IMPLICATIONS OF THE GALILEAN SATELLITES ICE ENVELOPE EXPLOSIONS. I. THE MOTION OF FRAGMENTS INSIDE AND BEYOND JUPITER'S SPHERE OF ACTION

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Abstract. Explosions of the electrolyzed ice envelopes of the Galilean satellites resulted in the appearance of a large number of ice fragments deep inside Jupiter's sphere of action. Gravitational perturbations by the Galilean satellites transferred these fragments from satellite orbits into the periphery of the sphere of action and beyond it. The fragments move initially in the direction of a satellite's motion tangentially to its orbit.

The fragments have a small angular momentum since they come from deep inside Jupiter's sphere of action. On reaching the periphery of the sphere, the fragments can acquire retrograde motion (even in the sidereal frame) because of the Sun's action.

If ejected from the zone of the Galilean satellites with a sufficient velocity, the fragments can leave Jupiter's sphere of action going both inside and outside its orbit, which leads to a substantial difference in the pattern of their subsequent motion in the vicinity of Jupiter's orbit.

The results obtained may be used to shed light on the origin of the irregular satellites (Paper 1) and Trojans (Paper 2).

1. Introduction

The hypothesis relating the formation of nearly all minor bodies in the Solar System with the explosion of electrolysis products in massive ice envelopes of the moonlike bodies (Drobyshevski, 1980a, b; 1981) has been able to explain from a common standpoint a number of observational facts. At the same time it continues to receive support from evidence which both substantiates the possibility of a volumetric electrolysis of ice and its explosion after saturation by electrolysis products and confirms the implications following from this hypothesis.

Indeed, although the scientific program of the Voyager missions in the Saturn systems did not include a special test of above-mentioned implications it was found that (1) the true size of Titan ($R = 2575$ km) disagrees strongly with the earlier estimate ($R = 2700$ km) while being close to the value ($R = 2585$ km) following from the hypothesis of its eruptive nature similar to that of Ganymede; (2) the peculiar dynamics of Saturn's rings (i.e., their being made up of a large number of ringlets) is apparently due to the presence in them, apart from cm-size grains, also of a km-size population; (3) Titan's atmosphere is massive and contains HCN which is probably a product of quenched high temperature equilibrium.

Recent analysis of the Voyager data and ground-based observations (Samuelson *et al.*, 1983, Lutz *et al.*, 1983, Muleman *et al.*, 1984) have revealed in Titan's atmosphere the

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presence of carbon mono- and dioxide which could originate (Drobyshevski, 1981) from an explosion of the stoichiometric mixture $(2H_2 + O_2)$ with an excess of hydrocarbons: i.e., at a general deficiency of oxygen. And while the presence of HCN could be attributed to photochemical processes in the atmosphere, this can more hardly be done for CO and, particularly, for CO_2 in the presence of atmospheric methane and of the surface which should be covered by hydrocarbons.

Analysis of space probe data on the structure of Saturn's rings has aroused an ever growing suspicion of their extremely young age (c.f., e.g., remark of P. Goldreich at IAU Symposium No. 75 in Toulouse, as quoted by Kerr, 1982). These data also support the conclusions (Drobyshevski, 1981) on the presence of explosion fragments which absorb charged particles between Rhea and Titan (Lazarus *et al.*, 1983).

Only our suggestion on the existence of liquid water on Titan's surface (Drobyshevski, 1981) has proved to have been somewhat hasty. As a matter of fact, we have been tempted to interpret accordingly the microwave measurements of Conklin *et al.* (1977) at $\lambda = 3.3$ mm which are apparently wrong (although one cannot exclude outflow of liquid water from under the ice crust during the observations). A further study (Drobyshevski, 1982) showed that in the time passed after the explosion ($\sim 10^4$ yr) the deep (~ 1000 km) water ocean on Titan should have become covered by an ice crust about 1 km thick.

Still untested remains at present only one, although very strong, prediction that Titan which continues to cool after the explosion (with the freezing of the ocean going on) should lose more energy (by 1.5 to 15%) than it receives from the Sun (Drobyshevski, 1982). This prediction can possibly be tested only by a probe landing on Titan.

Finally, calculation of conditions required for detonation of ices saturated by electrolysis products in the case of Phaethon with an assumed mass $0.5 M_☾$ implies that ice containing as little as 13–18 Wt% $(2H_2 + O_2)$ is already capable of exploding (Drobyshevski, 1985).

As already pointed out (Drobyshevski, 1981), both Chiron 2060 and Saturn's retrograde satellite Phoebe may represent fragments of the Titan's exploded ice envelope and thus be of a common origin. Within the framework of this new concept on the origin of minor bodies it would be only natural to consider some implications of explosions of the Galilean satellites envelopes – i.e., the possibility of shedding light on the origin of Jupiter's irregular satellites, the Trojans and, possibly, of some comets from Jupiter's family; i.e., of bodies related at present with Jupiter.

In the present paper serving to a certain extent as an introduction we are considering briefly the possible pattern of motion of fragments ejected by gravitational action of the Galilean satellites from the orbits of the latter.

2. Physical Basis for the Formulation of the Problem Concerning the Motion of Fragments from Explosions of the Galilean Satellites

According to Drobyshevski (1980b), the ices of the Galilean satellites exploded five to six times in all. The ices on Io exploded two or three times leaving the satellite bare, while the ice envelope of Europe exploded twice, and that of Ganymede once. Callisto's ices did not explode at all although they seem to be strongly saturated by electrolysis products as evidenced by central pits in some meteorite craters.

This is supported not only by the well known monotonic increase of ice content from Io to Callisto but also by an order-of-magnitude greater abundance of craters on Callisto's surface compared with Ganymede (contrary to expectations based on gravitational focusing by Jupiter), as well as by conclusions on the past variations of Jupiter's magnetic field which generates in the satellites electric current required for the electrolysis of ices. On the basis of the present day ideas concerning Jupiter's structure and the origin of its magnetic field, the latter can be shown to decay exponentially with a time-constant of about 0.8 Gyr.

