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EVOLUTION OF COMET-LIKE ORBITS OF METEORITE-PRODUCING GROUPS AND THEIR PARENT BODIES

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ABSTRACT. This paper presents the results of the study of evolution of Jupiter-family comet-like orbits of six meteorite-producing groups, including sporadic fireballs from the IAU MDC database 2007 [1], sporadic meteors from the SonataCo database [2], instrumentally observed H5 and L3.5 ordinary chondrites, as well as near-Earth asteroids which are potential parents of the examined groups. In order to verify the relationship between meteorite-producing groups and their potential parents, we performed backward numerical integration of the orbital motion of these groups' members over several millennia. The numerical integration was carried out using the Halley software [3]. The equations of motion factored in gravitational perturbations due to the major planets, radiation pressure effects and the Poynting-Robertson drag. The equations of motion were numerically integrated using the 11th-order Everhart method applicable to studying the motion of Jupiter-approaching short-period comets. The numerical integration of the mean orbital elements of a group, as well as those of the relevant meteorite and potential parent asteroid, over 5,000 years has shown that the respective perihelia, eccentricities and arguments of perihelion evolved in a similar manner over the specified period. The D_{SH}-criterion of Southworth and Hawkins [4], which is a quantitative measure of orbital similarity, has remained below 0.3 [5] for about 5,000 years in the groups of Neuschwanstein and Mason Gully meteorites and for about 3,500 to 4,500 years in the groups of Benešov and Park Forest meteorites. In the groups of the Košice and Pribram meteorites, the mean orbits and those of their potential parents remained similar as defined in terms of the D_{SH}-criterion over a relatively short period of about 2,000 to 3,000 years. We can infer from our findings that meteorite-producing sporadic fireballs and sporadic meteors are related to the H5 and L3.5 ordinary chondrites and their potential parents, i.e. near-Earth asteroids, in the investigated groups. The estimated time intervals, over which the evolving orbits of the groups' members have shown good similarity, are indicative of relatively recent formation of meteorite-producing groups as a result of fragmentation of their parent bodies.

АНОТАЦІЯ. У статті представлені результати аналізу еволюції кометоподібний орбіт сімейства Юпітера шести метеоритоутворюючих груп, що включають спорадичні боліди з метеорної бази даних IAU MDC-2007 [1], спорадичні метеори з SonatoCo бази даних [2], звичайні хондрити типу H5, L3.5, що спостерігалися інструментально, і навколоземні астероїди - потенційні батьківські тіла досліджених груп. Щоб перевірити зв'язок між метеоритоутворюючими групами і їх потенційними батьківськими тілами, ми виконали чисельне інтегрування орбітального руху членів метеоритоутворюючих груп протягом кількох тисячоліть. Інтегрування проводилося кількісно з використанням програмного забезпечення Halley [3]. Гравітаційні обурення великих планет, вплив радіаційного тиску і опір Пойнтінга-Робертсона враховувалися в рівняннях руху. Чисельне інтегрування рівнянь руху виконувалося методом Еверхарт 11-го степеня, які можуть застосовуватися для дослідження руху короткоперіодичних комет, які зазнають зближення з Юпітером. Чисельне інтегрування орбітальних елементів середньої орбіти групи, метеорита і потенційного батьківського астероїда за 5000 років показує, що перигелії, ексцентриситети і аргументи перигелію еволюціонують аналогічним чином за цей період часу. D_{SH}-критерій Саутворта і Хокінса [4], який є кількісною мірою подібності між орбітами, залишається нижче 0.3 [5] протягом близько 5000 років в групах метеоритів Neuschwanstein і Mason Gully і близько 3500-4500 років – в групах метеоритів Benešov і Park Forest. У групах метеоритів Košice і Pribram середня орбіта груп і орбіти їх потенційних батьківських тел залишаються близькими згідно D_{SH}-критерію на невеликому проміжку часу близько 2000-3000 років. Отримані результати дозволяють зробити висновки про зв'язок метеоритоутворюючих спорадичних болідів і спорадичних метеорів зі звичайними хондритами типу H5, L3.5 і їх потенційними батьківськими тілами – навколоземними астероїдами в досліджених групах. Отримані інтервали часу, протягом яких еволюціонуючі орбіти членів груп демонструють гарний збіг, вказують на відносно недавнє утворення метеоритоутворюючих груп в результаті фрагментації їх батьківських тел.

Keywords: evolution – orbit – group – fireball – meteorite – ordinary chondrite – comet-like – Jupiter-family.

