THE ERUPTIVE EVOLUTION OF THE GALILEAN SATELLITES: IMPLICATIONS FOR THE ANCIENT MAGNETIC FIELD OF JUPITER

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Abstract. The hypothesis considering the Jupiter–Sun system as a limiting case of a close binary star implies the initial relative ice abundances in all the Galilean satellites to be essentially equal. The satellites move in the Jovian magnetosphere; thus the unipolar current flowing through their bodies subjected their ices to volumetric electrolysis. Explosions of the electrolysis products resulted in a loss of ices. While Callisto did not explode at all, Ganymede exploded once, Europa twice, and Io two or three times.

An analysis of the magnetic field changes needed to create the modern ice abundances in the satellite shows:

(1) the initial field of Jupiter was $\sim 10^2$ times stronger when compared with the present-day field, and

(2) the field had to decrease exponentially with $\tau_{♃} \approx (0.6-1)$ Gyr, which means its relic nature.

There are two different approaches to the cosmogony of the solar system as a whole and the Galilean satellites; namely:

(1) Since the system's creation, there were no substantial changes in it, e.g. – the planets accumulated exactly in the loci corresponding to Bode's law – comets and meteorites are relics of the ancient processes; the modern distribution of ices among the Galilean satellites is the result of their formation conditions and analogous, somewhat, to the volatile distribution in the terrestrial and giant planets; etc.

(2) The present-day system is a result of a permanent evolution changing continuously, and materially, the structure of the system.

The first, static, approach is an echo of pre-Darwinian perception of the world and its preservation in the cosmogony in the form of nebular ideas, which go back to Kant and Laplace, can, perhaps, be explained only by the lack of new material accumulation in this field up to quite recent times. The outburst of information caused by the advent of the space era brought out many facts which were not predicted in this way, and often even cannot be explained in a simple manner if one remains in the first-approach frame. Their understanding can be achieved only from the evolutionary point of view.

The most impressive is the Voyager 1 discovery of active volcanism on Io (Morabito *et al.*, 1979; Smith *et al.*, 1979a). Its energetics is provided with the unipolar electric current flowing through Io's body (Drobyshevski, 1979a, b; Gold, 1979).

In the past, the Jovian magnetic field had to be much stronger and the Galilean satellites system was an original kind of the magnetic tape recorder; the satellites one by one fixing the magnetic field influence in their structural features. In what follows I

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shall attempt to take advantage of the evolutionary approach; and, making use of this tape recorder, try to reconstruct Jupiter's magnetic field history so as to realize why the Galilean satellites are so different today and what may await them in the future.

The explosive nature of Io's volcanism suggests the presence, even in the present-day Io, of large amounts of volatiles. This cast doubts on the validity of the 'micronebular' hypothesis of the Galilean satellites creation in a gaseous disc surrounding the contracting proto-Jupiter (PJ), where the high luminosity of PJ precluded 'ices' from condensation in its vicinity (Pollack and Reynolds, 1974). An alternative concept treats the origin of the satellites within the framework of consideration of the Jupiter–Sun system as a limiting case of a binary star, when many Moon-like and larger bodies condensed and grew within PJ near the first Lagrangian point while being suspended gas-dynamically in a jet of matter streaming from PJ to the Proto-Sun (Drobyshevski, 1978). The fast decrease in the mass of PJ overfilling its critical Roche lobe permitted these bodies to escape from the sphere of PJ action as soon as their mass reached $M \gtrsim M_{☾}$. In this way the other planets, including, possibly, Saturn, Uranus, and Neptune, originated (which is supported by non-monotonousity in their chemical composition (Drobyshevski, 1979c)). The last ice-rich, Moon-like bodies were not lost by PJ since outflow of matter from it had stopped due to its strong cooling. These bodies became the Galilean satellites.

