

ORIGIN AND EVOLUTION OF THE NATURAL SATELLITES

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Key Words tides, dissipation, dynamics, solar system, planets

1. INTRODUCTION

The natural satellites of planets in the solar system display a rich variety of orbital configurations and surface characteristics that have intrigued astronomers, physicists, and mathematicians for several centuries. As detailed information about satellite properties have become available from close spacecraft reconnaissance, geologists and geophysicists have also joined the study with considerable enthusiasm. This paper summarizes our ideas about the origin of the satellites in the context of the origin of the solar system itself, and it highlights the peculiarities of various satellites and the configurations in which we find them as a motivation for constraining the satellites' evolutionary histories. Section 2 describes the processes involved in forming our planetary system and points out how many of these same processes allow us to understand the formation of the regular satellites (those in nearly circular, equatorial orbits) as miniature examples of planetary systems. The irregular satellites, the Moon, and Pluto's satellite, Charon, require special circumstances as logical additions to the more universal method of origin. Section 3 gives a brief description of tidal theory and a discussion of various applications showing how dissipation of tidal energy effects secular changes in the orbital and spin configurations and how it deposits sufficient frictional heat into individual satellites to markedly change their interior and surface structures. These consequences of tidal dissipation are used in the discussions of the evolutions of satellite systems of each planet, starting with the Earth-Moon system in Section 4. Additional processes such as collisional breakup and reassembly of some of the smaller satellites associated with the ubiquitous equatorial rings of small particles are discussed, although ring properties and evolution are excluded (see Nicholson 1999). There is no attempt to include technical details of published explanations of the various phenomenologies. Rather, the explanations are described and the uncertainties in the assumptions and resulting conclusions are emphasized. The

outstanding gaps in our understanding of each system are pointed out, where additional knowledge about a system or one of its parts always seems to generate more interesting problems than it resolves. This is the first time all of the satellite systems have been discussed in any detail in one place, and it is hoped that the reader will find in one or more of these systems problems to which he can apply his own expertise. The Galileo spacecraft has already uncovered some amazing properties of the Jupiter's satellites, which have shaken some of our long-held beliefs about the satellites; the Cassini spacecraft approaching Saturn promises to do the same. Let us build the context, which this and other new information will alter and refine.

2. ORIGINS

The origins of the natural satellites are of course closely linked to the origin of the solar system and the formation of planets therein. So it is appropriate to outline our current understanding and necessary speculations about solar system formation to understand the creation of the satellite systems. The origin of the satellite systems of the major planets can be understood in terms of similar processes and events, sometimes with extreme examples of some events for each system. The Moon and probably Pluto's satellite, Charon, required special circumstances within the broader set of processes that occurred during the early evolution of our planetary system.

It is generally accepted that our planetary system formed from a flat dissipative disk of gas and dust that surrounded the young Sun. The disk is the natural consequence of the collapse of a rotating cloud with angular momentum conservation, where dissipation leads to both the flat geometry and the circular orbits of the disk constituents. This general picture is observationally confirmed, since all young stars appear to have such disks of material for some part of their early existence (Strom 1995, Beckwith & Sargent 1998)—consistent with theoretical expectations. As the disk cools, nonvolatile elements and compounds will condense into small particles that settle to the midplane of the disk, where they collect into larger and larger sizes chiefly through collisional coagulation (Weidenschilling 1995). The nonvolatiles will consist of rock and iron-type materials in the terrestrial planet region close to the Sun but will include water and other ices beyond ~ 4 AU from the Sun. The latter condensates increase the solids fraction of the nebular disk by a factor of ~ 3 compared with the terrestrial zone. All of the details of the early coagulation process are not well understood, but the gravitational instabilities in a very thin disk of solid particles thought to dominate the process (Safronov 1969, Goldreich & Ward 1973, Ward 1976) apparently are completely frustrated by shear-induced turbulence and persistent velocity dispersions for the solid bodies (Weidenschilling 1995). Both the shear-induced turbulence and the persistent velocity dispersion result from the fact that partial support of the nebular gas by a radial pressure gradient causes it to orbit the Sun at an angular velocity that is

slightly less than the Kepler velocity v_K (Whipple 1972). The deviation from the Kepler velocity is typically tens of meters per second (Weidenschilling 1977). As the solid particles are not supported by the pressure gradient, they tend to orbit at v_K . Hence, all particles large enough not to follow turbulent motions in the gas will face a headwind that causes them to spiral toward the Sun at rates inversely proportional to their linear size. It is therefore crucial that the planetesimals increase in size sufficiently rapidly to avoid being swept into the Sun while the gaseous part of the disk is still present. From observations of the disks around young stellar objects, the disk lifetimes—based on the theoretical ages of the central stars from their positions on the H-R diagram—are only 10 million–30 million years (e.g. Strom 1995).

Once the particles approach kilometer size and larger, the continued accumulation depends on a gravitationally enhanced cross section for two body encounters given by

$$\pi R_g^2 = \pi(R_1 + R_2)^2 \left(1 + \frac{v_e^2}{v^2}\right), \quad (1)$$

in which R_1, R_2 are the radii of planetesimals m_1, m_2 ; v is the magnitude of their relative velocity; $v_e = 2G(m_1 + m_2)/(R_1 + R_2)$ is an escape velocity from an equivalent planetesimal whose mass is $m_1 + m_2$ and whose radius is $R_1 + R_2$; and R_g is the maximum impact parameter that results in a collision. If we assume $m_1 = m_2 = m$ and $R_1 = R_2 = R$, we can write

$$\frac{dR}{dt} = \frac{\rho v}{\rho_p} \left(1 + \frac{8\pi G \rho_p R^2}{3v^2}\right), \quad (2)$$

where ρ is the mass density in the planetesimal disk, ρ_p is the density of the planetesimals, and v is now an average relative velocity.

What is interesting about Equation 2 is that when $v_e \gg v$, $dR/dt \propto R^2$, and the growth of the largest particle would run away to dominate all the nearby planetesimals. This runaway growth requires that the relative velocity of the accreting planetesimals be small compared with the escape velocity, and ordinarily one would believe that this condition would not prevail since gravitational scattering should lead to a velocity dispersion comparable with the escape velocity. However, there will always be a size distribution with larger numbers of smaller planetesimals, and the distribution of kinetic energies will tend toward equipartition. Stewart and Wetherill (1988) have shown that for reasonable size distributions, this equipartition is sufficient to keep the relative velocities of the larger particles small compared with their escape velocities and the runaway growth will continue until a planetary embryo has consumed most of the mass within its gravitational reach ($\Delta r/r = C(m/3M_\odot)^{1/3}$, with $C = 3-4$ and r being heliocentric distance). This notion has been verified by numerical three-body accretion calculations that include the effect of the Sun (Greenzweig & Lissauer 1990, 1992) and leads to planetary embryo masses of $m = 2 \times 10^{24} (Cr^2\sigma)^{3/2}$ (Lissauer 1987) with r in astronomical

units and surface mass density of the nonvolatile fraction of the nebula σ in grams per square centimeter. For a minimum mass nebula (nonvolatile constituents of the planets distributed over heliocentric distance and augmented with sufficient hydrogen, helium, and other volatiles until solar composition is attained), planetary embryos in the Earth zone of a few lunar masses and of near an Earth mass in the Jupiter zone result. Inclusion of the effects of gas drag (Kary & Lissauer 1993) in resupplying depleted planetesimals can augment these embryo masses, as can increasing the surface mass density of the condensed part of the nebula above its minimum value. Recent N-body calculations by Kokubo and Ida (1998) arrive at somewhat larger embryos with wider separations after the runaway accretions have ceased. This latter result illustrates the continuing evolution of ideas for the accretion process. The planetesimals and embryos will consist of rock and iron in the terrestrial planet region, but, beyond 4 or 5 AU from the Sun, most of the embryo mass will consist of water and other ices while also including the refractory constituents.

In this scenario, the planetary embryos form by runaway accretion in a relatively short time ($\sim 10^5$ years), but continued growth into planetary bodies requires a much longer stochastic process [$\sim 10^8$ years (Wetherill 1990) in the terrestrial planet region], where neighboring embryos are perturbed into crossing orbits where they may collide and merge into larger bodies. Numerical Monte Carlo calculations of this process have been remarkably successful in accumulating sets of terrestrial planets that resemble the solar system distribution (Wetherill 1990, 1991, 1996), including the characteristics of the asteroid belt (Wetherill 1992). The qualitative results of these Monte Carlo calculations have been confirmed with numerical calculations using a modification of a symplectic integrator (Wetherill & Chambers 1997).

Because Jupiter and Saturn contain a higher fraction of heavy elements than does the Sun, their formation in a two-stage process by the accretion of a massive core of the solid material with subsequent accretion of the gas onto this core is argued. However, for a minimum-mass solar nebula it takes too long to accumulate the required $10\text{--}15 M_{\oplus}$ core, and the nebula is gone before the gas can be attracted and held. This conclusion depends on the estimates of nebular lifetimes about young stars of 10 million–30 million years being correct and applying to the solar nebula. The necessary core can form quickly enough as an embryo by runaway accretion if the surface mass density of the nebula is increased by a sufficiently large factor over the minimum mass nebula as demonstrated by Lissauer (1987) and incorporated by Pollack et al (1996) in their scheme to form Jupiter. Although Pollack et al obtain the accretion of a complete Jupiter, including the gaseous part, several of the assumptions, such as maintenance of a very large gravitationally enhanced accretion cross section throughout the core formation, and neglected phenomena, such as the major scattering of the Jupiter core by nearby embryos of comparable size, mean that the two-stage formation of Jupiter and Saturn is still not convincingly demonstrated.

Boss (1997, 1998) has reopened the possibility that Jupiter and Saturn actually formed very quickly by a gravitational instability in the gaseous disk. In this case, a

problem remains in supplying a sufficient amount of heavy elements through later accretion of solid planetesimals. Also, the perturbations by full-sized Jupiter and Saturn would stir the planetesimal disk sufficiently to hinder the runaway growth that created the large embryos needed for the successful modeling of terrestrial planet formation. Some also question whether the nebula could be simultaneously cool enough and dense enough for Boss's conditions of gravitational collapse to be met. (Toomre's 1964 Q factor must indicate instability.) We must conclude that there has been no robust method demonstrated for the formation of Jupiter or Saturn within observational constraints.

Uranus and Neptune apparently formed their cores more leisurely since the nebula was by then too thin to contribute much gas to their bulk. Still, core formation at this distance from the Sun requires $>10^9$ years in a minimum-mass solar nebula (Stewart & Levison 1998), so perhaps these planets should have received less gas than is apparent.

The remaining problems with planet formation aside, however the major planets formed—either by the two-stage process or by gravitational instability—the material going into these planets would have had significant angular momentum relative to the center of mass of the forming planet. For Jupiter and Saturn, the ultimate spin of the planet is determined largely by angular momentum contributed by the gaseous component. Neptune and Uranus accreted a relatively small fraction of their mass as hydrogen and helium and the terrestrial planets, essentially none. So the planetesimal accretion determined the angular momenta of these planet-satellite systems. Each accreting planetesimal contributes part of its angular momentum to the spin and part to the orbit of the combined planet-planetesimal mass, the relative contributions being determined by the details of the collision. Thus, both the magnitude and the direction of the spin vector undergo random walks as the accretion progresses, where the magnitude of the steps grows with the sizes of the planetesimals (Dones & Tremaine 1993). The wide scatter of planetary spin vectors testifies to the fact that the last stages of accretion involved very large planetesimals, although Mercury and Venus have had their spins altered by dissipative processes. This stage is especially dramatic for Uranus, whose spin axis is inclined by 97° relative to its orbit normal.

For Jupiter and Saturn, the cross-section for continued accretion of solid planetesimals will be enhanced by an extended gaseous atmosphere, where those planetesimals that do not plunge directly into the planet will be captured by gas drag or collisions into orbits whose eccentricities and inclinations relative to the equator plane are damped by the continued atmospheric gas drag and collisions with other orbiting debris, and the orbit semimajor axes will decrease at rates that depend on the size of the planetesimal. Even after the accretion is nearly complete and the atmosphere has continued its collapse toward the planet as it cools, any remaining debris in orbit will damp down to circular equatorial orbits. This damping can be understood by considering a hypothetical ring of orbiting planetesimals that is inclined to the equator plane of the planet. Because each planetesimal has a slightly different orbit, the orbits will precess at different rates owing to the oblate

distribution of mass in the rotating planet. The ring will tend to spread into a cylindrical distribution where collisions in crossing orbits within the distribution will remove the components of velocity perpendicular to the equator plane. Eccentricities are similarly damped by dissipative collisions. The satellitoids will then accumulate into satellites on much shorter time scales than for the analogous accretional accumulation of the planets in the solar nebula (Pollack 1985). This rapid accretion into large objects may be crucial to the survival of satellite material as the drag from the waning gaseous component of the disk causes it to spiral into the planet. The debris around Uranus and Neptune relaxed to the oblique equator planes before accumulating into their equatorial satellites. Consistent with this picture of satellite formation, the orbits of the closer satellites of the major planets are nearly circular and nearly equatorial as shown in Table 1.

The regular satellites of the major planets thus form naturally by the accretion of debris in a dissipative disk much like the process in the solar nebula leading to the planetary bodies. The irregular satellites were later captured from the remaining planetesimal swarm either by three-body interactions within the planetary sphere of influence, by collision with debris already orbiting the forming planet, or by gas drag in the extended primordial atmosphere of the forming planet. The last capture mechanism may be the least effective, since sufficient gas to capture the satellite is most probably also sufficient to cause the satellite to spiral into the planet before the atmosphere dissipates. The two families of distant irregular satellites orbiting Jupiter (one family in retrograde orbits) could be products of a disintegration in which single parent bodies were shattered either in collisions causing the captures or by later collisions with high-speed cometary bodies. Alternatively, gas drag from the extended atmosphere has been proposed for both the capture and the breakup of weakly bound parent bodies. Although the timing and the rate of atmosphere removal are critical in this scenario if the captured satellites are not to spiral into the planet, the occupancy of orbital resonances by two of the retrograde satellites implies that at least a thin atmosphere was necessarily in place at the time of their capture (Saha & Tremaine 1993). The capture of an intact satellite by tidal torques on the single first pass is possible for such a minuscule volume of the phase space of initial conditions that it most probably did not occur (see Boss & Peale 1986).

The origins of the Moon and of Pluto's satellite, Charon, require special consideration related to the large amount of specific angular momentum in each system. The origin and evolution of the Moon has understandably received more attention than has any other satellite. The analysis began with GH Darwin (1879, 1880) when he realized that the consequences of the tidal distortion of the Earth by the Moon would lead to an orbital evolution requiring the Moon to have once been very close to the Earth. Darwin suggested that the Moon formed from the outer layers of the Earth—a variation of the rotational fission type of origin elaborated during this century. Several other theories of origin have been proposed and opposed over the intervening years, including intact capture. Each variation of these theories is criticized in detail by Boss & Peale (1986), and all are rejected except formation from the debris resulting from the giant impact of a Mars-sized body (Hartmann

& Davis 1975). This idea has grown in popularity because it naturally provides the large angular momentum of the Earth-Moon system, it can easily account for the lack of volatiles and iron on the Moon if the impacting body is differentiated, and it is much more probable than any means of intact capture (Cameron & Ward 1976). The debris from a giant impact does not follow ballistic trajectories, which would automatically reimpact the Earth. Pressure gradients and the distribution of mass in the ejected debris cause accelerations after the impact that leave material in initially stable orbits. Recall that we concluded earlier that the final stages of accretion of the terrestrial planets involved planetary embryos from Moon-to-Mars size, so it is entirely reasonable that such an impact occurred.

Although the giant impact origin of the Moon has surfaced as the only viable scheme by a process of elimination, the consequences of the impact depend very much on the choices of many free parameters, such as the initial angular momentum and mass of the impactor. Large regions of the parameter space have been and are being explored numerically with various amounts of condensible silicate-like material being placed in orbit beyond the Roche radius, where it can collect into the Moon (Cameron 1997, Canup & Esposito 1996, Ida et al 1997, Cameron & Canup 1998a,b and references therein). (Inside the Roche radius, ($r \sim 2.5R_E(\rho_P/\rho_C)^{1/3} \sim 2.9R_E$) tidal forces would break apart a fluid satellite and therefore inhibit accretion.) The orbiting debris from the impact would damp down to circular equatorial orbits through collisions, where it can accrete into the Moon. For many if not most of the sets of choices of the many parameters, insufficient material ends up in orbit beyond the Roche radius. Details along the route from impact to Moon are still uncertain, so improving the resolution and reliability of the numerical calculations remains an active area of research. These processes will be discussed further in Section 4.

A giant impact is also proposed as the origin of the Pluto-Charon binary system (McKinnon 1989, Stern 1991, Tancredi & Fernández 1991), and by the same process of elimination that was applied to the origin of the Moon, this method of origin again emerges as the only viable option (Dobrovolskis et al 1997).

The two satellites of Mars are in nearly circular equatorial orbits, which supports the argument of their accretion in situ from a debris disk in the equatorial plane left over from the planet's formation—like the regular satellites of the major planets. However, the Phobos mean density was estimated to be $2.0 \pm 0.5 \text{ g/cm}^3$ from Viking orbiter data (Christensen et al 1977, Tolson et al 1978), and that of Deimos $2.0 \pm 0.7 \text{ g/cm}^3$ (Duxbury & Veverka 1978). The difference from the mean density of Mars of 3.9 g/cm^3 lends support to the suggestion that the satellites are composed of material that did not originate in the vicinity of Mars, and albedos near 5% and reflection spectra are consistent with carbonaceous chondritic material (Pang et al 1978, Pollack et al 1978). Intact capture was considered (Pollack & Burns 1977, Mignard 1981b), but Szeto (1983) showed several seemingly insurmountable inconsistencies with the capture hypothesis independent of the impossibility of relaxing the captured satellites into the circular equatorial orbits where they are found. Despite the low density and spectral indications of carbonaceous chondrite

TABLE 1 Physical properties and orbital characteristics of the satellites.^a

Satellite	R^b (km)	m (10^{20} kg)	ρ (g cm^{-3})	P_o (days)	P_r (days)	a (10^3 km)	e	i (deg)
Earth	6378	59742	5.515					
E1 Moon	1737.5	734.9	3.34	27.322	S	384.40	0.0549	5.15
Mars	3394	6418.5	3.933					
M1 Phobos	11.2	1.08×10^{-4}	1.90	0.3189	S	9.377	0.0151	1.082
M2 Deimos	6.3	1.80×10^{-5}	1.76	1.2624	S	23.463	0.00033	1.791
Jupiter	71492	1.8988×10^7	1.326					
JXVI Metis	20			0.2948	S	127.96	<0.004	~ 0
JXV Adrastea	10			0.2983	S	128.98	~ 0	~ 0
JV Almathea	90			0.4982	S	181.3	0.003	0.40
JXIV Thebe	50			0.6745		221.9	0.015	0.8
J1 Io	1821	893.3	3.530	1.7691	S	421.6	0.0041	0.040
J11 Europa	1565	479.7	2.99	3.5518	S	670.9	0.0101	0.470
J111 Ganymede	2634	1482	1.94	7.1546	S	1,070	0.0015	0.195
J1V Callisto	2403	1076	1.85	16.6890	S	1,883	0.007	0.281
JXIII Leda	5			238.72		11,094	0.148	27 ^c
JVI Himalia	85			250.5662	0.4	11,480	0.163	28 ^c
JX Lysithea	12			259.22	0.53	11,720	0.107	29 ^c

JVII Elara	40			259.6528		11,737	0.207	28°
JXII Ananka	10			631R	0.35	21,200	0.169	147°
JXI Carne	15			692R	0.43	22,600	0.207	163°
JVIII Pasiphae	18			735R		23,500	0.378	148°
JIX Sinopie	14			758R	0.55	23,700	0.275	153°
Saturn	60268		5.6850×10^6					
SXVIII Pan	10			0.5750		133.583	~0	~0
SXV Atlas	16.4			0.6019		137.64	~0	~0
SXVI Prometheus	53		0.0014	0.6130	0.27	139.35	0.0024	0.0
SX VII Pandora	43		0.0013	0.6288	0.42	141.70	0.0042	0.0
SXI Epimetheus	60		0.0055	0.6946	0.63	151.422	0.009	0.34
SX Janus	90		0.0198	0.6946	0.65	151.472	0.007	0.14
SI Mimas	198.8		0.375	0.9424	1.14	185.52	0.0202	1.53
SII Enceladus	249		0.73	1.3702	1.12	238.02	0.0042	0.02
SIII Tethys	530		6.22	1.8878	1.00	294.66	0.0000	1.09
SXIV Calypso(T-)	10			1.8878		294.66	~0	~0
SXIII Telesto(T+)	12			1.8878		294.66	~0	~0
SIV Dione	560		10.52	2.7369	1.44	377.40	0.0022	0.02
SXII Helene(T+)	16			2.7369		377.40	0.005	0.2
SV Rhea	764		23.1	4.5175	1.24	527.04	0.001	0.35
SVI Titan	2575		1345.5	15.9454	1.881	1221.8	0.0292	0.33

(continued)

TABLE 1 (continued)

Satellite	R^b (km)	m (10^{20} kg)	ρ (g cm^{-3})	P_o (days)	P_r (days)	a (10^3 km)	e	i (deg)
SVIII Hyperion	146			21.2766	C	1481.1	0.1042	0.43
SVII Iapetus	718	15.9	1.02	79.3302	S	3651.3	0.0283	7.79 ^{c,f}
SIX Phoebe	110			550.48R	0.4	12952	0.163	175.3 ^c
Uranus	25559	8.6625×10^5	1.318					
UVI Cordelia	13			0.3350		49.752	0.000	0.1
UVII Ophelia	16			0.3764		53.764	0.010	0.1
UVIII Bianca	22			0.4346		59.165	0.001	0.2
UIX Cressida	33			0.4636		61.777	0.000	0.0
UX Desdemona	29			0.4737		62.659	0.000	0.2
UXI Juliet	42			0.4931		64.358	0.001	0.1
UXII Portia	55			0.5132		66.097	0.000	0.1
UXIII Rosalind	29			0.5585		69.927	0.000	0.3
UXIV Belinda	34			0.6235		75.255	0.000	0.0
UXV Puck	77			0.7618		86.004	0.000	0.3
UV Miranda	236	0.659	1.20	1.413	S	129.8	0.0027	4.22
UI Ariel	579	13.53	1.67	2.520	S	191.2	0.0034	0.31
UII Umbriel	585	11.72	1.49	4.144	S	266.0	0.0050	0.36
UIII Titania	789	35.27	1.71	8.706	S	435.8	0.0022	0.10

UIV Oberon	761	30.14	1.63	13.463	S	582.6	0.0008	0.10
UXVI Caliban	~30			580		71.7×10^5	0.0823	139.68 ^d
UXVII Sycorax	~60			1290		122.1×10^5	0.509	152.67 ^d
Neptune	24764	1.0278×10^6	1.683					
NIII Naiad	29			0.2944		48.227	0.000	4.74
NIV Thalassa	40			0.3115		50.075	0.000	0.21
NV Despina	74			0.3347		52.526	0.000	0.07
NVI Galatea	79			0.4287		61.953	0.000	0.05
NVII Larissa	96			0.5547		73.548	0.000	0.20
NVIII Proteus	209			1.1223		117.647	0.000	0.55
NI Triton	1353	214.7	2.054	5.8769R	S	354.76		156.834
NII Nereid	170			360.1362		5513.4	0.7512	7.23 ^c
Pluto	1170	131.5	2.0					
PI Charon	586	19.0	2.24	6.3872	S	19.405	0.0076 ^e	0

^aThese data are updated slightly from Yoder 1995.

