4

Formation and early evolution of Io

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The Galilean satellites – Io, Europa, Ganymede, and Callisto – form a relatively closely spaced, coplanar, prograde set of bodies of similar mass orbiting in Jupiter's equatorial plane. As such they must have formed from a dissipative disk of gas and/or dust in orbit around Jupiter. The heavily cratered surface of Callisto, the outermost moon, implies that this formation took place early in Solar System history. Beyond these fundamental facts there is little universal agreement. Nevertheless, spurred by new *Galileo* results for Jupiter and its satellites, progress has been made in detailing possible satellite formation and evolution scenarios. The leading model for the formation of the Galilean satellites posits inflow of gas and solids across a tidal gap in the solar nebula, once Jupiter has itself formed in the "core accretion" model of giant planet formation. This leads to a relatively low-mass ("gas-starved"), circum-Jovian accretion disk, in which Io and the other satellites accrete slowly while the gap exists, and are not lost due to gas drag or tidal torques. The composition of Io, aside from any late accreting ice, is predicted to be essentially solar. Tidal decay of Ganymede's orbit in the proto-satellite nebula could have allowed it to capture Europa and then Io into the Laplace resonance. Such an outside-in formation sequence, if true, would reverse the long-standing view that the Laplace resonance was formed from the inside-out later in Solar System history, and implies that the strong tidal heating of Io could be primordial.

4.1 FORMATION OF JUPITER AND THE GALILEAN SATELLITES

Any model for the formation of Io and the other Galilean satellites must start with the formation of Jupiter. The leading model for giant planet formation in our Solar System is the two-stage *core accretion–gas capture* model: formation of a massive ice–rock–gas core by coagulation of planetesimals in the solar nebula followed by an accelerating gravitational capture of a massive gas and dust envelope from the solar nebula (Mizuno, 1980; Stevenson, 1982; Bodenheimer and Pollack, 1986; Pollack *et al.*, 1996; Inaba *et al.*, 2003; Alibert *et al.*, 2005a; Hubickyj *et al.*, 2005; Klahr and Bodenheimer, 2006; Lissauer and Stevenson, 2006). The alternative gravitational instability model proposes that the solar nebula was sufficiently gravitationally unstable that a massive clump or subcondensation collapses directly, forming a giant gaseous proto-planet (Cameron, 1978; Boss, 2002; Mayer *et al.*, 2004; Durisen *et al.*, 2006). But, what do these different models for giant planet formation predict for satellite formation? In this chapter I follow the path posed by this question. I first review previous (pre-*Galileo*) work on giant planet satellite formation (Section 4.1.1), pausing long enough to update constraints on Io's time of formation (Section 4.1.2). The major focus of present research is on accretion disk models, and these are discussed in detail in Section 4.2. The implications for Io's composition and initial thermal state, especially in the case of slow-inflow, "gas-starved" accretion disks, are taken up in Section 4.3. Finally, I summarize how these new results may change our view of Io's long-term evolution (Section 4.4), and offer some concluding remarks (Section 4.5).

4.1.1 Classes of satellite-forming disks

As reviewed by Pollack *et al.* (1991), giant-planet satellite formation models have traditionally broken down into four classes (cf. Lunine *et al.*, 2004). In the *accretion disk* model, a circum-Jovian disk forms as solar nebula gas and entrained solid particles (dust to boulders) flow through the Roche lobes to feed the growing Jupiter during the rapid (runaway) gas-capture phase of the core accretion model (Coradini *et al.*, 1989; Pollack *et al.*, 1996; cf. Bate *et al.*, 2003; D'Angelo *et al.*, 2003a; Papaloizou and Nelson, 2005). In the *spinout disk* model, a circum-Jovian disk forms after gas capture terminates and the distended, hot Jupiter cools and contracts, stranding material in orbit in order to conserve angular momentum (Korycansky *et al.*, 1991; Magni and Coradini, 2004). A *blowout* or impact-generated circum-Jovian disk is also conceivable, but the requisite super-giant impact must not have perturbed Jupiter's obliquity (3°) by much, which is unlikely a priori (Canup and Ward, 2002). Finally, collisions of solid bodies within Jupiter's Hill sphere could have formed a gas-free *co-accretion* disk (Safronov *et al.*, 1986).

The accretion disk model was conceived in terms of the runaway growth of Jupiter. Jupiter's proto-planetary envelope is greatly distended as this phase initiates, but as the nebular gas supply reaches some maximum value the proto-planet contracts and gas accretes hydrodynamically into the collapsing proto-Jupiter (Lissauer and Stevenson, 2006). The runaway persists as long as there is gas in the vicinity of proto-Jupiter's orbit, but may last no longer than $\sim 10^4$ to 10^5 yr (Hubickyj *et al.*, 2005). Any circum-Jovian disk left after the end of this hydrodynamic phase should be better thought of as a spinout disk. Such a spinout disk is seen explicitly in the final thermal contraction phase of Magni and Coradini's (2004) 3-D numerical hydrodynamical model of Jupiter's formation by core accretion–gas capture (their fig. 15). An actual accretion disk, and one that can form satellites, requires late-inflowing gas containing sufficient angular momentum

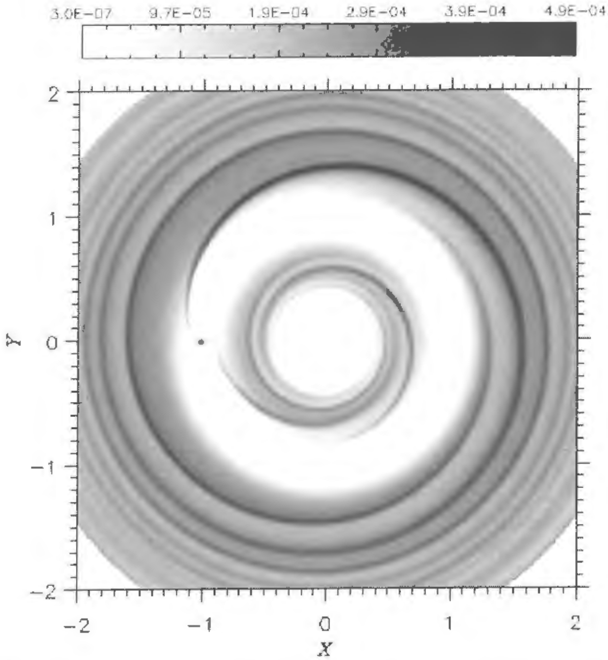

Figure 4.1. Global surface density around a 1 M_J planet orbiting a 1 M_{Sun} (solar mass) star at 5.2 AU and embedded within a low-mass disk (equivalent to 0.01 M_{Sun} within 20 AU) (modified from D'Angelo *et al.*, 2003a). In this numerical simulation, kinematic disk viscosity ν does not follow the α-model prescription, but is instead a constant $10^{15}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ (dynamically cold); the equivalent Shakura–Sunyaev α is near 10^{-2}. Scale bar indicates surface density, with 10^{-4} corresponding to $33\,\mathrm{g\,cm}^{-2}$.

for a centrifugal force balance at orbital distances compatible with satellite formation, and after proto-Jupiter has contracted to a scale of less than a few R_J (1 R_J = the current Jovian radius).

In this regard, it is now recognized that Jupiter's accretion probably did not terminate cleanly. Even if Jupiter opens a gap in the solar nebula around its orbital position, either through tidal torques or by simply drawing down the available nebular gas, inflow of solar nebula gas and dust across the gap continues, and potentially at a much reduced rate (Lubow *et al.*, 1999; Bryden *et al.*, 1999; Bate *et al.*, 2003; D'Angelo *et al.*, 2003a,b) (Figure 4.1). A low-mass accretion disk forms around Jupiter, and should last as long as the solar nebula exists to feed it (Stevenson, 2001; Canup and Ward, 2002; D'Angelo *et al.*, 2003a; Alibert *et al.*, 2005b). This is the genesis of the gas-starved disk model for the formation of the Galilean satellites (Canup and Ward, 2002, 2006) – the modern version of the accretion disk model. This model self-consistently solves or resolves a number of long-standing satellite formation issues (Stevenson *et al.*, 1986), and is discussed in detail in the next section.

The alternative, satellite formation model of Mosqueira and Estrada (2003a,b) is either a spinout or accretion disk model, depending on how one views the timing of their disk creation, but the important point is that they argue for a more massive circum-Jovian disk than do Canup and Ward (2002) (or Alibert *et al.* (2005b)), one closer to the classic minimum-mass (Jovian) sub-nebula (MMSN), wherein the rock + ice in the Galilean satellites is augmented by enough H and He gas to match solar composition (for a total of $\sim 0.02\,M_J$, where M_J is the mass of Jupiter (Lunine and Stevenson, 1982)).[1] Such a relatively massive accretion disk could in principle be created *after* proto-Jupiter contracted for a sufficient continuing inflow of solar nebula gas and dust; this is also discussed below.

