The young long-period comet family of Saturn

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ABSTRACT
The distributions of long-period comets with respect to the minimum distance \( D \) between their orbits and the orbit of Saturn or Jupiter, constructed by Konopleva using data up to 1972, exhibit a sharp peak at \( D < 0.5 \) au for the Saturnian family, while being fairly monotonic for Jupiter. Hence, in view of the appreciable eccentricity of Saturn’s orbit and the rotation of its perihelion longitude with a period of 47 kyr, the conclusion was drawn by Drobyshevski that the objects belonging to this peak are young (\( \leq 10 \) kyr).

Similar distributions constructed using more recent data show less pronounced differences between one another. Analysis of the distributions for various epochs shows that the initially noted difference is due to observational selection, being inherent to brighter comets. Since on average the cometary activity fades with age, the conclusion that the Saturnian family comets, forming the peak at \( D < 0.5 \) au, are young is all the more substantiated. The question concerning the origin of these comets, which in all likelihood were ejected over a period of a decade from deep inside the Saturnian sphere of influence, is still open. The only self-consistent hypothesis that we see now is that of their appearance as a result of an explosion of the electrolysed ice envelope of Titan. We encourage the development of other explanations.

Key words: celestial mechanics, stellar dynamics – comets: general – planets and satellites: individual: Saturn – planets and satellites: individual: Titan.

1 INTRODUCTION: KONOPLEVA’S EFFECT AND COMETARY COSMOGONY

When studying the distribution of long-period (LP) comets with respect to the minimum distance between their orbits and the orbits of Jupiter (\( \Delta_J \)) and Saturn (\( \Delta_S \)) on the basis of the first ‘Catalogue of Cometary Orbits’ by Marsden (1972), Konopleva pointed out a sharp peak at \( \Delta_S < 0.5 \) au for Saturn. At the same time, the distribution \( N(\Delta_J) \) for Jupiter exhibited no equally noticeable characteristic property [in constructing \( N(\Delta) \) dependences, only comets with orbits of a-, b- and c-quality and with a distance \( \Delta \) to the given planet less than that to any other planet were used]. Hence Konopleva came to the conclusion that the comets associated with this peak are young (Konopleva 1980, 1983).

The author of the present paper has previously put forward a hypothesis that the bulky ice envelope of Titan, saturated with the products of electrolysis, has recently exploded (Drobyshevski 1980b, 1981). As applied to the Galilean satellites, such a hypothesis provides an explanation for many facts that were poorly understood earlier, including distinctions and specific features of the structure and relief of the Galilean satellites, and the origin and properties of the Jovian irregular satellites and Trojans, some short-period (SP) comets, etc. (Drobyshevski 1980a, 1989; Agafonova & Drobyshevski 1985). For a comprehensive consideration of the cometary origin associated with the explosion of the electrolysed icy envelopes of moon-like bodies, and of the cometary properties related to the presence of inner sources of chemical energy in the form of the electrolysis products \( 2H_2 + O_2 \) dissolved in their ices, see e.g. Drobyshevski (1988, 1997) and Drobyshevski, Chesnakov & Sinitsyn (1995).

As for the hypothesis of Titan’s explosion, it has not only accounted for the origin of Titan’s atmosphere and recent orbital eccentricity, the young rings of Saturn and the reservoir of cometary nuclei between the orbits of Jupiter and Saturn, but has also made possible a large variety of predictions (Drobyshevski 1980b, 1981), of which quite a number were later substantiated by data from \textit{Voyager} fly-bys and Earth-based observations (e.g. the fact that the radius of Titan’s surface is 2585 km, the presence of \( N_2 \), HCN, CO and CO\textsubscript{2} in Titan’s atmosphere, the existence of a second, kilometre-sized population in the rings, etc.). Some of the predictions still remain to be validated: a somewhat different (as compared with synchronous) axial rotation of Titan; excessive (by 1.5–15 per cent with respect to that received from the Sun) thermal flux from Titan owing to freezing of its deep (\( \sim 700 \) km) liquid ocean; the presence of a \( \sim 1 \) km thick ice crust on its surface and of a well-defined rocky core, etc.