^bThe satellite radii are averages if the body is very asymmetric. See Yoder (1995) for more complete descriptions of satellite shapes, for uncertainties in the determinations of all table entries, and for the primary references.

^cRelative to the Laplacian plane.

^dRelative to the ecliptic plane of AD 2000 (P Nicholson. Private communication).

^eTholen and Buie (1997).

^fVienne & Duriez 1995. S, synchronous; C, chaotic; R, retrograde; T, Trojan.

material, the coplanar equatorial orbits indicate that these satellites must have formed from a dissipative disk of debris orbiting the planet. If that debris were indeed carbonaceous chondritic (which is not at all certain), one possible way it could have gotten into orbit about Mars would be from the shattering of such a planetesimal that was formed in the asteroid belt region of the nebula when it collided with a denser object already in orbit about Mars. The condition here would be that the pieces would have to be sufficiently small and of sufficient number to make a dissipative disk. Samples of both Phobos and Deimos would tell us if such a contrived origin were necessary. Any scheme to capture these satellites intact and bring them into their current orbits cannot survive close inspection of the assumptions involved.

Although consensus on many details is still elusive, we have plausible origins for all of the known natural satellites. It is well known that the current distribution of satellite orbits is not the initial distribution nor are even the masses and perhaps the total number the same. The larger satellites are likely to have remained intact under the bombardment of now high-speed comets or asteroid-type planetesimals, but the smaller ones may have been shattered and possibly recollected into new bodies several times in the history of the solar system. Some of the debris from such collisions remains as rings of smaller particles. The densely cratered surfaces of many of the satellites—the Moon, in particular—are testimonies to the flux of impactors after the satellites were formed.

The changes so far described have resulted from stochastic, short-time-scale events characterized by collisions. However, the most interesting changes in the satellite systems involve the orbital modifications and changes in the satellites themselves caused by gravitational tides raised on the primaries by the satellites and raised on the satellites by the primary. Angular momentum is transferred between a spinning planet and its closer satellites, causing either a reduction in the spin rate while expanding the satellite orbits or an acceleration of the spin while the orbit contracts. The direction of the transfer depends on the relative spin and orbital angular velocities. Differential expansion of the satellite orbits leads to the establishment of the many examples of orbital resonances in which the ratio of the orbital mean angular velocities is that of two small integers. The resonances are stable against further tidal evolution up to a point. Dissipation of tidal energy within the satellites has led to striking consequences. From Table 1, we see that all of the closer satellites are rotating synchronously with their orbital motion—a natural consequence of tidal evolution. But sometimes the tidal retardation of a spin leads to chaotic tumbling when synchronous rotation is unstable, as it is for Hyperion.

Several of the satellites have surfaces much younger than their age as indicated by the paucity of impact craters, which were probably erased by indigenous processes energized by tidal dissipation. Tidal dissipation may have maintained a liquid water ocean under the ice of the Jupiter satellite, Europa. It might have softened the interiors of Ganymede to account for its partial resurfacing and perhaps an interior sufficiently hot to support the observed intrinsic magnetic field (Kivelson et al 1997). The most striking consequence of tidal dissipation in a satellite remains

the remarkable volcanic activity on Io (Peale et al 1979, Morabito et al 1979, Smith et al 1979), which is the most volcanically active body in the solar system.

Whereas the dissipation in Io is ongoing, current configurations of other satellites do not imply tidal dissipation of sufficient magnitude to account for their observed resurfacing. In such cases historical configurations are inferred, in which past resonances could have forced orbital eccentricities of sufficient magnitude to cause the needed dissipation. Many of these inferred histories are uncertain; for several satellites, no history has yet been constructed that could account for current properties. Below we outline current ideas about the evolution of the satellite systems as constrained by the growing list of observational facts. There are some fascinating and unusual stories, and many of these stories are themselves evolving. We point out areas of research where plausible evolutions are still being sought to explain observed phenomenology. But first we describe briefly the most important process in this evolution—that of the tides.

3. TIDES

Every satellite or planet is distorted into a (slightly) prolate shape (i.e. exhibits a tide) by the gravitational field of another mass. The distortion is understood in terms of the gradient of the external field, where different parts of the body experience different accelerations leading to the distortion. By changing its shape, the tidally distorted body compensates the spatially varying accelerations from the external field by altering its own self-gravitational field and by internal stresses—thereby allowing the entire body to accelerate as one (See Peale 1999 for a heuristic discussion). For a spherically symmetric distribution of mass within the body acted on by the external potential, the potential due to the resulting tidal distribution of mass is proportional to the external potential evaluated at the surface. The potential decreases as $1/r^3$ outside the surface when the external potential is a second-order spherical harmonic (e.g. Love 1944). Hence,

$$V_T = -k_2 \frac{GMma_e^5}{2\mathcal{R}^5 r^5} [3(\vec{\mathcal{R}} \cdot \mathbf{r})^2 - r^2 \mathcal{R}^2], \quad (3)$$

is the dominant term in the potential at \mathbf{r} due to a tide raised by M located at $\vec{\mathcal{R}}$ or the potential at $\vec{\mathcal{R}}$ from a tide raised by m at \mathbf{r} . In Equation 3, G is the gravitational constant, a_e is the equatorial radius of the tidally distorted body, and k_2 is the potential Love number for the second-order harmonic potential. For a small satellite, k_2 is adequately approximated by its value for a homogeneous, rigid sphere (e.g. Love 1944).

$$k_2 = \frac{3/2}{1 + \frac{19\mu}{2\rho gR}} \approx \frac{3}{19} \frac{\rho gR}{\mu}, \quad (4)$$

in which μ is the rigidity, ρ is the density, g is the surface gravity acceleration, and R is the satellite radius. Because we use no other Love number, we replace the

subscript 2 with a letter symbol indicating the satellite or planet to which the Love number applies. Real planets and larger satellites are not homogeneous spheres, and k_2 must be calculated numerically as part of the solution of a boundary value problem for centrally condensed and layered planets and satellites (e.g. Alterman et al 1959).

If M and m are the same mass, then

$$\vec{\mathcal{R}}(t) = \mathbf{r}(t - \Delta t) = \mathbf{r}(t) - \frac{d\mathbf{r}}{dt}\Delta t + \dots,$$

In other words, $\vec{\mathcal{R}}$ is the position of m a short time Δt in the past relative to a coordinate system fixed in the tidally distorted body. This representation accounts for the phase lag in the response of the body relative to the tide-raising potential caused by dissipation of tidal energy. In determining the forces in the equations of motion owing to the tidal potential, one does not differentiate with respect to the coordinates $\vec{\mathcal{R}} = \mathbf{r}(t - \Delta t)$. That is, one only differentiates with respect to the coordinates of m considered as the body perturbed by the potential, not as the body raising the tide (Kaula 1964).

The dissipation parameter $Q = 2\pi E_0/\Delta E$, where E_0 is the maximum energy stored in an oscillation and ΔE is the energy dissipated over a complete cycle, is related to Δt by $\omega\Delta t = 1/Q$; ω being the frequency of oscillation of a particular term in the Fourier expansion of Equation 3 that accounts for the orbital and rotational motions. Constant Δt means Q is inversely proportional to frequency, and this formulation of the tidal interaction is entirely equivalent to the expanded form used by Kaula (1964), with Q having this frequency dependence. For numerical work, this form has the advantage of being applicable to arbitrary eccentricity and inclination of the relative orbit.

The above tidal model is about the simplest conceivable, as it is based on the assumption of an equilibrium tide justified by the fact that principal frequencies of tidal oscillations are small compared with natural oscillation frequencies of typical solar system bodies. For small tidal distortions, the distortion is proportional to the distorting force, which encourages the analogy with the harmonic oscillator. For a homogeneous solid sphere, the representation of the dissipation as a simple phase lag in the response of the body to the perturbation and the assumed frequency dependence of the dissipation resulting from constant Δt are also what results in a linearly damped harmonic oscillator. For $Q \propto 1/\text{frequency}$, dissipation vanishes for low frequency and becomes very large for high frequency. Both extremes are outside the range of applicability of the model—the former because a viscouslike creep can set in for sustained strains and the latter because inertial effects must be included in a non-dynamic analysis, and the equilibrium tide will not prevail. Showman et al (1997) invoke a Maxwell model solid, which behaves elastically for high-frequency oscillations but viscously for low-frequency oscillations. The Maxwell model has the advantage that the viscosity, and hence Q , can be given a model temperature dependence, which has profound and interesting effects in the coupled orbital and thermal evolution of Ganymede to which it is applied. For limited variation in temperature, $Q \propto 1/\text{frequency}$ seems to be appropriate for

liquids, but empirical studies of Q in Earth-like materials yield nearly constant values over many orders of magnitude in frequency (Knopoff 1964). Even though these tests do not approach tidal frequencies, constant Q is often assumed in calculations of time scales for tidal evolution. This assumption is probably a fair approximation if frequencies and properties of the planets and satellites involved do not change significantly over the time of evolution, or if the resulting time scales are so extreme that more elaborate models for Q would not affect the conclusions. We will adopt this practice in most of what follows, where the necessity for more elaborate models for the tides is pointed out where needed. One instance where traditional tidal models will probably have to be abandoned is in the determination of the dissipative properties of the giant gaseous planets, for it is becoming increasingly clear that the full dynamics of atmospheric response to the tide-raising potential must be considered (Ioannou & Lindzen 1993).

The simple tide is a poor representation of the tides in the oceans of Earth, where basins defined by the continents have sloshing periods that are comparable with those of the lunar and solar tides. The resultant tides are often far out of phase with the forcing potential. Despite this difficulty, the simple tide has been used for studies of the Earth-Moon history in hopes that the complicating effects of the oceans will average to something close to those of the simple tide. Formulating an evolutionary tidal model is difficult, since the effects of the ocean tides on lunar orbit evolution have changed in largely unknown ways as the continental configuration has changed. It is usually assumed that the tidal effective Q was larger in the past when the continents were joined. With the measured tidal effective Q appropriate to current expansion of the lunar orbit, the Moon would have been at the Earth surface less than 2 billion years ago. Attempts to invoke more complicated tidal models for the Earth have not produced qualitatively different plausible evolutions of the lunar orbit (Kaula 1969).

The phase lag in the response of the tidally distorted body results in misalignment of the tidal bulge with the body raising the tide and leads to the gravitational torque that transfers angular momentum between the spin of the tidally distorted body and the orbit of the body raising the tide (e.g. see Peale 1999). The angular phase lag in a periodic tidal oscillation is $1/Q$, and this lag leads to a geometric angle between an ideal tidal bulge and the direction to the tide-raising satellite of $1/2Q$ since the tide has a 180° geometric symmetry. The torque on a satellite in a circular equatorial orbit about a planet deduced from Equation 3 or a Fourier expansion thereof is (e.g. MacDonald 1964)

$$T = \frac{3}{2} \frac{k_2 G m_S^2 R_P^5}{a^6 Q_P}, \quad (5)$$

where the subscripts S and P refer to satellite and planet respectively, and a is the semimajor axis of the orbit. If the satellite is rotating relative to the primary, there will be a similar expression with the indices interchanged for the torque exerted on the planet. The equal and opposite torque on the tidally distorted body results

in a change in the spin angular velocity $\dot{\psi}$ at a rate given for a small satellite with constant Q by

$$\frac{d\dot{\psi}}{dt} = -\frac{45}{76} \frac{\rho n^4 R^2}{\mu Q} \text{sign}(\dot{\psi} - n), \quad (6)$$

where n is the mean orbital angular velocity (mean motion), the approximate form of Equation 4 has been used, and the moment of inertia, $2m_S R^2/5$, used is that for a homogeneous sphere.

Both the torque on the satellite by tides raised on the planet and the torque on the planet by satellite tides affect the orbital motion. However, the tidally evolved satellites will be locked in synchronous rotation, and tides raised on these satellites will not contribute to changes in the orbital angular momentum. For nearly all satellites, the spin angular momentum is such a small fraction of the orbital angular momentum that satellite effects on the orbital motion are negligible in any case. The rate of change of the orbital mean motion (mean orbital angular velocity) from the torque on an equatorial satellite in circular orbit is then (with Q_P constant) (Peale 1988)

$$\frac{dn}{dt} = -\frac{9}{2} \frac{k_P m_S}{Q_P m_P} \frac{R_P^5 n^{16/3}}{G(m_P + m_S)^{5/3}} \text{sign}(\dot{\psi} - n). \quad (7)$$

If m_S were also spinning nonsynchronously in the same sense as its orbital motion, but with nonzero obliquity (spin axis inclined relative to the orbit normal), the tidal bulge on m_S would be carried out of the orbit plane, and there would be a component of the torque perpendicular to the spin axis. Both the spin magnitude and its direction will thus change as a result of tidal dissipation. The obliquity of the spinning satellite, if initially small, would tend to increase from the tides, if the spin is fast. This behavior can be understood if we resolve the spin angular momentum into components perpendicular and parallel to the orbit plane. The tide is decreasing the magnitude of the perpendicular component at all points in the orbit, whereas it does not reduce the parallel component when that component is pointing toward or away from M . Averaged around the orbit, the fractional change in the perpendicular component exceeds the fractional change in the parallel component, and the obliquity increases. There is an equilibrium obliquity between 0° and 90° toward which the spin axis is driven where the fractional changes in the two components are the same (Goldreich & Peale 1970). This equilibrium is close to 90° for fast spins, but it decreases toward 0° as the spin is retarded. If the spin angular velocity $\dot{\psi} < 2n$, the equilibrium obliquity is 0° , so a satellite in a fixed circular orbit should approach synchronous rotation and zero obliquity simultaneously.

If the orbit is eccentric, the tidal torque averaged around the orbit vanishes at a spin angular velocity that is slightly larger than the synchronous value. From Equation 5 we see that the tidal torque on the satellite varies as m^2/r^6 . One factor of m/r^3 determines the magnitude of the tide, being the difference of $1/r^2$ forces, whereas the second factor of m/r^3 comes from the differential force on the two tidal bulges. As the maximum torque occurs at the orbit periape, the tides will

try to synchronize the spin with the instantaneous value of the orbital angular velocity at this point, which is larger than n . Satellites in eccentric orbits maintain synchronous rotation in spite of a slightly faster spin favored by the tides because much larger torques on the permanent, nonaxially symmetric distribution of mass force the long axis of such a satellite to librate about the direction to the planet when the satellite is at periaipse. It can only so librate while maintaining a spin that is a half-integer multiple of its orbital mean motion, where synchronous rotation is the overwhelmingly most common example. The spin of Mercury is locked at $1.5n$, but no satellite is in such a higher-order spin state. If the permanent deviation from axial symmetry is smaller than that induced by the tidal forces, the tides could win, and the endpoint of the evolution would be a spin slightly faster than synchronous. There is evidence that at least the surface ice layer on Europa may be rotating slightly faster than the synchronous rate (Geissler et al 1998, Greenberg et al 1998).

Tidal dissipation will persist in a synchronously rotating satellite in an eccentric orbit at a rate given by (Peale & Cassen 1978)

$$\frac{dE}{dt} = \frac{21}{2} \frac{k_S f}{Q_S} \frac{G m_P^2 n R_S^5 e_S^2}{a^6}, \tag{8}$$

where the factor $f \geq 1$ has been added to account for an increase in k_S if there is a molten core (Peale et al 1979). The tide will oscillate in magnitude as the satellite-planet distance varies, and it will oscillate in a direction relative to the coordinate system fixed in the satellite because the rotation is nearly uniform, whereas the orbital motion is not. This dissipation will tend to reduce the eccentricity e , as $e \neq 0$ is the cause of the dissipation. The spin angular momentum of the satellite is conserved because of the lock into synchronous rotation. The specific orbital angular momentum $[G(m_P + m_S)a(1 - e^2)]^{1/2}$ can thus not gain angular momentum from the satellite. The orbital energy, $-Gm_P m_S/2a$, must decrease if energy is dissipated in the satellite, and a must thereby decrease. But the conserved angular momentum means that e must also decrease if a decreases. At the same time, the tide raised on the planet by the satellite tends to increase the eccentricity. The greater tidal force on the satellite at the orbit periaipse tends to fling the satellite to a greater apoapse distance than it would have reached without the kick—thereby increasing e . The variation in the eccentricity from the two effects is (Goldreich 1963)

$$\frac{de}{dt} = \frac{57}{8} k_P n \frac{m_S}{m_P} \frac{R_P^5}{a^5} \frac{e}{Q_P} - \frac{21}{2} k_S n \frac{m_P}{m_S} \frac{R_S^5}{a^5} \frac{e}{Q_S}. \tag{9}$$

The dissipation in the satellite wins if $19k_P Q_S m_S R_S \rho_S^2 / 28k_S Q_P R_P \rho_P^2 < 1$. This situation is generally true for the giant planets, so free eccentricities of these satellites will tend to damp.

For large planets, those satellites for which the decay time constants depending on the satellite parameters (e.g. k_S, r, R, Q) are short compared with the age of the solar system, should be in nearly circular orbits and be synchronously rotating with their orbital motions with nearly zero obliquity. Table 1 shows that all the

satellites that would be expected to be synchronously rotating are doing so. Some of the orbital eccentricities are forced to significant values in orbital mean motion resonances, however, and the obliquity of the Moon is 6.67° .

The tidal evolution is toward zero obliquity if one assumes that the orbit was fixed in inertial space. The orbit of the Moon is inclined by $\sim 5^\circ$ to the ecliptic and, it precesses in a retrograde sense with a period of ~ 18 years while maintaining a nearly constant inclination. So we find that the tides are attempting to drive the spin toward an orbit normal that is itself moving. In this case the tides bring the spin to a Cassini state (named after Cassini's laws that describe Moon rotation), in which the normal to the ecliptic, the orbit normal, and the spin vector remain coplanar as the latter two precess about the first (Colombo 1966, Peale 1969). There are either two or four possible Cassini states where the spin is fixed in the precessing frame. In the latter case, state 4 is dynamically unstable, and state 3, with the spin retrograde, is secularly unstable to tidal dissipation (Peale 1974). For the Moon, only states 2 and 3 exist, with the Moon occupying state 2, where the tides would bring it from any initial state (Peale 1974). The regular satellites of the major planets are also in precessing orbits with nearly constant inclinations to the respective planetary equators. Here inclinations are so small that the Cassini state toward which the tides drive the spins have obliquities negligibly different from 0° . Iapetus is sufficiently far from Saturn that the rate of regression of the line of nodes on the orbit plane from the solar perturbation is comparable with the rate of regression of the line of nodes on the equator plane of Saturn caused by the latter's oblateness. In this situation, the Iapetus orbit maintains nearly constant inclination to a plane called the *Laplacian plane*, which is intermediate between the equator and orbit plane. This situation leads to an interesting choice of Cassini states, that we return to below. All of the larger natural satellites have their final evolutionary spin states tabulated in the work of Peale (1977).

If the planet and satellite are of comparable size, both can approach synchronous rotation and zero obliquity as the orbit expands. Once neither satellite is rotating rapidly relative to the orbital mean motion, the tides on both bodies eventually tend to reduce the eccentricity and the obliquities of both bodies relative to their mutual orbit plane. The natural endpoint in this case is a circular orbit with both planet and satellite rotating synchronously with zero obliquity. Pluto-Charon is the only known system to have reached this final state, although there is one observation of a nonzero orbital eccentricity that has not been confirmed (Tholen & Buie 1997).

Satellites approach rotations synchronous with their orbital mean motion, and their spin vectors approach one of two Cassini states with small obliquity owing to the dissipation of tidal energy within the satellite. At the same time, tides raised on the planet expand or contract the satellite orbits with corresponding changes in the spin angular momenta of the planets. These general conclusions account for much of what we observe within the satellite systems. However, there are exceptions to these rules, and complications abound among multiple satellites in the same system. Our goal is to deduce the histories that have produced the current states

of the complete systems as they have been changed by tidal evolution and, for the small satellites, by collisions. We turn to these details next for each system in turn.

4. EARTH-MOON SYSTEM

All are familiar with the one hemisphere of the Moon that is always more or less facing toward us on Earth—the most apparent example of rotation synchronous with the mean orbital motion that results from tidal dissipation according to Equation 6. If the Moon were formed at $3.5R_E$ (Earth radii), it would reach synchronous rotation in about 1 year from an initial period of 4 h ($\mu \sim 10^{11}$ dynes cm^{-2} , $Q_M \sim 100$). The Moon now occupies Cassini state 2, where the spin axis is fixed at constant obliquity in the frame precessing with the orbit in the plane defined by the lunar orbit normal and the normal to the ecliptic plane where it would have been brought by tidal dissipation from any initial configuration (Peale 1974). The spin axis is actually displaced from this Cassini equilibrium position by 0.26 arcseconds either because of tidal dissipation in the lunar mantle with $Q_M \approx 26$ or because of a possible liquid core-solid mantle interaction (Yoder 1981a, Dickey et al 1994). The unusually low value of the necessary Q_M compared with $Q \approx 100$ (Section 5) of Mars and the high seismic Q_M (Nakamura & Koyama 1982) make the core mantle interaction more probable (Yoder 1981a).