It is less clear what the gravitational instability model for giant planet formation (Boss, 2002) implies for satellites. This model does not naturally account for the cores of the giant planets (particularly, that of Saturn), much less the architecture of the rest of the Solar System (Lissauer, 1993), nor is it obvious that giant gaseous proto-planets are even sufficiently long-lived to cool and contract to become bodies like Jupiter and Saturn (Lissauer and Stevenson, 2006). Still, enormous progress in numerical simulations of nebular gravitational instabilities is being made (Durisen *et al.*, 2006), so this path to giant planethood remains in play (especially in relation to extrasolar giant planets; Bodenheimer and Lin, 2002). If Jupiter formed this way, it would have formed early (within $\sim 10^3$ yr to reach the giant gaseous proto-planet stage (Mayer *et al.*, 2004)) and during its Kelvin–Helmholtz cooling phase might have created a spinout disk. Given that the solar nebula would still exist at this time, subsequent formation of an accretion disk is likely as well, and may be more relevant to satellite creation. The properties of such an accretion disk are, however, obscure at present, as no model of giant gaseous proto-planet formation has ever been taken in a self-consistent manner to this late stage.

For completeness I note that the coaccretion model for the Galilean satellites has been recently revived by Estrada and Mosqueira (2006). The principal difficulties with the coaccretion model are: (1) an adequate supply of solid bodies after the solar nebula has dispersed (given that most local solids have presumably already accreted into the giant planets), and (2) the mean angular momentum of collisionally captured material is low ($\sim$zero). Estrada and Mosqueira (2006) acknowledge that these difficulties remain, and given that there is no obvious or natural explanation for the compositional gradient among the Galilean satellites in the coaccretion model, I do not consider it further.

4.1.2 When did Io form?

I end this section by discussing the absolute time frame for Io's formation. The models of Coradini *et al.* (1989), Canup and Ward (2002, 2006), Mosqueira and Estrada (2003a,b), and Alibert *et al.* (2005b) all peg the formation of the Galilean satellites to the end of Jupiter's hydrodynamic collapse phase. In the models of Canup and Ward (2002, 2006) and Alibert *et al.* (2005b) satellite accretion is protracted, and lasts as long as the solar nebula exists. Naturally, Jupiter (and Saturn) must form while the

[1] Mosqueira and Estrada (2003b) ultimately argue for a circum-Jovian nebula depleted in gas, perhaps by an order of magnitude.

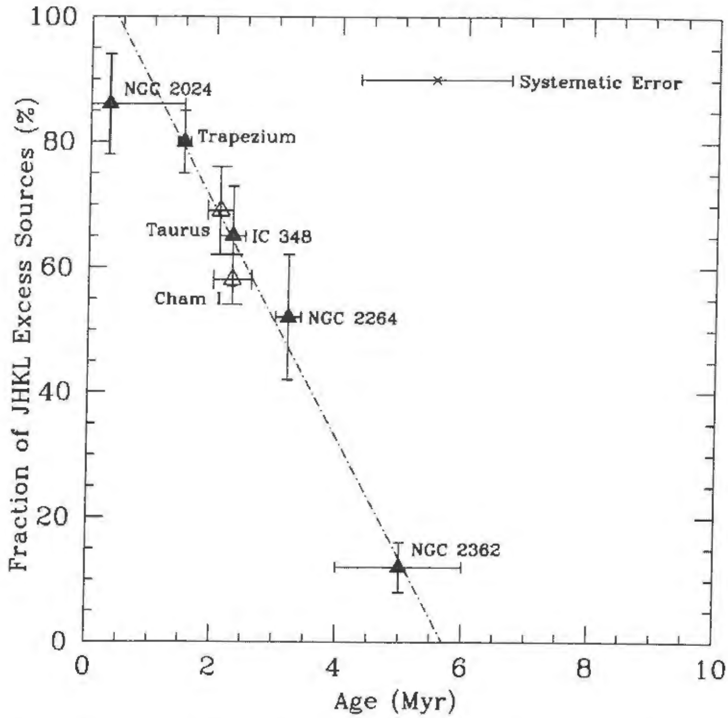

Figure 4.2. *JHKL* excess/disk fraction as a function of mean proto-stellar cluster age (from Haisch *et al.*, 2001). Disk ages depend on the spread of source ages from a single set of pre-main-sequence (PMS) model tracks. The systematic error from different PMS model tracks is indicated. The oldest cluster, at 30 Myr (not shown), had a single detected disk, for an excess fraction of $3 \pm 3\%$. The dot–dashed line is a least-squares fit to the data taken by Haisch *et al.* (2001) (filled triangles).

solar nebula exists in order for both to acquire their massive H–He envelopes. Based on the observations of young stars and disks, the lifetime of the solar nebula is generally taken to lie between a few to 10 Myr (Hubickyj *et al.*, 2005; Lissauer and Stevenson, 2006; Meyer *et al.*, 2006). Observations of infrared excesses in clusters of young stellar objects indicate that nearly all ($\geq$80%) form with optically thick circumstellar disks, and that the average lifetime of these disks is $\sim$3 Myr (Figure 4.2). Some of these "primordial" dust disks can apparently last appreciably longer, however (Hillenbrand, 2006). The observations in Figure 4.2, from Haisch *et al.* (2001), are based on near-infrared excesses (*L*-band is 3.4 μm) and are thus sensitive to hot dust close to the stars in question (within $\sim$0.1 AU). Nonetheless, the number of young stellar objects sampled is large, and age uncertainties are reduced by using stellar cluster averages. Results such as these validate earlier indicators of circumstellar disk lifetimes (Strom *et al.*, 1993), but with greatly increased confidence.

Survey results at N-band (10.3 µm), sensitive to warm (~300 K) dust in the terrestrial planet zone (~0.3–3 AU), yield similar results to Figure 4.2 (Mamajek *et al.*, 2004). Such results are now being augmented with observations from the *Spitzer Space Telescope* as well, which offers even greater sensitivity and wavelength coverage in the mid-infrared. All of these observations are consistent with a dispersion in disk lifetimes for young Sun-like stars between 1–10 Myr (Dullemond *et al.*, 2006; Hillenbrand, 2006). That is, Figure 4.2 should be thought of as a *cumulative* distribution; what we are most interested in is the underlying differential distribution of primordial disk lifetimes. The least-squares fit in Figure 4.2 corresponds to a uniform distribution of lifetimes between ~0 and 6 Myr. The "true" distribution may be more complicated, with a longer lived tail.

Direct measurement of gas abundance in primordial disks is more difficult than for dust, but observations to date are at least consistent with the above disk lifetime picture (Meyer *et al.*, 2006), and it is, of course, gas that dominates the mass of primordial disks and that is necessary to form the great bulk of gas giants such as Jupiter and Saturn (Meyer *et al.*, 2006; Hillenbrand, 2006). This observational situation will no doubt improve in the near future. Optically thick, hot and warm dust has, however, long been taken as a proxy for coexisting gas, especially as there is a close correlation of T Tauri ultraviolet excesses, a signature of disk accretion onto the central star, and optically thick hot dust infrared emission (Takeuchi *et al.*, 2005; Dullemond *et al.*, 2006; Hillenbrand, 2006; Lada *et al.*, 2006).

A final note on the stellar ages discussed here: zero is set at the stellar "birthline", as shown in the Hertzsprung–Russell luminosity–temperature diagram, where the proto-star begins its initial gravitational collapse (e.g., Sackmann *et al.*, 1993; Palla and Stahler, 1999). For the range of disk lifetimes discussed above, the formation of Jupiter, and that of Io and the other Galilean satellites, all take place while the Sun is still a PMS star, before hydrogen ignition.