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Looking for additional evidence in favour of the explosion of Titan’s ices, the author directed his attention to cometary and related data, since it would appear reasonable that ice fragments, resulting from the explosion, must reveal themselves as typical cometary nuclei. It is significant that the recently discovered asteroid-like bodies with low albedo, e.g. 2060 Chiron, which exhibits cometary activity even at its large distance, and 5145 Pholus, came deep inside the sphere of influence of Saturn several millennia ago: e.g. calculations by Oikawa & Everhart (1979) show that in 3800 bc Chiron had approached Saturn to within ~0.33 au; Kowal, Lilly & Marsden (1979) revealed its approach to within ~0.1 au in 1664 bc; while Scholl (1979) admits the possibility of Chiron penetrating the satellite system as close to Saturn as ~0.03 au in 1549 bc or, more probably, 1440 bc. Also, Phoebe moves along such an irregular orbit (its mean radius is 0.086 au) that it can be lost by Saturn (Szebehely 1979) to switch to an independent heliocentric orbit of the Centaur type. The transition is most likely to occur in the region of perihelion of Saturn, where the Saturnian sphere of influence shrinks.

The starting idea in localizing the explosion of Titan in time and space was to integrate the orbits of comets closely approaching the orbit of Saturn backwards over a period of several millennia (Drobyshevski 1980b, 1981). However, even a cursory examination of the problem has shown that such an approach is impracticable owing to both the large errors in determining LP cometary orbits and the impossibility of taking into account a large variety of other factors, including non-gravitational forces.

Therefore the results of Konopleva naturally caught our attention. In view of the fact that because the eccentricity \(e = 0.056\) the aphelion distance of Saturn exceeds the perihelion distance by ~1 au and the direction of the major axis of its orbit makes one revolution in 47 kyr (Brouwer & Clemence 1961), Drobyshevski (1980b, 1981) drew the conclusion that the objects associated with the peak should be dated at \(\approx 47000/4 \approx 11\) kyr – otherwise the peak would be smeared into two neighbouring cells 0 < \(\Delta S < 1\) au. Next, an analysis of the longitudinal distribution \(N(\Delta S, \nu)\) of the zones of closest approach for objects with 0 < \(\Delta S < 0.30 - 0.335\) au, 0.30 - 0.335 < \(\Delta S < 0.57\) au and 0.57 < \(\Delta S < 1.0\) au has shown that the explosion of Titan occurred when Saturn was in the region of its aphelion (\(\nu \approx 180^\circ\)), since in this case the fragments – cometary nuclei – were ejected mainly from deep inside its sphere of influence (0 < \(\Delta S < 0.3 - 0.335\) au = \(r_a\)) during nearly half of the orbital period of Saturn (Fig. 1). On the other hand, in the region of perihelion (\(\nu \approx 0^\circ\)) the fragments were ejected from the periphery of the sphere of influence (\(r_\nu = 0.33 - 0.335 < \Delta S < 0.57\) au = \(r_\nu\)) i.e. through the combined action of two factors, namely (1) the gradual outward diffusion of the fragments as a result of mutual (explosive) collisions and accumulation of perturbations, and (2) the sphere of influence shrinking in the region of perihelion.

In the present epoch the radius of Saturn’s sphere of influence \(r_\nu = a\nu(1 - e^2)\) \((1 + e \cos \nu)^{-1} (M_\text{Sat}/2M_\text{Sun})^{1/3} = 0.30 - 0.335\) au, and the radius of its Hill sphere \(r_H = 0.045a\nu(1 - e^2)\) \((1 + e \cos \nu)^{-1} = 0.428 - 0.453\) au [for comparison, Jupiter has \(r_H = 0.35\) au (Grebenkov 1976)]; ~3500 yr ago, at the moment of the supposed loss of Chiron, Saturn had \(e = 0.068\) and \(r_H = 0.57\) au (here \(a\) and \(e\) are the semimajor axis and eccentricity of the planetary orbit, and \(\nu\) is the true anomaly counted from the orbital perihelion).