It is natural to assume the initial abundance of ices in all Galilean satellites was more or less the same and close to 'normal', ~50% of H_2O and ~50% of 'rocks', if one proceeds from the density of Callisto ($\rho = 1.79\,\mathrm{g\,cm^{-3}}$ (Smith *et al.*, 1979a)) which apparently preserved the initial ice abundance (see below) and from the density of rocky Io $\rho = 3.53\,\mathrm{g\,cm^{-3}}$ (for the initial parameters of the satellites see Table I). Now what subsequent processes could result in the modern monotonous ice distribution?

(1) *High initial luminosity of PJ* (by Graboske *et al.* (1975) $L_{♃\,\max} \approx L_\odot/160$ for $\sim 10^3$yr) could not result in the evaporation of all ice even from Io (this evaluation assumed the absorbed energy to be expended only for the evaporation and removal of water from Io, radiation losses not having been taken into account; the albedo is 0.75). Moreover, the latest calculations of the hydrodynamic stage of PJ evolution carried out by Bodenheimer *et al.* (1980), with making use of the detailed calculations of opacity, show that $L_{♃\,\max}$ did not exceed $\sim 2.2 \times 10^{-6} L_\odot$ at all (with $T_{\rm eff} = 612\,\mathrm{K}$ and $R = 1.3 R_{♃}$). Thus, the equilibrium temperature of a rotating body with albedo 0.75, which is sited on Io's orbit, was never larger than 145 K. Whence it is clear that the excessive PJ luminosity was neither able to evaporate the water from Io or Europa nor to preclude the water condensation in a gaseous disc with solar composition; the disc would, somehow, be created around PJ. In this context, a comparison of PJ with Saturn seems to be paradoxical: there was $L_{♃\,\max} < L_{♄\,\max}$ (Bodenheimer *et al.*, 1980) and, nevertheless, Saturn has well-developed ice rings located close to its surface.

(2) *Gas-dynamic ablation of matter* as the Moon-like bodies moved, before their escape, within PJ filling its Roche lobe ($R \approx 500 R_{♃}$) could produce enrichment of Jupiter with volatiles with respect to the 'rocks' compared to solar composition (Drobyshevski, 1978). This factor apparently played the most important role in the

TABLE I

	Present day parameters				Initial parameters								
Satellite	B_0 μT	M_s 10^{23}kg	r_s km	ρ kg m^{-3}	M_{s0} 10^{23}kg	r_{s0} km	g m s^{-2}	v_{esc} km s^{-1}	$\frac{\Delta M}{M_{env}}$	Σ mho	J_{max} MA	B_{max} μT	Δt Myr
Io	2.0	0.892	1820	3530	1.784	2875	1.44	2.89	0.27	38	139	9.6	288
Europe	0.51	0.487	1565	3030	0.892	2280	1.14	2.28	0.42	30	94	8.3	247
Ganymede	0.125	1.490	2640	1930	1.713	2835	1.42	2.84	0.28	37	135	9.6	2.85
Callisto	0.023	1.065	2420	1790	1.065	2420	1.21	2.42	0.39	32	104	8.6	257

fate of Amalthea (Drobyshevski, 1979b). The role of ablation in the formation of the Galilean satellites can be estimated by a combined consideration of PJ's contraction after its sinking under the Roche lobe (with a rocky core already present) and of a set of versions of orbital evolution of these satellites including the gas-dynamic effects.

(3) The most probable and, moreover, inevitable process to be considered in more detail below seems to be *an explosion of the products of volumetric electrolysis in the ice envelopes* of the satellites moving in the planetary magnetic field B, which generated in them the unipolar electric currents, just as the Moon-like icy Phaethon which was flown round by the ancient solar wind carrying magnetic field, could explode (Drobyshevski, 1980a, Paper I).