Explosion of electrolysis products ejects from a satellite unexploded fragments of the outermost cold layers of its ice envelope. Ejection of fragments directly from a satellite's surface beyond Jupiter's sphere of action, as assumed for a long time by proponents of the classical eruptive theory of the origin of comets (Vsekhsviatski, 1967), requires fairly high eruption velocities ($\gtrsim 6\,\mathrm{km\,s^{-1}}$) and thus is hardly realistic. This aspect has always been a vulnerable point for criticism (cf., e.g., Radzievski, 1979). As pointed out by Drobyshevski (1981), a much more efficient process is the ejection of fragments from a planet's sphere of action originating from gravitational perturbations by the satellites, primarily by the exploded one.

Under these conditions the original velocity of fragments may only slightly exceed the escape velocity from the satellite's surface which is 2–3 $\mathrm{km\,s^{-1}}$. The fragments will move inside the planet's sphere of action traversing the orbit of the parent satellite. The subsequent process of fragment ejection beyond the planet's sphere of action can be divided into two major stages: (1) fast stage, of the order of $\sim 10^2$ satellite's orbital periods, when the satellite moving in its orbit sweeps it free of fragments following intersecting orbits and ejects a substantial fraction of them beyond the planet's sphere of action (basically, the maximum velocity which a point satellite can impart to a small body is twice the orbital velocity of the satellite); this is a powerful process capable of propelling fragments from deep inside the sphere as well as in an arbitrary direction; (2) slow stage, leading to a loss of fragments out of the sphere of action as a result of gradual accumulation by the fragments of small perturbations from orbits which do not intersect the orbits of large satellites; therefore, ejection occurs primarily through the inner Lagrangian point L_1 when the planet approaches its perihelion and its sphere of action contracts.

The existence of the two afore-mentioned stages follows directly from an analysis of the distribution of minimum inter-orbital separations from Saturn's orbit in true anomaly (for comets of the Saturnian long-period family, cf. Drobyshevski, 1981) which, on the other hand, provides evidence for a recent explosion of ices on Titan. In the case of Saturn's system the number of fragments ejected in the two stages is about the same. The estimated duration of the first stage of $\sim 10^2$ orbital periods can be obtained both from the abovementioned analysis of the distribution of Saturn's comets (10^2 Titan periods ≈ 4.5 yr) and from calculations by Lecar and Franklin (1973) of the characteristic time scale for the ejection of minor bodies intersecting Jupiter's orbit or moving close to it.

In the calculations that follow we will not consider in detail direct interaction of fragments with satellites but will rather restrict ourselves to studying the behavior of fragments inside Jupiter's sphere of action assuming them to be ejected from the satellite orbits with an initial velocity V_0 less than the parabolic escape velocity ($V_0 < V_{\text{orb}}\sqrt{2}$).

3. Mathematical Formulation of the Problem and Method of Solution

We limit ourselves to considering a planar circularly restricted three body problem. An important parameter determining possible motion of a material point is the Jacobi constant (Szebehely, 1967):

$$C = \mu_{♃}\left(r_1^2 + \frac{2}{r_1}\right) + \mu_{\odot}\left(r_2^2 + \frac{2}{r_2}\right) - V^2, \tag{1}$$

where $\mu_{♃} = m_{♃}/(M_{\odot} + m_{♃}) = 1/1048.355$ is the reduced mass of Jupiter, $\mu_{\odot} = M_{\odot}/(M_{\odot} + m_{♃})$; r_1 and r_2 are, accordingly, the distances from Jupiter or the Sun to the point in question, V is dimensionless velocity of a point in a frame rotating counterclockwise with Jupiter's angular velocity and with the origin at the centre of mass of the system; the linear scale is provided by the Jupiter–Sun distance (778.3×10^6 km), and the velocity scale, by Jupiter's orbital velocity (13.06 km s^{-1}); Jupiter's coordinates are $X_{♃} = 0.999\,046\,12$, $Y_{♃} = 0$.

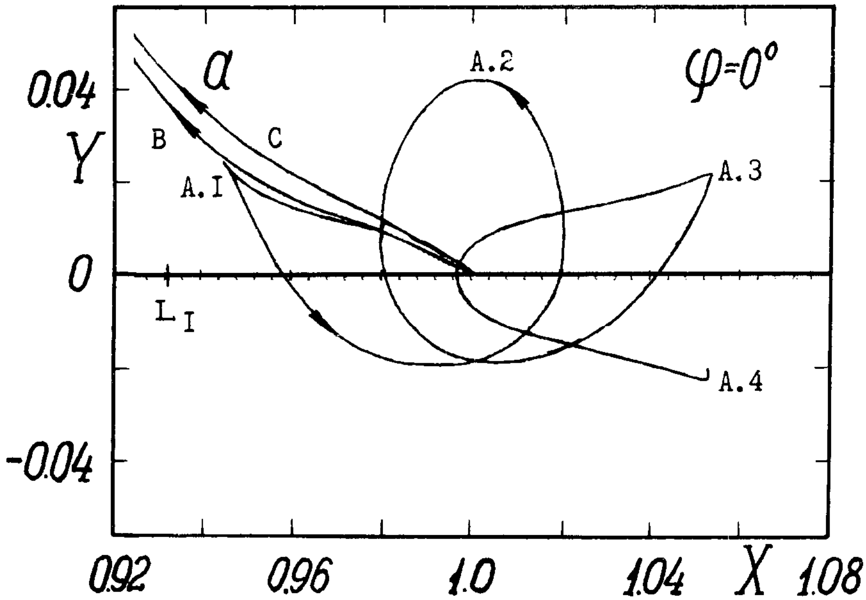
Then, by Szebehely (1967), for the first (inner) Lagrangian point L_1 ($X_1 = 0.932\,365\,59$, $Y_1 = 0$), we have $C_1 = 3.039\,713\,80$, for the second (outer relative to Jupiter) point L_2 ($X_2 = 1.068\,830\,52$, $Y_2 = 0$) we obtain $C_2 = 3.038\,441\,7$, while for the third (outer relative to the Sun) point L_3 ($X_3 = -1.000\,397\,45$, $Y_3 = 0$) we get $C_3 = 3.001\,906\,82$; finally, for the triangular libration points L_4 and L_5 ($X_{4,5} = 0.499\,046\,12$, $Y_{4,5} = \pm\,0.866\,025\,40$) $C_{4,5} = 3.0$. The Jacobi constants C' for (synodically fixed) points in orbits of the Galilean satellites are given in Table I.