4.2 THE CIRCUM-JOVIAN ACCRETION DISK

As discussed above, Io and Galilean satellites most likely formed in a circum-Jovian accretion disk supplied by inflow from the solar nebula after Jupiter formed (Coradini *et al.* 1989; Canup and Ward, 2002; Alibert *et al.*, 2005b; cf. Mosqueira and Estrada, 2003a). Figure 4.3 illustrates several key aspects of this picture. Solids and gas are delivered to circum-planetary orbit with a range of specific angular momenta such that they achieve orbit in the satellite-forming region, out to r_C (Canup and Ward, 2002). Because the gas in closer orbits moves faster than more distant gas, shear exists, and if there is viscous coupling in the gas, shear turbulence and dissipation. This causes mass to flow toward Jupiter, and angular momentum and some mass to flow outward. The model of Canup and Ward (2002) follows the classic accretion disk model of Lyden-Bell and Pringle (1974), except that the disk, or proto-Jovian nebula, is in steady-state. Mass is continuously fed into it from the solar nebula (at $\dot{M}_{\text{disk}}$), and through viscous spreading both inward and outward, achieves a steady-state distribution of surface density and temperature. Commonly, kinematic disk viscosity (ν) is parameterized by

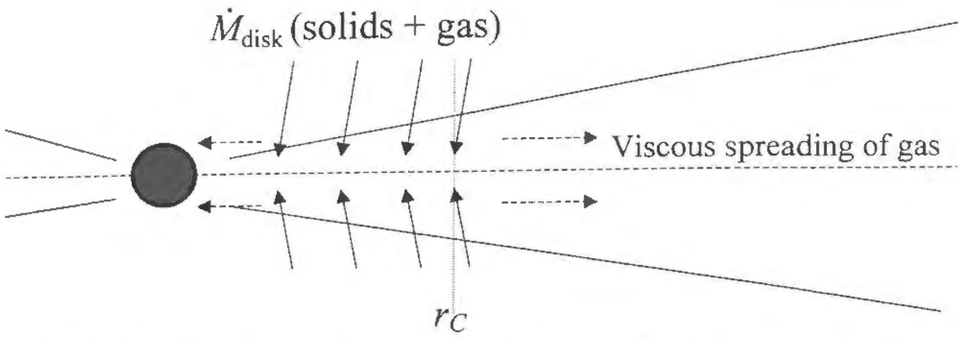

Figure 4.3. Schematic of circum-Jovian accretion disk model. $\dot{M}_{disk}$ is the flux of gas and solids from the solar nebula, which achieves centrifugal balance over the region of satellite formation ($0 \leq r \leq r_C$). Nominally, the disk spreads viscously inward and outward, and is both accreted by Jupiter and stripped by other processes beyond some outer radius (modified from Canup and Ward, 2002).

the Shakura–Sunyaev "α model", according to $\nu = \alpha c H \approx \alpha c^2/\Omega$, where c is the isothermal sound speed at the nebular midplane, H is the nebular scale height, and Ω is the Keplerian orbital frequency. The α model is intended to represent turbulent viscosity (molecular viscosity being unimportant by many orders of magnitude), where the source and strength of the turbulence are all folded into the dimensionless α parameter. Modeling of accretion disks around stars has long suggested α values in the range between 10^{-4} and 10^{-2} (e.g., Hartmann *et al.*, 1998; Stone *et al.*, 2000; Dullemond *et al.*, 2006), but the appropriate values for circum-planetary disks are much less constrained. Potential sources of turbulence include thermal convection when the disk is optically thick, mechanical instabilities driven by infall from the solar nebula, and magnetorotational instabilities when the disk is thin enough that galactic cosmic rays partially ionize the gas (this requires surface densities $\leq 10^2\,\mathrm{g\,cm^{-2}}$ (Dullemond *et al.*, 2006)).

Temperatures in the proto-Jovian nebula are set by the energy balance between heating due to proto-Jupiter's luminosity, the potential energy of infalling matter, viscous dissipation within the disk and illumination from the background solar nebula, and radiative cooling from the disk photosphere (Coradini *et al.*, 1989; Canup and Ward, 2002). Viscous dissipation proves to be dominant in the energy balance and in determining disk surface density, so the choice of α and $\dot{M}_{disk}$ is crucial. Figure 4.4 illustrates the disk surface density and temperature profile for the "nominal" steady-state model of Canup and Ward (2002). For this model $\alpha = 5 \times 10^{-3}$, the disk opacity K is $10^{-4}\,\mathrm{cm^2\,g^{-1}}$ (i.e., H–He gas opacity only), and the infall rate is $2 \times 10^{-7}\,M_J\,\mathrm{yr^{-1}}$. This is an example of a "gas-starved" nebula. The surface density σ, when integrated to its outer truncation radius, contains much less mass than the MMSN, whose surface density follows a function similar to:

$$\sigma = 1.2 \times 10^6 (5.9\,R_J/r)\,\mathrm{g\,cm^{-2}} \tag{4.1}$$

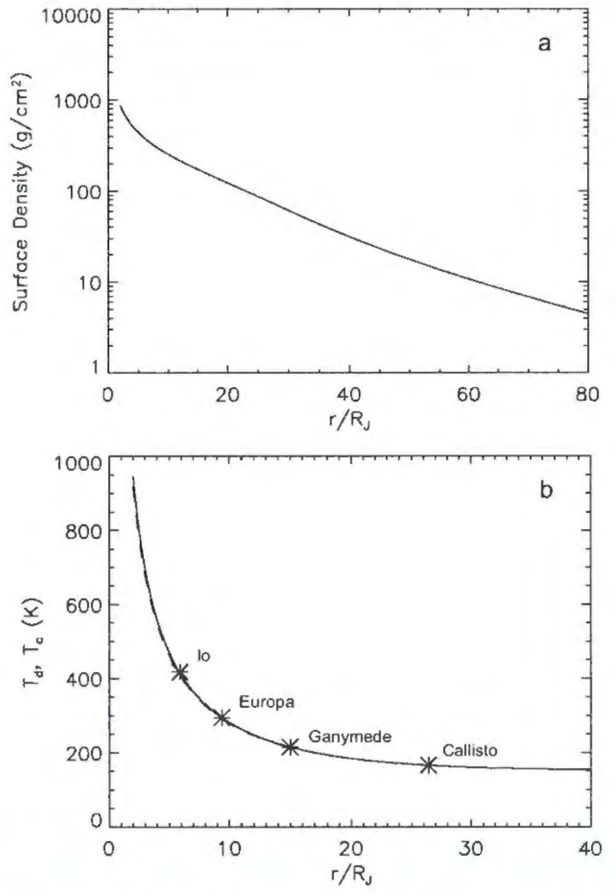

Figure 4.4. Steady-state (a) surface density σ, and (b) temperatures for a slow-inflow ($2 \times 10^{-7}\ M_J\ \mathrm{yr}^{-1}$), low-opacity ($10^{-4}\ \mathrm{cm}^2\ \mathrm{g}^{-1}$) circum-Jovian accretion disk (modified from Canup and Ward, 2002). The disk is optically thin, so the disk surface temperature (T_d, dashed) and midplane temperature (T_c, solid line) are equal. The present positions of Io and the other Galilean satellites are indicated.

(e.g., Mosqueira and Estrada, 2003a), where r is radial distance. A MMSN ($\sim 2 \times 10^{-2}\ M_J$) is processed through the gas-starved disk in Figure 4.4 every 10^5 yr, however, so as long as the condensable solids can accrete along the way, and be retained in orbit, Io and the Galilean satellites can form on this timescale. This is the deeper meaning of the MMSN, not simply the instantaneous mass distribution, but the minimum mass that has passed through the disk in its lifetime (cf. Lissauer, 1993). I note that at this stage in Solar System history the solar nebula is probably several million years old, so the ratio of gas to solids in the infalling material is likely to be *non-solar*. If so, the MMSN, when seen as integrated through time, could be larger or smaller than its nominal value.

4.2.1 Advantages of the gas-starved disk scenario

The gas-starved disk model solves a number of long-standing timescale issues with the proto-Jovian nebula (Stevenson *et al.*, 1986; Canup and Ward, 2002):

(1) In the MMSN, the Kelvin–Helmholtz cooling time of the disk, $\sim 10^3\,\sigma K$ yr, is several $\times 10^4$ yr at minimum and much longer than the Safronov accretion time of the Galilean satellites (of order 10–10^3 yr; cf. Shoberg, 1982). This leads to problems of rock-rich satellite survival (see below). For the gas-starved disk, the cooling times are $\ll 10^3$ yr, so the extent of condensation is essentially set by the steady-state temperature (Figure 4.4(b)).

(2) In the MMSN the gas drag timescale for small bodies in the solid-rich, disk midplane to drift inward and be accreted by Jupiter is short, $\sim 10^3 \times (R_s/1\text{ km})$ yr, where R_s is the body radius (Stevenson *et al.*, 1986), and the orbital decay time for individual large satellites is little better, $\sim 10^3 \times (R_s/2{,}000\text{ km})$ yr (Canup and Ward, 2002). In the slowly cooling MMSN, early (rock-rich) and later generations of planetesimals could be lost, although Mosqueira and Estrada (2003a) argue that gas drag actually assists the accretional growth of small bodies and allows them to reach sizes where gas drag induced drift is not important. In the gas-starved disk, gas drag timescales are much increased, and the peril mitigated.

(3) Large satellites' orbits also migrate inward because of angular momentum transfer by disk tidal torques (type I decay), or if they are sufficiently massive as to open a gap in the circum-Jovian disk, inward migration follows the viscous spreading of the disk (type II decay). Type I decay in the MMSN is rapid, $\sim 10^2$ yr for a Galilean satellite (Canup and Ward, 2002). Type II decay is slower, $\sim 10^4 \times (10^{-3}/\alpha)$ yr, but the ability of even Ganymede to open a gap is marginal unless α is low ($<10^{-3}$) (Canup and Ward, 2002). Thus, unless the MMSN disk viscosity is sufficiently low, it is unlikely that early rock-rich satellites could have survived long enough for ice condensation and accretion. In contrast, for the gas-starved disk Type I decay times are greatly increased (by ~ 3 orders of magnitude), so satellites can potentially survive over much of the gas-starved disk lifetime, and type II decay need not be invoked.