1. Introduction

According to the classical model for cometary nuclei being envisioned as conglomerates of volatile ices and dust grains, meteoroid streams form through the ejection of dust grains up to a few centimetres in size from comets [6]. After being ejected, these meteoroids travel in a heliocentric orbit just as their parent comet's nucleus does. The time required for the ejected dust grains to spread about the whole orbit of their parent forming a closed meteoroid swarm is estimated to be several hundreds of years [7]. Therefore, the time required to form a closed curve is short as compared to the age of meteoroid stream members which are several-thousand-year old. When cometary dust grains, whose orbits are Earth-crossing, reach Earth, they enter its atmosphere creating a meteor event. Meteor showers have been observed for millennia, with material being regularly fed into the stream throughout this period from the parent and material lost through the external effects, mainly under the action of gravitational perturbations by the planets and due to radiation pressure effects. The bulk of the scattered material forms the sporadic meteoroid background. Catastrophic break-up of cometary nuclei is another mechanism for producing meteoroid streams. Big boulders can be produced through such a mechanism as observed during the C/1999 S4 (LINEAR) comet break-up.

The idea of meteoroid streams and meteors asteroidal in origin has been considered previously [8-11]. Halliday *et al.* [12] analysed orbits of 89 fireballs – namely, 56 from the MORP (Meteorite Observation and Recovery Project network in western Canada) data and 33 from the PN (Prairie Network in central USA) list - which could survive the passage through the atmosphere with a non-zero terminal mass. The authors suggested existing of four possible meteorite-producing groups, among which group 1 included instrumentally observed Innisfree meteorite, and inferred the asteroidal origin of some fireball streams. Greenberg & Chapman [8] reported that stony-iron mesosiderites formed at the core-mantle interfaces of small asteroidal parents of 100-200 km in diameter while pallasites formed in smaller parent bodies of 50-100 km in diameter. The authors assumed that meteorites might be pieces of large main-belt asteroids derived primarily by cratering collisions rather than disruptive fragmentation. Shestaka [13] examined a swarm of meteorite-producing bodies containing the Innisfree and Ridgedale fireballs. The author found out that the investigated swarm also included nine small meteoric swarms, several asteroids and 12 fireballs photographed by the PN and MORP cameras. The orbit of this swarm approaches Earth's orbit annually in early February. With the aim of investigating the annual fireball activity profile, Beech [14] analysed the occurrence time data for 2,373 fireball events predominantly observed across Canada and documented in the Millman Fireball Archive. The author reported that all known cometary meteor showers producing prominent meteors and fireballs are represented as distinct peaks in the annual fireball activity profile. Several other peaks in the activity profile, which did not correspond to any recognised cometary meteor showers, were also identified; some of those could be related to asteroidal meteorite streams.

Unlike comets which regularly feed meteoroid streams when passing around the perihelion of their orbits, asteroids rarely experience disruptive events; hence, swarms of asteroidal meteoroids are likely to result from once-off events, which could be, for instance, asteroids smashing into each other or colliding with large meteoroids. Therefore, the spatial density of asteroidal meteoroid swarms should be lower while their meteor activity should differ from that of the meteoroid streams of cometary origin. No doubt that collisions (as impact events) result in disruption of the parent body with the debris in the form of small particles and bigger fragments, such as cobbles and pebbles, partially surviving in its orbit. In such a scenario, meteoroid swarms can only be produced from the collision of relatively large bodies with the asteroid-impactor of several tens of metres in diameter. Asteroid (4) Vesta with its fragments expelled through striking with the impactor can be an example of asteroidal origin of meteorites. Some of these fragments upon crossing Earth's orbit fall to the earth's surface as meteorites. Gravitational perturbations caused by Jupiter and other planets in the solar system, as well as rotational instability, can also cause disruption of near-Earth objects (NEOs). The situation when an asteroid-like object in the comet-like orbit may turn out to be a dormant comet in disguise, which is covered by a crust up to 10 m thick built up on its surface with time and has ceased to show any cometary activity, has been investigated in many studies.