The origin of the Moon as the consequence of a giant impact on the Earth in the latter stages of the accretion process was discussed in Section 2 as the only probable means to arrive at the large angular momentum of the Earth-Moon system as well as the volatile and iron depletion in the Moon relative to the Earth. Still, the geochemistry of Earth's mantle is not thought to be consistent with this scenario (Drake 1986, Ringwood 1989), although a geochemistry-inspired alternative to the giant impact origin that satisfies the above constraints has not been forthcoming. In addition, there are sufficient degrees of freedom that geochemical inconsistencies can be decreased by altering details in the collision process. Despite any reservations from geochemistry, we assume that dynamical constraints and the gross chemical differences between Earth and Moon are sufficiently compelling consistencies for adoption of the impact origin as the most likely. A characteristic of the giant impact scenario is that the debris that is to accrete into the Moon will settle down into the equatorial plane for reasons discussed in Section 2. That the Moon must have formed in the equatorial plane of the Earth is the natural consequence of almost all of the numerical calculations synthesizing the impact (Benz et al 1986, Benz et al 1989, Cameron & Benz 1991, Cameron 1997, Cameron & Canup 1998a,b). Given sufficient material outside the Roche radius of $\sim 2.9R_E$, there is no difficulty in accreting the Moon in a very short time (Stevenson 1987, Ida et al 1997), although the drastically different points of view in these last two publications—one hot and one cold—demonstrate our lack of understanding of the phenomenology between impact and final Moon formation. In the

cold-accretion scenario, it appears that a lunar-sized object can accrete outside the Roche radius only for impacts by a body twice the mass of Mars with twice the current angular momentum of the current Earth-Moon system (Canup & Esposito 1996), although this minimum mass for the impactor can be relaxed if the impact occurred when Earth's formation was only ~ 50 to 70% complete (Cameron & Canup 1998a,b). However, continued accretion by the Moon as the Earth completes its own accretion could lead to excessive siderophile or volatile contamination of the lunar surface layers that is not observed (Stewart & Canup, 1998). The diversity of the accretion scenarios demonstrates the inadequacy of theoretical models of the impact-generated disk.

In contrast to our ignorance of many fundamental parameters for all of the other satellites, we have detailed information on the geochemistry and ages of rocks from six sites on the Moon thanks to landings during the Apollo program. The ages of the surfaces all over the Moon can then be estimated from the calibration of the crater densities at each of the visited sites. The youngest surfaces range from 2.9 to 3.9 billion years old (Warren 1985), where repeated basaltic lava flows have covered vast areas called *maria*—usually the interiors of giant impact basins such as Mare Imbrium or Mare Serenitatis. The *maria* occupy only $\sim 17\%$ of the lunar surface; the remainder (lunar highlands) is a thick layer (thickness is estimated from assumed isostasy of lunar highlands floating on dense mantle basalts and from the depth of sampling by large impact craters) of low density rock that is $>75\%$ plagioclase (Ca, Na-aluminosilicate). So much plagioclase on the surface is thought to result from differential crystallization in a deep (~ 250 -km) magma ocean with the less dense plagioclase crystals floating to the top. The minimum depth of the ocean is controversial, but it is estimated as that necessary to provide the observed plagioclase if all the available plagioclase has floated to the surface. There are additional, more subtle geochemical indications of the existence of such a magma ocean on the early Moon (Warren 1985). Very few of the returned lunar rocks are older than 4.0 billion years, where older rocks are thought to have been destroyed by a continued heavy bombardment (late heavy bombardment) that persisted until ~ 500 million years after the Moon formed (Mottman 1977).

In the sections that follow, we invoke tidal dissipation (only sometimes successfully) to account for resurfacing of icy satellites with no other apparent sources of internal energy. However, one investigation of the contribution of tidal dissipation to lunar thermal history (Peale & Cassen 1978) yielded negative results. This study was motivated by the realization that the obliquity of the Moon would undergo large variations as it changed from equilibrium Cassini state 1 to a precession about and dissipative relaxation toward a still very inclined state 2 as the Moon passed through $\sim 34R_E$ from the Earth during the tidally induced growth of the semimajor axis of the Moon (Ward 1975). The obliquity reached as high as 77° during this process, which led to significant tidal dissipation within the Moon. However, the growth of the semimajor axis was sufficiently rapid during this transition that

the contribution to the lunar thermal budget was negligibly small (Peale & Cassen 1978). There is a possibility discussed below that tidal dissipation caused profound changes in the lunar interior during passage through an orbital resonance when the Moon was very close to the Earth.

Several authors (Darwin 1879, 1880, Gerstenkorn 1955, MacDonald 1964, Kaula 1964, Goldreich 1966) have attempted to constrain the origin of the Moon by integrating the motion approximated by Equation 7 backwards in time until the Moon was close to the Earth. The actual motion is much more complicated than implied by Equation 7. The lunar orbit has a variable inclination relative to the Earth's equator. The noncircular orbit precesses while maintaining a nearly constant inclination to the Laplacian plane, where that plane is nearly coincident with the Earth's equator plane when the Moon is close, but is now nearly coincident with the ecliptic. The Earth's spin rate is decreasing as angular momentum is transferred to the Moon and the Sun. The Earth's obliquity is changing in response to lunar and solar torques. The Earth's spin axis itself is precessing due to the torques on its oblate figure. The current rate of regression of the Moon was deduced long ago by the determination that the length of an Earth day was increasing 0.0016 s/century from the timing of solar eclipses. That rate has since been made more precise from lunar laser ranging to the Moon over the past 25 years ($da_M/dt = 3.82 \pm 0.07 \text{ cm year}^{-1}$) (Dickey et al 1994).

The first thing learned from the calculations of the Earth-Moon evolution was that the Moon would have been at the surface of Earth <2 billion years ago if the tidal-effective Q_E was maintained at that value yielding the current rate of lunar orbit expansion. As the major fraction of the Earth's tidal dissipation is in the oceans and as that dissipation depends on the configuration of continental shorelines, a reasonable solution to this problem is that the changes in the continental configurations have led to a tidal effective Q today that is less than its value in the distant past. The second result was that the Moon returned to an inclination relative to the Earth's equator of $\sim 10^\circ$ instead of to the equatorial plane. As the then popular coaccretion model of lunar formation had the Moon forming in the Earth's equator plane from a debris disk, this is referred to as the "inclination problem." This result has been confirmed in a modern Hamiltonian formulation of the problem and by a symplectic integration including the complete chaotic solar system, but with the same accelerated evolution rates and no dissipation in the Moon (Touma & Wisdom 1994). The currently popular giant impact origin of the Moon also leads to formation in an equatorial disk, so the problem remains. However, it takes only another large impact on the Earth or Moon after the Moon has formed to change the orbit inclination relative to the Earth equator and thereby provide a consistent tidal evolution (e.g. Stevenson 1987). But Touma & Wisdom (1998) have another solution.

In their 1994 paper, Touma & Wisdom note that the artificially accelerated rate of tidal evolution would drag the Moon through any orbital resonances it might have encountered such that the consequences of capture in such a resonance would

be missed. In addition, the evolution of the Moon is not time reversible because the Moon might be captured into an orbital resonance when approaching it from one direction, but not the other. Any viable representation of the Earth-Moon history must then involve a rate of tidal evolution reasonably close to the physical rate and must progress forward in time.

In an integration that produces the current configuration when the Moon has reached its current distance from the Earth, Touma & Wisdom (1998) start the Moon in the equatorial plane of the Earth at a separation of $3.5R_E$ with an eccentricity of 0.01, which is consistent with current expectations from the giant impact origin (e.g. Ida et al 1997). The initial obliquity of the Earth is 10° , and the initial Earth rotation period is five h. Realistic rates of tidal evolution are used in the symplectic integrations that include the entire chaotic solar system, and dissipation in the Moon is included at a variety of dissipation rates. A tidal model was used with the constant time lag as discussed in Section 3 but with the Mignard (1981a) formulation. The first strong resonance is encountered when the Moon is $\sim 4.5R_E$, where the period of the periaapse motion of the lunar orbit relative to an inertial reference is ~ 1 year. This resonance is called the *evection resonance* because the same term in the disturbing function gives rise to the 1.3° amplitude, 31.8-day periodic variation in the Moon's mean longitude called the evection. Capture into the evection resonance is certain if the eccentricity is < 0.07 as the resonance is approached and if the rate of tidal evolution is sufficiently slow. With the assumed parameters, capture occurs and the eccentricity grows rapidly to large values, where the maximum value reached before the system escapes the resonance is determined by the value of

$$A = \frac{k_M}{k_E} \frac{\Delta t_M}{\Delta t_E} \left(\frac{m_E}{m_M} \right)^2 \left(\frac{R_M}{R_E} \right)^3, \quad (10)$$

where k , Δt , m , and R refer to Love number, the constant tidal time lag, mass, and radius with subscripts referring to Earth and Moon, respectively. A is a measure of the relative rates of energy dissipation in the Earth and Moon. The current value of A from the lunar laser-ranging experiment is ~ 1.1 (Dickey et al 1994). For $A = 0$ (no dissipation in the Moon), the maximum eccentricity is ~ 0.5 before escape, and the eccentricity continues to climb after escape from the resonance because of tides raised on Earth and no dissipation in the Moon (Goldreich 1963). For $A = 10$ (high dissipation in the Moon), the maximum eccentricity is only ~ 0.15 . For $1 \leq A \leq 10$, the energy dissipated in the Moon in ~ 8000 years is in the range from $\sim 2 \times 10^{35}$ to 1.5×10^{36} ergs, which could lead to substantial melting (Touma & Wisdom 1998).

After escape from the evection resonance, the continued expansion of the orbit further decreases the prograde motion of the orbit periaapse and twice the time derivative of the evection resonance variable plus the retrograde motion of the lunar orbit node approaches zero. The term in the Hamiltonian corresponding to this resonance has $e_M^2 i_M$ in the coefficient, but this resonance affects the inclination more than the eccentricity. Touma & Wisdom name this resonance the *eviction*—

changing the e in *evection* to i to emphasize the inclination and noting that this resonance “evicts” the Moon from an equatorial orbit. If A is not too large, the eviction resonance is approached with high eccentricity in the wrong direction for capture. Passage through the resonance leaves the eccentricity large and excites an inclination of $2\text{--}3^\circ$. If A were now to increase drastically—perhaps because the continued high eccentricity has partially melted the interior—the dissipation in the Moon becomes so high that the semimajor axis is decreased as the eccentricity is reduced. This reduction in the semimajor axis takes the system through the eviction resonance from the other direction where capture and subsequent evolution force the inclination to values between 9 and 13° . Escape from the resonance is effected because of the continued decrease in e_M , but the remnant inclination is preserved. Subsequent evolution brings the Moon to the current configuration.

This analysis of the evolution of the lunar orbit is the first in which the Moon evolves from an equatorial orbit to its current configuration from the effects of tidal dissipation alone. For this to occur, the Moon must start relatively cold so that the parameter A above is comparable with or smaller than its current value. Under this condition, the eccentricity can grow to large values in the evection resonance. The system must pass through the eviction resonance while maintaining substantial eccentricity. The consequence of reasonably sustained high eccentricity must soften the Moon sufficiently to drastically increase the A parameter after eviction passage, where the now-enhanced dissipation within the Moon decreases the semimajor axis as well as the eccentricity. A second encounter with and capture into the eviction resonance then forces the inclination to precisely the range of values obtained by earlier workers in their time-reversal integrations of the lunar history. Although there are several special circumstances necessary for this scenario to solve the inclination problem, our ignorance of the circumstances of the initial accretion and the resulting interior properties of the Moon leaves this alternative as a possibility.

If the Moon were hot after its accretion, however, A would be large initially, and the eccentricity might never reach the necessary values for the Moon to complete its dance around the eviction. The gravitational binding energy of the Moon is $\sim 3Gm_M^2/5R_M = 1.2 \times 10^{36}$ ergs. Therefore, if the accretion is complete in <1 year, as found by Ida et al (1997) for moon-type bodies just outside the Roche radius, the accretion could conceivably produce the early magma ocean inferred by geochemical evidence (Warren 1985). The fraction of the accretional energy that is retained increases with the size of the accreting bodies if the impacts are infrequent, but most of the heat of accretion can be retained even with small particles if the accretion is sufficiently rapid. Radiation of the deposited heat is inhibited in this latter case. If the time scale for accretion is >1000 years or if accretion is inhibited by being too close to the Roche zone (Canup & Esposito 1995), the Moon might originally have been relatively cool, and the magma ocean would have formed later—perhaps through excitation of the eccentricity in the evection resonance (Touma & Wisdom 1998). The latter scheme would require a distribution of tidal heating in the Moon that would lead to the temperature exceeding the solidus first

in the outer layers—a condition that might not be consistent with the distribution of tidal heating found by Peale & Cassen (1978), where the highest heating rate of a solid Moon is in the center. On the other hand, if the Moon were initially softened in the outer layers during the accretion process, while leaving the interior cool, the tidal dissipation might well be concentrated in the outer layers, and the tides could finish the job of forming the magma ocean that was begun by accretion. This latter scenario would take some improbable fine tuning, however, if the Moon is to arrive at the eviction resonance with a large eccentricity.

In his analysis of the giant impact origin of the Moon, Stevenson (1987) finds that the initial Moon must have been largely molten—not from a rapid accretion of cold solid bodies as treated by Ida et al (1997) but from the retention of the giant impact energy within the debris disk. The turbulent combination of liquid and gas in the disk of material resulting from the impact evolves so quickly that the material spreads beyond the Roche radius and forms the Moon before it has time to cool and solidify. The initial Moon would then have been at least partially molten and hot throughout. The initially small A necessary for the start of the Touma & Wisdom scenario would be precluded. On the other hand, an initially hot Moon is not consistent with the results of Solomon & Chaiken (1976), who find that the limited change in the lunar radius since the current very old surface was emplaced suggests that no more than the outer 200 km was molten and that the interior started cold. Touma & Wisdom note that such an interpretation would also cause problems with their scheme for forming the magma ocean through tidal dissipation since their Moon would also be hot throughout (if not melted in the center) after the ejection-induced heating.

From the preceding paragraphs, it is clear that our understanding of the origin and evolution of the Moon is far from complete. Any geochemical inconsistencies notwithstanding, the giant impact initial event seems to be a relatively secure explanation for the large angular momentum of the Earth-Moon system and for the Moon's lack of volatiles and iron compared to the Earth. However, details in getting from the impact to an accreted Moon outside the Roche radius are obscure. Is the Moon accreted hot or cold? The former would eliminate the Touma & Wisdom solution to the inclination problem, and it is inconsistent with the small apparent decrease in the lunar radius during the last 3.8 billion years. The latter scheme has difficulty in placing enough material outside the Roche radius without extreme values of impactor mass and angular momentum. Perhaps effort for the near future should be concentrated on understanding and possibly constraining the physics of the accretion disk. Additional processes heretofore not considered, such as spiral density waves to redistribute angular momentum more efficiently, might allow smaller impactors. As always in this research, we desire a single, self-consistent scenario that carries the Moon from its origin to the current configuration of the Earth-Moon system with the minimum number of degrees of freedom while satisfying the maximum number of observational constraints. So far we have only somewhat disjointed pieces with uncertain parameters, so that none satisfy all of the apparent constraints.

5. MARS SYSTEM

From Table 1, we see that Phobos is located well inside the corotation radius of ~ 5.9 Martian radii (R_M), and Deimos is just outside this radius. The tides raised on Mars thus cause Phobos to be spiraling toward Mars and Deimos to be spiraling away. In fact Phobos is inside the Roche radius for a density of 1.9 g cm^{-2} and would be torn apart by tidal forces if it were a fluid. It needs only a shear strength of $10^5 \text{ dynes cm}^{-2}$ to resist disruption (Yoder 1982)—a loose rubble pile would survive (Soter & Harris 1977, Dobrovolskis 1982).

Phobos and Deimos are synchronously rotating. Deimos would have reached this state in $< 10^8$ years from an unlikely small initial spin period of 4 h, if a rigidity of $5 \times 10^{11} \text{ dynes cm}^{-2}$ and $Q = 100$ is assumed. Under the same assumptions, Phobos would have reached this state in $< 10^5$ years at its current separation from Mars and in $< 10^7$ years at its likely initial separation near the corotation radius. [See Peale (1977) for a detailed discussion of the rotation histories of all of the satellites known at that time.] We have already dismissed an intact capture origin for the satellites of Mars as untenable, given the regularity of the current orbits. A formation from accretion in a debris disk then implies that the initial orbits of Phobos and Deimos were also regular with near-zero eccentricities and inclinations to the equator plane of Mars.

The fact that Phobos and Deimos deviate considerably from spherical symmetry leads to special circumstances as they approach synchronous rotation. Both enter chaotic zones in the phase space surrounding that of stable libration about synchronous rotation where the spin axis is attitude unstable (Wisdom 1987b). This means the satellites will tumble chaotically with time scales comparable with the orbital periods until they are trapped into stable libration about the synchronous state. Tidal dissipation under these circumstances is like that for a nonsynchronous rotation, and the eccentricity will be damped at a much higher rate than it would have if the satellite were in synchronous rotation. Hence, the process of synchronizing the rotation of the satellites with the orbital motion will also effectively damp any eccentricity remaining from the accretion process. This damping precludes high eccentricities in the past and concern about collisions between Phobos and Deimos as discussed by Szeto (1983). The evolution of the system to the current configuration would then seem to require only the expansion of the orbit of Deimos from tides raised on Mars and the shrinkage of the orbit of Phobos from similar tides.

Although the effect of tides on the inclinations of the orbits to the Martian equator plane is negligible, it is of interest that the initial equatorial orbits will remain equatorial in spite of the chaotic, large amplitude variations in the obliquity of Mars (Ward 1979, Laskar & Robutel 1993, Touma & Wisdom 1993) and despite the precession of the spin axis of Mars (Goldreich 1965b). The solid angle described by the orbit normal as the satellite orbit precesses due to Mars's oblateness is an adiabatic invariant (Goldreich 1965b), as these precession rates for the Martian satellites [periods of 2.3 and 57 years for Phobos and Deimos, respectively (Peale

1977)] are fast compared with rates of change of Mars' spin axis direction relative to inertial space [timescales $O(10^5)$ years, Touma & Wisdom 1993].

Determinations of the Q of Mars lie between about 66 and 144 (Shor 1975, Sinclair 1978, Duxbury & Callahan 1981) from observations of the secular acceleration of Phobos' orbital mean motion. If we choose a constant value of $Q_M = 100$ with $k_M = 0.14$, the orbit of Deimos could have expanded by <200 km in 4.6×10^9 years. The initial semimajor axis of Phobos would have been $\sim 5.6R_M$ under the same assumptions. The rotation period of Mars would be essentially unaffected by the exchange of angular momentum with the satellites and would have been only ~ 10 min longer due to solar tides. Deimos has essentially its initial orbit; Phobos, having started inside the corotation radius, is consistent with the measured current value of $Q_M \approx 100$.

If we insist that both satellites started with nearly circular orbits, how then can we explain the current eccentricity of Phobos' orbit $e_P = 0.0151$? If the orbital motion is integrated backwards in time, this eccentricity grows to large values and collisions with Deimos would have been likely (Yoder 1982, Szeto 1983), even if there were no tidal dissipation in Phobos. Significant dissipation in Phobos reduces the time scale for a crossing orbit with Deimos to $<10^9$ years in the past (Yoder 1982). The current eccentricity cannot therefore be a remnant from tidal decay beginning 4.6×10^9 years ago. Yoder (1982) has identified three commensurabilities (defined when two characteristic periods in the description of the motion are in the ratio of small whole numbers) that Phobos has passed through within the past 10^9 years that provide likely gravitational excitations of the Phobos eccentricity during its inward spiral. The commensurabilities are encountered at $a = 3.8, 3.2,$ and $2.9R_M$, where the earliest resonance was encountered only 5×10^8 years ago. The first and third are 2:1 and 3:1 commensurabilities between the rotation of Mars and the orbital mean motion, where the resonant interaction is with the axial asymmetry of Mars. At $3.2R_M$, the 2:1 commensurability is between the apparent mean motion of the Sun and the periape of the orbit of Phobos, where the secular motion of the latter is caused by the oblate figure of Mars. This resonance is like the evection resonance for the Moon. There is also a 3:2 spin-orbit resonance excitation of the eccentricity when $a = 4.6R_M$, but this excitation happened so long ago that there would be no contribution to the current eccentricity. The eccentricity would have decayed after each excitation, and it plausibly arrives at the current eccentricity after the series of kicks and subsequent decays (Yoder 1982). Orbital inclination can also be excited, and, even though the resonance interaction is not as strong as it is for the eccentricities, the excited inclinations do not decay. Still, the current inclinations of the orbits are consistent with the resonance passages (Yoder 1982).

There is a condition on the dissipation in Phobos for this scenario to work. Yoder (1982) has calculated the dissipation in the satellite accounting for both the tidal dissipation caused by the eccentric orbit as discussed earlier and that caused by the forced libration of the very asymmetric satellite. This libration has an amplitude of 3.9° (Duxbury & Callahan 1981, Yoder 1982) and causes twice

the tidal dissipation in Phobos that would occur if Phobos were nearly axially symmetric in the same eccentric orbit (Yoder 1982). Both the dissipation in Phobos and that in Mars from tides raised by Phobos damp the eccentricity. There cannot be too much damping since the series of eccentricity excitations or the current eccentricity would be less than that observed. Because the dissipation in Mars can be presumed known from the measurement of Q_M , and the magnitude of the probable excitations can be reasonably estimated from the resonance passage analysis, the current value of e_P limits the contribution by Phobos. Yoder finds that $\mu_P Q_P > 3$ to 6×10^{12} dynes cm^{-2} or, if $Q_P \sim 100$, $\mu_P \gtrsim 10^{10}$ dynes cm^{-2} , which is about that of ice. The properties of Phobos are not sufficiently well known for one to be sure that the rigidity could satisfy this constraint, but this rigidity is not unreasonable.

During the spiral of Phobos toward Mars, it is likely that it passed through the 2:1 orbital mean motion commensurability with Deimos. Such a passage would excite an eccentricity of ~ 0.002 in the orbit of Deimos if the eccentricity of Deimos were much smaller than this before resonance passage. The time of this commensurability is known if the current dissipative properties of Mars have not changed substantially since the resonance encounter. This places a lower bound on the dissipation in Deimos if the current eccentricity is the tidal remnant from an initial value of 0.002 excited by the resonance passage. Yoder (1982) finds $\mu_D Q_D (1 - \alpha_D)^2 / \alpha_D^2 \lesssim 10^{10}$ dynes cm^{-2} , where $\alpha_D = 3(B - A)/C$, with $A < B < C$ being the principal moments of inertia of Deimos. This limit may be unreasonably low, but the dissipation in Deimos may be increased if the forced libration is nearly resonant with the free libration. The enhanced amplitude of libration would lead to higher dissipation and would relax the constraint on $\mu_D Q_D$. The free libration period could be better constrained by an estimate of α_D from a more accurate determination of the shape of Deimos along with an accurate measure of its physical libration amplitude.