Using the aforementioned numerical values, we can readily calculate the minimum velocity a body should possess to be able to move from one point in space to another.

TABLE I

Dynamics of particles ejected from the orbits of Galilean satellites. a – satellite orbit radius (in units ⊙-♃), V_{orb} – synodic orbital velocity of satellite, $\Delta V(C', C_1)$, $\Delta V(C', C_2)$, $\Delta V(C', C_{4,5})$ – minimum velocities required to transfer a material point from the orbit of a Galilean satellite to the Lagrangian points L_1, L_2, L_4, or L_5, C' – Jacobi constant for point in rest in the satellite orbit

	a	V_{orb} (km s^{-1})	C'	$\Delta V(C', C_1)$ (km s^{-1})	$\Delta V(C', C_2)$ (km s^{-1})	$\Delta V(C', C_{4,5})$ (km s^{-1})
Io	0.000 541 68	17.32	6.519 07	24.3608	24.3653	24.4995
Europa	0.000 862 28	13.74	5.209 58	19.2380	19.2436	19.4132
Ganymede	0.001 375 42	10.87	4.384 18	15.1432	15.1504	15.3652
Callisto	0.002 419 22	8.18	3.785 74	11.2803	11.2899	11.5766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A.2
A.3
A.4
A.I
B
C
L I
Y
X
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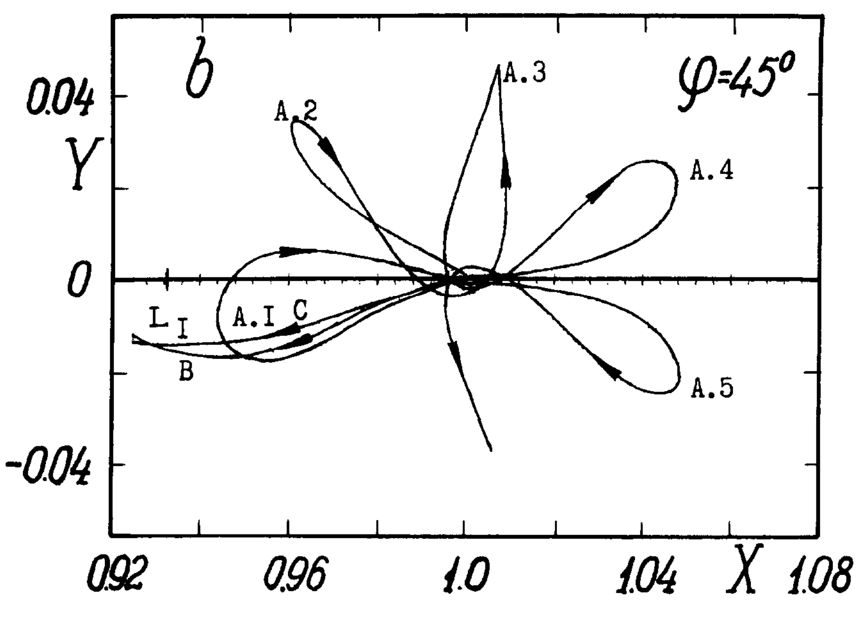
0
-0.04
0.92
0.96
1.0
1.04
1.08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A.3
A.4
A.5
A.I
B
C
L I
Y
X
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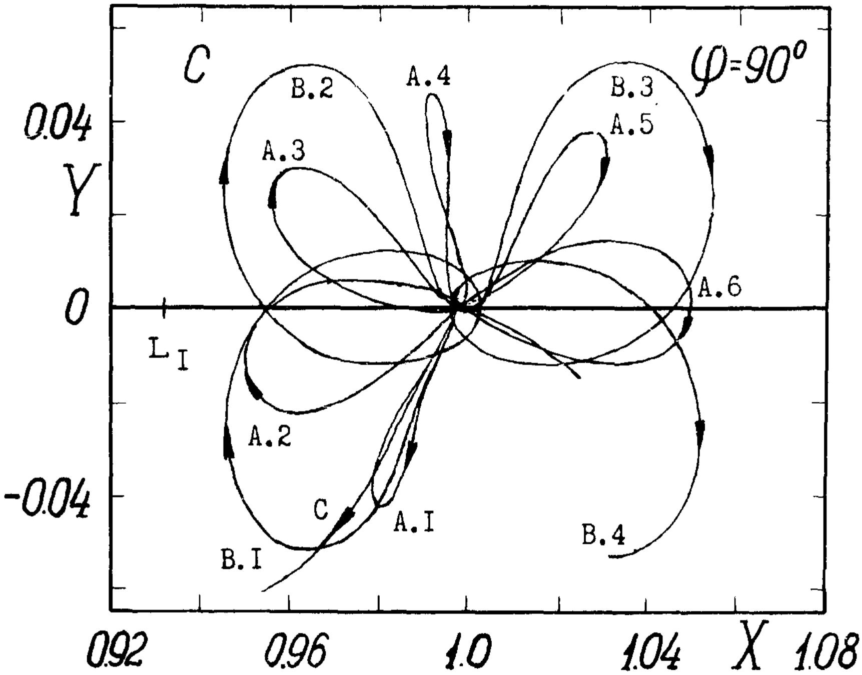
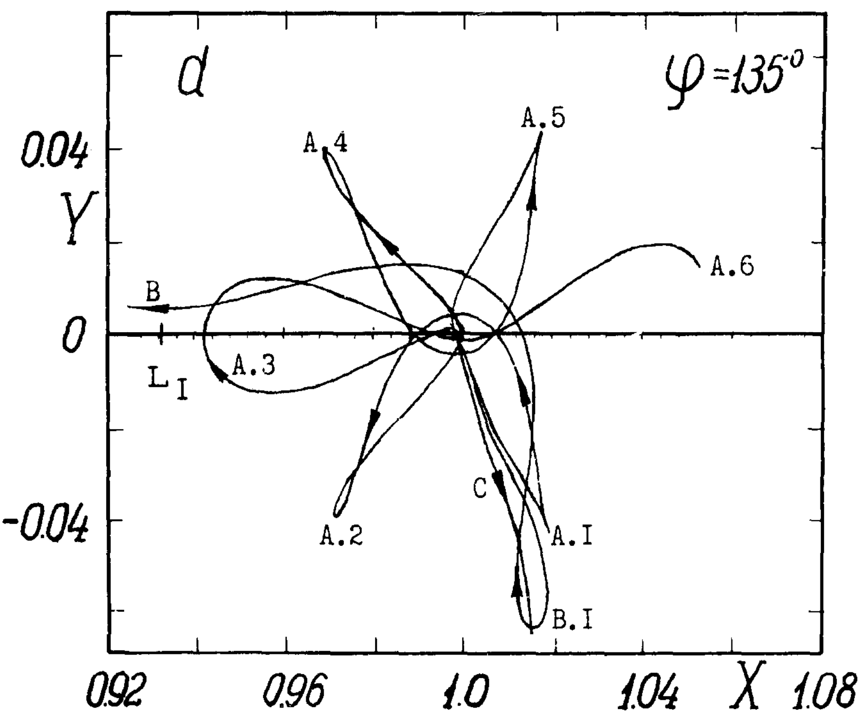
-0.04
0.92
0.96
1.0
1.04
1.08