2. Distribution of sporadic meteor and meteorite-producing fireball events throughout a year

Based on several sources of data, we performed the analysis of the annual activity of large and small sporadic meteors and meteorites, including 737 bright sporadic fireballs (brighter than -6 mag) from the International Astronomical Union Meteor Data Centre (IAU MDC) database [1], 1,416 small meteors (from -2.5 to -5.0 mag) from the SonataCo database [2] and 338 meteorites with known fall dates. The fireballs were selected if the following conditions were met: the fireball terminal height $H_e \leq 35$ km; pre-atmospheric velocity $V_\infty \leq 25$ km sec^{-1}; terminal velocity $V_e \leq 10$ km sec^{-1} and a non-zero terminal mass. The resulting data set was grouped into bins by an increment of 10 degrees in the solar longitude $L_\odot$. The distribution of the number of investigated events as a function of the solar longitude $L_\odot$ was plotted and analysed to identify the periods of activity of sporadic fireballs, meteors and meteorites with known fall dates throughout a year. The resultant distribution of sporadic meteor and fireball activity throughout a year is shown in Figs. 1 and 2. Several prominent peaks of activity lasting for 20-30 days can be observed at the solar longitude $L_\odot \approx 30°, 60°, 140°, 220°, 270°, 300°$ and 350°.

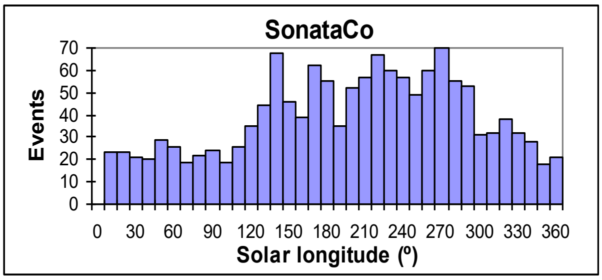

Figure 1: The number of sporadic meteor events versus the solar longitude $L_\odot$.

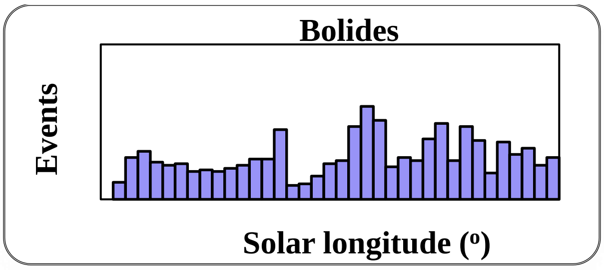

Figure 2: The number of meteorite-producing fireball and meteorite events versus the solar longitude $L_\odot$.

3. The selected groups of meteorite-producing meteoroids in Jupiter-family comet-like orbits and their plausible parent bodies

The constructed histograms of the annual activity of sporadic fireballs and meteors (Figs. 1 and 2) gave us an impetus to further study the issue of the existence of groups of meteorite-producing sporadic meteoroids in the near-Earth space. In the previous paper [15], the authors reported the detection of six groups of meteorite-producing meteoroids and L3.5 – H5 type ordinary chondrite meteorites observed over certain periods of the increased fireball activity. Those groups were named after the known member meteorites. The similarity between the orbits of members of each group established with application of the Southworth-Hawkins D_{SH} criterion as a quantitative measure of orbital similarity was the group-membership condition to be met. The value of $D_{SH} <= 0.3$ was adopted for the investigated groups. Nowadays, it is generally assumed that the method for associating groups of meteorite-producing sporadic meteoroids with their potential parents, i.e. comets or asteroids, based only on the D_{SH} orbital similarity function, is not sufficient.

Similarly to meteoroid swarms and their connection with their parents, the arrangement of meteorites into groups and their lifetime in the near-Earth space are governed by evolutionary processes. The relationship between meteorite-producing groups and their potential parents, i.e. NEOs, should be verified by the backwards analysis of their orbital evolution over a time span of several millennia. The possibility to associate a plausible parent body with a certain group and estimate the formation age of the group of genetically related meteorite-producing meteoroids is crucial for the establishment of the relationship between the meteorite-producing group and comets or asteroids, as well as for the study of the mechanism for yielding meteorite-producing meteoroid swarms.

4. Evolution of meteorite-producing groups and associated NEOs

In the studies of the orbital evolution of meteoroids and near-Earth objects carried out in recent years, a common approach to the research on this issue has been developed:

– Meteoroids within a swarm or group, as well as their probable parent body (NEOS), should have orbits similar by the D_{SH}-criterion of Southworth and Hawkins. It makes it possible to associate a plausible parent body with a group and determine the meteoroid group age. The determination of the age of meteorite-producing groups is essential for the establishment of relationship between meteorite groups and their parents, which could be either asteroids or extinct comets, as well as for the study of the mechanism of formation of the investigated meteorite groups.

– With a large number of the near-Earth asteroids discovered so far, there is a high probability of coincidental similarity between any two orbits at the current time. Therefore, the orbital evolution should be further studied to adopt as real couples of asteroids and groups only those ones whose orbits remained similar for a long period of time of about 5,000 years [9].