In any case, the Yoder hypothesis (that the satellite orbits have always been regular and current properties of the system then attributed to the effects of resonance passages by Phobos) is well supported. This hypothesis is consistent with our presumed origin from a dissipative disk of small particles. However, the necessary approximations in the developments and still uncertain dynamical properties of the satellites warrant a more thorough numerical exploration of the phase space of the system with the value of Phobos' rate of tidal orbit decay comparable with the real value.

6. JUPITER SYSTEM

The Jupiter system has four classes of satellites. The dynamical evolutions of the four small satellites closest to Jupiter, after the disk of gas and solid particles from which they formed had disappeared, are limited to the tidal retardation of their spins to synchronous rotation, unless there have been episodes of breakup

by collision and reassembly as we will imply for the small satellites of Saturn. From Equation 6, the satellite Thebe at $3.1R_J$ with rocklike characteristics would slow to synchronous rotation from an initial rotation period of 4 h in less than a few thousand years. The closer small satellites are of comparable size or larger and would spin down in shorter times. All of the Galilean satellites, the next class, are observed to be synchronously rotating to within observational error, which is consistent with a time of ≤ 2.5 million years to bring all to this state. However, Io and Europa may not have the internal strength or permanent asymmetry sufficient to stabilize synchronous rotation against the averaged tidal torque (Greenberg & Weidenschilling 1984, McEwen 1986).

The two families of distant irregular satellites, four in prograde orbit with semimajor axes near $160R_J$ and four in retrograde orbits with semimajor axes near $300R_J$, are too far away even for significant evolution of the spins except for the attainment of principal axis rotation. The largest of the prograde irregular satellites, Himalia, with icelike characteristics, would require $\sim 2 \times 10^{14}$ years for significant change in an initial 4-h rotation period, and the other irregular satellites would take even longer. Thus, the only changes in the rotation states of the distant, irregular satellites are those that have been induced by occasional impacts. Light curves for several of the irregular satellites indicate rotation periods in the range of 8.3 to 13.2 h (Degewij et al 1980, Luu 1991), which fall in the middle of the range of asteroid rotation periods (e.g. Harris et al 1992).

The orbits of the irregular satellites are highly variable due to solar perturbations, but there appears to have been some orbital decay for these satellites. Two of the retrograde satellites occupy orbital resonances where their apsides are locked to the apsis of Jupiter—Pasiphae (JVIII) continuously and Sinope (JIX) intermittently (Whipple & Shelus 1993, Saha & Tremaine 1993). Dissipation is required to bring the satellites to this state from an initially random orbit of the parent body. Decay of the orbits by gas drag in an extended primordial Jupiter atmosphere is not an unreasonable hypothesis, since the parent bodies for the two groups of irregular satellites may have been captured and split into the respective members of the groups from gas drag from the extended atmosphere just before the final collapse of that atmosphere (Pollack et al 1979). Capturing satellites by gas drag is tricky, however, because an atmosphere dense enough in its outskirts to capture a satellite is also dense enough to cause the satellite to spiral into the planet in a relatively short time. It appears that the time scale for atmospheric collapse would have to be less than the orbit decay time in the initial atmosphere for gas capture to work. One alternative is for capture of the parent bodies for each class of irregular satellites by three-body interactions or collisions within the sphere of influence at a time when the extended atmosphere was sufficient for some orbital decay but not so thick as to threaten the continued existence of the satellites. A second alternative would allow the parent body to decay to the resonance, which would halt the orbit decay while the atmosphere continued its collapse or was otherwise dissipated. The collision creating the family could then leave one of the resulting satellites in the resonance, a second nearly so and the other two scattered out. With the

atmosphere gone, rotations imparted at the breakup would not decay by gas drag. The details of origin are likely to remain speculative, but dissipation at some stage seems necessary to leave Pasiphae and Sinope in the orbital resonance.

The Galilean satellites have much more interesting histories than do the remaining satellites that still have not been totally unraveled in a way consistent with their observed properties. The active volcanism on Io (II) (Smith et al 1979, Morabito et al 1979) is almost certainly due to the dissipation of tidal energy sustained by the forced orbital eccentricity of Io in the Laplace orbital resonance (Peale et al 1979). But the orbital configuration resulting from a dissipative equilibrium (Yoder 1979, Yoder & Peale 1981) yields a dissipation rate that is only $\sim 1/2.5$ the measured heat flux from Io for the minimum *historical average* value of $Q_J = 6.6 \times 10^4$ (Veeder et al 1994). Observational evidence for a liquid ocean under the surface ice of Europa (III) continues to build (Greeley et al 1998, Khurana et al 1998), but tidal dissipation—apparently the only viable source of energy to keep the ocean from freezing with the current orbital eccentricity—may not be sufficient to maintain the ocean (Cassen et al 1980a, Ross & Schubert 1987). Ganymede (IV) is only slightly larger than Callisto (V), yet the former has extensive areas of grooved terrain from endogenic activity that occurred long after the ancient cratered surface of the latter was emplaced. In addition, Ganymede may be differentiated more than Callisto (Anderson et al 1996, 1997, 1998a), and it has an intrinsic magnetic field that implies a fluid conducting core (Kivelson et al 1998). One attempt to explain the dichotomy in the ages of the surfaces with the additional radioactive heat sources in the larger rocky core of Ganymede (Cassen et al 1980b) was judged unlikely adequate because of the necessary fine-tuning of unknown interior parameters (Showman et al 1997), and it almost certainly could not account for a fluid metallic core for the magnetic field generation. Tittlemore (1990) considered a 3:1 Europa-Ganymede resonance where he obtained large eccentricities for both satellites ($e_E = 0.14$ and $e_G = 0.06$), which he inferred to yield sufficient heating of Ganymede to account for the resurfacing. However, Tittlemore kept only the two-body Europa-Ganymede interaction, and he neglected dissipation in the satellites while obtaining the high eccentricities. His neglect of Io, presumably already locked in the 2:1 resonance with Europa, completely changes the dynamics. We shall see below that Europa's eccentricity cannot be changed arbitrarily while it is locked in a 2:1 resonance with Io, and this constraint on Europa is going to affect the Ganymede eccentricity. If satellite dissipation had been included during the evolution, the eccentricities obtained would not have been so large.

Showman et al (1997) note that significant tidal heating would have occurred in Ganymede if the system were captured into at least one Laplace-like (see below) historical orbital resonance on its way to the current configuration. Large thermal runaways generated by a rapid warming of Ganymede's mantle are the most attractive for resurfacing but are prevented by details of the model. Smaller runaways creating pockets of water or slush coupled with conduits to the surface may be capable of resurfacing. But the model dependence of these conclusions means that additional analysis is needed before a robust scenario leading to the

Ganymede-Callisto surface dichotomy can be obtained. If these implications are not sufficiently puzzling, analysis of variability of an induced magnetic field in Callisto is consistent with a conducting layer of liquid, salty water below the insulating ice crust (Khurana et al 1998). Sustaining such a layer of liquid water on Callisto over any significant time span seems totally implausible.

The apparent incomplete differentiation of Callisto is another mystery (McKinnon 1997), but it is significant that the last Callisto flyby by the Galileo spacecraft has considerably reduced the deduced $C_C/m_C R_C^2$ from ~ 0.4 from the two earlier encounters to 0.358 ± 0.004 (Anderson et al 1998a). McKinnon (1997) has pointed out that even a homogeneous Callisto will have $C_C/m_C R_C^2 = 0.38$ because of the compression of deeper layers and polymorphism of ice, so the latest value of $C_C/m_C R_C^2$ would indicate some differentiation. Next, the flyby data were interpreted under the assumption of hydrostatic equilibrium, and McKinnon (1997) finds that nonhydrostatic contributions to the gravitational harmonic coefficients J_2 and C_{22} could mimic an undifferentiated Callisto and by inference lead to $C_C/m_C R_C^2 = 0.358$, which still is too high. If one allows for a 3σ error as well, it seems that the conclusion that Callisto is only partially differentiated is not that secure. If there were to be no differentiation, the internal temperature and, in particular, the surface temperature could never exceed 273 K. If one assumes that all of the accretional energy must be radiated away at surface temperature T , the accretion time $t = 4\pi G \rho_C^2 R_C^3 / (9\sigma T^4)$ is $\sim 4.5 \times 10^5$ years for $T = 273$ K (DJ Stevenson, private communication), where σ is the Stefan-Boltzman constant and where only the gravitational binding energy is accounted for. This million-year accretion time scale is much longer than that obtained by McKinnon & Parmentier (1986), who find that both Ganymede and Callisto should have been substantially melted during accretion. A more detailed mapping of the Callisto gravitational field seems appropriate before theorists devote too much time to explaining incomplete differentiation.

The most striking characteristic of the Galilean satellite system is the set of orbital resonances where the orbital mean motions satisfy the relations

$$\begin{aligned}
 n_I - 3n_E + 2n_G &= 0, \\
 n_I - 2n_E + \dot{\varpi}_I &= 0, \\
 n_I - 2n_E + \dot{\varpi}_E &= 0, \\
 n_E - 2n_G + \dot{\varpi}_E &= 0,
 \end{aligned}
 \tag{11}$$

which lead to the following constraints on the mean longitudes:

$$\begin{aligned}
 \lambda_I - 3\lambda_E + 2\lambda_G &= 180^\circ, \\
 \lambda_I - 2\lambda_E + \varpi_I &= 0^\circ, \\
 \lambda_I - 2\lambda_E + \varpi_E &= 180^\circ, \\
 \lambda_E - 2\lambda_G + \varpi_E &= 0^\circ.
 \end{aligned}
 \tag{12}$$

The subscripts refer to Io, Europa, and Ganymede, respectively, and ϖ_i are the longitudes of periaapse with the dot indicating time differentiation. The Laplace relation is the first of both sets of equations. If we define $\omega_1 = n_I - 2n_E$ and $\omega_2 = n_E - 2n_G$, the Laplace resonance can be thought of as a 1:1 commensurability between ω_1 and ω_2 whose current value is 0.74° per day. The combination $\lambda_E - 2\lambda_G + \varpi_G$ is not constrained. At the conjunction of Io and Europa, Io is thus at its periaapse and Europa is at its apoapse, whereas at the conjunction of Europa and Ganymede, Europa must be at its periaapse and Io must be on the opposite side of Jupiter. The longitude of Ganymede's periaapse is not constrained at conjunction.

Because the phase-space volume for the Laplace relation is so small compared with that available, it has been long assumed that the resonances were assembled from initially random orbits through differential tidal expansion of the orbits (T Gold, personal communication, 1962; Goldreich 1965a). Yoder (1979), with elaboration in Yoder & Peale (1981), was the first to develop a consistent analysis of tidal evolution arriving at the current configuration, where the high tidal dissipation in Io was shown to be a vital consideration in damping the amplitude of libration of the Laplace angle to the current remarkably low value of $0.066 \pm 0.013^\circ$ (Lieske 1987). The damping of this libration to such a small value during evolution within the resonance was not possible without the high tidal dissipation in Io (Sinclair 1975).

Substitution of parameter values from Table 1 into Equation 7 shows that Io's orbit will expand more rapidly than Europa's and Europa's more rapidly than Ganymede's. Thus Yoder starts Io inside the 2:1 mean motion commensurability with Europa, so that it approaches this commensurability from a direction where capture into each of two eccentricity-type resonances corresponding to libration of the second and third angles defined by Equation 12 is certain if the respective eccentricities far from resonance are sufficiently small (e.g. Peale 1986). This condition for certain capture will surely prevail, since the secular decrease of the eccentricity e of a synchronously rotating satellite as a consequence of tidal dissipation will dominate the secular increase induced by tides raised on the planet and quickly reduce e to negligibly small values before resonance encounter (Peale et al 1980). (Time constant for decay of free eccentricity for a cold Io would be $8.2 \times 10^4 Q_I$ years with $\mu = 6.5 \times 10^{11}$ dynes cm^{-2} from Equation 9). Just after capture into the two eccentricity-type resonances at the 2:1 mean motion commensurability, $\omega_1 = n_I - 2n_E = -\dot{\varpi}_I = -\dot{\varpi}_E$ is considerably larger than the current value.

The retrograde periaapse motions are a resonance effect that dominates the ordinary prograde motion from Jupiter's oblateness and from the solar perturbation. The contribution to $\dot{\varpi}$ from the resonance term is inversely proportional to the eccentricity (Peale et al 1979) such that as tides raised on Jupiter by Io continue to reduce Io's mean motion, the decrease in ω_1 forces a similar decrease in the retrograde motions of $\dot{\varpi}_I$ and $\dot{\varpi}_E$ if the resonance is to be maintained. But since this rate is inversely proportional to the eccentricities, both eccentricities are forced to higher values as tides push Io deeper into the resonance, that is,

closer to exact commensurability of the mean motions. But higher eccentricities result in higher tidal dissipation in the satellites according to Equation 8, where $1 \leq f \leq 13$ in this equation for a two-layer Io model with $k_I \approx 0.035$ for a homogeneous, solid Io with rigidity between those of Earth rocks and the outer layers of the Moon (Peale et al 1979). This dissipation decreases the eccentricity at a rate given by Equation 9. Thus, tides on Jupiter are forcing Io deeper into the resonance and thereby increasing the eccentricity while tidal dissipation in Io and (much less so) in Europa from the forced eccentricities are tending to reduce the eccentricities. An equilibrium is approached where the two effects balance with e_I and e_E , ω_1 , $\dot{\omega}_I$, and $\dot{\omega}_E$ essentially constant as the locked pair of satellites move outward together as Io transfers angular momentum to Europa through the resonance interaction. It is easy to see that the values of the equilibrium eccentricities where the two dissipative effects balance determine the ratio $k_J Q_I / k_I f_I Q_J$ (Yoder & Peale 1981).

The locked pair of satellites continue to move away from Jupiter, leading to the eventual encounter of the 2:1 mean motion commensurability between Europa and Ganymede. Capture into the three-body Laplace resonance ($\omega_1/\omega_2 = 1$) has a probability of ~ 0.9 (Yoder 1979; Yoder & Peale 1981) with simultaneous capture into the eccentricity type 2:1 resonance involving Europa's periaapse longitude but not that of Ganymede. Initially there are free eccentricities induced that manifest themselves as large amplitudes of libration of the angles defined in Equations 12 about their mean resonant values. Subsequent evolution of the set from continued application of the torque from the tide raised on Jupiter by Io (The torques on Europa and Ganymede from their Jupiter tides are negligible by comparison.) forces larger eccentricities for the orbits of Io and Europa as ω_1 is pushed to smaller values, while the tidal dissipation of orbital energy in Io damps the libration of the Laplace angle. The evolution is such that the amplitude of libration of the Laplace angle approaches zero as e_I and e_E approach new equilibrium values. In this state, the three satellites move out together while maintaining fixed ratios of their mean motions. Angular momentum acquired from Jupiter by Io is transferred to Europa and from Europa to Ganymede through the resonant interactions to maintain the configuration.

The miniscule amplitude of libration of the Laplace angle is consistent with the current values e_I and e_E being equilibrium values. Consequently, the balance of the dissipation effects in Io (trying to decrease e_I) to those in Jupiter (trying to increase e_I) leads to $k_I f_I / Q_I \approx 900 k_J / Q_J$ (Yoder & Peale, 1981). The 1600 Q_J year age for the Laplace resonance, deduced by Yoder & Peale if the amplitude is an evolutionary remnant, was increased to 2100 Q_J years in a refined analysis by Henrard (1983) and to possibly an even greater age under circumstances to be explored below (Malhotra 1991). The age could be greater than any of these constraints if the amplitude was not a remnant of the Laplace resonance evolution but had been excited by an impact on one of the satellites or if it is a libration forced by the proximity of the (2074 ± 10) -day period of free libration to the 2076-day period of a term in the solar perturbation. It may be the case at the time

of this writing that the masses of the satellites have been sufficiently refined by the Galileo spacecraft encounters to determine the closeness of the two periods and thereby the expected forced libration of the Laplace angle.

The above plausible scenario for the establishment and evolution of the Laplace resonance is perhaps the simplest, but whether it actually occurred depends on the initial distribution of random orbits and on a sequence of probabilistic events. Yoder & Peale (1981) investigated passage of the system through other Laplace-like resonances where $\omega_1/\omega_2 = j/(j + 1)$. In particular, the $j = 1$ resonance would most probably have been encountered, with the system temporarily captured into libration in the above simplest evolution. Yoder & Peale noted no consequence of this resonance passage except for remnant free eccentricities that would be damped by dissipation within each satellite. The current free eccentricities of the orbits of Europa and Ganymede ($e_{E_{free}} = 9 \times 10^{-5}$, $e_{G_{free}} = 0.0015$) could then be remnants of such resonance passage if relatively recent. The fact that Ganymede's free eccentricity exceeds that forced by the Laplace resonance ($e_{G_{forced}} = 0.0006$) leads to the circulation of $\lambda_E - 2\lambda_G + \varpi_G$ rather than libration.

Malhotra (1991) bypassed the analytic approximations used by Yoder & Peale by numerically integrating the system from a variety of starting points, thereby encountering several Laplace-like resonances on the way to the current 1:1 resonance. Capture into several higher-order resonances was possible, with almost certain capture into $\omega_1/\omega_2 = 1/2$. The remarkable consequence of the latter resonance is that Ganymede's eccentricity is forced to large values, where larger tidal dissipation offered the possibility of modifying Ganymede's surface after most of the cratering was complete without affecting Callisto. Showman & Malhotra (1997) extended the range of initial conditions for the integrations and found much larger excitations of Ganymede's eccentricity from passage through the $\omega_1/\omega_2 = 2/1$ and $3/2$ resonances which brightened the prospects of accounting for the dichotomy between Ganymede and Callisto. A troubling aspect of this analysis was the necessity of changing the ratio $Q_I k_J / f k_I Q_J$, either suddenly or sinusoidally in order to disrupt the $\omega_1/\omega_2 = 2/1, 3/2$ resonances. There exist arguments that are not unreasonable for varying Q_I in episodic heating and cooling of Io (Greenberg 1982, Ojakangas & Stevenson 1986) and for varying Q_J (Iaonnou & Lindzen 1993), so sudden changes in $Q_I k_J / f k_I Q_J$ should probably be abandoned. Finally, capture into the $\omega_1/\omega_2 = 2$ and $3/2$ resonances is probable only if Ganymede's eccentricity is $\lesssim 0.001$ at the time of resonance passage (Showman & Malhotra 1997). The time constant for the decay of Ganymede's free eccentricity from Equation 9 is $\sim 2.2 \times 10^{-5} \mu Q$ years, which could approach the perhaps unlikely but possible value 1.5×10^9 years if a cold Ganymede had the rigidity of rock (6.5×10^{11} dynes cm^{-2}) with $Q_G = 100$.

The $\omega_1/\omega_2 = 1/2$ resonance became unstable naturally but produced lower values of e_G . However, even with passage through the $2/1$ and $3/2$ Laplace resonances, Showman et al (1997) found that conditions required to achieve a thermal runaway in the Ganymede ice layer were difficult to obtain. They used a Maxwell model where Q_G had an explicit temperature dependence based on ice rheology

and the orbital evolutions found by Showman & Malhotra (1997). A thermal runaway with likely extensive resurfacing required the eccentricity to reach large values in the resonance with a subsequently rapid plunge in Q_G . The rapid damping of the eccentricity with the low Q_G would deposit sufficient energy in a thermal runaway in the ice mantle to effect the resurfacing. However, radioactivity in a carbonaceous chondritic core would warm the ice too much before the resonance was approached, and the resulting higher dissipation would prevent the attainment of high eccentricity. The tidal energy would thereby be deposited more slowly over a longer period, and thermal runaway would not occur. Still, partial runaways could occur in which parts of the interior were melted or softened, and it may be possible to account for the resurfacing if conduits to the surface develop.

The authors are careful to point out the need for continued pursuit of a possible tidal origin of the Ganymede-Callisto dichotomy. First, the failure to obtain a thermal runaway in Ganymede during the resonance passage is model dependent, and motivation for modifying the assumptions may emerge in the future. Second, the tidal dissipation rates were accelerated by a factor of 1000 so the calculations could be completed in a reasonable time. Such accelerations are notorious for introducing numerical artifacts into the results if the tidal changes are not adiabatically slow. Such adiabaticity was inferred for evolution into the $\omega_1/\omega_2 = 3/2$ and 2 resonances from the ratio of the restoring torque in each resonance to the tidal torque of 10^4 and 10^2 , respectively (Showman & Malhotra 1997). However, in chaotic regions of the phase space, Tittlemore & Wisdom (1988) have shown that numerical artifacts develop during the integrations unless the evolution is as much as a factor of 10^3 slower than that which satisfies the ordinary adiabatic invariance criterion for representations in two degrees of freedom. If a higher dimensionality of the problem must be considered, the evolution rate may have to be that set by physical constraints to avoid the artifacts (Tittlemore & Wisdom 1990). The uncertainty of whether the variations in Q_I/Q_J necessary for disrupting these resonances would actually occur and the uncertainty of the time scales if they did, the uncertain damping time of Ganymede's eccentricity, and the uninvestigated nature of many details such as a numerical verification of invariance of the results with rate of evolution mean that the continued pursuit of a means of tidally resurfacing Ganymede encouraged by Showman et al is well founded. Although it is possible that a robust tidal origin of the Ganymede-Callisto surface dichotomy can be found, it will be more difficult to maintain a molten core for Ganymede's magnetic field generation.