c
φ=90°
0.04
Y
0
-0.04
L I
B.2
A.4
B.3
A.5
A.3
A.6
A.2
C
A.I
B.I
B.4
0.92
0.96
1.0
1.04
X
1.08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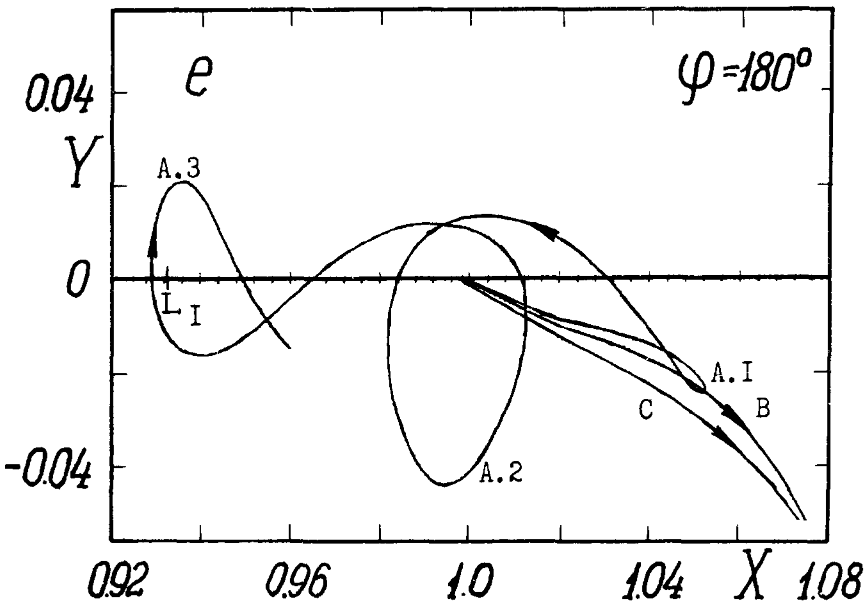
Y
0
-0.04
A.4
A.5
A.6
B
A.3
L I
C
A.2
A.I
B.I
0.92
0.96
1.0
1.04
X
1.08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Y
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L I
A.2
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C
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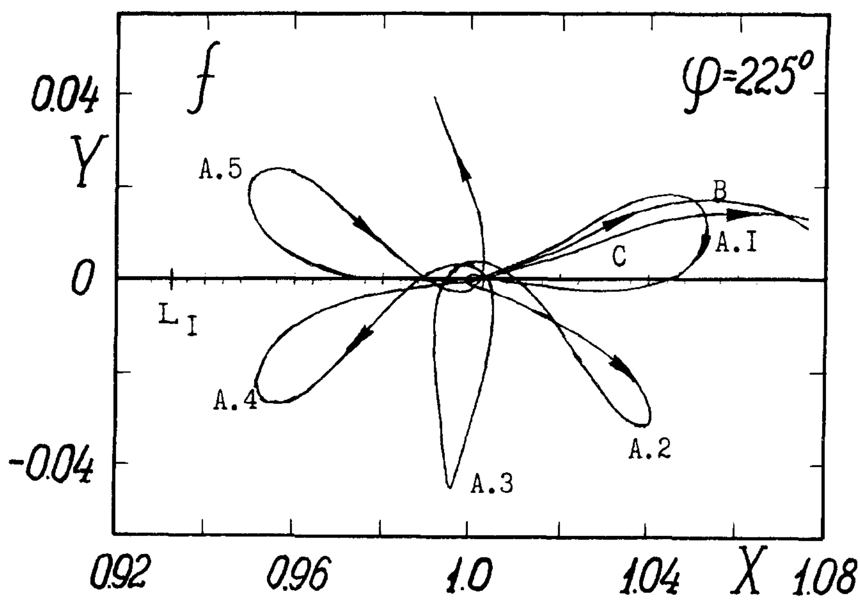
X
1.08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Y
0
-0.04
A.5
B
A.I
C
L I
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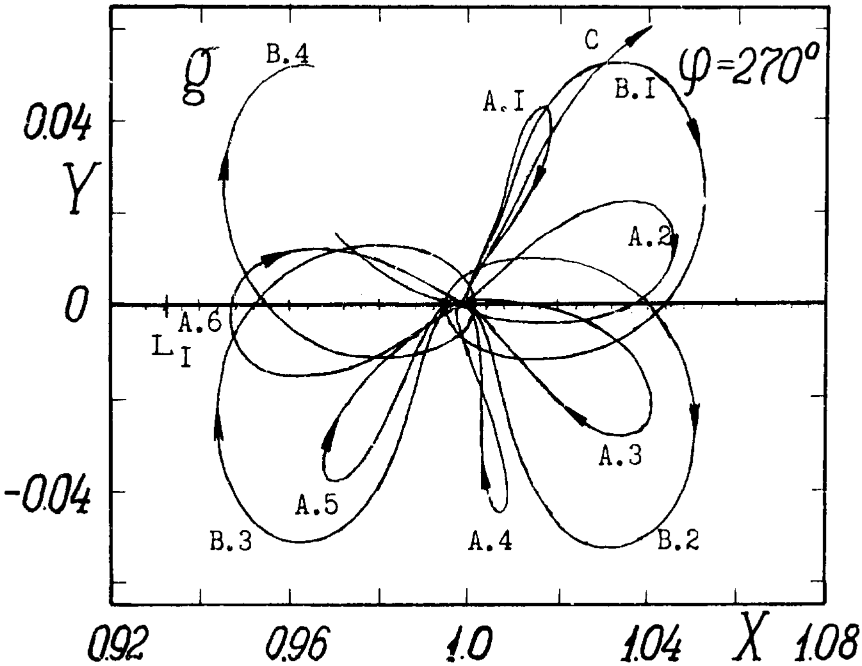
A.2
A.3
0.92
0.96
1.0
1.04
X
1.08