– In addition to dynamic properties, common taxonomic features can also be indicative of the common origin of meteoroid groups and their parents – near-Earth objects – in the solar system.

To analyse the orbital evolution of the meteorite-producing groups investigated in this study, the equations of motion were numerically integrated using the 11th-order Everhart method, which is one of the most precise methods for examining the orbital evolution of the solar system bodies and is applicable to studying the motion of Jupiter-approaching short-period near-Earth objects. The backward numerical integration of the orbital motion equations of the group members was carried out over a period of 5,000 years using the Halley software [3]. The equations of motion factored in gravitational perturbations due to the major planets, radiation pressure effects and the Poynting-Robertson drag.

4.1. Orbital evolution of the Benešov group, meteorite (L3.5, H5 type) and near-Earth asteroid 2000 JF5

The Benešov fireballs and meteorite were observed over a period of 1 Min ($L_\odot \approx 60°$) increase in the fireball activity. The backward numerical integration of the mean orbital elements of the group (Mean) and near-Earth asteroid 2000 JF5 was carried out over a period of 5,000 years. The relevant perihelia q, eccentricities e and arguments of perihelion ω evolved in a similar manner throughout the whole specified period. The D_{SH}-criterion of similarity between the mean orbit of the group and that of NEA 2000 JF5 remained below 0.25 for about four and a half thousand years which may indicate that the meteoroids broke off from the parent asteroid in the beginning of the specified period.

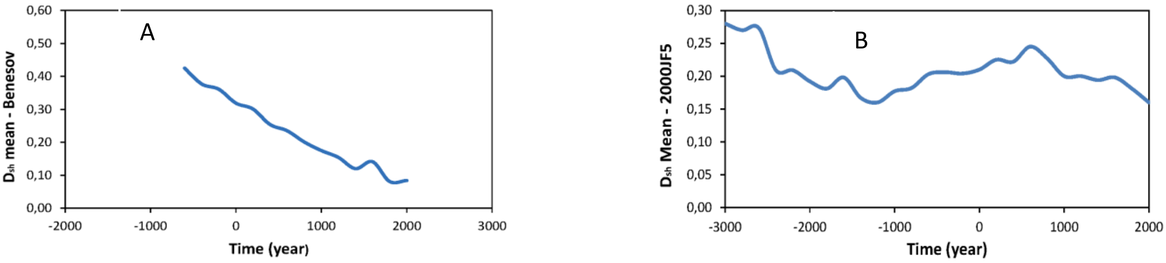

Figure 3: Evolution of the D_{SH}-criterion of similarity between the mean and Benešov meteorite orbits (A) and the mean and NEA 2000 JF5 orbits (B) over 5,000 years.

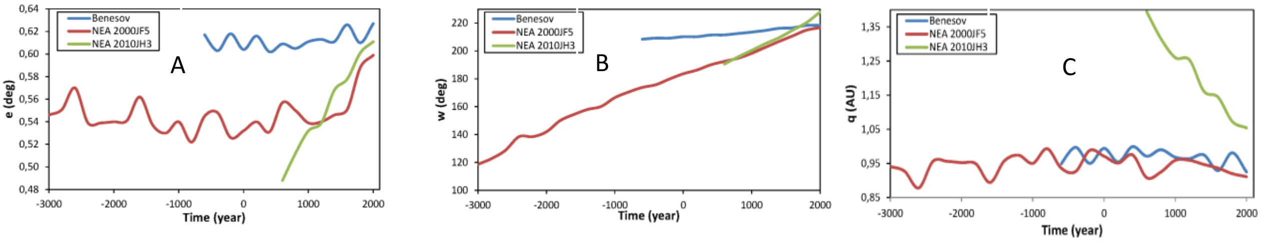

Figure 4: Evolution of the orbital elements (A – the eccentricity e; B – the argument of perihelion ω and C – the perihelion q) of the Benešov meteorite, NEA 2000 JF5 and NEA 2010 JH3 over 5,000 years.