Critical to all of the scenarios above is sufficient torque from Jupiter to force enough orbital evolution to allow assembly of the resonances from initially random orbits. We have so far considered only a tidal torque that acts principally on Io. There is also an electromagnetic torque $N_{EMF} = \pi I R_J B_J a_I$, where $I \sim 2.8 \times 10^6$ A (Acuna et al 1981) is the current flowing along the tube of force induced by the $\mathbf{v} \times \mathbf{B}$ electric field across Io, R_J is the Jupiter radius, and $B_J = 0.02G$ at Io's distance a_I (Goldreich & Lyndon-Bell 1969). The electromagnetic torques are not sufficient to relax the limits of $6.6 \times 10^4 \lesssim Q_J \lesssim \times 10^6$ established by

the above evolutionary scheme and current configuration of the satellites (Yoder & Peale 1981). The lower bound on the *average* Q_J results from the proximity of Io to Jupiter after expanding from just outside the synchronous orbit with the Laplace resonance assumed to exist for 4.6×10^9 years. The upper bound depends on the current eccentricity of Io being nearly the equilibrium value leading to (Yoder 1979, Yoder & Peale 1981)

$$\frac{k_I}{k_J} \left(\frac{R_I}{R_J} \right)^5 \left(\frac{m_J}{M_I} \right)^2 \frac{Q_J f_I}{Q_I} = 4200, \quad (13)$$

from which, $Q_J f_I / Q_I = 1.24 \times 10^4$. From Equation 8, the tidal heating exceeds the radiogenic heating rate of Io of 6×10^{18} ergs/s if $Q_I / f_I < 370$ (Yoder & Peale 1981). This inequality is almost certainly satisfied since the Moon most probably has radiogenic heating comparable with that of Io but is largely unmelted, so the high temperature of Io needs considerable tidal heating. This bound on Q_I / f_I then imposes $Q_J < 4.6 \times 10^6$. More likely $Q_I / f_I < 100$ by comparison with other rocky bodies such as Mars and the solid Earth. This latter upper bound on Q_I / f_I leads to $Q_J < 1.2 \times 10^6$, which we nudge up to 2×10^6 to be conservative.

The upper bound on Q_J is lower than several estimates of the Q_J to be expected from turbulent viscosity in Jupiter's gaseous interior—the most extreme being $Q_J \approx 10^{13}$ (Goldreich & Nicholson 1977). A value of Q_J much larger than the above upper bound means there would be insufficient torque from Jupiter to assemble the resonances and to maintain the current hypothesized equilibrium. This insufficiency would mean that the dissipation in Io would be currently decreasing the eccentricity, increasing $\omega_{1,2}$, and disassembling the Laplace relation and associated two-body resonances. Could the Laplace relation simply be decaying from an original state much deeper in the resonance? Libration of the Laplace angle $\sim 180^\circ$ becomes unstable if $e_I > 0.012$, $\omega_1 < 0.14^\circ/\text{day}$, and the time to decay from $e_I = 0.012$ to $e_I = 0.0041$ is only a few tens of millions of years with the current dissipation in Io (Yoder & Peale 1981). However, there is another stable stationary state with libration of the Laplace angle $\sim 0^\circ$ with $\omega_1 < 0$ (Sinclair 1975). Greenberg's (1987) attempt to store the system here for subsequent decay to the current configuration requires a series of improbable events, not the least of which is the establishment of the Laplace relation at the time of satellite formation within the small amount of phase space allowed by the resonances. The unlikelihood of this scenario is in spite of possible paths between the two stationary states ($\omega_1 > 0$ and $\omega_1 < 0$, respectively), along which stable libration could apparently be maintained (Greenberg 1987).

In support of the Yoder (1979) hypothesis of an equilibrium configuration and the route thereto or modifications of that route by Malhotra (1991), two theoretical determinations of the tidal Q_J are well below the upper bound established by the observed dissipation in Io. Stevenson (1983) invokes hysteresis in the tidally induced condensation and evaporation of Helium raindrops to obtain the necessary dissipation, whereas Ioannou & Lindzen (1993) abandon the equilibrium tides used almost exclusively in the past and treat the dynamic response of Jupiter's

fluid atmosphere and interior to the tidal forcing by Io to obtain Q_J as low as 10^3 . This latter result depends on some parts of Jupiter being stably stratified with a Brunt-Väisälä frequency, the frequency of adiabatic oscillations of an element in the stably stratified region, the same as the tidal forcing frequency $2(\dot{\psi}_J - n_I)$ at some depth, where $\dot{\psi}_J$ is Jupiter's rotational angular velocity and n_I is Io's mean motion.

If Io's eccentricity is indeed very close to the equilibrium value, it can be used in place of the unknown interior properties of the satellite to express the energy dissipation in Io in terms of Q_J alone. If the three satellites have reached the equilibrium configuration, ω_1 , ω_2 , the ratio of the semimajor axes and all the forced eccentricities are nearly fixed as the system continues its expansion from the tides raised on Jupiter by Io. Conservation of angular momentum and energy requires

$$\frac{d}{dt}(L_I + L_E + L_G) = T, \quad (14)$$

$$\frac{d}{dt}(E_I + E_E + E_G) = n_I T - H, \quad (15)$$

where T is the torque on Io and H is the energy dissipation rate in Io. We have neglected the tidal torques on Europa and Ganymede as well as the energy dissipation therein as these are small compared with these parameters for Io. The second equation follows from the fact that dissipation in the satellites must come from the orbits because of the fixed synchronous spins. With $L = m\sqrt{Gm_J a(1 - e^2)}$, $E = -Gm_J m/2a$, and $a_I^{-1} da_I/dt = a_E^{-1} da_E/dt = a_G^{-1} da_G/dt$ from the constancy of the semimajor axis ratios, we have (Lissauer et al 1984)

$$H = n_I T \left(1 - \frac{1 + \frac{m_E a_I}{m_I a_E} + \frac{m_G a_I}{m_I a_G}}{1 + \frac{m_E}{m_I} \sqrt{\frac{a_E}{a_I}} + \frac{m_G}{m_I} \sqrt{\frac{a_G}{a_I}}} \right), \quad (16)$$

for the rate of energy dissipation in Io, where we have neglected e_i^2 .

If we use the lower bound on the averaged $Q_J = 6.6 \times 10^4$ in Equation 5 for T , H in Equation 16 or $H = dE/dt$ in Equation 8 corresponds to a surface flux density of heat on Io of ~ 1000 ergs $\text{cm}^{-2} \text{sec}^{-1}$. The comparison of this surface flux density with a measured value of 2500 ergs $\text{cm}^{-2} \text{sec}^{-1}$ (Veeder et al 1994) is the source of the discrepancy between the maximum dissipation rate in Jupiter and that necessary to account for the measured energy dissipation in Io. This discrepancy has led several authors to propose that the tidal heating of Io or the release of the energy from the surface may be episodic with the current values of the heat flux near a maximum of the fluctuations (e.g. Greenberg 1982, Ojakangas & Stevenson 1986). However, this maximum rate of Jupiter dissipation is based on a minimum averaged Q_J over all of history, where the minimum is derived from the proximity of Io to Jupiter. But notice that the discrepancy would be removed if the current Q_J were only a factor of 2.5 smaller than the minimum averaged

value, and there is no real reason for excluding a change in Q_J with time. Indeed, Ioannou & Lindzen (1993) find that the current Q_J could be even much lower than this, and their work suggests a possible mechanism for the current Q_J being much lower than it was in the ancient past. According to Ioannou & Lindzen, a low Q_J requires that some of the outer layers of Jupiter be stably stratified. It is probable that the early Jupiter was fully convective, but as it aged and cooled some layers may have become stably stratified leading to a much higher rate of dissipation of tidal energy.

In principle, Q_J can be determined by measuring the secular acceleration of Io's mean motion. There is a possibility of doing so because reasonably precise observations of eclipses of the Galilean satellites date back >300 years. Unfortunately, neither of the current determinations of dn_I/dt is consistent with the observed heating of Io in an equilibrium configuration. In this state, $(dn_I/dt)/n_I \approx -7.4 \times 10^{-11}/\text{year}$ ($da_I/dt \approx 2.1 \text{ cm/year}$)—if we assume $Q_J = 6.6 \times 10^4$, its minimum averaged value, and 2.5 times this value if Q_J is lowered to 2.6×10^4 —to be consistent with the current measured heat flux from Io. Lieske (1987) finds $(dn_I/dt)/n_I = -0.74 \pm 0.87 \times 10^{-11}/\text{year}$ —more than 1 order of magnitude too small to account for the dissipation in Io in an equilibrium configuration. Goldstein & Jacobs (1995) find $(dn_I/dt)/n_I = 4.54 \pm 0.95 \times 10^{-10}/\text{year}$, which would imply that the Laplace relation is rapidly being destroyed. In fact with zero torque from Jupiter, this rapid increase in Io's mean motion would require the surface heat flux density from Io to be $\sim 6000 \text{ erg cm}^{-2} \text{ s}^{-1}$ in a steady state—2.4 times the measured value! Any torque from Jupiter would require even more dissipation in Io. It would seem that any attempt to resolve these large discrepancies of observationally estimated fractional rates of change in n_I from a value consistent with the observed dissipation in Io must await another analysis of the ancient eclipse data and the timing thereof.

Perhaps nothing in solar system science causes as much excitement today as the possibility of a current liquid ocean under the ice of Europa. The images from Voyager 1 revealed cracks and blocks of ice that were displaced and rotated, resembling the patterns on terrestrial ice flows (Smith et al 1979). Many more examples of disrupted surfaces viewed with much higher resolution by the Galileo spacecraft show lateral displacements and rotations of blocks that retain the groove patterns of the undisrupted surface, and the blocks can thereby be reassembled into original relative locations (Carr et al 1998). Gravity experiments from recent Galileo flybys of Europa imply a differentiated satellite with a low-density layer (ice and water) perhaps 150 km thick (Anderson et al 1998b), whereas the properties of the blocks discussed by Carr et al (1998) imply an ice thickness of only a few kilometers at the time of the surface disruption. Estimates of the surface age are controversial, but the disrupted surface may be no more than 10^8 years old and could be much younger—implying that the processes leading to breakup of the surface and displacement of the blocks may be ongoing (Carr et al 1998). The global patterns and superpositions of large cracks in the surface are consistent with fracture perpendicular to tidal stress fields in an ice layer that slowly shifts

in longitude relative to a synchronous rotation rate, and the triple ridge pattern of these global features could result from the periodic pumping of water to the surface as the cracks open and close during the Europa eccentric orbital motion (Greenberg et al 1998). Finally, induced magnetic fields mapped by the Galileo spacecraft are consistent with a conducting, liquid ocean under the European ice (Khurana et al 1998).

Tidal energy deposition as a result of relatively large orbital eccentricity is perhaps the only viable energy source available to prevent such an ocean from freezing (e.g. Cassen et al 1979). However, this source may be only marginally able to maintain the ocean (Cassen et al 1980a, Ross & Schubert 1987). Substitution of Europa parameters into Equation 8 yields $dE_E/dt = 1.05 \times 10^{20} f_E/Q_E$ erg/s compared with $2.2 \times 10^{21} f_I/Q_I$ erg/s for Io. This substitution justifies its neglect in the above determination of the body independent value of the dissipation in Io as a function of Q_J . It remains to be seen whether a robust case can be made for this dissipation rate, f_E being determined by Europa's structure and rheology, and whether it can maintain the currently inferred liquid ocean beneath the ice layer.

The future of the Laplace resonance and a historical evolution of the Galilean satellite system that can account for the current heat flux from Io, the Ganymede-Callisto surface dichotomy, the Ganymede magnetic field, and the now probable liquid ocean on Europa may ultimately rest on confidence in a sufficiently low Q_J to bring it all about.

7. SATURN SYSTEM

In some respects the Saturn satellite system is the simplest in the solar system in the sense that all but 2 of its 18 satellites are regular. But it may be considered the most complicated, as those regular satellites display a rich variety of orbital resonances, satellite-ring interactions, an exotic rotation state, and, for the inner small satellites, probable repeated destruction and reassembly in a process that must be responsible for much of the debris in the rings (Smith et al 1982). Because of gravitational focusing by Saturn, Smith et al (1982) find that the cratering rate is presently twice as high on Rhea as on Iapetus and 20 times higher at Mimas. Starting with the crater density on Iapetus and estimates of cratering rates based on the flux of impacting cometary bodies, Smith et al (1982) deduce that from Dione inward all of the satellites have experienced at least one impact with enough kinetic energy to leave a crater the size of the satellite—probably disrupting the satellite. The inner satellites would have experienced such collisions many times, and the current distribution of these small satellites is most likely the result of repeated disintegrations and reassemblies. This process could account for the coorbital satellites Janus (SX) and Epimetheus (SXI). Disintegration of a parent satellite likely resulted in the F-ring along with its two shepherds, Prometheus (SXVI) and Pandora (SXXVII). Telesto (SXIII) and Calypso (SXIV), the leading and trailing

“Trojans” of Tethys (SIII), are probable remnants of or reaccumulations from the last disintegration of Tethys, with a similar origin of Helene (SXII), the leading “Trojan” of Dione (SIV), from the last disintegration of Dione. Atlas (SXV) is the A-ring shepherd that could be a remnant of the A-ring parent as is Pan (SXVIII), the shepherd creating the Encke gap in the A-ring (Showalter 1991), although Atlas could equally likely have come from the F-ring parent.

From Equation 6, it is easy to show that all of the numbered satellites out to and including Iapetus should be tidally evolved to synchronous rotation. All of the large regular satellites, with the exception of Hyperion (SVIII), are observed to be synchronously rotating, and synchronous rotation for Janus and Epimetheus among the small inner satellites has been verified (Yoder 1995). Although Hyperion is tidally evolved, its very asymmetric shape and highly eccentric orbit force it to tumble chaotically on time scales comparable with the orbit period (Wisdom et al 1984). The only rotational evolution suffered by distant Phoebe, like the outer satellites of Jupiter, is an occasional change caused by impact with subsequent relaxation to principal axis rotation. Voyager observations of Phoebe indicate a rotation period of ~ 9 h (Smith et al 1982). The Titan (SVII) synchronous rotation has been verified only recently by observation through methane windows in the atmospheric haze (Lemmon et al 1995). Although all of the synchronous satellites will also have reached a stable Cassini obliquity, the small orbital inclinations make these satellites unremarkable except for Iapetus.

At the distance of Iapetus from Saturn, the rates of its orbit precession due to the oblateness of Saturn and the solar perturbations are comparable—3.320 and 4.073 arcmin year⁻¹, respectively (Ward 1981)—so the Laplacian plane nearly bisects the angle formed by the Saturn orbit and equator planes. Ward derives the expression giving the angle of inclination of the Laplacian plane of 14.84° relative to the Saturn equator. The Iapetus orbit precesses with a period of about 3200 years while maintaining a nearly constant inclination of $\sim 8^\circ$ relative to the Laplacian plane (Ward 1981). In this precessing orbit, the Iapetus spin should have evolved to either Cassini state 1 or 2, where state 2 would be the end point if Iapetus is near hydrostatic equilibrium and state 1 would result from an internal strength sufficient to support moment differences comparable with those of the Moon (Peale 1977). Hydrostatic equilibrium would favor a predominantly icy satellite, whereas significant internal strength would imply a more rocklike constituency. The density of Iapetus (1.15 ± 0.08 g cm⁻³) implies ice and perhaps hydrocarbons (Tyler et al 1982), so we might expect to find Iapetus in Cassini state 2. This prediction can be verified by the approaching long-term observations by the Cassini spacecraft since the spin axis in state 1 is near the orbit normal, whereas the obliquity will be $> 8^\circ$ in state 2 (Peale 1977).

The high inclination of the Iapetus orbit to the Laplacian plane could mean that Iapetus was a captured satellite instead of one accreted within a dissipative disk. The latter process should have produced Iapetus very close to the local Laplacian plane, and it should remain near that plane if the position of the plane changes slowly compared with the rate of precession of the line of nodes (Ward 1981).

Ward points out that the position of the Laplacian plane is influenced greatly by the mass in the disk and that a relatively rapid dissipation of the disk that violated the adiabatic condition, thereby rotating the Laplacian plane, could leave Iapetus with its present inclination while preserving its origin in a dissipative disk, as its small eccentricity seems to imply.

The leading hemisphere of Iapetus is very dark (albedo ~ 0.04), whereas the trailing hemisphere is very bright (albedo ~ 0.5) (Smith et al 1982). It has been suggested that this dichotomy came about because dust from Phoebe that was spiraling in due to Poynting-Robertson drag would impact only on the leading hemisphere of Iapetus because of the retrograde motion of Phoebe (Soter 1974, Hamilton 1997). Smith et al (1982) point out that the transitions between the bright and dark regions are often sharp and that craters on the bright side have dark interiors—characteristics that are not consistent with a dusting from Phoebe debris. However, Smith et al (1982) also point out difficulties with an endogenic origin of the dichotomy. Hamilton (1997) would have Iapetus being dusted on all sides during a billion-year period as it slowed to synchronous rotation. Iapetus would have then been coated with frost but with only the leading side kept dark with continued Phoebe contamination. Dark floored craters on the bright side are then the excavation down to the dark Phoebe material collected during the first phase. But it would take meticulous cratering indeed to just go down to a relatively thin layer of Phoebe dust without penetrating to the ice below. The frost layer would have to be kilometers thick as well, and the boundaries between light and dark are still too sharp for the dusting hypothesis. These caveats and the lack of a model for endogenic origin leave the origin of the albedo dichotomy on Iapetus still not understood.

Six sets of orbital mean motion resonances between satellites persist in the Saturn system, and there is a secular resonance where the line of apsides of the Rhea orbit librates about that of the Titan orbit (Greenberg 1975; Pauwels 1983). The 2:1 mean motion resonance of Mimas (SI) and Tethys is the only inclination (*i*-type) resonance in the solar system in which the coefficient in the term in the disturbing function controlling the resonant motion contains the product of the two orbital inclinations instead of an eccentricity (*e*-type), and the argument of that term contains the longitudes of the ascending nodes instead of a periaapse longitude. Enceladus (SII) and Dione are in a 2:1 *e*-type mean motion resonance, and Titan and Hyperion are in a 4:3 *e*-type resonance. We have already pointed out the satellites in 1:1 coorbital resonances: Janus-Epimetheus, Telesto-Tethys-Calypso, and Helene-Dione. In the Janus-Epimetheus resonance, Epimetheus describes a horseshoe orbit in a frame rotating with the average of the two mean motions; Janus, the more massive, follows a shorter loop. Yoder et al (1983) give a clear analysis of this resonance and show how the mass of each member can be determined by the distance of closest approach during the reversal of the relative motions (see also Yoder et al 1989). Telesto and Calypso librate about the L4 and L5 Lagrange equilibrium points in the Tethys orbit in the frame rotating with the mean motion of Tethys, and Helene librates about the L4 point in the Dione orbit. There are many

descriptions of such librations in tadpole-shaped trajectories about the equilibria, where the restricted three-body problem is the basis for analysis (e.g. Brown & Shook 1964). Libration in eccentricity-type resonances also has many description, but see Peale (1976) for a heuristic description of the physical mechanism of stability. Conjunctions of Enceladus and Dione always occur near the periapse of the Enceladus orbit with a corresponding forced eccentricity in the Enceladus orbit like that discussed for the Jupiter Galilean satellites. Conjunctions of Titan and Hyperion always occur near the Hyperion apoapse, and the resonance forces the Hyperion eccentricity. The mixed i -type resonance of Mimas and Tethys is considerably more complicated than the simple e -type resonances, in which both orbital inclinations are forced [but see Greenberg (1973a) for a lucid description of the physical mechanism of libration and stability]. Conjunctions of Mimas and Tethys librate about the average of the ascending node longitudes of the two orbits on the equator plane of Saturn. It is the goal of analyses of evolutionary schemes to understand how these three resonances among the somewhat larger, classical satellites came to be and at the same time to account for the exotic properties of the satellites involved. We shall see that both Mimas-Tethys and Enceladus-Dione resonances could have been assembled from initially random orbits from orbit-expanding torques, but that such an origin for the Titan-Hyperion resonance is far from robust.

We consider first the Mimas-Tethys resonance. From Equation 7, we find $dn_M/dt - 2dn_T/dt = -3.7 \times 10^{-19}/Q_S = -2.2 \times 10^{-23} \text{ rad sec}^{-2}$, where the fluid Love number for Saturn, $k_S = 0.317$ (Yoder 1995), and $Q_S = 1.7 \times 10^4$, the minimum average value that would bring Mimas from the edge of the A-ring to its present position in 4×10^9 years, are used. The negative value means the Mimas orbit is approaching that of Tethys sufficiently quickly to be captured and driven deeper into a resonance at the 2:1 commensurability—a necessary condition for a tidal origin of the resonance (e.g. Peale 1986). This conclusion assumes the same value of Q_S for both satellites. There are several slowly varying frequencies at the 2:1 commensurability of mean motions where those with the lowest order coefficients are $(2n_M - 4n_T + 2\dot{\Omega}_M)$, $(2n_M - 4n_T + \dot{\Omega}_M + \dot{\Omega}_T)$, $(2n_M - 4n_T + 2\dot{\Omega}_T)$, $(n_M - 2n_T + \dot{\omega}_T)$, $(n_M - n_T + 2\dot{\omega}_M)$. Mimas and Tethys are locked in the mixed i -type resonance corresponding to the second frequency. The time variations in the node and periapse positions are sufficiently rapid due to Saturn oblateness that these frequencies are actually well separated. Compare the 78.8-year libration period of the Mimas-Tethys resonance variable with the separation of the first two frequencies $\dot{\Omega}_M - \dot{\Omega}_T = -293^\circ \text{ year}^{-1}$. This separation motivates the treatment of each resonance as isolated. But why did the system choose to occupy the second resonance?

As the Mimas-Tethys system approaches the 2:1 commensurability, $n_M - 2n_T$ is decreasing, and the resonances are encountered in the order given above if only the secular perturbations of the node and periapse are considered. (e.g. The first slowly varying frequency is the first to vanish.) However, from the Lagrange Planetary equations (e.g. Danby 1988) applied to a disturbing function that selects

the resonant arguments, an approach to resonance induces the variations

$$\left(\frac{d\varpi_M}{dt}\right)_{res} = n_M \frac{m_T}{m_S} \frac{a_M}{a_T} C_1 \frac{1}{e_M}; \quad \left(\frac{d\Omega_M}{dt}\right)_{res} = n_M \frac{m_T}{m_S} C_2 \frac{a_M}{a_T} \frac{i_T}{i_M}, \quad (17)$$

for the simple lowest-order e and mixed i -type resonances, where C_1, C_2 are negative constants. For small e , $d\varpi/dt$ will be large and negative. The node can have a large negative motion if $i_M \ll i_T$, but the presence of i_T in the numerator means that the node motion will almost always be dominated by the nonresonant secular perturbations. It is much more likely that a small e will induce such a large retrograde motion in ϖ that a simple e -type resonance can be encountered before any of the inclination resonances and the system can automatically enter into the e -type resonance libration. However, from Equation 17 $e_M < 1.3 \times 10^{-6}$ in order for $|d\varpi_M/dt| > |d\Omega_M/dt|$. Since such a small average e_M is highly unlikely, it appears safe to assume that the Mimas-Tethys system first encountered the well separated inclination resonances in the order given (Yoder 1973; Peale 1976). We need but account for its avoidance of the first i -type resonance and capture into the second.