g
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C
B.4
A.I
B.I
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Y
A.2
0
A.6
L I
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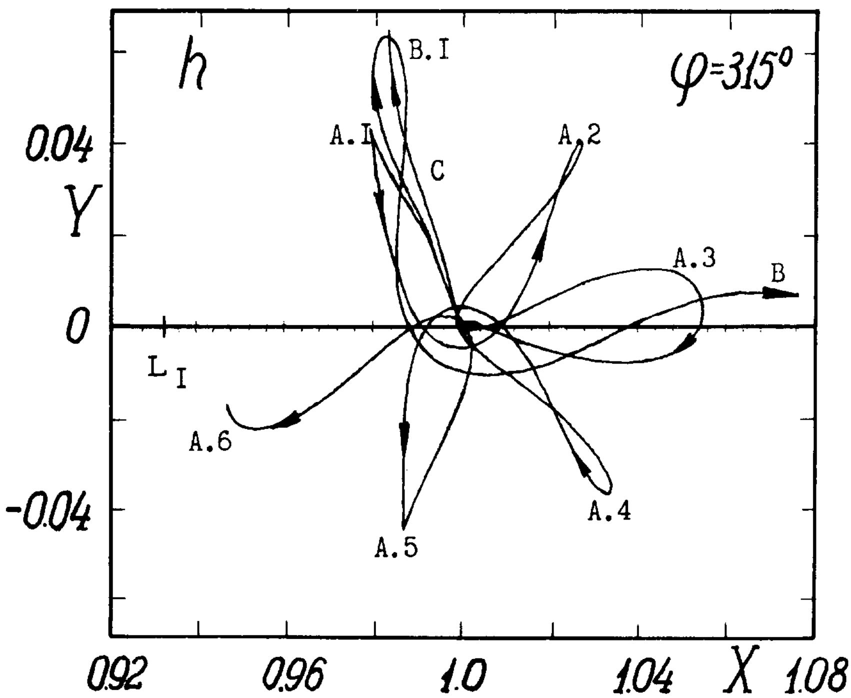
A.5
B.3
A.4
B.2
0.92
0.96
1.0
1.04
X
1.08


h
B.I
φ=315°
0.04
A.I
A.2
C
Y
A.3
B
0
L I
A.6
-0.04
A.4
A.5
0.92
0.96
1.0
1.04
X
1.08

In order for a body to get, say, from L_1 to L_2, it should have at point L_1 a velocity $\Delta V_{1-2} = 0.466\,\mathrm{km\,s^{-1}}$, and from point L_1 to $L_{4,5}$, a velocity $\Delta V_{1-4,5} = 2.603\,\mathrm{km\,s^{-1}}$. Table I lists the velocities in satellite orbits required to reach the point L_1, L_2, and $L_{4,5}$.

The motion of material points in the Jupiter–Sun system was calculated by a method of Everhart. The precision of computation was checked by the constancy of C. The computation was stopped when in a close encounter of a body with Jupiter the magnitude of C varied by more than 10^{-4}.

4. Ejection of Particles from the Roche Lobe and the Effect of the Sun on their Motion

We have calculated the motion of fragments (considered as material points) ejected tangentially to the Galilean satellites' orbits counterclockwise from different longitudes φ (reckoned from the X-axis in the direct sense). As an illustration, we are presenting here the result obtained for the particles ejected from Ganymede's orbit. The calculations were carried out for different initial velocities at the satellite's orbit corresponding to $V_{L1} = 0.5, 1.0\ 1.5, 2.0$, and $2.603\,\mathrm{km\,s^{-1}}$ at the L_1 point. In principle, all these fragments should eventually escape from Jupiter's critical Roche lobe (contacting L_1) in the zone of the Sun action. However, their lifetime in the Roche lobe and the final trajectory depend strongly on the initial velocity and ejection longitude (see Table II and Figure 1a–h). For small values of V_{L1} ($\lesssim 0.3\,\mathrm{km\,s^{-1}}$) the lifetime of particles in Jupiter's sphere of action was studied by Heppenheimer and Porco (1977).