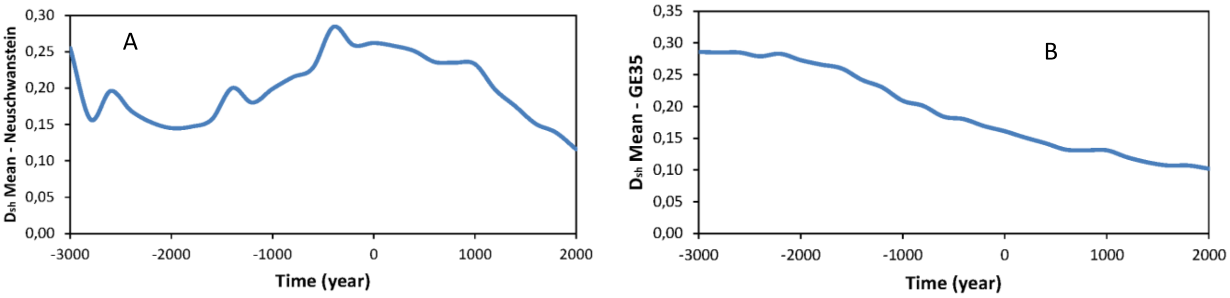

Figure 5: Evolution of the D_{SH}-criterion of similarity between the mean and Neuschwanstein meteorite orbits (A) and the mean and NEA 2010 GE35 orbits (B) over 5,000 years.

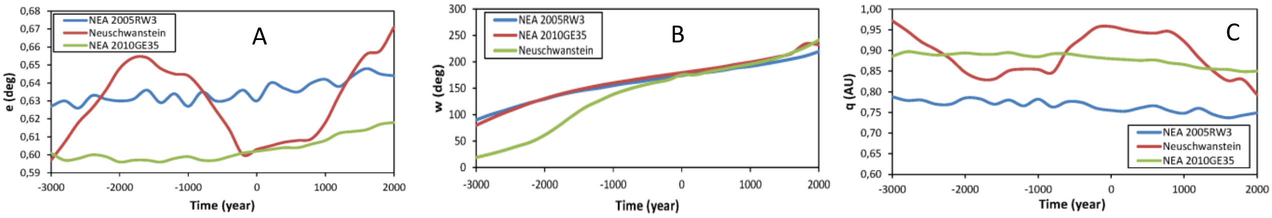

Figure 6: Evolution of the orbital elements (A – the eccentricity e; B – the argument of perihelion ω and C – the perihelion q) of the Neuschwanstein meteorite, NEA 2010 GE35 and NEA 2005 RW3 over 5,000 years.

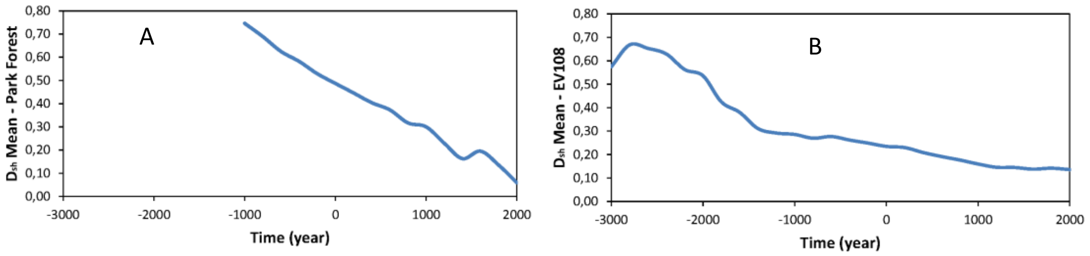

Figure 7: Evolution of the D_{SH}-criterion of similarity between the mean and Park Forest meteorite orbits (A) and the mean and NEA 2013 EV108 orbits (B) over 5,000 years.

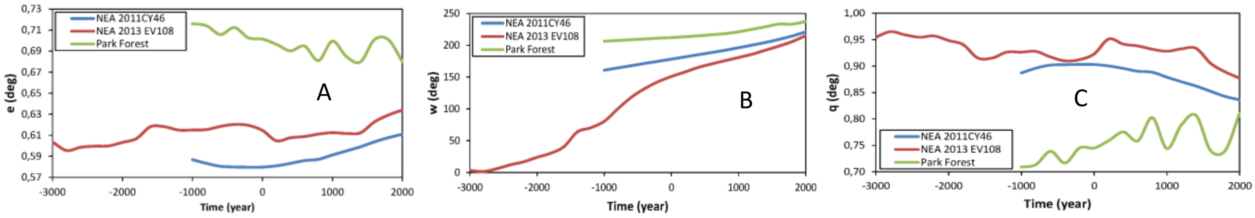

Figure 8: Evolution of the orbital elements (A – the eccentricity e; B – the argument of perihelion ω and C – the perihelion q) of the Park Forest meteorite, NEA 2013 EV108 and NEA 2011 CY46 over 5,000 years.