The current amplitude of libration of the resonance variable $2\lambda_M - 4\lambda_T + \Omega_M + \Omega_T$ corresponding to the second frequency (λ s are mean longitudes) is 97° . By numerically integrating the resonance evolution backwards in time, Allen (1969) determined $i_M = 0.42^\circ$ and $i_T = 1.05^\circ$ at the time when the libration amplitude was 180° , that is, at the time of capture into the existing resonance about 2.2×10^8 years ago. With this value of i_M , Sinclair (1972, 1974) numerically calculated a capture probability of only 4.3% into the existing resonance, which was obtained analytically by Yoder (1973). The value of $i_M = 0.42^\circ$ now applies, as the Mimas-Tethys system passed through the first encountered, simple i -type resonance, which yields a capture probability into this first resonance of 7.3%, numerically and analytically by the respective authors. We can thus account for Mimas-Tethys skipping the first resonance encountered and stopping in the second because the captures are probabilistic.

Although this scenario makes a nice, self-consistent story of the evolution of the Mimas-Tethys system into and within the resonance, it was developed without the benefit of modern nonlinear dynamics and high-speed numerical computations. Champenois and Vienne (1999a,b) find that secondary resonances between the libration frequency and newly discovered long-period terms in the mean longitude of Mimas introduce chaos into the system that may have been important at the time of capture. The inclination of the Mimas orbit at the time of capture may have been quite different than the above value calculated by Allen (1969). If the Tethys eccentricity before capture was much larger than it is today, the calculation of the capture probabilities is more complicated than the single, isolated resonance theory used above. Although Champenois and Vienne find that a moderate eccentricity in the Tethys orbit could increase the capture probability into the current inclination resonance, tidal damping of that eccentricity would appear to preclude much enhancement. The full richness of the Mimas-Tethys dynamical history is

just beginning to be explored with modern techniques, and we might expect to find alternative routes to the current configuration and perhaps a more robust selection of the current resonance among those at the 2:1 commensurability of mean motions.

Finally, there is the puzzle of the currently large eccentricity (0.02) of Mimas. From Equation 9, the time constant for damping the Mimas eccentricity is somewhat $> 10^8$ years, where Mimas is assumed to be a homogeneous sphere of ice with rigidity $\mu = 4 \times 10^{10}$ dynes cm^{-2} and $Q_M = 100$. Mimas eccentricity would have had to have been excited only a few time constants ago for such a large remnant to have survived to the present.

Before the Voyager observations, the origin of the 2:1 Enceladus-Dione simple e -type resonance was accounted for by the same differential tidal expansion of the orbits that we used for the Mimas-Tethys resonance (e.g. Sinclair 1972, 1974; Yoder 1973; Peale 1976). Dione is $> 14\times$ more massive than Enceladus, but this mass is less than the factor by which the Tethys mass exceeds that of Mimas, so the Enceladus orbit expands sufficiently fast to approach the 2:1 commensurability. The current eccentricity ($e_E = 0.0044$) is less than the maximum value that would allow certain capture ($e_E = 0.019$) (Sinclair 1972; Yoder 1973; Peale 1976), and was smaller in the past; apparently Enceladus has automatically evolved into the 2:1 libration. However, the existing resonance, in which the Enceladus eccentricity is forced, is the last resonance to be encountered in the set of resonances listed above in the Mimas-Tethys discussion. Moreover, the small inclinations, $i_E \approx i_D \approx 0.02^\circ$, would have led to certain capture into any of the i -type resonances. The i -type resonances could have been avoided only if the inclinations were bigger in the past to make the captures probabilistic. Sinclair (1974) shows how the inclinations could be reduced from such larger values in probabilistic escapes from the inclination-type resonances to arrive at their current values prior to a probabilistic escape from the first eccentricity resonance and certain capture into the second where we find the system today. If the current eccentricity corresponding to the libration amplitude of 1.5° (Sinclair 1972) is carried backward to the time of capture, the average eccentricity would have been only 1.15×10^{-4} (Yoder 1973; Peale 1976). For this value of e_E , $\dot{\omega}_{Eres} + \dot{\omega}_{Esec} = -952^\circ/\text{yr} \ll \dot{\omega}_E = -152^\circ/\text{yr}$, where Equation 17 was used. If Dione eccentricity was no smaller before capture than it is now, $\dot{\omega}_{Dres} + \dot{\omega}_{Dsec} = 24.7^\circ/\text{day}$. Hence the simple e -type resonance in which we find Enceladus and Dione was librating long before any of the other resonances were encountered. This libration does not affect the evolution through the other resonances, so the conditions for avoiding capture in these resonances still apply (Sinclair 1983). Note that we would have overlapping resonances here without necessarily creating chaotic motions, since the inclinations are independent of the eccentricities as long as both are small. Recall that Io and Europa are librating simultaneously in two first-order e -type resonances at the same commensurability with no chaos. On the other hand, there may be some interesting dynamics when the system passes through the mixed e -type resonance while librating in the first-order resonance involving e_E . (Note the contrast with the situation with Io, where

essentially the same eccentricity is thought to be an equilibrium value and accounts for the hot Io interior through tidal dissipation. The equilibrium eccentricity for Enceladus would be 0.03, if the satellite remained a homogeneous sphere with $\mu = 4 \times 10^{10}$ dynes cm^{-2} , $Q_E = 100$ and $Q_S = 1.7 \times 10^4$, the minimum average value.) Numerical integrations through the resonances at rates sufficiently slow to avoid artifacts, with a thorough coverage of the likely available phase space, and with interpretations in terms of modern nonlinear dynamics, have not been done. In addition, the appearance of Enceladus and its surrounds strongly indicates that evolution into the simple 2:1 e -type resonance with Dione may be only part of a more exotic history experienced by this strange satellite.

Enceladus is the most geologically evolved and youthful of all of the Saturn satellites (Smith et al 1982), so its evolution must have been very special indeed. The youngest terrain is crater-free at a resolution of 4 km with an upper limit on its age of $\sim 10^9$ years (Smith et al 1982). The geometric albedo is 1—as if the surface has a fresh dusting of frost; the E-ring of Saturn, a diffuse thick ring extending from 3 to 8 Saturn radii (R_S), has its maximum surface brightness at the distance of Enceladus from Saturn. The ring particles are of the order of $1 \mu\text{m}$ in size and have relatively short lifetimes in orbit (Horanyi et al 1992). The circumstantial evidence thereby points to Enceladus as the active source of the E-ring particles to account for the concentration of particles at that distance from Saturn and to restore the losses (Pang et al 1984). Study of the dynamics of the E-ring particles—assumed to originate from the surface of Enceladus under the control of gravitational, radiation, and electromagnetic forces—leads to a distribution of particles that reproduces the observable characteristics of the ring (Horanyi et al 1992, Horanyi 1996). Such activity requires an energy source, and the only viable source proposed is again tidal dissipation within the satellite.

The apparent erasure of surface features by deposition of material from the interior implies that some part of the interior is in a molten state. According to Squyres et al (1983), the minimum heating rate required to initiate melting in Enceladus is $\sim 2 \times 10^{17}$ ergs/s, whereas current tidal heating provides only 6.2×10^{14} ergs/s, where a homogeneous body with $Q_E = 20$ and rigidity $\mu = 4 \times 10^{10}$ dynes cm^{-2} are assumed. If Q_E were a sufficiently rapidly decreasing function of tidal stress, the growth of the Enceladus eccentricity e_E to large values might trigger a melting episode (Yoder 1981b). But because the rate of energy input due to the Enceladus-Dione resonance alone is small, the time scale for eccentricity growth may be too long for this process to be important. If the eccentricity forcing were removed, a largely molten Enceladus would quickly damp the eccentricity and could freeze by conduction and radiation alone in 5×10^7 years.

Squyres et al (1983) find that the orbital eccentricity must be at least 5–7 times the current value of 0.0044 to maintain a molten interior against the cooling effects of convection, conduction, and radiation if the interior is pure-water ice, and it must be higher by a factor of 20 to initiate melting of an initially completely frozen body. The model here is of a solid-ice crust of varying thickness over a completely melted inner core. Since the equilibrium eccentricity varies as $Q_S^{-1/2}$

(Yoder & Peale 1981), the latter eccentricity of nearly 0.09 to initiate melting of a solid Enceladus could never occur unless Q_S were reduced by a factor of 10 from the minimum average used above to determine the equilibrium-forced eccentricity of 0.03. If the thermal conductivity was reduced by the inclusion of clathrate hydrates in the icy material, a significant enhancement of the present eccentricity would still be required to initiate melting, but it might be possible to maintain a molten interior and allow geologic activity with the present eccentricity. However, the conditions are too specific to be likely, and the supposition does not pass the Mimas test as pointed out by Squyres et al (1983). Mimas is comparable in size with Enceladus, it has a much larger eccentricity, and it is close to Saturn. Yet Mimas does not show any sign of tidal heating. If Enceladus contains a significant amount of ammonia along with water, the heating required is a few times less than 10^{17} ergs/s (Stevenson 1982; Squyres et al 1983). Could Enceladus have more NH_3 than Mimas, and thereby decrease, the heating requirement? Maybe, but no NH_3 has been detected on the surface.

In another attempt to account for the geologic activity, Lissauer et al (1984) noticed that Janus (SX) was just outside the 2:1 commensurability with Enceladus. Spiral density waves generated by Janus in the A-ring lead to torques on the satellite that would place it at the 2:1 commensurability only ~ 15 MY ago. If Janus were locked in the 2:1 eccentricity resonance that forced the Enceladus eccentricity, the relatively strong ring torques might force sufficient eccentricities on Enceladus for a melting episode. If we insert $T = 8.78 \times 10^{20}$ g cm² sec² (Lissauer & Cuzzi 1982), for an assumed ring-surface density of 50 g cm⁻², into Equation 16 along with the parameters for the Janus-Enceladus-Dione system assumed to be in a Laplace-type resonance, $H = 6.8 \times 10^{16}$ ergs/s for the three-body case and 4.5×10^{16} ergs/s if Dione is not involved. These values are close to those required by Squyres et al (1983) for melting Enceladus. Only Enceladus would have a significant forced eccentricity in either the two-body or the three-body cases (Lissauer et al 1984), so all the energy is deposited in Enceladus.

There are numerous problems with this scenario. First, the small mass of Janus means the 2:1 resonance is not very stable. The small width of the resonance means that fluctuations from other perturbations (e.g. from Titan) could disrupt the resonance. A Janus-Enceladus resonance is not likely to survive the encounter with Dione since the latter would induce fluctuations that were larger than the resonance width, while Enceladus was still far from the 2:1 resonance with Dione. Since the time to freeze Enceladus after the eccentricity has damped is at most $\sim 5 \times 10^7$ years (Squyres et al 1983), the resonance must have been as its peak a shorter time into the past if Enceladus is to be still active in keeping itself white and in supplying E-ring particles.

Lissauer et al (1984) point out that the ring torques are so strong that it is a puzzle that the small satellites inside Mimas have remained so close. All of these satellites would have been at the outer edge of the A ring only 50 MYA if the torques are correctly determined. Having some of the small satellites trapped in resonances with the intermediately sized satellites farther out would allow transfer

of angular momentum that would permit their continued proximity to the rings, but we have already seen some of the difficulties with this scenario. Having these satellites recently formed from the debris of a catastrophic disruption of a larger body is another possibility as discussed above. But a more serious problem is that the amount of angular momentum available in the A-ring could not supply the small satellites for more than $\sim 10^8$ years (Lissauer et al 1984). This situation poses another potential problem for the Janus-Enceladus resonance in providing the energy for resurfacing, since Squyres et al (1983) argue that the resurfacing has been going on for much longer than this.

It is clear that the means by which tidal dissipation could have resurfaced Enceladus has not been secured. A careful numerical analysis of the system from the modern dynamics point of view should be undertaken with a thorough exploration of the phase space. There may be chaotic behavior and/or secondary resonances that could significantly increase the dissipation beyond that deduced by Equation 8. At the same time, there are no obvious dynamical means to account for the resurfacing of relatively small parts of Dione, Rhea, and Tethys as pointed out by Smith et al (1981, 1982).

In the Titan-Hyperion 4:3 *e*-type orbital resonance, conjunctions librate about the Hyperion apoapse with an amplitude of 36° and a period of 2 years. The distance of close approaches is thereby maximized, and Hyperion owes its continued existence to the resonance. The evolution of the Hyperion shape is easy to understand given the local dynamics. Impacts repeatedly chip away at all small satellites, but normally much of the material escaping from the surface is recollected in a relatively short time or reassembled into new satellites as must happen in the small satellite-ring region. However, anything escaping from Hyperion is likely to have sufficient initial velocity to escape the protective resonance with the giant Titan. No longer protected from close approaches to Titan, the escaped material is quickly eliminated from the region and relatively little of it reaccretes onto Hyperion (Farinella et al 1990). The remnant of this process is the flattened hamburger shape (Smith et al 1982). The large gravitational torques on the asymmetric satellite coupled with the highly eccentric orbit do not permit the normal tidal evolution to synchronous rotation. Tides slow the satellite until it enters a chaotic zone where it is condemned to tumble chaotically for its remaining lifetime in the resonance (Wisdom et al 1984).

Analytic descriptions of the Titan-Hyperion 4:3 orbital resonance are generally not adequate representations of the motion (Sinclair & Taylor 1985). The close proximity of the orbits and the high eccentricities cause very slow convergence of the series expansions. Still, it was used as the model for a simple *e*-type resonance, which led to an understanding of capture into such resonances as the inner orbit was expanded by tides (Greenberg 1973b). Colombo et al (1974) demonstrated capture as the Titan orbit was expanded by tides, but their conclusions are suspect because they accelerated the evolution by 10 orders of magnitude to allow the numerical computation to proceed. Such accelerations are known to introduce artifacts into the calculations (Tittmore & Wisdom 1988), although artificially

high evolution rates are more likely to frustrate capture rather than to cause it. Tidal origin of the Titan-Hyperion resonance would seem to be precluded, since Q_S for Titan's tides must be >1 order of magnitude smaller than the minimum average tidal $Q_S = 1.7 \times 10^4$ established by the proximity of Mimas to Saturn (Colombo et al 1974). However, our limited knowledge of dissipative processes in gaseous planets does not prohibit Q_S having sufficient amplitude and/or frequency dependence to be low enough for Titan for significant tidal expansion of the Titan orbit while being high enough for Mimas to keep the latter close to Saturn. A careful investigation of the dynamics of the Saturn atmosphere as perturbed by the tide-raising potentials would seem appropriate (see Ioannou and Lindzen 1993).

Peale (1995), while assuming that significant tidal expansion of the Titan orbit occurred, has shown that Hyperion would suffer close approaches to Titan long before the orbits approached the 4:3 commensurability unless the satellites were trapped in a secular resonance that kept the lines of apsides nearly aligned during the tidal approach ($\varpi_H - \varpi_T$ librates about 0°). Moreover, the initial value of a_T/a_H must be $\gtrsim 0.806$ to prevent capture into other resonances before the 4:3 resonance was encountered. The current characteristics of the resonance are produced for initial conditions $(a_H, e_H, f_H, \varpi_H) = (1.171, 0.02, 36^\circ, 0^\circ)$ and $(a_T, e_T, f_T, \varpi_T) = (0.944, 0.025, 0^\circ, 0^\circ)$, where the semimajor axes are in units of the current a_T and f is the true anomaly. To move Titan from $a_T = 0.944$ to 1.0, in 4.6×10^9 years, $Q_S \approx 900$. This Q_S necessary for the 5.9% expansion in the Titan orbit is smaller than that obtained by Colombo et al (1974), who used 1.5 instead of 0.317 for the Saturn Love number. Capture into the 4:3 resonance is always certain once Hyperion is in the secular resonance with Titan. Hyperion eccentricities large enough for probabilistic capture lead to circulation of $\varpi_H - \varpi_T$ with inevitable destruction of Hyperion or escape to solar orbit.

The resonance could also be approached from initially nonresonant orbits if Titan experienced little or no tidal evolution, but Hyperion spiraled in from a larger orbit due to a nebular drag. This drag would act the same way as the solar nebular drag acts on planetesimals because of the differential orbital velocities between the gas and solid bodies. As a Saturn nebula would be rather short-lived, this drag evolution would have to be fairly rapid. But a few numerical integrations with nebular drag on Hyperion show that the libration is almost completely damped. Only if the current libration amplitude of 36° could be regenerated from the cometary collisions that chipped away at the original Hyperion could this origin of the resonance be viable. This possibility has not been investigated.

An alternative to a tidal or nebular drag origin of the 4:3 resonance would be for Hyperion to have accreted from material previously trapped within the secular and/or the 4:3 mean motion resonances. If Titan formed by runaway accretion, it would have been in existence before the smaller Hyperion could have formed and would have cleaned out all the material that was not protected by libration within the resonances. But accretion within the 4:3 resonance, in addition to having less material available, might be prevented because of the increased velocity dispersion for the nonresonant bodies induced by Titan. These bodies would crash into

the resonant satellitesimals, the pieces would scatter into nonresonant orbits and eventually be eliminated from the region. Of course, other small bodies would be scattered into the resonance by the same collision process and could accrete onto the forming Hyperion. The investigation of the efficiency of accretion in the 4:3 resonance while particles perturbed by Titan into high relative velocities are bombarding the resonance zone may decide the feasibility of a primordial origin.

The tidal origin of the current 4:3 resonance suffers from the requirement that Q_S be relatively small for Titan-induced tides while requiring a high Q_S for Mimas-induced tides. The nebular drag origin suffers from the necessity to regenerate the libration amplitude that would be damped to nearly zero. The primordial origin suffers from the rapid elimination of all nearby material not in resonance and the high velocity dispersion of that material, which can lead to chipping away at the resonant material before it can accumulate into a Hyperion-sized body. It is clear that we do not yet know how to create the Titan-Hyperion orbital resonance in a robust scenario.

8. URANUS SYSTEM

The Uranian satellite system consists of 10 small satellites inside 3.4 Uranus radii (R_U) (Smith et al 1986): the classical satellites of Miranda (UV), Ariel (UI), Umbriel (UII), Titania (UIII), and Oberon (UIV), distributed from 5 to $17R_U$, as well as two recently discovered retrograde satellites (Gladman et al 1998, Nicholson et al 1998) at 278 and $477R_U$. All of the satellites are regular except the last two, although the Miranda orbital inclination of 4.22° might lead to an irregular classification. However, we shall see that this inclination is due to evolution from an initially small value within an orbital resonance (Tittlemore & Wisdom 1989; Malhotra & Dermott 1990). There are no current orbital resonances among these satellites.

Like the irregular satellites of Jupiter, the evolution of the two outlying satellites, after their probable capture from close encounter or collision of heliocentric planetesimals within the Uranus sphere of influence, is limited to occasional change in orbital and rotation states from collisions with Uranus family comets with subsequent relaxation to principal axis rotation. The inner satellites are embedded in an extensive ring system, where repeated collisional disruption and reassembly have led to the current configuration of small satellites and rings (Smith et al 1986; Colwell & Esposito 1992). In particular, the shepherd satellites of the ϵ ring, Cordelia (UVI) and Ophelia (UVII), are likely products of a collisional disruption of a 100-km radius precursor satellite that simultaneously created smaller particles now confined to the ϵ ring (Colwell & Esposito 1992). Application of Equation 6 shows that the most distant inner satellite, Puck (UXV) at $3.36R_U$, slows from an initial 4-h period to synchronous rotation in $\sim 2 \times 10^4$ years, where a homogeneous sphere with rigidity $\mu = 4 \times 10^{10}$ dynes cm^{-2} , $\rho = 1 \text{ g cm}^{-3}$ (ice), and $Q = 100$ being assumed. The rotational decay times of the closer satellites are at

most about twice this value. The most distant of the larger satellites, Oberon, would reach synchronous rotation from an initial 4-h period in $<3 \times 10^7$ years, where $\mu = 10^{11}$ dynes cm^{-2} and $Q = 100$ were assumed. The closer large satellites reach synchronous rotation in shorter times, and observations verify synchronous rotation for all five satellites (Yoder 1995).

The five larger regular satellites show a wide variety of surface characteristics. The cratering record implies that Oberon and Umbriel have very old surfaces, although the uniformly dark surface of Umbriel implies some kind of recent blanketing by fine debris whose nature and source are unknown (Smith et al 1986, Croft & Soderblom 1991). Whether Umbriel and Oberon have had extensive resurfacing is controversial (Croft & Soderblom 1991); if so, the resurfacing would have had to occur early in the accretion process to allow the preservation of the large numbers of large craters (>100 km diameter). Ariel, Miranda, and Titania show extreme to moderate resurfacing at times reasonably distant from the time of diminished bombardment. Titania has a surface age that is intermediate between that of Ariel and those of Umbriel and Oberon, and its lack of very large craters emplaced during the heavy bombardment means it has been completely resurfaced since that time (Plescia 1987a). Ariel has also been completely resurfaced since the heavy bombardment, and a second wave of resurfacing has yielded the youngest surfaces among these five satellites with the exception of Miranda (Plescia 1987a). Smith et al point out that varying crater densities on fault scarps and on smooth terrain in the bottom of grabens on Ariel implies that the resurfacing on this satellite persisted over much of the period of small crater emplacement. Ages of the various surface units on Ariel are model-dependent and very difficult to constrain, but Plescia (1987b) finds that all the new surfaces on Ariel were emplaced over a relative short period $>2.6 \times 10^9$ years ago.

Miranda has one of the most bizarre surfaces of any satellite in the solar system. Older terrain cratered densely with the smaller craters is interrupted with oval and trapezoidal patterns of concentric grooves and ridges (called *coronae*)—as if viscous material welled up from the interior at three particular spots (Pappalardo et al 1997) [but see Greenberg et al (1991) and Croft & Soderblom (1991), where the latter favor an infilling of impact-generated giant basins]. The discussion of Miranda is complicated by differing points of view on the cratering history and chronology of the various surface emplacements as pointed out in Greenberg et al (1991), but the coronae on Miranda are among the youngest surfaces in the Uranus system (Plescia, 1988). Grabens on Miranda, Ariel, and Titania imply a moderate global expansion—possibly due to internal heating after a very cold formation (Croft & Soderblom 1991). Extrapolation of the cratering flux at Oberon to Miranda implies that Miranda was probably broken up by catastrophic impact at least once in its early history (Smith et al 1986, McKinnon et al 1991, Marzari et al 1998). Perhaps such a breakup and reassembly could account for the initial resurfacing of Ariel and Titania as well.