A strong interaction of Jovian satellites with the planetary magnetosphere is a well-documented fact. Io's interaction is known to be responsible for an intensive radio-band emission from Jupiter's system, and there are some indications of a similar behavior of Europa. The current strength of 4.8 MA in one wing of Io's magnetic force tube was measured by Ness *et al.* (1979a) during the Voyager 1 encounter with the Jupiter system, so that the total unipolar current flowing through Io should be $\approx$ 10 MA. A very strong and complex interaction of Ganymede with the magnetosphere was revealed by Ness *et al.* (1979b) when Voyager 2 passed within 62 000 km of the satellite.

The suggestion of the important role of electrolysis in the icy bodies is supported, besides the monotonous increase in the Galilean satellites' ice abundances, by the giant planets having, in addition to Moon-like satellites, many small ones and also rings. This makes the hypothesis that a great majority of them, just as the asteroids, are products of the break-up of Moon-like bodies or of ejections from them.

The total break-up of a body of 'normal' composition after electrolysis of 1/5–1/4 of all water in this way can occur if its mass does not exceed $(0.5-1) \times 10^{23}$kg. At a higher mass, only a part of the matter is removed. This can possibly account for the fact that all the icy satellites either exceed this value in mass or lie much below it; in the latter case the volumetric electrolysis should be inefficient because of the absence of convective mixing, so the products of decomposition would accumulate near alien inclusions serving as electrodes thus screening them; also, hydrogen escapes easily from small bodies at $T \gtrsim 32$ K.

In the foregoing estimates of the efficiency of convective heat transport and energy release, the latter being proportional to B^2, I used the method of estimations and the numerical values of parameters adopted in Paper 1.

Since, in real situations, the magnetic Reynolds number $\gtrsim 1$, an assumption was made that the current flowing through the satellite body creates its own induced field which equals the primary surrounding field: so $J \approx 2\pi B r_s/\mu_0$; and within a factor of 2 this estimate has been confirmed by Ness *et al.*'s (1979a) current measurements in the Io magnetic force tube. The electric conductivity Σ of the satellite body was determined as $\Sigma = 1.31 r_s \sigma$, which corresponds to the conductivity of a homogeneous sphere of radius r_s with electrodes of diameter r_s applied to the opposite sides of the sphere (see, e.g., Auerbach, 1921); the electric energy input in Io is spread over the band between latitudes ± 30° (Drobyshevski, 1979b), but in each given epoch it concentrates in a circle of 30° radius). A substantial part of the satellite rocky core is dispersed through all the ice volume by the convective motions. The specific conductivity of the dirty ice is $\sigma \approx 10^{-5}$ Si. The thermal flux carried by convection in ice is $q = 2(K\Delta T/\delta)(Ra/Ra_c)^{1/3}$, where $Ra = \beta\rho g c_p \delta^3 \Delta T/\nu K$ is the Rayleigh number ($Ra_c = 10^3$); $K = 3\,\mathrm{W\,m^{-1}K^{-1}}$ is the heat conductivity; $\rho = 1200\,\mathrm{kg\,m^{-3}}$ is the density; $c_p = 2.5\,\mathrm{kJ\,kg^{-1}K^{-1}}$ is the heat capacity; $\beta = 1.5 \times 10^{-4}\,\mathrm{K^{-1}}$ is the thermal expansion coefficient; $\nu = 2 \times 10^8\,\mathrm{m^2\,s^{-1}}$ is the viscosity of the ice; and ΔT is the temperature drop in the layer of thickness δ. The energetic efficiency of the electrolysis was assumed to be 0.05.

When a 'thin' condensed envelope M_{env} explodes on the planetary surface (its contribution to gravitation is negligible, and the products of detonation (the adiabatic index = 3) accelerate up to maximum velocity without marked lateral spreading), the ejected fraction of the mass ΔM is (cf. Stanyukovich, 1971)

$$\Delta M/M_{\mathrm{env}} = 1 - v_{\mathrm{esc}}/(6Q)^{1/2},$$

where $v_{\mathrm{esc}} = (2GM_s/r_s)^{1/2}$, and Q is the energy released per unit mass of the envelope (we take $Q = 13/5$ MJ per kg of ice). In the case of a 'thick' envelope, $\Delta M/M_{\mathrm{env}}$ should be somewhat larger. The values of ΔM_{env} are listed in Table I. It is seen immediately from Table I that there was only one explosion of Ganymede's envelope, two explosions were enough to create modern ice abundance in Europa, and two or three in Io.