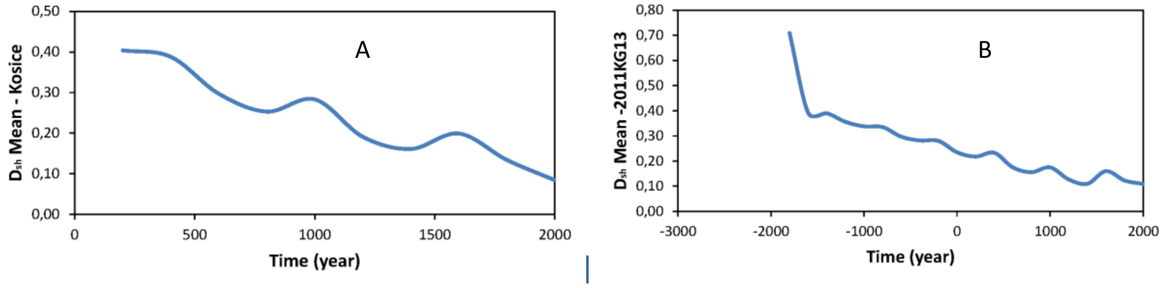

Figure 9: Evolution of the D_{SH}-criterion of similarity between the mean and Košice meteorite orbits (A) and the mean and NEA 2011 KG13 orbits (B) over 5,000 years.

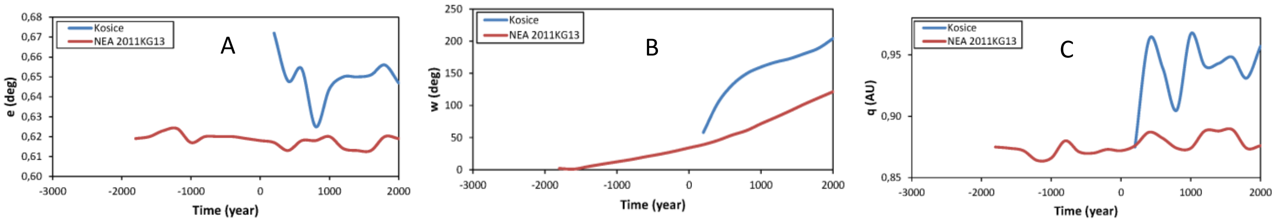

Figure 10: Evolution of the orbital elements (A – the eccentricity e; B – the argument of perihelion ω and C – the perihelion q) of the Košice meteorite and NEA 2011 KG13 over 5,000 years.

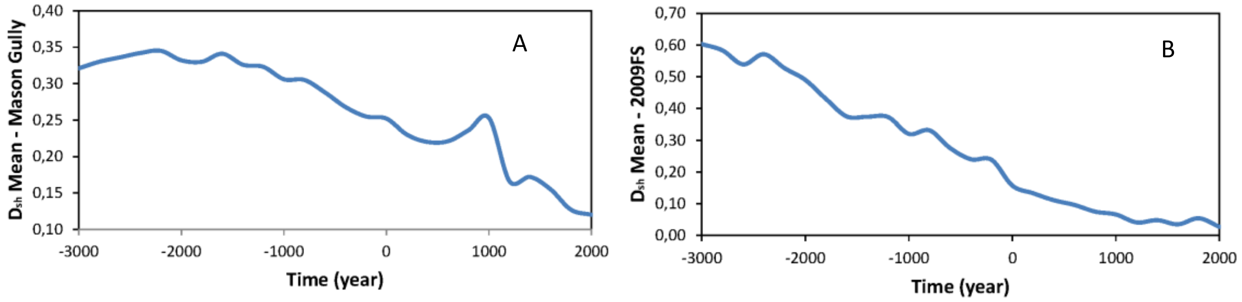

Figure 11: Evolution of the D_{SH}-criterion of similarity between the mean and Mason Gully meteorite orbits (A) and the mean and NEA 2009 FS orbits (B) over 5,000 years.

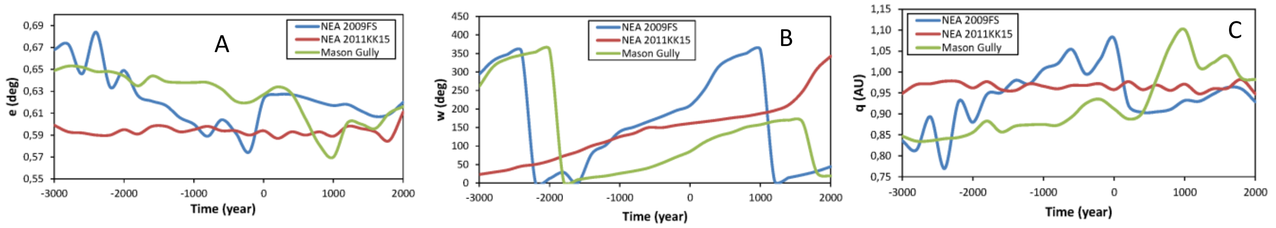

Figure 12: Evolution of the orbital elements (A – the eccentricity e; B – the argument of perihelion ω and C – the perihelion q) of the Mason Gully meteorite, NEA 2009 FS an d NEA 2011 KK15 over 5,000 years.