At $V_{L1} = 2$ and $2.603\,\mathrm{km\,s^{-1}}$ the particles escape immediately through arbitrary points on the sphere of action in time $t \approx (0.05–0.3)P_4$ without completing a single turn around Jupiter. As a result, their subsequent trajectories may lie both within Jupiter's orbit (at $-30° \lesssim \varphi \lesssim 150°$) and outside it (at $165°\ (-195°) \lesssim \varphi \lesssim 315°\ (-45°)$) (see Figure 2).

Fig. 1(a–h). Particle trajectories inside Jupiter's sphere of action and in its immediate vicinity. The particles are ejected tangentially to Ganymede orbit from different longitudes φ (with φ measured from the continuation of the Sun–Jupiter line in the direction of Jupiter rotation) with an initial velocity $V_0 = 15.1514$ (curve A), 15.2173 (curve B), and $15.3652\,\mathrm{km\,s^{-1}}$ (curve C) (which corresponds to the velocities $V_{L_1} = 0.5$, 1.5 and $2.603\,\mathrm{km\,s^{-1}}$ when/if the particle reaches the L_1 point). The trajectories of particles which do not leave the sphere of action are drawn until $t = 0.8P_{♃}$. The apojovia passed after ejection are marked by consecutive Arabic numerals.

Note the following three points:

(1) On reaching the periphery of Jupiter's sphere of action ($r_1 \approx 0.06$) the particles begin to move frequently in retrograde (clockwise) direction, particularly at moderate V_{L_1};

(2) At high values of V_{L_1} ($\gtrsim 1.5\,\mathrm{km\,s^{-1}}$) the particles leave Jupiter's sphere of action in the directions of $X > 1$ (outward from Jupiter's orbit) and $X < 1$ (inward) with about the same probability; at low V_{L_1} ($\lesssim 0.5\,\mathrm{km\,s^{-1}}$) they leave it predominantly in the $X < 1$ direction (through the L_1 region);

(3) The shape of a particle's trajectory inside Jupiter's sphere of action and the direction of its ejection from the latter depend strongly on φ.

TABLE II

Lifetime (in units of $P_{♃} = 11.862$ yr) and direction of motion ($X < 1$ – inside, and $X > 1$ – beyond Jupiter's orbit) from Jupiter's sphere of action of fragments ejected from Ganymede's orbit vs longitude φ and initial ejection velocity V_0 (V_{L_1} is the velocity of a particle entering L_1). If the direction of ejection is not specified, the particle at the given time undergoes a close encounter with Jupiter, or the lifetime in Jupiter's sphere of action exceeds $10P_{♃}$

V_0 (km s^{-1})	V_{L_1} (km s^{-1})	φ 0°	45°	90°	135°	180°	225°	270°	315°
15.1514	0.5	2.43 $X < 1$	> 10	2.04	> 10	1.69 $X > 1$	10	2.05	> 10
15.1762	1.0	0.117 $X < 1$	0.086 $X < 1$	0.33	0.41	0.17 $X > 1$	0.83 $X < 1$	10	0.82 $X < 1$
15.2173	1.5	0.077 $X < 1$	0.066 $X < 1$	2.75 $X < 1$	0.272 $X < 1$	0.090 $X > 1$	0.265 $X > 1$	7.85 $X > 1$	0.265 $X > 1$
15.2747	2.0	0.064 $X < 1$	0.055 $X < 1$	0.097 $X < 1$	0.320 $X > 1$	0.070 $X > 1$	0.315 $X > 1$	0.10 $X > 1$	0.313 $X > 1$
15.3652	2.603	0.047 $X < 1$	0.040 $X < 1$	0.077 $X < 1$	0.196 $X < 1$	0.06 $X > 1$	0.190 $X > 1$	0.077 $X > 1$	0.186 $X > 1$

The trajectories of the particles ejected from a satellite's orbit near intermediate angles $\varphi \sim (-15° – -30°)$ and $\sim (150°–180°)$ as they leave Jupiter's sphere of action lie close to Jupiter's orbit and, therefore, have initially an irregular pattern due to the strong gravitational action of Jupiter. The motion of the remaining particles until the completion of a full revolution in the rotating frame and a new encounter with Jupiter is fairly regular.

The 'inner' and 'outer' particles differ however substantially in the pattern of their motion, At $V_{L1} = 2.603$ km s^{-1} the inner particles move with a period $\approx 0.65–0.8P_{♃}$, and the outer ones, with $\approx 1.1–1.7P_{♃}$: Accordingly, the first approach of the inner particles to Jupiter's orbit (in aphelion) occurs within an arc $\sim 30°–110°$ (reckoned from the Sun–Jupiter line), and the second, within 70°–230°. At the same time the outer particles approach Jupiter's orbit (in the perihelion) within $\sim -50° – -290°$. Note that in the rotating frame the trajectories of such approaching particles at $V_{L1} \gtrsim 2.5$ km s^{-1} form a small retrograde loop, with the particles velocity relative to Jupiter dropping down to a few hundred m s^{-1}. The above features and the difference in motion between the inner and outer particles are of considerable importance for the problem of the origin of the Trojans (Agafonova and Drobyshevski, 1983, 1985b – Paper III).

At $V_{L1} = 1.5$ km s^{-1}, particles can usually make several revolutions in Jupiter's Roche lobe before escaping from it although they still can leave it in both directions relative to Jupiter's orbit with about the same probability.