Hence it follows that the ejection of fragments – cometary nuclei – from the sphere of influence of the planet was extended in time over the orbital period of Saturn, as a minimum, and the backward integration of the orbits of LP comets and Chiron-like objects, proposed initially, cannot be used for unambiguous localization of the explosion point on the orbit of Saturn. The duration of ejection of fragments in itself counts in favour of the disintegration of a body (or bodies) moving initially along an orbit located entirely in the sphere of influence of the planet, and counts against any possible tidal, outburst or impact disintegration in Saturn’s sphere of influence of a giant comet or some other body that had entered from the outside with an initially high velocity, since in this case the fragments would also have an initially high velocity and would leave the sphere of influence at once. Moreover, it is not to be supposed that all the fragments from the explosion of Titan were immediately thrown out of the sphere of influence into LP orbits. The first to be created, after a decade orbiting inside the sphere of influence, were SP orbits. Undoubtedly, a major role was played in the evolution of these initially SP orbits by planetary perturbations and, in the first place, by the subsequent close encounters with Saturn.
2 FRESH DATA: SOME CONTRADICTIONS?

About two decades have passed since the above-mentioned studies were performed; the number of newly discovered LP comets has increased by nearly a quarter, and the quality of many orbits has improved noticeably. Therefore it seems natural to find out to what extent new data confirm the above conclusion that the comets with \( \Delta_S \leq 0.5 \) au are young.

However, calculations of \( \Delta_S \) and \( \Delta_J \) based on the 9th ‘Catalogue of Cometary Orbits’ (Marsden & Williams 1994) give somewhat puzzling results.

On the one hand, the distribution \( N(\Delta_J) \) has changed in such a way that the conclusion that the cometary ejection event occurred in the region of aphelion of Saturn’s orbit becomes more statistically significant, since the number of objects with \( r_S \sim 180^\circ \) and \( \Delta_S < r_S \) increased markedly (Fig. 1). It is significant that this has occurred not only because of the newly discovered objects [earlier a similar fig. 2 in Drobyshevski (1981) included 91 objects; now we have 95 objects], but also as a result of the improved quality of orbits of the earlier known comets – many of the previously parabolic orbits became elliptic in the latest catalogues.

On the other hand, despite the fact that the sharp maximum at \( \Delta_S \approx 0.5 \) au is preserved, the distribution \( N(\Delta_J) \) now exhibits a more pronounced maximum at \( \Delta_J \approx 1 \) au and a maximum in the region \( 2.5 \approx \Delta_J \approx 3.0 \) au.

The latter maximum results from the discovery of the Kreutz sungrazers by SOLWIND (five comets in 1981–84) and SMM (10 comets in 1987–89) (Marsden 1989). Grouping of all these comets with respect to their orbital parameters suggests, in itself, that both these subgroups (SOLWIND and SMM) result from an early cascade disintegration of a single large body. Eventually, the subsequent disintegrations gave birth to comets – members of each of these subgroups. It seems plausible that there also exist other, as yet undiscovered, subgroups of comets that are the products of primary disintegration. This is suggested by small peaks in all the previous old distributions \( N(\Delta_J) \), in which belong all the previously known comets of the Kreutz sungrazer type. The question as to when and where the secondary events of disintegration have occurred is open to speculation: obviously not near Jupiter or Saturn, but most possibly in a close encounter with the Sun (Marsden 1989) by virtue of its triggering internal energy sources in the splitting nuclei.

From the above point of view, it seems plausible that the maximum at \( \Delta_J \approx 1 \) au, which is broader than in the case of Saturn, is also due to disintegration of comets in close encounters with Jupiter. This is well exemplified by the disintegration of P/Shoemaker–Levy 9 into 20+ fragments (West 1994). In this case, the disintegration is presumably due not to tidal fragmentation but to explosive initiation of internal energy sources in the cometary nucleus by electric currents induced in the comet during its motion through Jupiter’s magnetosphere at a velocity of \( \sim 50 \) km s\(^{-1}\) to generate an electric potential difference of \( \sim 10^3 \) V across the nucleus (Drobyshevski 1997), as indicated by the fact that the disintegration continued for months (!) after the passage of perijovium (Sekanina 1995). On the other hand, it should be noted once again that fragments of bodies, which have entered the sphere of influence from outside and have disintegrated there, escape almost at once, so that distributions \( N(\Delta_J, r_J) \) of the type presented in Fig. 1 for Saturn exhibit no statistically significant features in the case of Jupiter (we do not give these data here).