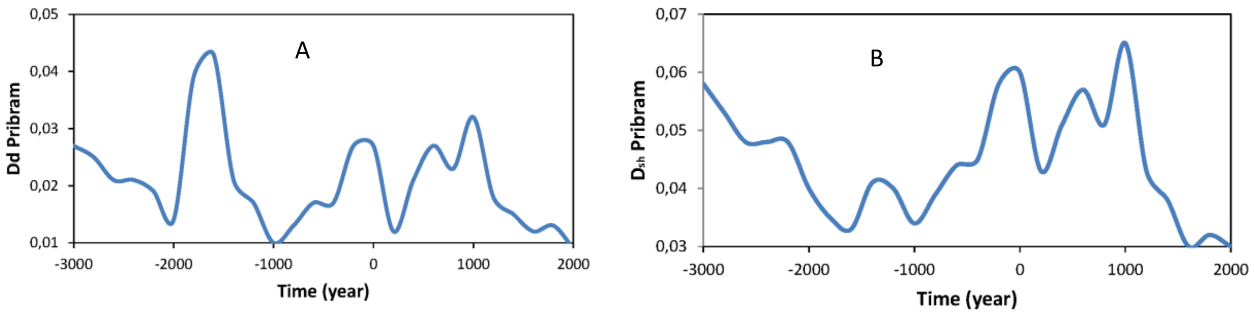

Figure 13: Evolution of the D_D-criterion (Fig. 13A) and D_{SH}-criterion (Fig. 13B) of similarity between the orbits of the Pribram and Neuschwanstein meteorites over 5,000 years.

4.2. Orbital evolution of the Neuschwanstein meteoroid group, meteorite (EL6 type) and near-Earth asteroid 2010 GE35.

The Neuschwanstein fireballs and meteorite were observed over a period of 1 Maj ($L_\odot \approx 30°$) increase in the fireball activity. The results of the backward numerical integration of the mean orbital elements of the group (Mean) and near-Earth asteroid 2010 GE35 over a period of 5,000 years are illustrated in Figs. 5 and 6. The relevant perihelia q, eccentricities e and arguments of perihelion ω evolved in a similar manner throughout the whole specified period. The D_{SH}-criterion of similarity between the mean orbit of the group and that of NEA 2001 GE35 remained below 0.2 for about five thousand years which may indicate that the meteoroids broke off from the parent asteroid in the very beginning of the specified period.

4.3. Orbital evolution of the Park Forest meteoroid group, meteorite (L5 type) and near-Earth asteroid 2013 EV108.

The Park Forest meteorite was observed on 27 March 2003. The Park Forest fireballs and meteorite were observed over a period of 1 Maj ($L_\odot \approx 30°$) increase in the fireball activity. The results of the backward numerical integration of the mean orbital elements of the group (Mean) and near-Earth asteroid 2013 EV108 over a period of 5,000 years are depicted in Figs. 7 and 8. The relevant perihelia q, eccentricities e and arguments of perihelion ω evolved in a similar manner throughout the whole specified period. The D_{SH}-criterion of similarity between the mean orbit of the group and that of NEA 2013 EV108 remained below 0.3 for about three and a half thousand years which may indicate that the meteoroids broke off from the parent asteroid in the beginning of the specified period.

4.4. Orbital evolution of the Košice meteoroid group, meteorite (H5 type) and near-Earth asteroid 2011 KG13

The Košice meteorite was observed on 28 February 2010. The Košice group and meteorite were observed over a period of 6 Maj ($L_\odot \approx 300°$) increase in the fireball activity. The results of the backward numerical integration of the mean orbital elements of the group (Mean) and near-Earth asteroid 2011 KG13 over a period of 5,000 years are presented in Figs. 9 and 10. As can be inferred from the figures, the D_{SH}-criterion of similarity between the mean orbit of the group and that of the Košice meteorite remained below 0.4 for about two thousand years while the mean orbit and that of the plausible parent, i.e. NEA 2011 KG13, were similar for about three and a half thousand years. The relevant perihelia q, eccentricities e and arguments of perihelion ω evolved in a similar manner throughout the whole specified period which may be indicative of the age of the Košice meteoroid group.