The time during which a particle may remain in the Roche lobe may depend substantially on the initial longitude of ejection from the satellite's orbit. Obviously, this relates in the first place to the angles at which the trajectory is oriented from the very beginning in the direction of L_1 or L_2. Indeed, at $V_{L1} \approx 1–0.5$ km s^{-1} particles, on making a few revolutions around Jupiter, escape from the Roche lobe primarily through the L_1 region

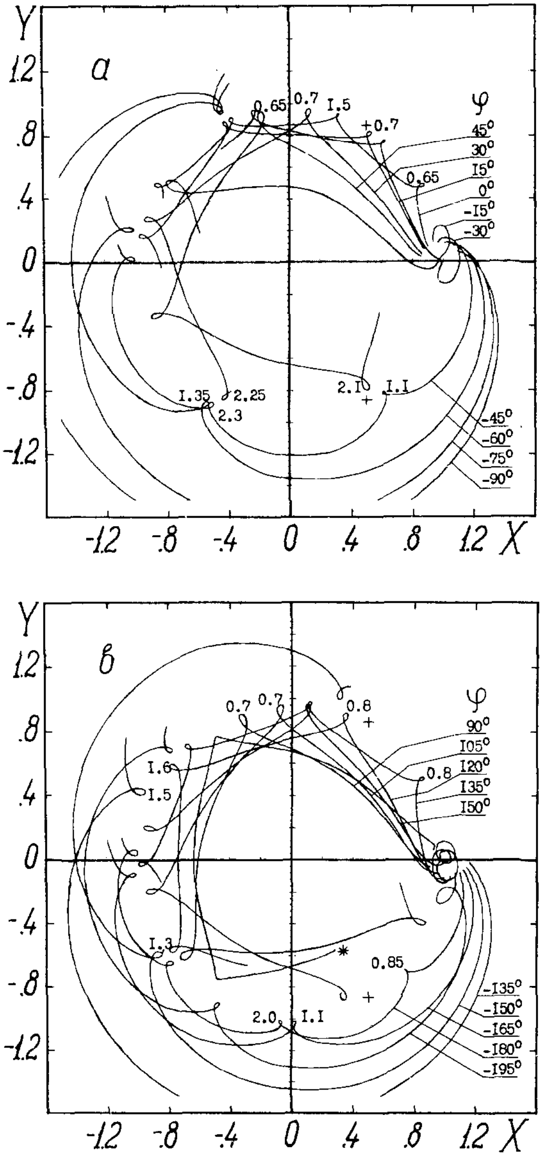


Fig. 2 (a–b). Particle trajectories outside Jupiter's sphere of action. Just as in Figure 1, the particles are ejected from different longitudes φ in Ganymede orbit, but with an intial velocity V_0 = 15.3652 km s^{-1} (V_{L_1} = 2.603 km s^{-1}, $C = 3.0$). Note that the first aphelia of particles entering inward Jupiter's orbit crowd around the preceding triangular libration point L_4 within $\sim \pm \pi/3$ whereas the perihelia of particles with trajectories outside Jupiter's orbit reveal almost no such crowding near the following L_5 point. As the particles of both types approach the circle of unit radius, their velocities relative to Jupiter decrease strongly (the numbers give the time elapsed from the moment of ejection from the satellite's orbit to aphelion or perihelion approach in units of $P_{♃}$).

Fig. 2b shows also for comparison trajectory corresponding to V_0 = 15.2173 km s^{-1} (V_{L_1} = 1.5 km s^{-1}) and $\varphi = 90°$ (marked by asterisk). This trajectory does not approach the circle of unit radius as close as trajectories with $C = 3.0$ do.

although, as follows from a comparison of the values of C_1 and C_2 (see earlier), up to $V_{L1} = \Delta V_{1-2} = 0.466\,\mathrm{km\,s^{-1}}$ they can also leave through L_2. However, under a favorable orientation of ejection from the satellite's orbit a particle with $V_{L1} = 1\,\mathrm{km\,s^{-1}}$ (at $\varphi \sim 0°$–$45°$) is ejected immediately through the L_1 region or (at $\varphi \sim 180°$–$225°$) through L_2.

When propelled from the satellite's orbit with a velocity $< \Delta V(C', C_1)$, the particle within the framework of our approximations, cannot leave the Roche lobe at all.

5. Particle Motion Inside the Roche Lobe

The trajectories of particles moving inside the Roche lobe deserve particular attention. If a fragment is ejected from the circular orbits of the Galilean satellites lying deep in the Roche lobe directly with a slightly above circular velocity, it will move in an ellipse tracing out a retrograde rosette in the synodic frame.

As the ejection velocity increases, the elliptical trajectory will undergo ever greater deformation in its aphelion part, with the result that at apojovium the particle will begin moving in retrograde direction. At perijovium the motion will retain its direct sense.

An idea of the magnitude and direction of particle velocity in the rotating frame for apojovia oriented toward the Sun can be obtained from Figure 3. It shows two curves corresponding to the orbits of particles tangential at perijovium to the orbits of Jo or Ganymede but calculated under the assumption that the Sun does not act upon the motion. The difference in the initial values of the angular momentum results naturally in different velocities at apojovium. Indeed, for $r_1 > 0.0315$ and $r_1 > 0.040$ for the particles ejected from the orbit of Jo and Ganymede, accordingly, the velocity at apojovium in the synodic frame reverses direction, the trajectory exhibiting a retrograde loop and thus acquiring a figure-of-eight pattern (here r_1 is the distance from Jupiter).

Actually, the trajectory becomes distorted not only because of a transition from the sidereal to synodic frame which is a purely kinematic factor. The increase of r_1 entails the appearance of two dynamic factors which shift the particle velocities at apojovium found in the restricted circular problem approximation, as a rule, above the aforementioned curves for Jo and Ganymede (Figure 3).

