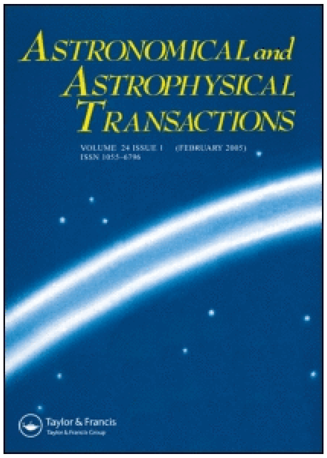

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Post-Perijove splitting and Lithium overabundance in Shoemaker-Levy 9 favor its planetary origin

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POST-PERIJOVE SPLITTING AND LITHIUM OVERABUNDANCE IN SHOEMAKER-LEVY 9 FAVOR ITS PLANETARY ORIGIN

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The SL-9 nucleus splitting into 20+ fragments well after the perijove, and continuing during several months, cannot be explained by stretches due to a tidal process. Here one can track an analogy with the standard behavior of short-period comets usually developing their maximum activity after the perihelion and experiencing outbursts correlated with the solar activity. The outbursts can also be followed by the nucleus break-up and take place at distances where water practically does not sublimate.

The lithium emission detection in the plume formed after the impact of the fragment L onto Jupiter was puzzling as nobody has observed Li in comets up to now. This discovery speaks for cometary origin of Li and for its concentration solely in a part of the SL-9 nucleus. The comet formation of grains condensed in a turbulized gas nebula is hardly able to account for such local overabundance of Li which is known to be a rare and highly dispersed element.

These difficulties are solved in a natural way by the New Explosive Cosmogony (NEC) of minor bodies. It considers the cometary nuclei as fragments of global explosions of Ganymede-type bodies having icy envelopes saturated with the ice electrolysis products, $2H_2+O_2$. These fragments, in turn, are also saturated with $2H_2+O_2$, that provides the inner energy source needed for (distant) outbursts and nucleus break-ups which can be initiated by the electric current generated by the nucleus motion in magnetic fields of the solar wind or of giant planets. Besides, due to geochemical, hydrothermal etc. processes of the element separation having place in parent planets, these fragments can contain isolated ore nests of different elements, including Li.

KEY WORDS Shoemaker–Levy 9, SL-9 planetary origin, comet splitting, cometary Li

1 INTRODUCTION. COMETS AS PRODUCTS OF EJECTION FROM ICY PLANETS

Interpreting numerous discoveries made in recent years in cometary astronomy, we will proceed from Lagrange's idea, modified by Vsekhsvyatskii (1967), on ejection of comets from distant Moon-like icy bodies. At present, two physically plausible mechanisms of ice ejection from planets are conceivable: by collision or by explosion.

The collision mechanism is suggested to operate in the not-too-distant (∼ 50–3,000 AU) planeto-cometary cloud (not to be confused with the Oort cloud or the Kuiper belt which contain no planets) composed of dozens of Pluto-like or larger planets and fragments of their icy envelopes – the nuclei of long-period (LP) comets ejected in extremely rare planetary collisions. The existence of a planeto-cometary cloud is predicted by our cosmogony considering the Jupiter–Sun system as a limiting case of a binary star (Drobyshevski, 1978). Some of these nuclei are introduced into the inner Solar System either after their impact formation or as a result of perturbations by the cloud planetary members.

The concept of a close (40–100 AU) Kuiper comet belt was actively developed in recent years (Levison, 1991; Luu, 1994), which was in part stimulated by the discovery of several trans-Neptunian objects with moderately eccentric orbits and three Centaur asteroids on orbits partially located within Saturn's orbit (Jewitt and Luu, 1993). However, this approach faces difficulties in explaining the origin of these objects (Stern, 1995). On the other hand, Stern (1991) recently also arrived at the conclusion that a cloud of Pluto-like planets possibly exists on the periphery of the ordered planetary system.

As for the Centaur objects, two of them (2060 Chiron and 5145 Pholus) may well be fragments that have originated from the recent explosion of Titan's ice (Drobyshevski, 1981), which is confirmed by calculations of their past orbits, indicating close encounters with Saturn. The fragments can leave the Saturnian sphere of action some time after their formation as a result of explosive collisions or accumulated perturbations.