If the gas + solids inflow rate is markedly increased over that in Figure 4.4, to $\sim 10^{-4}\,M_J\,\text{yr}^{-1}$, the steady-state disk surface densities increase, but for α in the 10^{-4} to 10^{-1} range, disk temperatures are much too high for water ice condensation in the region of the Galilean satellites, and even silicate condensation in the Io region becomes problematic (Coradini *et al.*, 1989; Canup and Ward, 2002, their fig. 4). Temperatures are even higher if grains contribute to the opacity, as opposed to gas opacity only. Such a fast-inflow accretion disk corresponds to Jupiter at the time of runaway gas accretion or immediately thereafter (Section 4.1) (Coradini *et al.*, 1989; Mosqueira and Estrada, 2003a; Bate *et al.*, 2003; D'Angelo *et al.*, 2003a). To condense and accrete the Galilean satellites, such a thick, hot disk must first cool (Coradini *et al.*, 1989; Mosqueira and Estrada, 2003a), which returns us to the epoch of slow (and diminishing) inflow from the solar nebula.

To create (or maintain) a circum-Jovian accretion disk with a mass comparable to the MMSN requires a low α, so that the disk does not spread viscously too rapidly and accrete onto Jupiter. If the disk is to have "reasonable" temperature structure (i.e., one that predicts ice condensation near Ganymede or Callisto's formation region), then α must be very low, $\sim 10^{-6}$ or less (essentially inviscid) (Lunine and Stevenson, 1982; Canup and Ward, 2002). Mosqueira and Estrada (2003a) in fact use such a MMSN model with an assumed temperature profile to "predict" α values in the 10^{-6} to 10^{-5} range in the Io to Ganymede region, with the temperatures maintained against radiative losses to space by very weak viscous dissipation.

Such a very low viscosity MMSN would necessarily be long-lived, with a viscous lifetime of 10^6 to 10^7 yr. From points (2) and (3) above, any satellites then formed would almost certainly have been lost to Jupiter via gas drag or type I decay. In this case the only hope for Io and the other Galilean satellites would be gap opening and type II decay, which would proceed on the same extended viscous timescales. This is the scenario advocated by Mosqueira and Estrada (2003b). Canup and Ward (2002) counter that the presence of Galilean-sized satellites themselves generates, through density–wave interactions, an effective $\alpha \gg 10^{-6}$, and thus a correspondingly more rapid type II orbital decay. Mosqueira and Estrada (2003b) maintain, in a complex argument, that density waves launched by Ganymede may "clear" the sub-nebula inside its orbit, thus stranding all three inner satellites, Io, Europa, and Ganymede (though how viscous evolution of the inner disk and type II decay are avoided in this case is unspecified).

On balance, the above physical arguments strongly indicate a preference for the gas-starved accretion disk origin for Io and the Galilean satellites, as opposed to formation in a more massive, MMSN. There seems little doubt that an accretion disk forms about Jupiter after it opens a gap in the solar nebula (e.g., D'Angelo *et al.*, 2003a,b). Jupiter's final growth is likely processed through such a disk, but ultimately, the inflow must abate as the solar nebula "reservoir" is depleted by: (1) growth of Jupiter and Saturn; (2) viscous accretion of the inner solar nebula onto the Sun; and (3) photoevaporation or other "T Tauri" loss processes. Io and the other Galilean satellites must have formed in this waning stage of *solar* nebula evolution.

The partially differentiated structure of Callisto also provides an independent argument for prolonged accretion ($>$ a few $\times 10^5$ yr) of the Galilean satellites, which is consistent with the gas-starved disk model (Canup and Ward, 2002), and discussed in Section 4.3.2. Mosqueira and Estrada (2003a) prefer to argue an independent accretion scenario for outermost Callisto. Given that Ganymede and Callisto are so similar in orbit, density, and mass, however, it would seem more economical, if not preferable, to seek a common origin for both, and indeed for all four Galilean satellites.

4.2.2 Time-varying disk models

Strictly speaking, the model of Mosqueira and Estrada (2003a,b), like that of Lunine and Stevenson (1982) before it, is not an accretion disk model at all, but a static, passive disk. The model of Canup and Ward (2002) is a true accretion disk, but because its parameter space is explored in terms of a constant inflow from the solar nebula, the model is stationary or steady-state. Inflow from the solar nebula onto the circum-Jovian disk must have declined with time, however, and ultimately stopped when the solar nebula itself vanished. The consequences of such a time-evolving inflow have been recently explored by Alibert *et al.* (2005b) and Canup and Ward (2006). Alibert *et al.* (2005b) begin by assuming that the declining inflow, $\dot{M}_{\rm disk}$, is given by:

$$\dot{M}_{\rm disk} = \dot{M}_{\rm disk,0}(1 - t/\tau) \tag{4.2}$$

where $\dot{M}_{\rm disk,0} = 9 \times 10^{-7}\, M_{\rm J}\,{\rm yr}^{-1}$, $\tau = 5.6 \times 10^{5}\,{\rm yr}$, and the choice of $t = 0$ is arbitrary. Figure 4.5(a, b) shows the surface densities and temperatures obtained in their disk as a function of time, for a "fiducial" constant α of 2×10^{-4}. Alibert *et al.* (2005b) chose this relatively low α to satisfy some very simplified satellite decay and compositional arguments, but for the purposes of this review these calculations can simply be taken as an interesting counterpoint to those in Figure 4.4.

The model of Alibert *et al.* (2005b) is a "gas-starved" disk model, as can be seen by comparing (4.1) with Figure 4.5(a). A key physical difference, however, between this model and that of Canup and Ward (2002, 2006) is that in Alibert *et al.* (2005b) the inflow accretes to the outer boundary of the disk, here at 150 $R_{\rm J}$ (0.2 × the Hill radius), is viscously processed, and ultimately accreted by Jupiter. Thus, Io and the other Galilean satellites are presumed to accrete and migrate inward over rather great distances. Details of satellite accretion and survival are not developed in Alibert *et al.* (2005b), though, and it is not obvious why a more extended regular satellite system would not form from such an extended disk, reaching out to the prograde irregular satellites.[2] In contrast, in Canup and Ward (2002, 2006), infalling material is delivered to the inner part of the circum-Jovian accretion disk (Figure 4.3), where the solids locally accumulate into larger bodies, and it is the solid-depleted residual gas that spreads viscously into the extended disk. At the time of writing, unfortunately, the pattern of inflow near Jupiter is not well resolved (D'Angelo *et al.*, 2002, 2003a,b; Bate *et al.*, 2003), and both quasi-vertical infall (Figure 4.3) and quasi-Keplerian midplane inflow may turn out to be important for satellite-forming accretion disks.

The temperature evolution in Figure 4.5(b) is worth comment. By $t = 0.4$ Myr, about one MMSN (0.02 $M_{\rm J}$) worth of infalling matter remains to be accreted, and one may suppose that Io and the Galilean satellites more or less formed from this final solar bequest. Yet at 0.4 Myr temperatures everywhere in the disk exceed the condensation temperature of water ice (~175 K in the outer disk), which may make accreting sufficient ice in the satellites difficult. The high temperatures are a consequence of using high, interstellar dust based opacities for the disk ($K \geq 1\,{\rm cm}^2\,{\rm g}^{-1}$ (Alibert *et al.*, 2005a)). Coagulation almost certainly reduces the contribution of grain opacity in the proto-Jovian nebula, however (Podolak, 2003). The temperatures reached after infall ends (at 0.56 Myr in this model; after which the disk is "allowed" to viscously expand outward while it continues to accrete to Jupiter),

[2] This criticism applies with even more force to the model of Mousis and Gautier (2004), which provides neither sufficient mass to build the Galilean satellites nor a mechanism for them to migrate to their present positions.