What has caused the resurfacing of the Uranian satellites? The system is remarkable in having no orbital resonances in contrast to the satellite systems of

Saturn and Jupiter. But the resurfacing of the satellites, as well as the anomalously high 4.2° inclination of the Miranda orbit, has motivated extensive investigations of possible past orbital resonances, their tidal dissipation within, and their ultimate disruption (Peale 1988, Tittlemore & Wisdom 1988, 1989, 1990, Dermott et al 1988, Malhotra & Dermott 1990, Tittlemore 1990). Most have used the nominal masses for the satellites in these studies, but Peale (1988) demonstrates a variety of evolutions that depend on the satellite masses within the errors of their determinations. The 1σ errors for the satellite masses have been reduced by about a factor of 2 (factor of 3 for Miranda) since the Peale study (Jacobson et al 1992), and the nominal masses of Miranda and Ariel would now have to be changed by $\sim 3\sigma$ in opposite directions to change the current divergence of the orbits under differential tidal expansion to convergence. Although this mass dependence of possible evolutions should be kept in mind as refined mass determinations are made, we shall assume the nominal masses adopted by the authors of tidal evolution scenarios yield the correct directions of approach to the resonances. The evolutionary scenarios have been at best only marginally or speculatively successful in obtaining sufficient tidal dissipation in the satellites to account for the resurfacing of Ariel or Miranda, but they have been so successful in accounting for the high orbital inclination of Miranda due to the 3:1 Miranda-Umbriel orbital mean motion commensurability that a reasonably robust upper bound of $Q_U/k_U \lesssim 3.9 \times 10^5$ is determined to ensure that the system passed through this resonance (Tittlemore & Wisdom 1989).

Dermott (1984) remarked that since the gravitational coefficient $J_2 = 0.003343$ (Yoder 1995) for Uranus is small, the several resonances at each of the commensurabilities may not be separated sufficiently in frequency to be treated under the single resonance theory discussed by several authors (e.g. Yoder 1973; Henrard 1982; Henrard & Lemaître 1983; Peale 1986, 1988) and used above for the Saturn and Jupiter satellite orbital resonances. The resulting possibility of widespread chaos during resonance passage meant that the predictions of the single-resonance theory discussed by these authors are not valid for the Uranian satellites. The single-resonance theory was indeed found not to apply to most of the Uranus resonances discussed, when modern numerical and analytical techniques were used (Tittlemore & Wisdom 1988, 1989, 1990; Dermott et al 1988; Malhotra & Dermott 1990; Tittlemore 1990). Two fundamentally new dynamical results came from the analysis of the Uranus satellite resonances: first, the rate at which a chaotic system could be carried through a resonance (i.e. the magnitude of the tidal torque) without introducing artifacts into the results of the integrations was 10 to $1000 \times$ slower than the rate that satisfied the adiabatic invariance of the action integral in single-resonance theory (Tittlemore & Wisdom 1988, 1989, 1990); second, a librating system in a stable resonance could be trapped into a secondary resonance between the libration frequency and other nearby frequencies, such as the circulation frequency of another resonance variable associated with the same mean motion commensurability, and dragged during continued tidal evolution into a chaotic zone thereby disrupting the original resonance (Tittlemore & Wisdom 1989). This

secondary resonance evolution can be displayed dramatically in the circular inclined or planar elliptic approximations where two degrees of freedom allow the construction of surfaces of section. But the secondary resonance capture persists in the full problem with its several degrees of freedom (Tittmore & Wisdom 1989). Malhotra & Dermott (1990) and Malhotra (1990) elaborated the theory of secondary resonances.

For quasiperiodic motion, it is clear that the results of an integration will not represent a real resonance encounter and the action of the librational motion will not be adiabatically conserved if the rate of evolution is so high that there is a significant change in the libration frequency during the time of a single libration. Hence, $\dot{\omega}\tau/\omega \ll 1$ is a necessary condition for adiabatic invariance of the action integral, and the results of the integration would normally be expected to be invariant as long as the rate of evolution was slow enough for this inequality to be satisfied. Here ω is the frequency of libration, τ is its period, and the dot indicates time differentiation. However, if the motion is chaotic from the interaction with nearby resonances, invariance of the integration results are attained for rates slower than some maximum only if a chaotic adiabatic invariant exists that is defined for a two-degree-of-freedom problem as the phase space volume enclosed by the energy surface containing the chaotic zone (Brown et al 1987). The chaotic adiabatic invariant exists if the trajectory in phase space has time to thoroughly explore the chaotic zone before there is significant change in the configuration (Tittmore & Wisdom, 1988). The rates of evolution consistent with this criterion, where results become independent of the rate of evolution, were shown to be 10 to 1000 times slower (depending on the resonance), than those allowed by the criteria for adiabatic invariance in the single resonance theory. The maximum rate of evolution in this case can be determined only by numerical experiment. In some resonances, the results of the integrations remained dependent on the rate of integration even at rates less than those allowed by the physical constraints (Tittmore & Wisdom 1990).

We now investigate the consequences of differential tidal evolution of the orbits where the Uranus Q_U is assumed the same constant for all of the satellites. Ariel's orbit expands faster than that of Miranda in spite of its greater distance from Uranus since its mass is so much larger. This expansion requires the average $Q_U/k_U \gtrsim 66,000$, since the two orbits would be coincident 4.6×10^9 years ago for Q_U/k_U at the lower bound. Peale (1988) has shown the important first- and second-order resonances that could have been encountered for this maximal evolution of the system. Miranda would have passed through the 4:3, 3:2, and 5:3 commensurabilities with Ariel, but close approaches between Miranda and Ariel inside the 4:3 resonance would have eliminated Miranda from the system, so the lower bound on the average Q_U/k_U would have to be increased over the above value to start the system outside the 4:3 resonance. Because the differential tidal expansions cause the orbits to diverge, all of the Miranda-Ariel resonances are approached from the wrong direction for capture (e.g. Peale 1986, Tittmore & Wisdom 1989). Still, passage through the large chaotic zone of the 5:3

commensurability leads to chaotic variations of the eccentricities and inclinations of both satellites with maxima $e_M \lesssim 0.03$, $e_A \lesssim 0.007$, $i_M \lesssim 1.5^\circ$, $i_A \lesssim 0.35^\circ$, where values of the inclinations and eccentricities before resonance encounter for both satellites were 0.005 radians and 0.005, respectively (Tittlemore & Wisdom 1990). The system leaves the 5:3 resonance region with e_M and i_M about twice the initial values and e_A and i_A slightly below their initial values. There is insignificant heating of Miranda or Ariel either during or after this resonance passage as the eccentricities damp according to Equation 9 (Tittlemore & Wisdom 1990). It is noteworthy that there is no chaotic adiabatic invariant for this resonance down to an evolution rate within the physical constraints, so the integrations were carried out at a rate corresponding to $Q_U/k_U = 1.1 \times 10^5$, the tentative lower bound justified below.

After leaving the 5:3 commensurability with Ariel, Miranda passes through the 3:1 commensurability with Umbriel with profoundly important consequences. For inclinations and eccentricities before resonance encounter at 0.005 radians and 0.005, respectively, for both satellites, the resonances are encountered in the order $(\lambda_M - 3\lambda_U + 2\Omega_M)$, $(\lambda_M - 3\lambda_U + \Omega_M + \Omega_U)$, $(\lambda_M - 3\lambda_U + 2\Omega_U)$, $(\lambda_M - 3\lambda_U + 2\varpi_U)$, $(\lambda_M - 3\lambda_U + \varpi_M + \varpi_U)$, $(\lambda_M - 3\lambda_U + 2\varpi_M)$. The most important event in the passage through this series of resonances at the 3:1 commensurability is capture into either the i_M^2 or the $i_M i_U$ resonance corresponding to the first two resonance variables involving the node of the Miranda orbit. In either of these resonances the Miranda inclination is driven to large values as tidal evolution of the orbits continues. As the inclination grows, the frequency of libration within the resonance increases and approaches low-order commensurabilities with the circulation frequency of the i_U^2 resonance variable third in the above list. The system can be trapped in one of these secondary resonances where subsequent evolution drags the trajectory into the chaotic zone where the system ultimately escapes the primary resonance involving the Miranda node. The value of i_M after escape from the resonance depends on the particular trajectory through the phase space, but it is always comparable with the observed large value of 4.22° (Tittlemore & Wisdom 1989, 1990). There appears to be a correlation of the peak of the distribution of remnant inclinations of the Miranda orbit with the particular secondary resonance that drags the trajectory into the chaotic zone. The 2:1 secondary resonance produces inclinations that tend to be too high, the 4:1 too low, and the 3:1 close to the observed value (Malhotra & Dermott 1990). This natural explanation for the anomalously high inclination of the Miranda orbit leads one to infer that the system must have passed through this resonance. This requirement places a reasonably robust upper bound on $Q_U/k_U \lesssim 3.9 \times 10^5$ (Tittlemore & Wisdom 1989).

After escape from the inclination resonances at the 3:1 commensurability of mean motions, the Miranda-Umbriel system passes into a large chaotic zone associated with the eccentricity resonances corresponding to the three resonance variables that include the longitudes of periape. The Miranda eccentricity may reach values as large as 0.05 or 0.06 (Tittlemore & Wisdom 1990) during the chaotic fluctuations, but the short time scale of these excursions leads to

negligible heating of the interior. From Equation 8, the rate of energy dissipation in Miranda is $dE/dt \approx 7.4 \times 10^{18} e_M^2$ ergs sec^{-1} , where the rigidity of ice $\mu = 4 \times 10^{10}$ dynes cm^{-2} and $Q_M = 100$ are used. During a peak in the fluctuation of $e_M \approx 0.042$ averaged over 3 million years, a total energy deposition of $\sim 1.2 \times 10^{30}$ ergs would raise the average temperature of Miranda only ~ 1 K. If one treats a conductive body in thermal equilibrium, imposes a low thermal conductivity by assuming a methane-water clathrate outer layer (Stevenson 1982) and a low melting point by assuming that much of Miranda is made of an $\text{H}_2\text{O}-\text{NH}_3$ eutectic with a melting point of 175 K (Cynn et al 1988) and assumes a phase space trajectory that keeps the eccentricity high through the chaotic zone and leaves a high remnant eccentricity after escape from the resonance, and perhaps throws in some remnant heat from accretion (Squyres et al 1988), one could melt some of the interior of Miranda in the 3:1 resonance with Umbriel. But these conditions are too numerous and too special to be likely, although Croft & Soderblom (1991) argue for the $\text{H}_2\text{O}-\text{NH}_3$ composition.

During the excursion through the chaotic zone associated with the eccentricity resonances, Miranda inclination remains near its escape value of $\sim 4^\circ$, albeit while undergoing small, chaotic oscillations. Most importantly, the high inclination always survives the eccentricity resonance passage to emerge as the observed remnant. Throughout the evolution through this commensurability, the eccentricity and inclination of Umbriel undergo chaotic oscillations but of small amplitude, and its remnant eccentricity and inclination are negligibly different from initial values. The remnant Miranda eccentricity could be relatively large or small, but the largest remnant eccentricity obtained by Tittlemore & Wisdom (1990) for the full three-dimensional problem was only 0.02. Finally, we note in passing that the three-dimensional problem (eccentric, inclined orbits) with its interconnected chaotic zones apparently has no chaotic adiabatic invariant when Miranda inclination is large—down to evolution rates less than those imposed by physical constraints. Therefore the rate of evolution through this resonance cannot be accelerated above the physically realistic rate without introducing artifacts into the integrations of the full three-dimensional problem (Tittlemore & Wisdom 1990).

The 3:1 Miranda-Umbriel resonance was the last chance to heat Miranda in a resonance, which we see can result in melting part of the interior by only a rather unlikely set of contrived circumstances. How then can one account for the youngest surface area among all of the major satellites surrounded by heavily cratered terrain? The catastrophic disruption and reassembly of Miranda has been suggested as a possible energy source for the ensuing geologic activity (Smith et al 1986, McKinnon et al 1991, Marzari et al 1998). Even the cratered terrain is younger than the old Umbriel and Oberon surfaces because large craters are missing. Calculations of both initial accretion (Squyres et al 1988) and reassembly after catastrophic disruption (Marzari et al 1998) show very short time scales for the process ($\lesssim 1000$ years). The accretional heating may create a warm, buoyant mobile zone tens of kilometers below the surface if NH_3 and CH_4 are major constituents of the ice, but little resurfacing could be initiated if pure H_2O ice

dominates the interior (Squyres et al 1988). On the one hand, these conclusions are model-dependent and may be no more secure than those from the tidal heating hypothesis. On the other hand, the bouyant layer somewhat below the surface would be consistent with an upwelling of viscous material to form the coronae on the Miranda surface (Pappalardo et al 1997), but other processes are not ruled out (Greenberg et al 1991). The model dependence of schemes to resurface Miranda may mean we shall never find a secure explanation, but accretional heating during reassembly after disruption may be the most probable.

Another attempt to heat Miranda with tidal friction (Marcialis & Greenberg 1987) relies on the fact that very deformed satellites enter a zone of chaotic tumbling as they approach synchronous rotation (Wisdom et al 1984, Wisdom 1987a,b). In this scheme, a shattered early Miranda reaccretes into a sufficiently asymmetric body that it undergoes chaotic tumbling while in a reasonably high eccentricity orbit. This scheme is analogous to the chaotic tumbling of Hyperion, which, however, is still extant because its eccentricity is kept high by the 4:3 orbital resonance with Titan. Miranda would maintain chaotic tumbling only during the decay of its eccentricity and perhaps a short time after e_M was small and/or its asymmetry was relaxed before being trapped into synchronous rotation. If one assumes that any *tumbling* after the eccentricity is small is of inconsequential duration, then the total energy that can be deposited in the satellite is $\sim e_{M0}^2 E_M$, where e_{M0} is the initial value of e_M and E_M is the current orbital energy of the satellite. This result follows from the fact that the spin angular momentum of Miranda is only a few parts in 10^5 of the orbital angular momentum, so the chaotic tumbling results in only small fluctuations in the latter. The orbital angular momentum being essentially conserved on the average is $\sqrt{GM_U a_M (1 - e_M^2)}$, and we can relate de_M^2/dt to dE_M/dt through da_M/dt . If $e_{M0} = 0.1$, as assumed by Marcialis and Greenberg, the total energy available would be $\sim 0.01 E_M = 3.8 \times 10^{32}$ ergs or 5.8×10^9 ergs per gram. With a specific heat for ice of $\sim 1.3 \times 10^7$ ergs $g^{-1} K^{-1}$, the energy is sufficient to raise even water ice to its melting point and to melt a considerable fraction of the interior if all of the heat were contained. This energy is available if the satellite is tumbling or if it is locked in synchronous rotation during the decay of the eccentricity. The only difference between the two situations is that the eccentricity would be damped rapidly if chaotic rotation prevailed and slowly if synchronous rotation prevailed. The rapid deposition of the energy in the former case would allow insufficient time for much of the energy to escape through conduction or solid-state convection and more likely lead to internal melting.

As attractive as this scheme may seem from the energy point of view, there are several problems with it. First, it is very unlikely that Miranda could accrete gently in large pieces after being broken up by a catastrophic collision. The products of the collision would most likely suffer additional collisions and be further broken up before relaxing to a dissipative disk. From such a dissipative disk, the final eccentricity of the reaccreted satellite is likely to be small rather than 0.1 as assumed by Marcialis & Greenberg. Next, after the reaccretion there has to be sufficient

time to establish the densely cratered surface on Miranda before the resurfacing took place. But the time scale for damping the eccentricity and simultaneously softening Miranda to relax to a nearly spherical shape could be as short as 6000 years (Greenberg et al 1991)—much too short for all of the geologic scenarios to have taken place. We are left without an acceptable means to account for the bizarre surface of Miranda.

If Miranda and Umbriel necessarily passed through the 3:1 mean motion commensurability, then Ariel and Umbriel passed through the 5:3, which is the most recent first- or second-order resonance to have been traversed (e.g. Peale 1988). The only treatment of passage through this resonance is the planar approximation by Tittlemore & Wisdom (1988). The eccentricity resonances at the 5:3 mean motion commensurability involve a large chaotic zone separating circulation and libration of the resonance variables. The probability of not being captured in the resonance is no longer determined by a uniform distribution of random phases as in the single resonance theory (e.g. Peale 1986) because the trajectory in phase space can spend a considerable amount of time in the chaotic zone. The numerically determined probability of escape from this resonance is $\sim 30\%$ in the planar approximation (Tittlemore & Wisdom 1988), where significant remnant orbital eccentricities might account for the somewhat high current eccentricities of the orbits of Umbriel and Ariel. However, at no time were eccentricities maintained in either the Ariel or the Umbriel orbit during and after the resonance passage sufficient for significant tidal heating.

Including dissipation in the satellites as well as inclination terms in the analysis could significantly change the evolutionary results of this study—the first by keeping the eccentricities at lower values than those obtained by Tittlemore and Wisdom and the second by possibly forcing higher eccentricities (Tittlemore & Wisdom 1988). Given the results of the planar problem, it is probably the case that a complete three-dimensional treatment of passage of Ariel and Umbriel through the 5:3 commensurability, including dissipation in the satellites, will not alter the conclusion of Tittlemore and Wisdom that Ariel could not have been heated sufficiently to account for its resurfacing. But we have been surprised many times in the past, so it would be prudent to carry out the calculations to be sure.

One last attempt to resurface Ariel through tidal dissipation involves a possible 2:1 resonance between Ariel and Umbriel (Peale 1988; Tittlemore & Wisdom 1990). If this resonance is to be encountered $Q_U/k_U < 1.1 \times 10^5$. If the resonance is approached with small eccentricities in both orbits, as is likely, the motion is dominated by quasiperiodic behavior, and capture into libration for both resonance variables, $((\lambda_A - 2\lambda_U + \varpi_A), (\lambda_A - 2\lambda_U + \varpi_U))$, is apparently certain (Tittlemore & Wisdom 1990). No chaotic separatrices (regions in phase space separating circulation from libration) are crossed in this capture for small eccentricities. Noncapture into the resonance becomes increasingly likely for approach eccentricities > 0.03 for Ariel, where the now interacting resonances at the 2:1 commensurability create substantial chaotic zones. However, approach at such a high value of eccentricity is very unlikely (Tittlemore & Wisdom 1990). Upon

capture into the resonance, the eccentricities grow as tides raised on Uranus force Ariel deeper into the resonance until an equilibrium eccentricity is approached that remains constant thereafter because of dissipation in the satellite. This process was discussed above for the Jupiter satellite Io. If we include the torque T_U on Umbriel in equations analogous to Equations 14 and 15 but with only two satellites, the energy dissipated in the two satellites in an equilibrium configuration is (Peale 1988)

$$\begin{aligned}
 H &= n_A T_A \left[1 - \frac{1 + (m_U/m_A)(a_A/a_U)}{1 + (m_U/m_A)\sqrt{a_U/a_A}} \right] \\
 &\quad + n_U T_U \left[1 - \frac{1 + (m_A/m_U)(a_U/a_A)}{1 + (m_A/m_U)\sqrt{a_A/a_U}} \right] \\
 &= 0.249 n_A T_A,
 \end{aligned} \tag{18}$$

where the symbols are analogous to those in Equation 16 and where the final form uses $T_U/T_A = (m_U/m_A)^2(a_A/a_U)^6 = 0.0469$. Nearly all of this maximum energy dissipation is in Ariel (Peale 1988). From Equations 5, 8, and 18, the equilibrium eccentricity $e_A = 0.018$ for $Q_U/k_U = 1.1 \times 10^5$. Thus, the maximum rate of energy dissipation in Ariel at the time of the necessary disruption of the resonance is 7.7×10^{16} ergs sec $^{-1}$ or 5.69×10^{-8} ergs g $^{-1}$ sec $^{-1}$ averaged over the mass of Ariel. The resonance must be disrupted when $n_A = 1.234 n_{A0}$, with n_{A0} being the current value, if the system is to reach the current configuration (Peale 1988).

If Ariel and Umbriel spent a considerable time in the resonance, then Q_U/k_U would have to be smaller to allow the resonance to begin somewhat before the necessary disruption, n_A and T_A would correspond to smaller semimajor axes, and the corresponding dissipation would have been larger. With a density of 1.67 g cm $^{-3}$, a water ice (1 g cm $^{-3}$) mantle and a rocky core (2.8 g cm $^{-3}$) comprising 61% of the mass would yield a radiogenic heat production rate of $\sim 0.61 \times 1.6 \times 10^{-7}$ ergs g $^{-1}$ sec $^{-1}$ averaged over the Ariel mass, where a time average radiogenic heating rate estimated for the Moon is used (Peale 1988). The tidal heating given above, the minimum at the end of the resonance existence, is about half of the averaged radiogenic heating rate. Although tidal heating would have been larger earlier in the resonance existence, it appears inadequate to account for any melting and resurfacing of Ariel, even if the 2:1 resonance with Umbriel had persisted.

There is a much more serious problem with the 2:1 Ariel-Umbriel resonance—there is no known way to disrupt the resonance once established (Titemore & Wisdom 1990). If the eccentricities were allowed to increase to large values within the resonance, increasing chaos offers the possibility of escape, although capture in secondary resonances (so important in the 3:1 Miranda-Umbriel resonance) do not appear to drag the system into the chaotic zone. Still, such continued growth of the eccentricities would almost certainly result in disruption of the resonance, except dissipation in the satellites places a modest upper bound on $e_A \lesssim 0.02$. Eccentricity would increase to the equilibrium value and sit there indefinitely as the system librates for the remaining existence of the solar system. At least the secular

perturbations (terms in the Hamiltonian with $\varpi_i - \varpi_j$ in the arguments) from Titania do not appear to disturb the resonance (Tittlemore & Wisdom 1990). Perhaps something has been missed that will appear with an integration of the complete system in all its degrees of freedom, and that could disrupt this 2:1 resonance after it was established. For now we must assume that the system never encountered the resonance or it would still be locked within. The almost certain avoidance of this resonance and the almost certain encounter of the 3:1 commensurability between Miranda and Umbriel that so nicely accounts for the large orbital inclination of the former means $1.1 \times 10^5 < Q_U/k_U < 3.9 \times 10^5$ are apparently rigorous bounds on the dissipative properties of Uranus (Tittlemore & Wisdom 1990).

Although a convincing argument for using tidal dissipation to resurface the Uranian satellites may ultimately be constructed, we have so far failed to account for any of the young surfaces on these satellites in a rigorous way. It is significant that Titania has extensive resurfacing but sits between Umbriel and Oberon whose ancient surfaces are completely undisturbed. Titania could have occupied no orbital resonances of first or second order (Peale 1988), although Tittlemore (1990) looked at a possible passage of Ariel and Titania through the 4:1 mean motion commensurability. Here, the Ariel eccentricity could grow to large values that, however, could raise its temperature only ~ 20 K. Titania was still unaffected thermally by this resonance. Higher-order resonances are weaker because of additional factors of e or i in the coefficients of the resonance terms, and one needs to check the stability of such a resonance to perturbations by the other satellites before embracing its consequences. Still, Titania remains untouched by tidal dissipation even if it had occupied third-order resonances with Ariel (Tittlemore 1990).