The icy explosion becomes possible only when certain definite conditions are satisfied. At $B > B_{\mathrm{max}} \approx 10\,\mu\mathrm{T}$, and correspondingly $J > J_{\mathrm{max}} \approx 100$ MA (for all four satellites, see Table I), convection in ice can no longer balance heat removal ($\Delta T = \Delta T_{\mathrm{max}} \approx 150$ K), and liquid water will appear between the rocky core and the ice envelope. Without contact with the core, the ice crust will lose foreign inclusions which are also practically absent in the liquid phase; besides, a peculiar instability will develop with an increase of B above B_{max} by a few tens percent producing a substantial thinning of the ice crust (convective transport is replaced here by thermal conduction). Therefore, the volumetric electrolysis may be considered to stop at $B > B_{\mathrm{max}}$. Energy will begin to accumulate only at $B \leqslant B_{\mathrm{max}}$. At $B = B_{\mathrm{max}}$, electrolysis of 1/5 of all ice will take the time Δt (see Table I), so that at $B = \kappa B_{\mathrm{max}}$ (where $\kappa < 1$), the required time increases up to $t = \Delta t/\kappa^2$. Note also that for the exponentially decaying field, $B = B_{\mathrm{max}} \exp(-t/\tau_{♃})$, the explosion will be possible only if $\tau_{♃} \geqslant 2\Delta t$. Table I contains the values of $B_{\max}$. It is seen that B_0 could hardly lead to an explosion in 4.5 Gy even on Io. For the ices on Ganymede to explode, the field should have exceeded the present-day value by 20 times during 4.5 Gy.

If one excludes the possibility of the satellites' increasing greatly their distance from Jupiter, one has to assume a change in the Jovian magnetic field. There are no reliable data on the possibility of its periodic variations (Hide and Stannard, 1976), a monotonic decrease of the field seeming to be a rational hypothesis. There is no theory for the generation of the Jovian magnetic field; however, one believes it to be produced by some dynamo process with the convection interacting with rotation. Although it is the presence of the field proper which is considered as an argument in favor of the convective energy transport taking place also in the metallic hydrogen region (e.g., Hubbard *et al.*, 1974).

To conclude on the possible pattern of the field changes in the past, one has to turn to Jupiter's history. Graboske *et al.* (1975) showed that Jupiter's luminosity dropped 20–25 times in the recent 4 Gy (at $L_{♃} \propto t^{-(1.4-2.0)}$) and the radius decreased by only 10% (so that the angular velocity Ω could hardly have changed markedly). The generated magnetic field could be determined, e.g., from the equipartition of magnetic and turbulent energy ($B^2/8\pi \approx \rho v_c^2/2$), from the α-effect ($B^2 \propto v_c\Omega$ which is the Coriolis force; cf. Levy and Rose, 1974), or the battery effects (for the field produced by the Coriolis emf's, $B \propto L_{♃}\Omega$; cf. Cowling, 1945; Drobyshevski and Ergma, 1976). Use of the mixing-length theory for convection yields $v_c \propto L_{♃}^{1/3}$ (Baker and Temesvary, 1966) so that the latter mechanism could produce the strongest field. But even in this case, the law of the field change ($B \propto L_{♃}$) is such that even all the available time is too short to accumulate the energy needed for one explosion on Europa, and especially on Ganymede.

Within the framework of our hypothesis of the Galilean satellites having initially had similar structure and composition (whose validity is supported, besides cosmogonical considerations, also by the presence of the volatiles and the eruptive nature of volcanism on Io, and by a successive explanation of the known properties of asteroids from the standpoint of the icy Phaethon undergoing an explosion) and taking into account that the adopted values of the parameters cannot be changed substantially, the only possibility left to us is to try to find another explanation for the nature of the Jovian magnetic field.