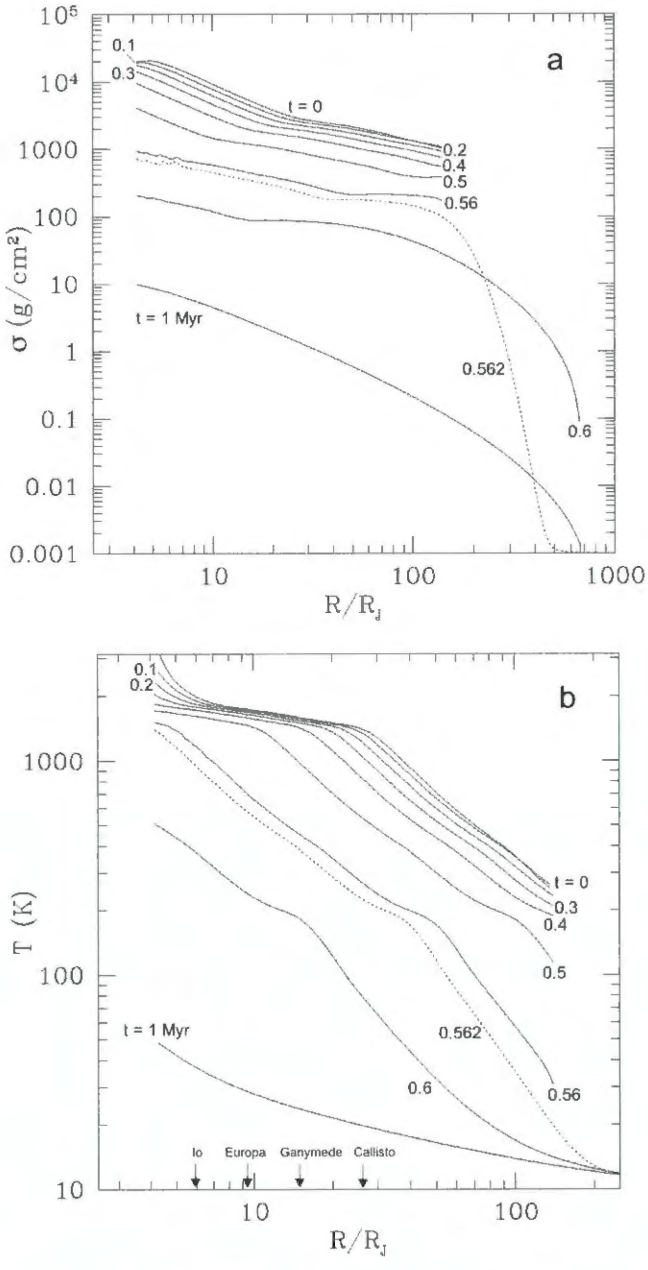

Figure 4.5. (a) Surface densities and (b) midplane temperatures for a declining inflow ($< 10^{-6}\,M_J\,\mathrm{yr}^{-1}$), high-opacity ($\geq 1\,\mathrm{cm}^2\,\mathrm{g}^{-1}$), circum-Jovian accretion disk (modified from Alibert *et al.*, 2005b). In both panels, the dotted line refers to 2,000 yr after 0.56 Myr (the epoch at which outward diffusion of the disk begins). The present positions of Io and the other Galilean satellites are indicated.

are in contrast rather low (<50 K). This model neglects the early luminosity of Jupiter, which is important for Io, and is set in the context of a very cold solar nebular background. These points are returned to below.

The gas-starved accretion disk model of Canup and Ward (2002, 2006), and the related model of Alibert *et al.* (2005b), are clear advances; they illuminate a path forward in understanding the accretion of Io and the Galilean satellites. Important matters requiring further rigorous attention are the inflow rate to the circum-Jovian disk, its strength, time history, and specific angular momentum (the latter especially, as it determines the radial scale of disk), the origin of disk viscosity, and the myriad details of disk structure and satellitesimal formation and aggregation. The latter is a focus of the most recent work by Canup and Ward (2006), in which multiple generations of satellites are formed, and it is only the final set of large satellites of Jupiter that survive type I orbital decay, as the modeled solar nebula inflow rate declines exponentially.

4.3 ACCRETION OF IO

4.3.1 Composition

I turn now specifically to the composition of the building blocks that originally made up Io. I do this in the context of the gas-starved accretion disk models above. A fundamental inference is that the solids that ultimately built Io were fed into the circum-Jovian accretion disk from solar orbit. Thus, their initial chemistry is one characteristic of planetesimals near the orbit of proto-Jupiter, as opposed to materials from the terrestrial planet zone, the inner asteroid belt, or the more distant comets (e.g., Schubert *et al.*, 2004). Logically, the closest analogs to, or survivors from, this primordial planetesimal population are the dark, reddish asteroids of the outer asteroid belt and Trojan clouds, specifically the P- and D-type asteroids (Gradie *et al.*, 1989). In detail, not much is known about these asteroid types.[3] Based on remote sensing it is presumed that they are largely similar to the C-type asteroids of the main asteroid belt and grossly chemically and mineralogically similar to the carbonaceous chondrites that are thought to come from the C-types, but more primitive (see below).

Only one meteorite has been proposed as possibly coming from a P- or D-type asteroid, the Tagish Lake carbonaceous chondrite, which fell in Canada in 2000 (Brown *et al.*, 2000). Hiroi *et al.* (2001) proposed the link based on spectral similarities in the visible and near-infrared, and analysis of the fireball trajectory indicates an aphelion of 3.3 ± 0.4 AU (Brown *et al.*, 2000), compatible with origin on a P-type parent body at least. Tagish Lake is a breccia at all scales; its major component is a fine-grained, opaque matrix of phyllosilicates, sulfides, and magnetite, surrounding aggregates of olivine, pyroxene, other minerals and inclusions (Zolensky *et al.*, 2002).

[3] Indeed, the D-type asteroids may have largely been dynamically injected into cis-Jovian orbits at a later epoch in Solar System history (Morbidelli *et al.*, 2005; H. Levison, pers. commun., 2006).

Low-temperature aqueous alteration is pervasive but incomplete, and the carbon abundance is high (~4 wt%; Brown *et al.*, 2000), with "record levels" of preserved interstellar materials (Zolensky *et al.*, 2002). All of these characteristics are consistent with an origin far from the Sun.

The mineralogy of Tagish Lake is also consistent with what is inferred spectrally for P- and D-type asteroid surfaces. Although historically the red visible–near-infrared spectral slope of these asteroids has been ascribed to some "ultracarbonaceous" material (e.g., Gradie *et al.*, 1989), Cruikshank *et al.* (2001) and Emery and Brown (2004) have shown that anhydrous mafic silicates such as pyroxene, in combination with a neutral absorber such as carbon black, better reproduce the major spectral features. The 3-μm hydration feature, characteristic of phyllosilicates, is not seen in absorption for these asteroid types, and this has long been interpreted as implying that the surfaces of P- and D-type asteroids are dominated by anhydrous as opposed to hydrous and hydrated silicates (Jones *et al.*, 1990; Lebofsky *et al.*, 1990; Rivkin *et al.*, 2002). Cruikshank *et al.* (2001) and Emery and Brown (2004) are careful to point out that up to 10–40 wt% phyllosilicates may be present on these asteroid surfaces (depending on the asteroid), but be spectrally undetectable (the neutral absorber suppresses the 3-μm band). In this interpretation of P- and D-type asteroids, anhydrous nebular condensates and interstellar materials are accreted together with water and other ices at Jupiter's distance from the Sun, but water ice melting and aqueous alteration were limited in extent (Jones *et al.*, 1990; Lebofsky *et al.*, 1990).

A key aspect of primitive carbonaceous chondrite mineralogies, such as those represented by Tagish Lake, is that in terms of refractory solids, metal, and silicates, the elemental abundances are essentially solar (Brown *et al.*, 2000; Lodders, 2003). As meter-scale and smaller boulders of such composition follow the gas inflow into the circum-Jovian accretion disk (Canup and Ward, 2002, 2006), they should encounter shocked regions (Lubow *et al.*, 1999; D'Angelo *et al.*, 2002, 2003a). The effects of these shocks on the entrained solids has not been studied, but heating and mechanical disruption are possible outcomes. Accreting onto the circum-Jovian disk at or near the position of Io in the model of Canup and Ward (2002) would subject the solids to temperatures sufficient to vaporize any ices and dehydrate most hydrated silicates (e.g., serpentine breaks down above 250–300 K at midplane pressures near Io's position in the model in Figure 4.4 (Fegley, 1999)). Most organics would also be lost (Nakano *et al.*, 2003), along with associated volatile sulfur compounds.[4] If much higher temperatures are encountered, as in the model of Alibert *et al.* (2005b) or calculations of D'Angelo *et al.* (2003a), then all (or nearly all) of the solar nebula solids should vaporize and subsequently recondense as the circum-Jovian nebula cools.

What solids should condense from a hot circum-Jovian nebula can be judged from the classic papers of Prinn and Fegley (1981, 1989), in which thermochemical equilibrium calculations in a solar-composition gas were combined with kinetic or rate considerations. Further elucidation of gas–grain reactions can be found in Fegley

[4] A "pristine" frozen sample of Tagish Lake gave off a sulfurous odor when allowed to warm to room temperature (Zolensky *et al.*, 2002).