As for the distinctions and specific features noted by Konopleva [the presence of a sharp peak in the distribution \( N(\Delta_S) \) at \( \Delta_S < 0.5 \) au and, conversely, a rather monotonic distribution \( N(\Delta_J) \)], they are most pronounced for comets discovered before the 20th century, i.e. in the pre-photographic epoch (Fig. 2). For the 20th century comets, both the Jupiter and Saturn distributions become more alike. Hence it follows that the distinctions between the distributions for these two epochs are due to observational selection, since in the 20th century, especially after 1972, discoveries of faint comets have acquired much importance.
3 CONCLUSION: THE GENUINE YOUTH OF KONOPLEVA’S PEAK COMETS

A crushing inference would follow, at first sight, from the above reasoning. It follows that both the conclusion drawn by Konopleva that the comets belonging to the peak with $\Delta S < 0.5$ au are young, and the dating of their origin and emergence from Saturn’s sphere of influence at $\approx 10$ kyr are absolutely groundless.

However, if we get to the root of the problem, we inevitably arrive at the conclusion that, on the contrary, the initial findings of Konopleva as well as the estimates of the time of the event are not unreasonable. Moreover, they are additionally substantiated, so that, in a sense, their weight is doubled. The point here is that young comets have several most general reasons to exhibit, on the average, higher activity, i.e. to be brighter [this is confirmed by plentiful statistics for SP comets (e.g. Vsekhsvyatskii 1967; Kresak 1994)]. As regards LP comets, there even exist such terms as ‘new’ and ‘old’ comets. By the latter are meant objects that have repeatedly visited the inner Solar system and, therefore, have lost the major part of their surface volatiles.

Hence the distributions $N(\Delta S)$ and $N(\Delta S)$ related to the prephotographic times inevitably include mainly the brightest and, consequently, in the mean, the youngest comets! Thus the monotonic nature of the old distribution $N(\Delta S)$ and the absence in it of a peak at $\Delta S < 0.5$ au indicate a deficiency of young comets in the distribution in the given case. Conversely, the presence of a strong, statistically significant peak at $\Delta S < 0.5$ au in the distribution $N(\Delta S)$ of (bright) comets is one more argument for its members being young, so that the conclusions of Konopleva and the surprisingly early dating of their origin acquire additional importance. Moreover, we can say with reasonable confidence that even disintegration of a large comet inside Saturn’s sphere of influence would not lead to the appearance of a large number of highly active comets. This statement is substantiated by the fact that many of the LP and SP comets of the Jovian family that have penetrated deep inside its sphere of influence are undoubtedly the products of such disintegration events, and are not very active [e.g. fragments of P/Shoemaker–Levy 9 discovered more than nine months after perijovian passage showed practically no gas production (West 1994)]. In addition, the much broader peak ($0 < \Delta J < 1$ au) in the distribution of (faint) comets of the Jovian family together with the smaller size of Jupiter’s sphere of influence as compared with that of Saturn may indicate two features: (1) a large age of the constituent objects [note that Jupiter’s aphelion and perihelion distances differ by only 0.5 au at a rotation period of the semimajor axis of Jupiter’s orbit of about 0.3 Myr (Brouwer & Clemence 1961)]; (2) the secondary nature of these comets, associated with their non-simultaneous birth and manifestation via, e.g. capture (possibly with disintegration) of cometary nuclei from the reservoir between Jupiter and Saturn or from the Trojan reservoir, these reservoirs being initially formed by the very same explosion of Titan, or by much earlier explosions of ices of Galilean satellites (Agafonova & Drobyshhevskii 1985; Drobyshhevski 1989).

Hence the presence of a narrow peak in the distribution $N(\Delta S)$ for the most easy-to-discover comets, together with the possible escape of large Centaurs from Saturn’s sphere of influence and the somewhat delayed (see Fig. 1) escape of some cometary nuclei, provides additional evidence for a large-scale catastrophe that occurred in Saturn’s system $\approx 10$ kyr ago. This fact, along with the (borne out) predictions concerning Saturn’s rings, Titan’s different characteristics and the different properties of comets, counts in favour of the explosion of electrolysed ices of Titan. Nevertheless, we admit that, for the facts presented above, there could be proposed some other explanations that we have overlooked.

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