The first factor is the gravitational action of the Sun grows increasingly compared with that of Jupiter as a particle moves toward the periphery of its sphere of action. If a particle moves from Jupiter toward the Sun, then (being closer to the latter) it will be forced to revolve around the Sun with a somewhat greater angular velocity than Jupiter does. If, however, a particle moves from Jupiter and away from the Sun, it will tend to acquire a smaller angular velocity than Jupiter. A similar reasoning can be applied to a particle moving along Jupiter's orbit in the direction of its motion (indeed, because of its velocity being added to Jupiter's orbital velocity the Sun will tend to deflect the particle to an orbit beyond that of Jupiter) or against it (in which case the particle will transfer to an orbit sunward from Jupiter). In any case a particle ejected from deep inside Jupiter's sphere of action toward its periphery will tend to assume retrograde motion.

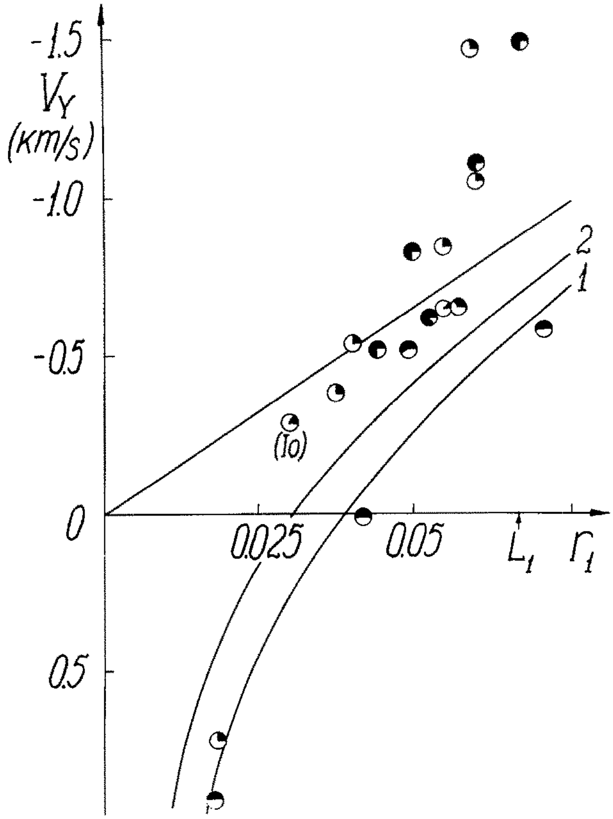


Fig. 3. The longitudinal component of velocity V_y at apojovia in the rotating frame on the Sun–Jupiter line ($Y \approx 0$) for particles ejected from different longitudes in Ganymede's and Io's orbits in the direct sense. The straight line is the velocity of a particle at rest relative to Jupiter in the fixed frame, curve 1 is the velocity at apojovium of a particle moving in an ellipse tangential at perijovium to Ganymede's orbit (without taking the Sun's action into account), curve 2 is the same for an ellipse tangential to Io's orbit.

The figure illustrates the onset of retrograde motion at apojovium as a result of three effects: (1) a purely kinematic effect due to the frame's rotation; (2) due to the Sun's gravitational action (see text), and (3) due to 'randomization' of motion inside Jupiter's sphere of action because of the latter's nonsphericity. Due to the latter effect, the retrograde velocities at apojovium may become very high, up to ~ 1.5 km s^{-1} (depending on the longitude φ of particle ejection from the orbit of a regular satellite, the longitude being equal to the angle of the corresponding filled sector of the point in the figure).

The other factor affecting noticeably the retrograde motion are the initial conditions; namely, the velocity and longitude of fragment ejection from the orbit of a Galilean satellite. Indeed, as we have seen (Figure 1), a particle with a sufficiently high initial velocity may either be immediately ejected from Jupiter's sphere of action ($\varphi \sim 0°$, $\sim 180°$) following a clearly pronounced direct trajectory or pass through retrograde section on its way, depending on the initial longitude φ. This is a consequence of the gravitational potential in the periphery of Jupiter's sphere of action deviating strongly from spherical symmetry. As a result, at some longitudes φ ($\sim 90^\circ$, $\sim 270^\circ$) particles even with a comparatively high initial velocity (corresponding to $V_{L1} = 0.5$–$1.5\ \mathrm{km\ s^{-1}}$) turn out to be trapped – as it were – inside Jupiter's sphere of action for a certain time, their motion becoming randomized to an extent because of 'reflections' from the non-spherical boundary of the Roche lobe. Therefore, when such particles come close to the surface containing the L_1 point they will acquire the above-mentioned high velocities even when moving in retrograde direction.

As a result of these two effects particles at apojovium have, as a rule (except at $\varphi \sim 180^\circ$), a strongly pronounced retrograde excess of velocity (the points in Figure 3 lie above the curve corresponding to ejection from Ganymede's orbit with only Jupiter's gravitation considered). This observation has to be taken into account when discussing the origin of the irregular satellites (Agafonova and Drobyshevski, 1985a – Paper II).

Note that retrograde motion manifests itself the more strongly, the smaller the initial positive angular momentum imparted to a particle in its ejection from the orbit of a regular satellite – i.e., the closer to Jupiter lie the initial orbit and the corresponding perijovium.

6. Conclusion

The present paper should serve as an introduction to the papers studying the origin of Jupiter's irregular satellites (Paper I) and the Trojans (Paper II) from the standpoint of implications of explosions on the Jovian regular icy satellites.

Ejection of explosion fragments from the immediate vicinity of Jupiter – i.e., from deep inside its sphere of action, with a small angular momentum – places them in complex trajectories as the fragments reach the periphery of the sphere, and later as they emerge out of it. In the first case, due to the action of the Sun and, hence, due to the gravitational potential near Jupiter lacking spherical symmetry, the motion of the fragments acquires frequently a retrograde pattern, which should facilitate their becoming retrograde satellites. In the second case, ejection of fragments through the region of the inner or outer Lagrangian points introduces asymmetry into their subsequent motion inside and outside Jupiter's orbit, which obviously results in the conditions of possible capture at the preceding (L_4) and following (L_5) libration points being different.

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