(1999). It turns out that even the gas-starved disks exemplified by Figures 4.4 and 4.5 are denser, higher pressure disks than classic solar nebula models (e.g., Lewis, 1974), meaning that pressures are higher at a given temperature (by up to two orders of magnitude). (They are, of course, lower pressure environments than the minimum mass giant planet sub-nebulae examined in detail in Prinn and Fegley (1981, 1989).) In this circumstance, the corrosion of Fe alloy to troilite (FeS) in the presence of sub-nebular H_2S gas remains facile at the FeS stability temperature of $\approx$710 K (Fegely, 1999). Oxidation of remaining iron to magnetite (Fe_3O_4) at $\approx$370 K is also kinetically favored. What is likely to be kinetically inhibited, and in contrast to the MMSN prediction in Prinn and Fegley (1989), is the hydration of mafic silicates to form minerals such as serpentine at still lower temperatures (see Fegley, 1999, figs. 2 and 3).

The implications for Io's bulk composition are clear. Refractory oxides, metal and silicates, whether delivered directly from solar orbit or condensed from a hot circum-Jovian disk, should have existed in *essentially solar proportions*. The sulfur abundance, as sulfide, should also have been solar, or nearly so (especially as the volatile sulfur species in Tagish Lake, for example, are likely to have been products of aqueous alteration in its parent body, and such heliocentric parent body alteration could have taken place well after Jupiter and its satellites formed).[5] Much of Io's iron metal may have accreted as magnetite – an oxide – although it should be recognized that much if not all of the magnetite in Tagish Lake (and other carbonaceous chondrites) is a product of low-temperature aqueous alteration as well (Zolensky *et al.*, 2002), and so might not have yet formed within solar-orbiting planetesimals near Jupiter at the time of Io's accretion. Such early aqueous alteration would depend on early ice melting, which could have been driven by heating due to decay of ^{26}Al and ^{60}Fe (e.g., Grimm and McSween, 1989).

In contrast, Io is likely to have been initially carbon-depleted compared with solar abundances, owing to elevated temperatures in the Io-forming region, although retention of some refractory organics and/or graphite is likely (Prinn and Fegley, 1989; Nakano *et al.*, 2003; Lodders, 2003, 2004). It would also be a challenge for Io to acquire much bulk water. Even if the gas-starved disk model of Canup and Ward (2002) in Figure 4.4 is adopted (as a cool end member), infalling icy (or merely "wet") planetesimals should be heated and lose much of their water before accretion into the growing satellite. This dehydration may have been less than 100% effective, however, especially for larger solar planetesimals that may have been directly captured by gas drag into the circum-Jovian disk (Canup and Ward, 2002; McKinnon and Leith, 1995). If Io had accreted from completely hydrated silicates, it would upon differentiation have formed an ice shell of comparable thickness to Europa's (McKinnon and Zolensky, 2003). This seems an unlikely prospect for Io, but there is the question of ice accretion in the cooling sub-nebula model of Alibert *et al.* (2005b). From

[5] I note that the solar sulfur abundance of primitive carbonaceous chondrites (Lodders, 2003) is in itself fatal to the diffusive drawdown argument of Pasek *et al.* (2005), for depleting nebular H_2S in the region of the main asteroid belt.

Figure 4.5(b), there is at least the possibility of a thin ice veneer forming on Io at late times in the circum-Jovian disk.

The black-body temperature (T_e) of a flat disk (adequate for the argument that follows) in equilibrium with proto-Jupiter's luminosity (L_{PJ}) is given, following Chiang and Goldreich (1997), by:

$$T_e \approx \left(\frac{2}{3\pi}\right)^{1/4}\left(\frac{R_{PJ}}{a}\right)^{3/4} T_{PJ} \tag{4.3}$$

where R_{PJ} and T_{PJ} are the proto-Jovian radius and black-body temperature, respectively, and a is Io's distance from the planet. T_{PJ} can be simply scaled from $(L_{PJ}/L_{Sun})^{1/4}(R_{Sun}/R_{PJ})^{1/2}T_{Sun}$, where L_{Sun}, R_{Sun}, and T_{Sun} are the Sun's present luminosity, radius, and effective temperature, respectively. For $a = 5.9\,R_J$, $R_{PJ} = 1.6\,R_J$, and $L_{PJ} = 10^{-6}\,L_{Sun}$ (the baseline model in Hubickyj *et al.* (2005)), $T_e \approx 115$ K, too low to prevent ice condensation *at the midplane* unless the disk is substantially optically thick. If proto-Jupiter's luminosity following envelope collapse is, however, $\sim 10^{-5}\,L_{Sun}$ (Burrows *et al.*, 1997; Fortney *et al.*, 2005), then $T_e \approx 200$ K, and water-ice condensation may be prevented at Io's position. Pending resolution of the issue of Jupiter's early luminosity, the question of minor ice accretion onto Io remains open. A late, final "frosting" of ice in the Io region could also account for the inferred but otherwise enigmatic iciness of Amalthea (Takato *et al.*, 2004; Anderson *et al.*, 2005).

Regardless, this calculation also makes clear that the long-held idea that Jupiter's early luminosity is responsible for the compositional gradient of the Galilean satellites (Kuiper, 1952; Pollack and Reynolds, 1974) may not be correct. Viscous dissipation is probably more important than Jovian insolation in determining disk radial temperature structure. Figures 4.4 and 4.5 illustrate this point. An additional luminosity source is the boundary layer between the circum-Jovian disk and proto-Jupiter (Papaloizou and Nelson, 2005), as close-in orbiting material "brakes" from Keplerian velocity to the slower equatorial rotation speed of proto-Jupiter. This luminosity, $\approx \dot{M}_{disk}M_J/2R_{PJ}$, is of order $10^{-5}L_{Sun}$ for slow inflow/accretion rates of $10^{-7}\,M_J\,\text{yr}^{-1}$ (i.e., Figure 4.4), but how important this geometrically confined luminosity source is for the rest of the disk is not obvious.

In this overall context, it is also worth noting that the temperature of the Io-forming region of the circum-Jovian disk probably cannot be supported by the background solar nebula radiation bath either. While classic analytical solar nebula models (e.g., Lewis, 1974) propose temperatures near 150 K, close to the present-day solar insolation temperature at Jupiter (~120 K), modern accretion disk models obtain lower temperatures near 5 AU (see, e.g., Wood, 2000). An extreme example is the solar nebula model of Hersant *et al.* (2001), where midplane temperatures evolve with time and drop below 20 K at 5 AU after 5 Myr of viscous evolution, and the effect of a comparable nebular boundary condition can be seen in Figure 4.5(b) (cf. Bell *et al.*, 1997).

Sophisticated proto-planetary disk models, which incorporate heating by dissipation *and* the central star (missing in Hersant *et al.*, 2001), dust evolution, and vertical *and* radial radiative transport, support a more nuanced view (D'Alessio *et al.*, 1999, 2001). The latter models, for 0.5–$M_{\rm Sun}$ T Tauri stars, consistently show midplane temperatures near ~60 K at Jupiter's present position, even for very low accretion rates onto the star. While similar models for a 1–$M_{\rm Sun}$ T Tauri star would no doubt lead to modestly higher temperatures, the position of the circum-Jovian accretion disk within the solar nebula is also important. Nestled deep within the gap in the solar nebula opened by Jupiter, the satellite-forming disk would find itself plunged into shadow; no direct solar radiation would reach the disk (D'Angelo *et al.*, 2003a), and the background solar nebula would no longer fill 4π steradians. The circum-Jovian disk would be exposed to space (or whatever the birth environment of the Sun was) and to ionizing cosmic radiation. Its outer boundary would almost certainly have been colder than 150 K (cf. Canup and Ward, 2002; Figure 4.4(b)), and this may ultimately play an important role in the formulation of a realistic, time-dependent, thermo-chemical accretion disk model for Io and the Galilean satellites.

4.3.2 Thermal state

Io should have accreted solid material more or less as fast as solids were supplied to its "feeding zone" within the proto-Jovian nebula, either by infall or condensation. In other words, and as discussed in Section 4.2.1, sweep-up for small bodies is rapid, and faster than overall sub-nebular evolution times in either the gas-starved (Canup and Ward, 2002, 2006) or MMSN models (Mosqueira and Estrada, 2003a). In the context of the gas-starved sub-nebula, accretion times would be long enough (set by the declining infall rate) and accreting bodies small enough (possibly m-scale) that accretional heating may be severely limited by radiative losses to space (Stevenson *et al.*, 1986). This can in principle provide the necessary cold or lukewarm start to Callisto, consistent with its present inferred state of partial differentiation (Schubert *et al.*, 2004), but obviously also implies limited accretional heating for Io as well. It also goes without saying, in the gas-starved model, that there is insufficient sub-nebular gas to form an optically thick, convective envelope about Io (Lunine and Stevenson, 1982) as it accretes.