The explosive process is made possible by the accumulation of $2H_2+O_2$, the products of bulk electrolysis of the dirty ice constituting massive envelopes of Ganymede-like bodies, in the form of a solid solution in the ice. The electrolysis proceeds under the action of an electrical current (Drobyshevski *et al.*, 1995) induced in these bodies owing to their motion in the solar wind or in the magnetospheres of the giant planets. The surviving icy fragments resulting from such explosions (nuclei of short-period (SP) comets) are saturated with electrolysis products up to concentrations just below the critical value. With additional energy supply, such ices are combustible and even able to detonate (Drobyshevski, 1980a, 1986).

Although planetary perturbations can transfer some SP comets into LP orbits and vice versa, the presence of an inner energy source in the nuclei of the majority of SP comets directly provides an unconstrained explanation of the long-known difference in behavior between the SP and LP comets. The former exhibit the highest activity after the perihelion passage, owing to the gradual development of combustion, while the latter not infrequently sublimate the majority of volatiles from their surfaces before perihelion.

Below (Section 2), we are going to sum up, in the context of the approach described above, the explanations of unexpected and incomprehensible phenomena which were discovered during the last apparition of P/Halley and defy unambiguous interpretation in terms of the conventional purely sublimation-photochemical hypotheses for cometary activity. Next we will show that the observed comet outbursts, frequently leading to the break-up of nuclei and correlating with the solar activity, may be well accounted for in terms of combustion. In Section 3, the inconsistency and unsoundness of the scenarios of tidal splitting of the P/Shoemaker–Levy 9 (SL-9) nucleus, discussed thus far, will be highlighted. The break-up of the heterogeneous nucleus, which lasted for months *after passing* the perijove, and the activity of nucleus fragments are shown to be well attributable to the ignition of combustion in the nucleus by an electric current induced by the comet's motion in Jovian strong magnetic field. In Section 4, we will demonstrate that the presence of lithium in the hot plume generated after impact of the fragment L of SL-9 into Jupiter also favors the planetary origin of comets, since the process of concentration of trace Li in ice or rock is possible only as a result of large-scale geo- or hydrochemical processes. Finally, in Section 5, we will point out once again that, during fifteen years of development, the NEC has encountered no scientifically grounded objections at all. It appears that only impediment to the recognition of this theory is the considerable inertia of the old condensation-sublimation paradigm.

2 COMBUSTION OF ELECTROLYZED ICES AS THE ENERGY SOURCE IN SP COMETS

Our prediction that combustion is possible in SP comets (Drobyshevski, 1980a) is to be considered as fully substantiated as a result of in situ studies of P/Halley (for details see Drobyshevski, 1988b). Indeed, the surprisingly high nucleus temperature and energetics of the cometary activity, when jet emission of water molecules together with dust proceeds from $\lesssim$ 10% of the illuminated nuclear surface, whereas an amount of solar energy collected by at least 40% of the surface is necessary for their sublimation to occur, may be accounted for only by the presence of an intrinsic high-power energy source switched on by the radiation. The classical problems related to the shorter lifetime of "parent" molecules in the solar radiation field as compared with laboratory measurements, to the presence of positive, negative and complex organic ions in the vicinity of the nucleus, to the origin of C_2, C_3, and atomic C, etc., are easily solved under the assumption that combustion occurs in the products of sublimation of ice containing, in addition to organics, also free oxygen and hydrogen. Since the oxygen concentration is close to the stoichiometry only in relation to hydrogen, the combustion proceeds, in general, under oxidizer-deficiency conditions. The latter fact makes understandable the large excess of CO over CO_2, the appearance of soot (C, C_2, C_3), the condensation on the mineral dust of submicron particles of smoke (CHON particles), which subsequently partially evaporate under the action of solar radiation to supply additional CO at a certain distance from the nucleus, etc. Chaizy *et al.* (1991) point to the fact that "as negative ions are easily destroyed by solar radiation at 1 AU, an efficient production mechanism, so far unidentified, is required to account for the observed densities". Crovisier (1992) noted that the detection of "the presence of CO^+ in P/Schwassmann–Wachmann 1 is also a puzzle due to the slow photoionization rate of CO at that a heliocentric distance".

