant and primitive remnants of the molecular cloud versus material condensed locally around Jupiter – each carry with them their own set of questions and problems. Determining the deep abundance of the most important non-hydrogen/helium element, oxygen, will help resolve this issue. Still troubling, with respect to Jupiter's composition, is the apparent contradiction between the measured under-abundance of helium in the atmosphere and the lack of evidence for helium differentiation from interior models constrained by the gravitational moments. The explanation in the past for contradictions of similar ilk has been substantial uncertainties in the equation of state of hydrogen and helium at high pressures. These certainly remain, though a steady stream of experiments and models are slowly providing a better understanding of the behavior of these dense exotic fluids. At the same time, the interpretation of the *Galileo* noble gas data will remain tainted by the possibility that selective fractionation of the elements in the metallic phase has altered the measured atmospheric values relative to the bulk abundances; for various reasons it may be more difficult to obtain experimental data relevant to addressing this problem.

Modern computational power and commensurate techniques provide a remarkably detailed picture of the accretion of gas during the formation of Jupiter, and as well seem to suggest that the formation process indeed leaves gas behind in a form, and with an angular momentum, appropriate to the formation of regular satellites. But the most plausible formation mechanism for the Galilean satellites, one that explains their basic properties, requires that the source of the satellite-forming disk be solar nebula material, and that the addition of this material to circum-jovian orbit be gradual. The hydrodynamical modeling of the accretion of Jupiter, of the evolution of the surrounding nebular environment, and of the formation of satellites – all separate efforts – seem to be pointing in promisingly parallel directions, but the highly desirable coupling of these to each other and to the details of the chemistry probably will have to await the next generation of enhanced computational power and speed.

Future spacecraft missions to Jupiter should be designed to measure the deep oxygen abundance, by probes or sensitive microwave remote sensing, as well as extend the determination of the shape of the gravitational field to sense the presence of a large heavy element core. Direct sampling of comets to better quantify the abundance of molecular nitrogen and other key indicators of volatile composition should come from the ESA *Rosetta* mission. Close study of Saturn's Galilean-sized moon Titan will provide chemical constraints on the composition of the primitive volatiles that supplied the atmosphere. This information constrains the extent to which Titan was formed of solar nebula versus subnebula-processed material, a test of the Canup and Ward formation model extended to Saturn. But there is no substitute, in the comparative planetology of the giant planets, for deep probes into Saturn, Uranus and Neptune in order to compare against the results for Jupiter.

For extrasolar giant planets, the prospect a decade from now of moderate-resolution optical and infrared spectroscopy from planned 20- to 30-meter ground-based telescopes and the James Webb (Next Generation) Space Telescope makes it possible to contemplate comparing the planet's heavy element abundance to that of its parent star, and hence constraining the formation mechanism (Lunine 2001).

Models of the formation of giant planets have always had the reputation of being complex, and delicately dependent on assumed initial conditions. Indeed, on this basis giant planets were once accused of being rare. They *are* complex, as agglomerations of gas and solids, much more so than terrestrial planets. But rare they are not – and their existence, their variety, their origin or origins, deserve solid physical explanations.

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APPENDIX: DEFINITIONS

In this appendix we present the definition of various parameters used in the literature to define the helium abundance, and corresponding values in Jupiter from *Galileo* measurements (von Zahn *et al.* 1998).

Helium mole fraction $q(\text{He})$ = ratio of He atom number density to total atom and molecule number densities

Jovian $q(\text{He}) = 0.1359 \pm 0.0027$

Abundance ratio R of helium (He) relative to hydrogen = ratio of He atom number density to H_2 molecule number density

Jovian $R = 0.157 \pm 0.003$

Ratio $R_{\rm m}$ of helium mass density over the sum of helium and hydrogen mass densities

Jovian $R_{\rm m} = 0.238 \pm 0.005$

Helium mass fraction Y = helium mass density over the total mass density

Jovian $Y = 0.234 \pm 0.005$ (assuming a 1.9% contribution of all elements other than H and He)

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