The characteristic length scale for thermal conduction in an accreting satellite is κ/u, where κ is the thermal diffusivity of the accreted material ($10^{-6}\,\mathrm{m^2\,s^{-1}}$ is typical for solid rock) and u is the radial growth rate (McKinnon, 2002). For Io, and assuming a constant rate of *mass* accretion:

$$\frac{\kappa}{u} \sim 0.5\ \mathrm{m} \times \left(\frac{\kappa}{10^{-7}\,\mathrm{m^2\,s^{-1}}}\right) \times \left(\frac{\tau_{\rm Io}}{10^5\,\mathrm{yr}}\right) \tag{4.4}$$

where $\tau_{\rm Io}$ is Io's accretion time and a reduced $\kappa \sim 10^{-7}\,\mathrm{m^2\,s^{-1}}$ is assumed appropriate for *porous* rock + metal. Heat buried greater than this depth is *not* in good conductive communication with the accreting surface, and cannot be efficiently radiated to space as Io accretes. This estimate implies that for Io to remain cool it must accrete m-sized satellitesimals on timescales $\gg 10^5$ yr or that the accreting particles are $\ll 1$ m in scale.

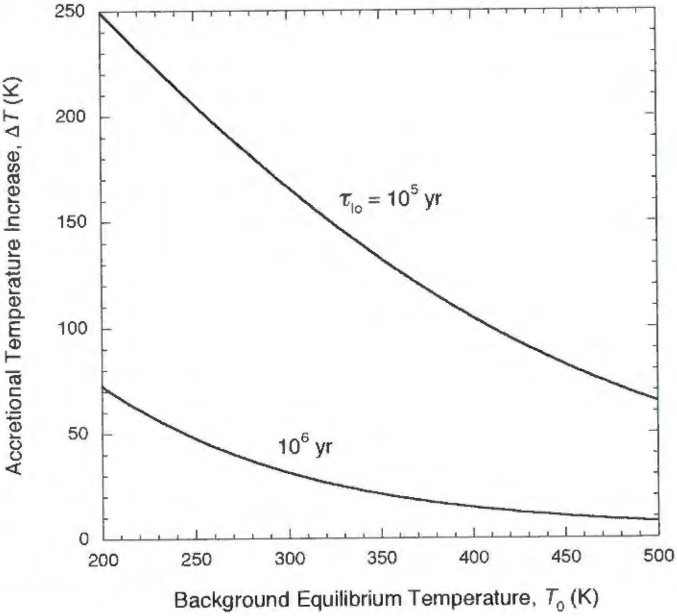

Figure 4.6. Temperature increase for Io in the limit of small satellitesimal accretion (4.5), as a function of background radiative equilibrium temperature. The contribution of satellitesimal encounter velocity is ignored, and mass accretion rate is assumed constant over the accretion time τ_{Io}.

How cool might this be? Following Stevenson *et al.* (1986):

$$T(R) = \left[\frac{1}{4\pi R^2 \sigma_{SB}}\left(\frac{GM(R)}{R} + \frac{\langle v \rangle^2}{2}\right)\frac{dm}{dt} + T_0^4\right]^{1/4} \tag{4.5}$$

where $T(R)$ is the accretional temperature profile, $M(R)$ the mass contained within a radius R, G the gravitational constant, σ_{SB} the Stefan–Boltzmann constant, $\langle v \rangle$ the mean encounter velocity, dm/dt the mass accretion rate of the satellite, and T_0 the background radiative equilibrium temperature (which for an optically thin nebula is not necessarily the nebular gas temperature). Figure 4.6 shows $\Delta T = T(R) - T_0$ as a function of T_0 for Io for accretion times of 10^5 and 10^6 yr. Note that for $dm/dt =$ constant and $\langle v \rangle = 0$ the accretional temperature increase is constant throughout the satellite. These modest to miniscule temperature increases are the smallest possible for Io. For accretion times $\leq 10^5$ yr, accretional energy dominates the background term in (4.5) over the T_0 range illustrated (e.g., for a fiducial τ_{Io} of 10^5 yr, Io's initial interior temperature is ~500 K).

If Io accreted from bodies that were larger than the limit implied by (4.4), which need be no greater than 10–100 m in diameter, then some satellitesimal kinetic energy must be trapped as heat. The fraction trapped in a symmetrically accreting uniform satellite, as a function of depth, is $hGM(R)/R$, where $0 \leq h \leq 1$ and I have again neglected the mean encounter velocity[6] (e.g., Schubert *et al.*, 1981; Stevenson *et al.*, 1986). For a characteristic rock + metal STP heat capacity of 920 J kg^{-1} K^{-1} (Kirk and Stevenson, 1987), accretional temperature increases in Io's outer layers could have reached $\approx 350\,\mathrm{K} \times (h/0.1)$. The factor h is empirical, and can in principle be determined by detailed calculation, but an upper limit near 0.1 is obtained by requiring ice melting in Callisto to be restricted to that body's outer layers (Schubert *et al.*, 1981).

Although the total gravitational potential energy of Io's assembly is more than adequate to melt it, its prolonged accretion in the gas-starved circum-Jovian nebula and a likely bias toward smaller satellitesimals probably limited its initial interior temperatures to $\lesssim$800–900 K (assuming accretional conditions similar to those illustrated in Figure 4.4 and some buried beat). While non-trivial (e.g., serpentine breaks down at pressure in this temperature range; McKinnon and Zolensky (2003)), such temperatures fall short of the Fe–FeS eutectic melting temperature ($\approx$1,250 K), at which point downward percolation of iron sulfide melt occurs, and formation of a metallic core begins.

The presence and characteristics of Io's core deserve some comment here. The density and moment of inertia determined by *Galileo* imply the existence of a substantial metallic core within Io (see the detailed review by Schubert *et al.*, 2004). Internal structural models can further constrain the properties of this core, and the surrounding mantle, subject to unavoidable assumptions of composition, chemistry, and temperature. For example, by modeling Io as a pure olivine mantle surrounding a solid Fe–FeS core, Sohl *et al.* (2002) find Io's bulk Fe/Si ratio to lie between 1 and 1.25 for solid mantles and between 1.25 and 1.5 for partially molten ones. Kuskov and Kronrod (2001) found, by basing mantle chemistries on chondritic meteorites and assuming plausible but uniform core densities, that Io's Fe/Si ratio probably lies within the 0.8–1.2 range, and that Io overall is most compatible with an L- or LL-chondrite composition. Obviously, these two works do not agree in detail on the important point of iron content. Subtle (and not so subtle) differences in modeling assumptions underlie this difference, but both conclude that Io's Fe/Si ratio is less than the solar value of $\approx$1.7 (Lodders, 2003).

There is, however, no obvious way to fractionate iron from rock in the context of the gas-starved accretion disk model, given the continuous input of solar-composition "feedstock". Temperature is obviously important for strongly tidally heated Io, and if one allows for a molten core and a full solar abundance of S, then it is *possible* to construct internal models of Io with higher, if not solar Fe/Si (McKinnon and Desai, 2003). In this case Io's core would be relatively large ($\sim$1,000 km in radius) and S (and possibly O) rich. Such a large, fluid interior would serve to maximize tidal flexing and dissipation in the (mostly) solid mantle, for a given orbital eccentricity (e.g., Cassen *et al.*, 1982). While such a model cannot be proven by gravity data alone, it is cosmochemically compatible with the oxidation state of Io's mantle (similar to that of the

[6] Mostly for convenience, but this neglect is justifiable when the eccentricities of the accreting satellitesimal swarm are low, which obtains for very small bodies orbiting in the presence of nebular gas.

Earth's upper mantle (Zolotov and Fegley, 2000), and consistent with the early argument of Lewis (1982) that Io could not have directly formed from a metal-bearing (as distinct from sulfide-bearing) chondritic assemblage, such as L- or LL-chondrites (McKinnon, 2004)).

I end this section with a note on Io's rotational history. Peale (1977) estimated that Io would have been despun by tides raised by Jupiter from an initially rapid rotation to its present synchronous period of 1.77 d in only $\sim 5000 \times (Q/100)$ yr, where Q is the specific dissipation factor. Even with modern parameter values (density, moment of inertia, etc.), this timescale is so short for plausible Q values that it is likely that Io accreted in synchronous lock. The despinning time goes as a^6, however, so if proto-Io first formed in a more distant orbit and migrated inward (discussed in the next section), it may have despun while it was migrating and accreting.

4.4 EARLY EVOLUTION OF IO

It is fitting, in this penultimate section, to briefly discuss one of the more interesting applications of the slow-inflow accretion disk model for the formation of Io and the Galilean satellites. Io's special place in the geophysical pantheon is owed to the tidal heating that follows from the satellite's resonant orbital configuration with Europa and Ganymede – the Laplace resonance. A subject of much research, the Laplace relation has long been thought to have been a by-product of the outward tidal evolution of Jupiter's satellites. As discussed in the comprehensive review of Peale (1999), Io post-formation should evolve outward under the action of Jovian tides more rapidly than Europa, and both more rapidly than Ganymede. As Io does so, it first captures Europa into the 2 : 1 mean-motion resonance, and then the coevolving pair capture Ganymede into the 2 : 1 with Europa.