The question of the existence of an internal energy source has been the subject of debate for a long time (e. g. Shulman 1987, and refs. therein), primarily in an attempt at explaining the outburst activity of comets which sometimes results in a breakup of the nucleus and ejection of the fragments thus formed with velocities up to $\sim$ 10 m/s (Kresak, 1981). It should be stressed that even the conventional outflow of cometary material is nonstationary and flare-like, which can be accounted for only by a sudden production of large amounts of gas corresponding to an instantaneous evaporation, in $\sim$ 9 min, of up to $\sim 4.2 \times 10^8$ kg of water ice (Larson *et al.*, 1990). The energetics of the mechanisms proposed until now (gas dissolved in ice or contained in separate pockets, transition from amorphous crystalline ice, quasisolvated ions and radicals, exothermal reactions of the hydrocarbons decomposition, or conversely of HCN polymerization, etc.), all of which are bearing shade of ad hoc hypothesis, are obviously not sufficient to account for the above phenomena.

The widespread suggestion (e. g., Larson *et al.*, 1990) that gas or internal stresses could eject small icy grains out of the cracking ice, thus increasing many times the surface irradiated by the Sun, is inconsistent with the submillimeter measurements of Jewitt and Luu (1992) and does not help much. First, extending the results of laboratory experiments on the cracking of pure water ice (which may contain also volatile gases like CO and CO_2) to dirty ice containing viscous and sticky nonvolatile organics ($\sim$ 10%) and mineral matrix ($\sim$ 10%) of chondritic composition, and coated by a dark crust consisting of the residuals of these components, appears hardly justifiable. Second, the observed time of outburst development (and, accordingly, the daughter products' appearance) may be less than the breakup time of the parent molecule in the solar radiation field (Shulman, 1987), and cometary outbursts have been known for a long time to correlate with solar activity (e. g., Golubev, 1979; Hughes, 1990). In particular, according to Intriligator and Dryer (1991), a (double?) outburst of P/Halley at 14.3 AU can also be correlated with a solar flare. The penetration of the flare-initiating electric current flowing at the solar wind sector boundaries, or of the solar particle fluxes likewise, cannot be explained within the sublimation framework which assumes the dense near-nucleus cometary atmosphere to be cold and non-ionized. The only conceivable process yielding preionization is combustion, as a result of which electric currents from the solar wind penetrate into the vicinity of the nucleus, and eventually, along the hot ionized gas jets of the combustion products into the nucleus, with subsequent initiation there, in the regions of enhanced organics and oxygen concentration, of new sites of burning.

3 REASONS FOR DISINTEGRATION OF P/SHOEMAKER–LEVY 9 (SL-9)

It is generally believed that the break-up of SL-9 resulted from tidal rupture of its nucleus in passing the perijove at a distance of 95.220 km from Jupiter's center on July 8, 1992. The initial nucleus diameter is estimated at 2–10 km (Jupiter's radius is 71.300 km). To allow for tidal disintegration of the nucleus at such a distance from Jupiter ($\sim 1.5 R_J$ from its center) and to account for the manyfold difference in the velocities of dust and large fragments, the following strong and contradictory assumptions have to be postulated (Sekanina, 1993, 1995; Scotti and Melosh, 1993; Sekanina *et al.*, 1994):

i) The strength of the nucleus material must be extremely low ($\sigma \sim 10^2$–10^3 dyn/cm^2), which also implies a low nucleus density ($\rho = 0.2$–0.3 g/cm^3) and, furthermore, a rotation period $\gtrsim 7.5$ h.

ii) The nucleus must split in several hours (~ 1.5 h) after passing the Roche limit; the positions of some of the fragments (B, F, P, T, J, M) indicate that they could have separated from larger fragments after weeks or *even months* at a relative velocity as high as ~ 1 m/s!

iii) The velocities of the fragments must be thermalized in their collisions for small fragments to fly apart at a higher velocity, with the initial randomness of velocities being set by the original nucleus rotation.