Titania may be telling us something about our difficulties in obtaining sufficient tidal dissipation to resurface those satellites that did occupy or pass through orbital resonances. If new surfaces on Ariel are indeed 2.6×10^9 years old (Plescia 1987b) and if internal activity can persist as long as one billion years after the initial heat pulse from disruption and reaccretion, perhaps the resurfacing is more due to the accretional heating than to tidal dissipation. Even this scheme may require an $\text{H}_2\text{O}-\text{NH}_3$ eutectic to lower the melting point, and it seems to fail in any case for Miranda (Squyres et al 1988). On the other hand, it is hard to believe that what we see on the surfaces of the Uranian satellites is independent of the evolution caused by the tides.

9. NEPTUNE SYSTEM

The dominant characteristic of the Neptune satellite system is the existence of the large satellite Triton (NI) in a close, circular, retrograde orbit (obliquity 156.8°). Neptune also has relatively few known satellites compared with the other major planets, and all but two of those, Triton and Neriid (NII), were unknown until the Voyager spacecraft observations (Smith et al 1989). Except for Neriid, there are no satellites outside the Triton orbit, and the Neriid orbital eccentricity of 0.75

brings it no closer than $\sim 1.4 \times 10^6$ km from the center of Neptune because of its extremely large semimajor axis of 5.51×10^6 km ($222.6R_N$)—well outside the Triton distance of 3.54×10^5 km ($14.3R_N$, $R_N = 24766$ km). The newly discovered satellites, designated NIII to NVIII from the closest to the farthest, are relatively small satellites in circular, equatorial orbits with the exception of innermost Naiad (NIII), whose orbit is inclined 4.7° to the Neptune equator. All of the small satellites except Proteus (NVIII) are inside the radius where the orbital angular velocity matches the spin angular velocity of Neptune (corotation radius), and the inner four satellites are inside the Roche radius of $2.7R_N$ ($\rho = 1.2 \text{ g cm}^{-3}$). There are two narrow, dusty rings of material, and one wide ring among the inner satellites at $2.54R_N$, $2.15R_N$, and $1.69R_N$, respectively, plus several other less well defined rings and a suspected continuous distribution of dust at very low optical depth everywhere inside $2.38R_N$ (Smith et al 1989). The outer narrow ring contains the famous arcs, which turned out to be three distinct regions of higher optical depth in an otherwise continuous ring (Smith et al 1989).

The massive satellite Triton is blamed for most of the features of this unusual system. The retrograde orbit means that Triton was almost certainly captured intact from heliocentric orbit, most probably by colliding with a satellite already in orbit around Neptune with a mass a few percent of the Triton mass (Farinella et al 1980; McKinnon 1984; Goldreich et al 1989). Such a collision would have been sufficient to capture Triton into a very eccentric orbit extending a major fraction toward the Hill sphere boundary at $r_H \approx (m_N/3m_\odot)^{1/3}a_N \approx 4.5 \times 10^3 R_N$ ($a_N =$ heliocentric distance) while not destroying it. For $1 - e_T \ll 1$, the most relevant evolution rate is that for a_T at fixed periaipse $r_p = a_T(1 - e_T)$, $a_T^{-1} da_T/dt = -(21nR_T^5 k_T)/(64\mu r_p^6 Q_T)$. With plausible estimates of $k_T \approx 0.1$ and $Q_T \approx 100$, Goldreich et al (1989) find that an initial Triton orbit with semimajor axis $a_T \approx 10^3 R_N$ would damp to nearly its current circular orbit with $a_T \approx 14.3R_N$ from tidal dissipation in Triton in ~ 4 to 5×10^8 years—comfortably less than the age of the solar system. The tremendous amount of energy dumped into Triton would melt and differentiate it completely, so Q_T was probably smaller than that assumed during most of the damping time and that time was correspondingly shorter. Consistent with this capture scenario and subsequent melting, Titan was found to have a young and active surface, although that surface activity is almost certainly solar-driven (Smith et al 1989).

While the orbit was so extended, Triton played havoc with the probably initially regular satellite system. Solar perturbations would have periodically driven the Triton periaipse distance down to values as low as 5 to $8R_N$, depending on the initial semimajor axis, before the periaipse asymptotically approached the final circular radius (Goldreich et al 1989). All the satellites outside the minimum periaipse distance of the elongated orbit of Triton have been either consumed by Triton, scattered into Neptune, or put onto escape trajectories—except for Neriid. The latter could have escaped the fate of the others if its initial presumably circular orbit were sufficiently far from Neptune, but not without suffering repeated perturbations that could easily account for the currently very large semimajor axis, eccentricity

and inclination of its irregular orbit (Goldreich et al 1989). Those satellites inside the minimum periaapse distance did not survive unscathed. Current perturbations of the inner satellites by Triton are not significant, but when the Triton orbit was very eccentric an inner satellite would have suffered impulsive perturbations each time Triton passed periaapse. The perturbations of a satellite with semimajor axis greater than $\sim 2R_N$ would have led to chaotic diffusion of the orbital eccentricity and inclination. Outside $\sim 3R_N$ the eccentricity would have reached values such that the satellite apoapse distance could approach the periaapse distance of Triton. Thus Triton probably disposed of some fraction of the inner satellites as well, with any survivors expected to have persisting, substantial orbital inclinations (Goldreich et al 1989). The lack of such inclined orbits among the inner satellites must mean that there are no survivors among those early inner satellites.

The scenario excludes the possibility of collisions among the inner satellites (Banfield & Murray 1992). There are likely to have been several satellites inside the periaapse distance of Triton by comparison with the regular systems of the other major planets. Orbit eccentricities would have been limited to maximum values ~ 0.3 , since the rate of decrease of the eccentricity by tidal dissipation within the satellite exceeds Triton's ability to increase it for larger values (Banfield & Murray 1992). Two satellites with semimajor axes of $3R_N$ and $5R_N$ would have overlapping orbits that would persist in overlapping for times at least of the order of the eccentricity damping time of $\sim 10^8$ years. Recall that Triton eccentricity damps in a time scale several times this value. A collision between any of the current inner satellites of Neptune with its neighbor would lead to their mutual destruction. This follows from the relation (Stevenson et al 1986)

$$\frac{1}{2}m_i v_i^2 \sim m_s S + \frac{3}{5} \frac{G m_s^2}{\gamma R_s}, \quad (19)$$

where m_i and m_s are the masses of the impactor and satellite, respectively, v_i is the relative velocity at impact, R_s is the satellite radius, $S \sim 10^6$ erg g^{-1} is the material binding energy, and $\gamma \sim 0.1$ is a factor introduced to account for the inefficiency in converting the impact kinetic energy into kinetic energy of the fragments. The impactor kinetic energy must exceed the energy stored in material strength plus the self-gravitational energy by a sufficient amount to break up the body. From Equation 19 and eccentricities of 0.3, Naiad (NIII) could destroy all of the satellites except Proteus (NVIII), and any of the satellites NIV to NVII could destroy Proteus. This result implies that the current satellite system could not have existed prior to Triton orbit circularization (Banfield & Murray 1992). The debris from the first generation of satellites would settle into the equatorial plane in circular orbits and recollect into a second generation of inner satellites with nearly circular orbits and zero inclinations, where all memory of Triton perturbations would thereby be lost.

The current system of inner satellites is thought to be still a later generation than that first accreted after the Triton orbit circularized. Only Proteus is thought sufficiently large to have survived estimated cometary impacts (Smith et al 1989).

Banfield & Murray (1992) thus apply Equation 7 only to Proteus to estimate the lower bound on the average Neptune $Q_N = 12,000$ (4×10^9 years/ T_C), where T_C is the time before the present that the Triton orbit circularized. This follows from the condition that Proteus could not have started inside the current corotation radius of $3.25R_N$.

The evolution of the distribution of masses and orbits of the inner five satellites is completely speculative with the exception of the 4.7° inclination of the orbit of innermost satellite, Naiad. All five inner satellites are inside the corotation radius and are therefore spiraling toward Neptune at rates determined by Equation 7. Naiad is so small that its semimajor axis is decreasing from tides raised on Neptune at a rate that is slower than that of any of the other four in spite of its closer proximity to Neptune. Therefore, various mean motion resonances between Naiad and any of the other four satellites are approached from a direction (orbits approaching each other) that allows capture into and evolution within the mean motion resonances. The strongest inclination-type mean motion resonances have i_1^2 , $i_1 i_2$, or i_2^2 in the coefficient of the appropriate term in the disturbing function, where i refers to the respective orbital inclinations to the Neptune equator plane for the two satellites. The importance of these resonances is that orbital inclinations are forced to grow while the system is forced deeper into the resonance by the Neptune tides, which could account for the Naiad inclination of 4.7° (Banfield & Murray 1992), as for the Uranus satellite Miranda (Section 8). Only those resonances with the Naiad inclination in the coefficient need be considered, since such a resonance increases only that inclination and not that of the other resonance member. The other satellites still have orbital inclinations near their initial very small values.

Banfield & Murray (1992) have determined capture probabilities for 35 possible inclination-type resonances between Naiad and the next four satellites. Although the individual capture probabilities are small, the probability that Naiad was captured in one of these particular resonances is $\sim 76\%$. The resonances are disrupted when a secondary resonance between an adjacent primary resonance and the libration drags the system into a chaotic zone (Section 8). The inclination established within the resonance remains after the resonance is disrupted. Three resonances were found to be disrupted when the orbital inclination of Naiad was near the observed 4.7° —NIII-NV 12:10, NIII-NV 11:9, NIII-NV 10:8. The first has the greatest probability of occurrence, and it was chosen by Banfield & Murray (1992) as the best candidate for accounting for the inclination of Naiad. The total probability of occurrence of 4% includes capture into the primary resonance, capture into a 2:1 secondary resonance, and escape at the right inclination. Although this probability is not large, the fact that the probability of getting captured into 1 of 35 primary inclination resonances is 76% means that Naiad probably got caught in one, and this one is as likely as any of the others—and it matches the observations (Banfield & Murray 1992). If the NIII-NV 12:10 resonance did indeed cause the inclination in the Naiad orbit, an upper bound, $Q_N \leq 330,000$ (4×10^9 years/ T_C), is established. This upper bound follows from the necessity that the NIII-NV system

has passed through the 12:10 mean motion resonance. Although Thalassa (NIV) was also likely captured into inclination resonances that increase its inclination, there are numerous ways in which the likely inclination of escape was not significantly different from that observed ($\sim 0.21^\circ$). Capture into resonances at the same commensurabilities that could affect the other satellite inclinations apparently did not occur.

Of course there is an assumption here that the distribution of masses for the inner satellites has been as it is now for most of the $\sim 4 \times 10^9$ years since the Triton orbit circularized. Any cometary fragmentation and redistribution of mass among reformed satellites after their initial formation following Triton circularization must have been confined to reasonably early times. The existence of satellites within the Roche radius is not limited to Neptune. Banfield & Murray (1992) hypothesize that they could either have formed outside the Roche radius but inside the corotation radius and be transported inwards by tidal friction or that they accreted there in spite of the opposing tidal forces through the pieces sticking together by nongravitational forces. Neither of these hypotheses has been investigated in detail to establish a self-consistent scenario. Given the uncertainty in the collisional and reformation history, any attempt to refine the history of the inner satellites must always remain nondefinitive, and limited scientific return from such an exercise is probably not worth the considerable effort involved. The conjectured possibilities for the collisional and dynamical history of the inner satellites of Neptune constructed by Banfield & Murray (1992) are representative of what might have happened.

Triton is spiraling into Neptune in its retrograde orbit. Chyba et al (1989) conjectured two possible Cassini states (Peale 1969), which fix the Triton obliquity in the frame precessing with the orbit. In Cassini state 1, Triton obliquity would be nearly zero, whereas in state 2, the obliquity would be $\sim 100^\circ$ with vastly different rates of tidal dissipation in Triton and, hence, different rates of orbital decay for the two cases. Voyager 2 data (Smith et al 1989) revealed Triton to have a very small obliquity consistent with occupancy of state 1. In this case, Chyba et al (1989) find that Triton will reach the Roche radius in $\sim 3.6 \times 10^9$ years. If Triton is mostly solid at that time, it can continue to smaller orbital radii still intact, although it probably would not survive all the way to the surface. The breakup of Triton within the Roche radius would lead to a spectacular set of rings with initially much more total mass than those of Saturn.

10. PLUTO-CHARON SYSTEM

It was highly fortuitous that the Pluto satellite Charon was discovered sufficiently far in advance of our passing through the Pluto-Charon orbit plane that a well organized series of observations allowed a remarkably rich characterization of such a distant and otherwise obscure system. Mutual eclipses and occultations during the orbit plane passage allowed radii, masses and albedo distributions to be

determined (Binzel and Hubbard 1997). Subsequent observations with the Hubble Space telescope indicate a deviation from the circular orbit expected from tidal evolution (Tholen and Buie 1997). Yet we still know relatively little about this system compared with all the others, since we have not had the benefit of close observations by spacecraft instrumentation. As a result there are perhaps fewer constraints that we must respond to in the context of the evolutionary history of the system. Still, the system displays its own unique features, and increasing knowledge of the system may provide needed constraints on the nature of the objects in the furthest reaches of the solar system.

If we assume the Pluto-Charon system is the consequence of a giant impact by a planetesimal whose mass is comparable with the initial Pluto mass (Farinella et al 1979, Dermott 1978 (unpublished); Dobrovolskis 1997), some of the debris from the impact will escape the system and some will fall back onto Pluto, but sufficient debris must end up outside the Roche radius in order to collect into the observed satellite (e.g. Cameron 1997 and references therein). The debris will settle to the equatorial plane and the orbits of individual particles will be circularized through collisional dissipation. Charon will accrete most of its mass from this disk within a few hundred years (Thompson and Stevenson 1988), and it should then end up with a nearly circular orbit with nearly zero inclination relative to the equatorial plane of Pluto. We assume, therefore, that Charon began its existence as a satellite in circular, equatorial orbit at $3R_P$ (Pluto radii). The system will be assumed to have its current angular momentum for this initial condition with the total mass and mass ratio derived from Table 1. From this initial configuration it tidally evolves to its current state of dual synchronous rotation, which has been observationally confirmed (Buie et al 1997).

From Equation 6, Charon would reach synchronous rotation at a separation of $3R_P$ from a 4-h initial period in about 25 years ($\mu = 4 \times 10^{10}$ dyne cm^{-2} , $Q_C = 100$). The actual Q should be much less than this, as Charon will have just accreted and may be partially melted. Regardless of assumptions, Charon should be locked into permanent synchronous rotation almost immediately after formation. Torques from tides raised on Charon should thus be unimportant in the subsequent orbital evolution except for helping to keep the eccentricity damped.

Integration of Equation 7 for $Q_P = \text{constant}$ from an initial orbital period of 11.6 h at time t_i to the current period of 6.39 days at time t_f yields $t_f - t_i = 1.6 \times 10^3 Q_P / k_P \approx 1.7 \times 10^7$ years, where $\mu = 10^{11}$ and $Q_P = 100$ were assumed. The time to reach the dual synchronous rotation state is short compared with the age of the solar system. Although we expect the Pluto-Charon dual synchronous system to have a circular orbit, recent observations with the Hubble Space Telescope have indicated an orbital eccentricity, between 0.003 and 0.007 (Tholen and Buie 1997), although this determination has not been confirmed (Tholen, private communication, 1998). Two means of exciting such an eccentricity in the face of tidal damping have been proposed—direct collision of a Kuiper belt object with Charon or Pluto (Tholen and Buie 1997) and differential perturbations by passing Kuiper belt objects (Levinson and Stern 1995). The latter study finds collisional excitation very unlikely but the KBO perturbations can be sufficient,

depending on the total number of Kuiper belt objects, to account for the Tholen and Buie observations. An eccentricity decay time scale e/i of about 10^7 years (Dobrovolskis 1997) was assumed. So the ultimate end state of tidal evolution for the Pluto-Charon system may be slightly prevented by continuing stochastic perturbations by passing objects. With the limited information now available for this system, there do not appear to be any major inconsistencies in or outstanding problems with our proposed origin and evolution—although we are likely to be surprised by future in situ observations by spacecraft.

11. SUMMARY

We have developed reasonably robust scenarios for the origin and evolution of all the natural satellites in the solar system. The nearly coplanar, circular orbits of the regular satellites are consistent with their origin by accretion in dissipative disks in the equatorial planes of the forming planets, the smaller ones close to their primary the result of repeated breakup and reaccretion. The distant irregular satellites as well as the retrograde Triton result naturally from capture of planetesimals from heliocentric orbit, where the necessary loss of energy effecting the capture could come from three body interactions or collisions within the planetary sphere of influence, or, less likely, from atmospheric drag. The Earth-Moon and Pluto-Charon seem to require giant impacts with the primary for their creation to account for the high specific angular momenta, and, for the Moon, the marked difference in chemical constituents from its primary. Rich interplays of the consequences of tidal evolution and past and present orbital resonances have guided our thoughts from plausible initial conditions after accretion or capture to current configurations and properties of individual satellites. Still, explanations for many observed surface characteristics, interior properties or orbital configurations remain elusive or uncertain—some simply because available techniques have not yet been applied to the problems, whereas others await identification of the proper approach.

An ingenious dynamical dance of the Moon through the evection and eviction resonances allows its evolution from an equatorial orbit to its current configuration—a solution of the inclination problem. But the uncertainties in the properties of the disk resulting from the giant impact, in the physical processes that took place, and in the accretion of the Moon within the disk, may allow initial properties of the Moon that prevent this dance. Other processes not yet investigated (with the exception of a second giant impact) and perhaps not even thought of would then be required to get the Moon from the equatorial orbit to its current orbit as tides push it away from the Earth. A reasonably robust evolution of Phobos through several orbital resonances as it spirals toward the surface of Mars leaves its remnant orbital characteristics comparable to those observed and allows a formation of both Phobos and Deimos by accretion in Mars equatorial plane. This latter accretion in a dissipative disk seems necessary to account for the nearly circular, coplanar orbits of these satellites. If the composition of the two satellites turns out to be

drastically different from that of Mars, as perhaps indicated by their low densities, we should look for ways to make this material the major constituent of a dissipative disk in the equatorial plane of Mars for accretion in equatorial orbits.

Jupiter satellite Io almost certainly owes its high temperature to tidal dissipation resulting from a substantial eccentricity forced by the Laplace orbital resonance. Yet we strain to account for the Ganymede-Callisto dichotomy in surface characteristics, Ganymede's magnetic field and a sustained liquid ocean beneath the European ice with that same tidal dissipation. This frustration is in spite of clever tricks with past orbital resonances or interior properties. Understanding the dissipation of tidal energy in Jupiter should be a primary goal, as the torque from Jupiter on satellites within resonances ultimately constrains how much energy can be deposited in the satellites through their own tidal flexing. At Saturn, the existence of the Mimas-Tethys and Enceladus-Dione orbital resonances can be understood in terms of differential tidal expansion of their orbits with perhaps some fine tuning to pick the existing inclination type resonance for Mimas-Tethys among the selection at the 2/1 orbital mean motion commensurability. Such an origin for the 4/3 Titan-Hyperion resonance seems remote, but the viability of accreting Titan and Hyperion simultaneously while in the resonance has not been investigated. The real enigma is Enceladus, whose snow-white appearance and the circumstantial evidence for its being the continuing source of the E-ring particles imply a heated interior. How can such a wimpy little satellite still be warm? The forced eccentricity in the current resonance with Dione causes little tidal heating, and a past resonance with Janus is probably too weak to remain stable very long even if Enceladus were once captured. We hope for some surprises when modern nonlinear dynamics, with all degrees of freedom, is applied to the systems involving Enceladus. In contrast to these mysteries, we can be a little smug in our understanding of Hyperion's evolution to its current rotation state of chaotic tumbling.

At Uranus we are unable to account for any of the young surfaces on the satellites in a robust way from tidal heating within resonances. Especially puzzling is the moderate resurfacing of Titania, which could have participated in no orbital resonance—and it lies between Oberon and Umbriel with their apparently older surfaces. Ariel is extensively resurfaced, yet its possible orbital resonances in the past do little heating. Even a 2/1 resonance with Umbriel would probably fail to warm Ariel enough. The extreme stability of the Ariel-Umbriel 2/1 resonance means that Ariel probably started outside this resonance. We can relish the understanding of how Miranda got its high inclination within a past 3/1 resonance with Umbriel, and we can also relish the added insights into chaotic dynamics obtained during the analysis of this resonance—secondary resonances and the role of a chaotic adiabatic invariant. That Miranda must have passed through the 3/1 resonance with Umbriel to account for its orbital inclination, coupled with the exclusion of Ariel-Umbriel from the 2/1 resonance places rather tight bounds on the dissipative properties of Uranus—more so than for any other gaseous planet. The capture and subsequent decay of the orbital eccentricity of the retrograde

Neptune satellite Triton seems to yield a self-consistent history leading to the current configuration and surface properties of the satellites. The small inner satellites are second or higher generations—the products of repeated breakup and reaccretion. The high orbital inclination of Naiad in spite of its accumulation in a dissipative equatorial disk is nicely accounted for by capture into and evolution within an inclination type orbital resonance—like Miranda except here the orbits are spiraling toward the primary rather than away. Pluto-Charon have reached the endpoint of tidal evolution of dual synchronous rotation. The corresponding relaxation to circular orbit may be slightly frustrated by the perturbations of passing Kuiper belt objects.

We have observed the striking uniqueness of each satellite system within the solar system, and we have had several successes in understanding the origin of current configurations and properties of the several systems. However, we have also pointed out a significant number of remaining interesting problems that will occupy clever minds for years to come as they are resolved one by one. Greater understanding will uncover even more problems as our knowledge of the satellites is refined.

ACKNOWLEDGMENTS

It is a pleasure to thank the following colleagues for commenting on particular sections of the manuscript: R Greenberg, A Harris, H Levison, R Malhotra, N Murray, A Stern, D Stevenson, J Wisdom, and C Yoder. They detected errors and omissions and generally offered good advice. Special thanks are due MH Lee, who read the entire manuscript and offered many suggestions for improving the clarity and consistency. The author received support for this work from the Planetary Geology and Geophysics Program in NASA under grant NAG5 3646.

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