Stevenson and Ashcroft (1974) and Stevenson (1976) estimated the ohmic decay time for the Jovian magnetic fields as ≈ 1 Gy. Thus the field in Jupiter could have survived from the time of collapse of the pre-solar cloud.

A more natural approach, which agrees with modern ideas concerning the origin of the fields of celestial bodies, would be a combination of the relic and generation concept (e.g., Drobyshevski and Ergma 1976). Indeed, at the initial stage, Jupiter's luminosity exceeded the present day level by ~ 3 order of magnitude (see above), and it had a strong magnetic field which could be produced by the Coriolis emf, say. (It is interesting that MHD, viz. 'equipartition' and α-effect, mechanisms were not able to create the field of needed strength.) When a degenerate metallic core with a high conductivity began to

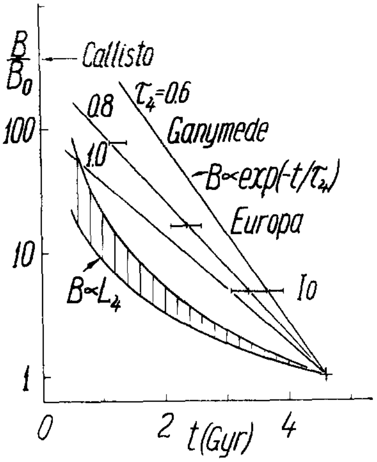

Fig. 1. Jovian magnetic field vs. time. B_0 is the present-day field (denoted by +). Horizontal lines show $B = B_{\text{max}}$ are the field values, below which the satellite envelope becomes icy and the energy accumulation in form of the volumetric electrolysis products begins. The length of the line between marks shows a time Δt (≈ 0.3 Gy) necessary for accumulation of energy needed for explosion (the electrolysis of 1/5 ices) at $B = B_{\text{max}} =$ const. The number of lines for each satellite gives the number of its explosions.

Two versions of the magnetic field variation are presented: (1) $B \propto L_{\text{♃}} \propto t^{-(1.4-2)}$ is the maximal value of the magnetic field with its continuous generation by convective motions: (2) $B \propto \exp(-t/\tau_{\text{♃}})$ is the decay of the frozen field by virtue of ohmic dissipation.

Since the accumulation of energy needed for explosion is possible only when $\tau_{\text{♃}} \geqslant 2\Delta t$ (≈ 0.6 Gy) (see text), the comparison of slopes of these two versions' curves shows the first version to be incapable of providing for the explosion of Ganymede's and Europa's envelopes. The explosions are feasible with $\tau_{\text{♃}} \approx 0.6-1.0$ Gy only.

form, it trapped and preserved this strong magnetic field. At present, the MHD processes in Jupiter can only modulate somehow its relic field.

Strong support for the Jovian field being of a relic nature comes from Figure 1 which shows the probable dependence of B_{max}/B_0 on the time. The positions of the points corresponding to the modern field, the B_{max} field of Callisto (with no explosions of the envelope), and Ganymede (with one explosion at an early stage) can hardly be subject to strong doubt.

Thus it is clear that the initial field lay somewhere in the region $\sim 100B_0$; and this, under assumption of the field continuous exponential decay, imposes rather strict limitations on the decay constant – viz., $\tau_{\text{♃}} \approx 0.8$ Gy – in full agreement with estimations available (see above). This magnitude of $\tau_{\text{♃}}$ corresponds rather well to the values of $\Delta t \approx 0.3$ Gy (see Table I) if one takes into account the square dependence of the rate of the electrolysis products storage in the satellite icy envelopes vs. magnetic field. The progressive increase in the envelope explosion number in more inner satellites allows one to suggest that (1) the initial magnetic field strength was close on the lower possible limit so that Ganymede had time only for one explosion, and/or (2) some growth of $\tau_{\text{♃}}$ with Jupiter age (say, from $\tau_{\text{♃}} = 0.6$ to 1.0 Gy) takes place, which is quite natural since cooling of Jupiter leads to the gradual growth of conductivity and dimensions of its metallic core.