Furthermore, the collisional evolution postulated by Sekanina *et al.* (1994) to account for the high velocities of small fragments implies the preservation of their integrity in collisions at velocities of several m/s, which is obviously inconsistent with the assumption of the low strength of substance in the SL-9 nucleus.

In view of the well-documented high probability of break-up of cometary nuclei ($\sim 10^3$ events in $\sim 4 \times 10^5$ years of dynamic lifetime of each SP comet, Chen and Jewitt, 1994), which occur far from planets and correlate with comet outbursts (and with the solar activity as well), it is reasonable to suppose that the primary role in the SL-9 break-up was also played by the inner energetics activated by the motion of the comet in Jovian magnetic field. On the average, the magnetic field strength at Jupiter's surface is ~ 5–10 Gauss, so that in July, 1992 the comet moved in a field of ~ 2–3 Gauss, which induced, at a velocity of ~ 50 km/s, a potential difference $\Delta U = 100$–150 kV across the nucleus 10 km in diameter (a value comparable with $\Delta U = 400$ kV for Jovian satellite, which induces a current of ~ 5 MA; Ness *et al.*, 1979). The comet moved in Jovian magnetosphere plasma which served as an external circuit bringing to completion the current path through the nucleus. The current was capable (as at boundaries of the solar wind sectors) of initiating combustion and subsequent sporadic detonation in sites of increased $2H_2$+O_2 content in the cometary ice, which resulted in the subsequent break-ups of the nucleus. It should be noted that, in perfect analogy to the behavior of SP comets generally exhibiting the maximum activity after perihelion passages as a result of the gradual development and inertia of combustion, here the most active combustion also developed after passing the perijove. This accounts for the fact that the process of splitting (occasionally of explosive nature) of the SL-9 nucleus and its fragments was fairly prolonged and lasted for several months, far beyond the Roche limit (Sekanina, 1995). It is reasonable that, in explosive splitting of the nucleus, smaller fragments should immediately acquire much higher velocity than the larger ones, which is difficult to explain in terms of the tidal model. Eventually, all the large fragments lost all their volatiles, including water, as it happened with Phobos after combustion was initiated there by the Stickney impact (Drobyshevski, 1988a). Therefore, by the moment of discovery, no traces of water could be found in SL-9 (Weaver *et al.*, 1994). No water could be also found in the sites of impact of its fragments onto Jupiter (West, 1994).

4 LITHIUM IN P/SHOEMAKER–LEVY 9 AND HETEROGENEITY IN COMETARY NUCLEI AS EVIDENCE OF GEOCHEMICAL PROCESSES IN PARENT PLANETS

Li is one of the least abundant elements in the Universe. Therefore, in contrast to all other more or less predictable phenomena with model – independent explanation, accompanying the impact of SL-9 onto Jupiter at a velocity of $\sim$ 60 km/s, when the temperature behind the shock wave was as high as tens of thousand K and molecules of any compound should have decomposed, the unambiguous detection of Li emissions in the impact plume of the fragment L of the comet (West, 1994; Crovisier, 1995) posed numerous questions. Among these the following two main questions stand out: whether Li is of cometary origin, and if so, why it has never been observed before, even in Sun-grazers. This is the more strange as the boiling temperatures of basic compounds of other observed alkali elements are not too much different. The high Li abundance in one of the fragments of SL-9 is hardly explicable, without contrivance, in terms of standart hypotheses for condensation of primordial cometary grains in a more or less uniform protoplanetary cloud, where high gradients of chemical composition are impossible due to turbulent stirring of the gas.

4.1 Distinctions between Comets and Heterogeneities in Cometary Nuclei as a Consequence of Their Planetary Origin

Strictly speaking, the same difficulties, though less dramatic, are encountered in explaining the reason why each comet has its own outlook and the structure of cometary nuclei is so heterogeneous. Although the LP comets are well known to differ in their average parameters from the SP comets, here the degree of sublimative evolution of a nucleus is conventionally referred to; there even exist such terms as "young" and "old" comets. Unfortunately, this approach is far from being always appropriate. For example, it is not easy to understand why some comets carry large amounts of carbon-containing compounds, while in others, e. g. in comet Yanaka 1988XXIV(r) (Fink, 1991), these compounds are practically lacking.