Difficulties with the required extent of orbital evolution by gravitational tides alone as well as with maintaining Io's present volcanic power prompted Greenberg (1982, 1987) to offer that Io, Europa, and Ganymede were actually evolving out of a deep, primordial resonance. There was never a concrete mechanism to account for such a primordial resonance, however, until now. Simply put, assembly of the satellites in a slow-inflow, gas-starved disk predicts inward type I migration as the satellites grow to larger and larger sizes (Canup and Ward, 2002, 2006). Ganymede is by far the most massive of the three, and as type I drift is proportional to satellite mass and nebula surface density, Ganymede can in principle migrate faster. Peale and Lee (2002) demonstrated numerically that in doing so Ganymede can capture Europa into the 2 : 1 mean-motion resonance, and then the pair can migrate fast enough to capture Io as well (Figure 4.7). Given Io's greater mass than Europa, and the arguably greater disk surface density closer to Jupiter, Io's capture into the 2 : 1 with Europa depends on it not evolving faster than Europa after Europa is captured into resonance with Ganymede. Thus, Io can run, but it cannot bide.

Io's eccentricity in Figure 4.7, as well as that of Europa, are well above current values. They are due to tidal interactions with the spiral density waves launched in the

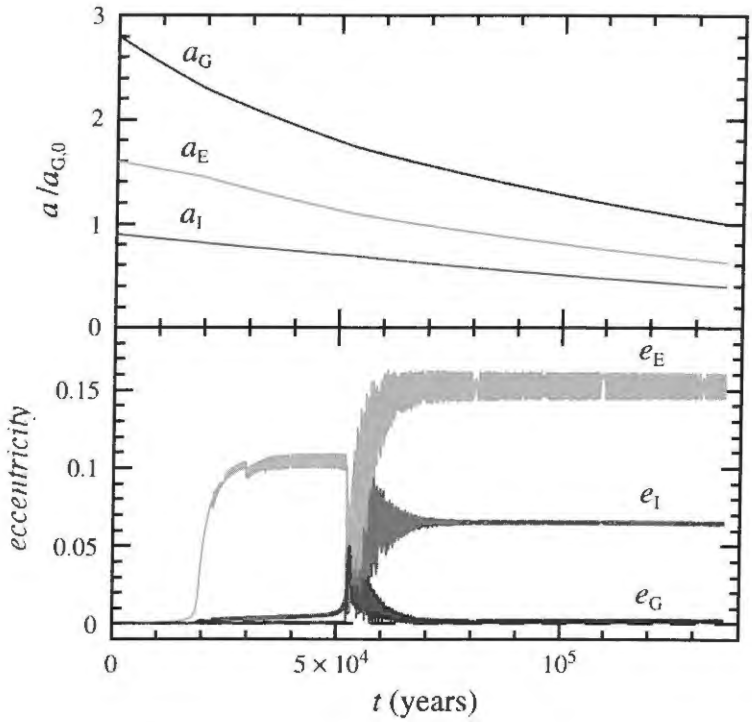

Figure 4.7. Nebula-induced evolution of the Galilean satellites into the Laplace resonance. The semimajor axes of Io (a_I), Europa (a_E), and Ganymede (a_G) are normalized to Ganymede's current distance from Jupiter, $a_{G,0}$. e_I, e_E, and e_G are the eccentricities of Io, Europa, and Ganymede, respectively. Inward migration and eccentricity-damping timescales are imposed; and the initial orbits are circular and coplanar. After circum-Jovian nebula dispersal, eccentricities are damped by solid-body tides within each satellite (modified from Peale, 2003).

circum-Jovian disk by the satellites. As the disk dissipates (i.e., as infall from the solar nebula abates), these eccentricities should begin to decline due to tidal dissipation within the satellites. Peale and Lee (2002) show that the entire system (Io–Europa–Ganymede) natnrally relaxes to its current Laplace configuration.

To some, the model of Peale and Lee (2002) may be distressing, in that it removes an attractive solution to the Ganymede–Callisto dichotomy from the playing field (see, e.g., Showman and Malhotra, 1997). Yet this primordial, outside-in assembly of the Laplace resonance is both elegant and comprehensive in its predictions. One of the latter is that Io's history of high internal temperatures and extreme volcanism is likely to have begun very early (Peale, 2003). As an illustration, the decay of Io's primordial $e_I \approx 0.063$ in Figure 4.7 to the present-day value of 0.004 would imply dissipation within Io and a minimum temperature increase of $GM_J e_I^2/2C_P a_I \approx 600$ K. This estimate is a minimum because it (1) assumes Io at its present semimajor axis, whereas Io, Europa and Ganymede have almost certainly tidally evolved outward over Solar System history (Peale, 1999); and (2) neglects any torque from Jupiter that would have acted to retard the eccentricity decay. A heat impulse of this magnitude, when added to Io's likely warm initial accretional state (Section 4.3), implies that eutectic melting and core formation started soon after the circum-Jovian nebula disappeared and accretion ended (within a few Myr). With this, Io entered the realm of enhanced tidal flexing and dissipation, which is fortunate, as both are necessary to explain its prodigious volcanic output (e.g., Schubert *et al.*, 1981).

4.5 CONCLUSION

Our understanding of the origin of Io and the Galilean satellites has evolved from early, nebulous discussions (e.g., Pollack and Fanale, 1982) into modern, quantitative analyses of accretion disk models around Jupiter (e.g., Canup and Ward, 2006). Much of this work is driven by vigorous advances in understanding star and giant-planet formation, a part of the new field of extrasolar planets. While many details remain to be worked out, it seems clear that formation of Jupiter in the core accretion–gas capture model inevitably ends with an accretion disk around the planet, and as Jupiter at some point must stop accreting gas and solids, that circum-Jovian disk must become one of the slow-inflow, gas-starved variety. Alternative models for satellite formation have and are being proposed (Mosqueira and Estrada, 2003a,b; Estrada and Mosqueira, 2006), but these have not yet been tied to models of Jupiter's formation in a direct or compelling way or necessarily account for the physical or compositional characteristics of the satellites themselves.

In fairness, the gas-starved circum-Jovian disk models to date rely on assumptions of mass and angular momentum inflow from the solar nebula that have not been robustly established. This will probably require the next generation of 3-D and thermohydrodynamic giant-planet formation models, ones that can resolve circum-Jovian disk structure within the inner 10% of Jupiter's Hill sphere ($\sim 75\ R_J$). Regardless, the slow-inflow accretion disk in principle allows satellites to grow over a protracted length of time ($>10^5$ to 10^6 yr), and in low-gas-density environment. This slows losses to Jupiter by gas drag and disk tidal torques, and provides for a cool to warm start, thus protecting Callisto from extensive melting. The latter is an important Galileo-derived constraint.

If sufficient mass is processed through the circum-Jovian accretion disk, then multiple generations of satellites may be formed and lost (Canup and Ward, 2006). The Galilean satellites then are the last generation, formed more or less from the inflow of the last MMSN worth of solar matter. Even at this late stage, the non-volatile solids that accreted to form Io and the others should be essentially solar in composition. The thermal environment at Io's formation distance is determined mostly by the subnebula itself, and should have been hot enough to largely devolatilize any small, accreting satellitesimals. At the very end of the circum-Jovian disk's lifetime, however, temperatures in the disk must inevitably fall, and late accretion of hydrated rock, or even minor ice, is not precluded.

Io traveled a great deal in its youth. It probably began accreting well outside its present position, and continued accreting while migrating inward due to disk tidal torques. The migration would have sped up once Io was captured into the Laplace resonance with Europa and Ganymede, which had been migrating inward as well, and more rapidly (Peale and Lee, 2002). Their joint orbital decay probably brought Io much closer to Jupiter than it is today while the circum-Jovian disk evanesced. Subsequently the weaker action of Jovian tidal torques slowly pushed all three satellites back outward, to their present positions, over Solar System history.

The combination of subnebular heating of inflowing solar solids, the potential energy of accretion onto Io, and tidal heating from the subnebular epoch probably pushed Io past the threshold for core formation. Once such a relatively deformable, dissipative internal structure was created, the conditions for vigorous volcanism from long-term tidal heating were assured. This early heating would have been more than sufficient to drive any and all accreted water out of Io, but the oxidation of rock and metal by water, with loss of hydrogen, was likely very important in establishing Io's overall chemical and oxidation state (e.g., Lewis, 1982).

Further work on satellite formation in a gas-starved accretion disk is likely to prove fruitful. This is, perhaps, one of the more subtle results of the *Galileo* mission. Sufficient new information, and attention, has led, perhaps for the first time, to a quantitative, believable model for satellite formation around gas giant planets.

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