The positions of $B_{\max}$ for Europa and Io presented in Figure 1 give an idea of times of their envelopes' explosions. The practical absence of meteoritic craters on the icy surface of Europa is evidence of a relatively recent explosion of its ices saturated with the products of electrolysis. On Ganymede many craters are seen because its ices exploded long ago. Callisto is the most heavilv cratered body in the solar system (Smith *et al.*, 1979a, b) – it has more craters than Ganymede by an order of magnitude – and this says both on preservation of its primary ices and explosions of the neighbor Ganymede ices. The recent origin of Europa's ice-cover and its faster convective restoration, due to the more powerful energetics, may account for a higher albedo compared with Ganymede (and that of Ganymede, compared with Callisto). On Ganymede (and particularly on Callisto), the sublimation of ice proceeded long enough to reveal the impurities contained in it. This is why the Callisto's surface is covered mainly by rocks.

It is difficult to estimate the extent to which the envelope of Callisto (and those of the other satellites) is saturated, at present, by the products of electrolysis. The large-scale concentric structures observed on it (similar features have been found recently on Ganymede; cf. Smith *et al.*, 1979b) could be traces of ice outflows caused by ascending convective motions in ice. The surface age which is proportional to the impact crater density increases when one moves from the center to the periphery of a such structure (Smith *et al.*, 1979a). This would imply that Callisto received substantial additional energy in the past. The outermost ice layers should be depleted in the products of electrolysis because of their volatilization into space intensified by the meteorite impact mixing. From this viewpoint, the shape of the ice craters observed on the Galilean satellites is certainly peculiar: indeed, in contrast to the Moon's impact craters with central peaks, many ice craters have central pits. It is interesting that craters having pits are created by meteorite impacts on the fresh surface, whereas the peak craters are due to impacts on a surface processed by previous impacts (e.g., a small peak crater inside a great pit crater in the left lower corner in the photograph on p. 212 of *Sky and Telescope,* Vol. 58). This feature can be accounted for by the presence in ice of the electrolysis products, and by the possibility of their detonation at the additional strong compression produced by meteorite impacts. These pits could then form as a result of a more intensive burnout because the concentration of $H_2 + O_2$ increases with depth. The additional energy release is able to lead to the ejection of icy chunks into space (comets). This implies the content of the explosive mixture in Callisto's ice to be close to critical. Such a saturated 'ice' could serve as an energy source in future landing missions. The possibility of detecting and studying transient atmospheres created on the icy Galilean satellites by meteoritic impacts is of a certain interest. Moreover, sooner or later an impact of a large meteorite can assist the propagation of detonation into the bulk of the icy envelope, where the concentration of $H_2 + O_2$ is still higher because of the pressure produced by the overlying layers, with the eventual explosion of the satellite's envelope. The satellite acquires a massive atmosphere. It is this event which apparently occurred (see

Drobyshevski, 1980b, 1981) on Titan, and which accounts for the existence of its atmosphere and liquid water surface; the idea of volcanic origin of the Titan's atmosphere and the comet ejection from Galilean satellites was advocated for a long time by Vsekhsviatskii (1966). The explosion will produce a large number of comets formed by fragments of the outer layers where the concentration of the electrolysis products is insufficient for detonation to occur. These fragments may explode in their turn when colliding with sufficiently fast meteorites (some families of asteroids could have formed in this way in the past after the main explosion of Phaethon (Paper 1)). Their appearance in the inner Solar system will increase the meteoritic hazard for the Earth-group planets. However the danger involved should hardly reach the scale of the Imbrium event.

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