Even taken alone, the outburst cometary activity strongly supports the heterogeneity of the nucleus itself. This is easily understood if the nucleus is assumed to be a fragment of icy envelope of a Ganymede-like body, which, on the one hand, has been subjected to a large-scale solid-state convection and, on the other hand, has experienced geochemical differentiation. Traces of such a primary local layered structure ("crater chains" or "veins") can be seen at Phobos (Drobyshevski, 1988a), and it is along the outcrops of such layers that the sources of the outflowing gas jets travel on the surface of the nucleus (Sekanina and Larson, 1986; Sekanina, 1987). A strong inhomogeneity in the distribution of combustible compounds in the cometary ices, together with the possibility of their being ignited by solar radiation, sheds light on ways of solving the problem of "how the discrete regions on the nucleus become activated" (Sekanina, 1990). It is the global differentiation of substance in envelopes (and cores) of parent bodies that makes comets so much different from the very beginning. As it is well known, the primary differentiation of planetary matter is of purely gravitational nature, favoring precipitation of iron and stone core and separation of a hydrosphere and an atmosphere. Secondary differentiation is governed by geochemical properties of some mineral-forming elements. In the appearance of the hydrosphere, the primary role is played by hydrothermal processes of rock washing out and transfer of soluble compounds and also by merely mechanical transportation of suspensions, leading to the formation of a variety of sedimentary rock, concentration of individual elements into ore bodies etc.

In the present case of distant icy planets, all the above-mentioned processes should take place. In particular, Ganymede-like bodies had originally possessed deep oceans formed by drops and icy bodies falling from the outside as well as by the liquid liberated from the rock cores during their heating and compression. In these oceans, soluble compounds were washed out of the rock and rock particles were attacked by water and, subsequently, after freezing of the oceans, carried along by solid-state convection into the bulk of the icy envelope to form a mineral matrix in the ice. Traces of the action of water on mineral components of meteorites and cometary particles have been reported repeatedly (e. g., Shock and McKinnon, 1991; Fomenkova *et al.*, 1992). Heavy and light organic fractions were subjected first to differentiation in the liquid phase and then to inhomogeneous redistribution in the ice. It is also believed that bulk electrolysis and spreading of its products in the ice also proceeded inhomogeneously.

Further on, after the ice saturated with electrolysis products exploded, some part of the planetary mass was lost and an ocean was again formed after condensation of the explosion products, with the hydro-chemical evolution repeating itself to a certain extent. Again the heavy fraction of, this time, pyrolized organics settled down while the light fraction floated up, soluble compounds were washed out and redistributed, etc. We seemingly observe traces of such a separation at Ganymede's surface, and now a similar process is underway at recently exploded Titan, where the ocean has not yet frozen to the bottom (Drobyshevski, 1981). Therefore, in the secondary global explosions of the envelope, ice fragments are being ejected, which markedly differ in composition from those ejected in the first explosion.

4.2 Geochemical Reasons for Local Li Overabundance Sites in the Cometary Ice

Li is a lithophilic element, and, therefore, in the course of igneous differentiation it concentrates, together with Na, in residual acid rocks (pegmatites of Na–Li type), so that its relative content in the rock, by mass, varies from 0.15 ppm for bazalts and gabbro and 0.5 ppm for dunites (basic and ultrabasic rock) to 20 ppm for diorite and andezites (neutral rock) and 40 ppm for granites (acid rocks) (Poluektov *et al.*, 1975).

Li is a dispersed element which is similar to potassium in this respect. In contrast to Na whose salts are easily washed out to concentrate in oceanic water, K is adsorbed by active substances, such as mud, clay etc., so that it is scattered, being accumulated in soil, sludge and the like. The Li content in sedimentary rock varies from 17 ppm for sandstone to 60 ppm for clays and shales, whereas soils contain 30 ppm. Although about 150 Li-containing minerals are known, these rarely occur in nature as large deposits. Of primary practical importance are spodumene $LiAl[Si_2O_6]$ (with Na_2O, CaO, MgO, Cr_2O_3 as impurities) and lithia mica, lepidolite, $KLi_{1.5}Al_{1.5}[Si_3AlO_{10}]$ [F,OH] (with MgO, FeO, Cs_2O, and Rb_2O as impurities).