4.5. Orbital evolution of the Mason Gully meteoroid group, meteorite (H5 type) and near-Earth asteroid 2009 FS

The Mason Gully meteorite (observed on 13 April 2010) and the relevant group of fireballs were observed over a period of 1 Maj ($L_\odot \approx 30°$) increase in the fireball activity. The results of the backward numerical integration of the mean orbital elements of the group (Mean) and near-Earth asteroid 2009 FS over a period of 5,000 years are plotted in Figs. 11 and 12. As can be seen from the figures, the D_{SH}-criterion of similarity between the mean orbit of the group and that of the Mason Gully meteorite remained below 0.35 for about five thousand years while the mean orbit and that of the plausible parent, i.e. NEA 2009 FS, were similar ($D_{SH} < 0.35$) for about three and a half thousand years which may be indicative of the time of the group formation. The relevant perihelia q, eccentricities e and arguments of perihelion ω evolved in a similar manner throughout the whole specified period.

In Figs. 4, 6, 8 and 12 which illustrate the orbital evolution of meteorites and their probable parent asteroids (NEAs), for the sake of comparison, the evolution of orbital elements of two near-Earth asteroids is shown; in particular, one of these NEAs has been chosen as a parent asteroid (red line) while another NEA (green line) depicts the evolution of an orbit different from those of the group, meteorite and chosen parent asteroid.

4.6. Orbital evolution of the Pribram (H5 type) u Neuschwanstein (EL6 type) meteorites

The Pribram meteorite was observed on 27 March 2003. The Pribram group was observed over a period of 1 Maj ($L_\odot \approx 30°$) increase in the fireball activity. The results of the backward numerical integration of the mean orbital elements of the Pribram and Neuschwanstein meteorites over a period of 5,000 years are shown in Fig. 13. Based on the results of the numerical integration, the D_D-criterion and D_{SH}-criterion of similarity between the meteorite orbits were calculated with an increment of 200 years. At the present time (epoch 2000.0) both criteria are extremely small (D_D = 0.009 and D_{SH} = 0.025) which enables to deduce that the Pribram and Neuschwanstein meteorite orbits evolved in a similar manner over the specified period and preserved the similarity of their orbits.

In the study [13], a near-Earth asteroid with the structure similar to that of asteroid Itokawa was considered as a potential parent of the Pribram and Neuschwanstein meteorites. The disruption of the asteroid with such a pattern might result in ejecting both large fragments (cobbles and pebbles) and smaller debris (meteoroids) which could form a group of meteorite-producing meteoroids in the near-Earth orbit.

5. Conclusions

– The evolutionary analysis using the method of backwards numerical integration of the mean orbital elements of a group, as well as those of the relevant meteorite and potential parent near-Earth asteroid over a period of 5,000 years has shown that the respective perihelia, eccentricities and arguments of perihelion evolved in a similar manner throughout the specified period.

– The D_{SH}-criterion, which is a quantitative measure of orbital similarity, has remained below 0.3 for about 5,000 years in the groups of Neuschwanstein and Mason Gully meteorites and for about 3,500 to 4,500 years in the groups of Benešov and Park Forest meteorites. In the groups of Košice and Pribram meteorites, the mean orbits and those of their potential parents remained similar as defined in terms of the D_{SH}-criterion over a relatively short period of about 2,000 to 3,000 years.

– Our findings enable us to infer that meteorite-producing sporadic fireballs and sporadic meteors are related to the H5 and L3.5 ordinary chondrites and their potential parents, i.e. near-Earth asteroids, in the groups of Neuschwanstein and Mason Gully meteorites and also those of Benešov and Park Forest meteorites. The estimated time intervals, during which the evolving orbits of the groups' members exhibit good similarity, are indicative of relatively recent formation of the examined meteorite-producing groups as a result of fragmentation of their parent bodies.

– The data on the mean orbit of a group of meteorite-producing meteoroids enable to relate the group to its probable origin which is either asteroidal or cometary. The results indicating the existence of groups of meteorite-producing meteoroids in Jupiter-family comet-like Earth-crossing orbits suggest that relatively large and solid meteoroids, which are members of these groups, can survive the passage through the atmosphere and fall to the surface as meteorites. In such a case, these meteorites are potentially samples of cometary material which can be examined using laboratory techniques.

– The investigated groups can still contain objects which are potentially hazardous for the Earths' biosphere and nowadays may fall to Earth as meteorites. This can provide a strong incentive to carry out targeted monitoring of the fireballs and meteors in these groups at their radiant points over specified periods of the group activity.

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