At 18° C, the water solubility of LiF (0.1 mole/liter) is low as compared with NaF or KF (1.1 and 15.9 mole/liter, respectively), and, by contrast, LiCl is much more soluble (18.6 mole/liter) than NaCl or KCl (5.8 and 4.5 mole/liter, respectively) (Nekrasov, 1962).

Therefore, in high-temperature igneous processes, in those cases when gas-phase transfer is essential, Li is carried out as LiF, whereas in hydrothermal processes it may remain in a concentrated form in the final solution. A unique example of such a deposit is the saline water of the salt lake Sears (California, USA), where LiCl content is as high as ~ 0.02–0.03 wt.% (Hader *et al.*, 1951).

It is well known that, as aqueous solutions of mineral salts freeze, the salts concentrate in the final intercrystalline solution, while the ice crystals are nearly totally composed of fresh water. Therefore, we may assume that the whole set of processes of ocean freezing at the planet, along with the igneous activity in the rocky core have led to the concentration of Li salts as separate deposits in the ice. It is possible that electrolytic processes were also involved to a certain extent. In particular, the electric conductance of minerals is known (Farrington and Briant, 1974) to be frequently due to H^+, O^{-2}, and Li^+ ion mobility. Therefore, Li can be electrolytically transferred into local zones of electric current concentration at the surface of the rocky core, from where it is subsequently washed out by the water of the icy envelope or transferred, in an ionic form, into channels of a warmer ice, where the electric current paths mainly lie and where the ice located at the boundaries of foreign inclusions is capable of forming a quasi-liquid layer. Naturally, such channels also serve as zones of upward convective flows in the ice mantle, the outcrops of these giving rise to the observed giant concentric structures at Callisto's surface (Drobyshevski, 1980b).

Presumably, the fragment L of SL-9 was just a piece of such an ice containing a nest of excessive concentration of Li compounds. From this standpoint, the reason why Li was detected in only one of all the plumes – traces of impact of various fragments of SL-9 – is quite clear. In this respect, it would be of interest to try to find, in the spectra of this same plume, lines of halogens, which most likely produce water-soluble salts of alkali metals.

5 SUMMARY

It is evident from the foregoing that the whole body of cometary evidence obtained after P/Halley's apparition in 1986 and all the in situ studies of this comet along with the previously incomprehensible cometary phenomena which were no more considered as enigmatic, partly as a result of being "overgrown" with a great deal of ad hoc hypotheses, and partly from force of habit, are all readily interpreted in terms of the NEC (Drobyshevski, 1988b), thus confirming its validity. The incomplete combustion of products of sublimation of cometary ices containing products of electrolysis $2H_2+O_2$ and organics, unambiguously accounts for the appearance of such active components as atomic carbon, atomic oxygen, sulphur dimer, negative and positive ions, CO in excess over CO_2, smoke particles (CHON-particles) etc. in the close vicinity of the nucleus.

The existence of an inner energy source in cometary nuclei makes understandable distant comet outbursts, whereas the presence of ionized combustion products near a cometary surface, where the relatively dense gas has previously been considered as neutral, enables penetration of electric currents from the solar wind into the nucleus and ignition of new centers of combustion, thus making clear the long-known correlation between comet flare-ups and solar activity. It is this process that provides the simplest way of accounting for all the specific features of the prolonged splitting of P/Shoemaker–Levy 9's nucleus after its passage through Jovian magnetosphere in July, 1992, whereas the tidal hypothesis of the break-up is inconsistent with a number of facts.

The NEC readily accounts for the unexpected discovery of Li emission at the site of impact of only one fragment, L, of SL-9 by the possibility of local geochemical concentration of this element in the body of the parent planet. It is hardly possible to provide an explanation for such a concentration in terms of the condensation formation of cometary nuclei. Strictly speaking, the same applies to pronounced inhomogeneties in the structure of cometary nuclei themselves and to the impressive composition distinctions between comets, which have become customary, being not surprising solely for this reason.

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