Orbital evolution of near-earth asteroids associated with the april chi-librid meteor shower

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The results of multifactor and orbital analyses of near-Earth Apollo-group asteroids (2013 WM, 2015 DU180, 2011 BT59, 2013 YC), which exhibit a genetic relationship with the April Chi-Librid meteor shower, are presented. The hypothesis that these asteroids are extinct fragments of a previously disintegrated cometary body has been confirmed.

Keywords: meteoroid shower, asteroid, extinct comet, near-Earth asteroids, orbital evolution, orbital resonances.

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The study of small bodies of the Solar system, namely asteroids, comets, meteoroids and meteoroid streams, is an extremely relevant area in modern astronomy and planetary science. Since these objects are remnants of the material from which the Solar System was formed, their study allows us to answer fundamental questions about the origin and evolution of our planetary system [1].

Our approach to identifying the connections between small celestial bodies is based on the following concept: some objects currently observed, such as near-Earth asteroids, are actually extinct cometary nuclei or their fragments [2]. Comets are conglomerates of dust and gas, which, moving in orbit and passing close to the Sun, heat up, resulting in the disintegration of the cometary nucleus — gas, dust, etc. are released. Extinct cometary nuclei appear when a comet has lost its volatile component and, due to repeated passage through perihelion, its surface is covered with a thick dust crust that prevents cometary activity and has a low albedo, which makes it possible to observe them as asteroids. The possibility of formation of a thick dust crust on the surface of the comet nucleus is confirmed by the results of spectral observations of comets and the study of comets using spacecraft. Extinct comets can be sources of meteoroid fluxes, even if they are not currently showing cometary activity. This phenomenon is possible because they were previously comets, had cometary activity, and ejected a significant amount of dust and gas, which remained along the orbit, forming a meteoroid swarm with an orbit similar to that of the parent comet.

The author's synthetic method for identifying parent bodies is described in Ref. [3,4]. We have supplemented it with Kholshevnikov metrics. The addition was made by adding two more Kholshevnikov metrics. Initially only the Kholshevnikov metric was included ρ^2 in the synthetic method described in Ref. [3,4]. Its peculiarity is that it is introduced in a certain factor space with constant values of the focal parameter p, the eccentricity e, the slope i and the longitude of the ascending node Ω, so how little they change, but with different directions to the pericenter ω. The metrics ρ_1 and ρ_3 have been added to the modified synthetic method. Their main feature is that in order to exclude the influence of disturbances, some values in each of the metrics are considered constants. The change in the method was made in order to expand the synthetic method to increase the accuracy of objects identified in the meteoroid stream.

By identifying the meteoroid stream April chi-Librids with the near-Earth asteroids of the Apollo group, it was found that this stream is related to four near-Earth asteroids — 2013 WM, 2015 DU180, 2011 BT59, 2013 YC. The identification of the April chi-Librids meteoroid stream with near-Earth asteroids was carried out using the author's synthetic method. The method is based on the use of a set of criteria of genetic similarity and is described in detail in Ref. [3,4]. The synthetic method is a set of criteria for the genetic community of orbits — the Drummond criterion, the natural Kholshevnikov metric, quasi-stationary parameters, the Tisserand constant and the perihelion argument. The criteria combined by the synthetic method are criteria that take into account gravitational and non-gravitational interactions. The main criteria of the synthetic method are the Drummond criterion and the Kholshevikov metric. The Drummond criterion is a D-criterion, which is dimensionless, and the Kholshevnikov metric is dimensional, natural, and has the dimension of the square root of the distance between the orbits. Despite the different specifics of determining the distance between orbits, both of these criteria, the Drummond criterion and the Kholshevnikov metric, allow us to calculate the distance between the orbits of small bodies. Quasi-steady-state parameters do not identify the distance between the orbits, but they are included in the method because they take into account the dynamic evolution of the orbits. The Tisserand constant relative to Jupiter is a way of separating orbits by cometary and asteroid type, included in a synthetic method in order to identify the cores of extinct comets or their fragments. The longitude of the perihelion π is the sum of the longitude of the ascending node Ω and the argument of the perihelion ω. This parameter is constant over long time intervals and is added to the method for analyzing the nature of changes in the orbits of the studied meteoroid stream and its associated asteroid. To identify the asteroid belonging to a specific meteoroid stream, an interval estimation method was developed for the calculated values of the criteria of the synthetic method between the orbits of asteroids and the average orbit of the meteoroid stream. The interval estimation method implies: 1) calculation of the values for each of the criteria of the synthetic method between the orbit of the asteroid and the average orbit of the meteoroid stream; 2) detection of the value calculated in paragraph 1 in the interval, which is set for each criterion of the synthetic method as a threshold value $\pm$ standard deviation σ. For this purpose, thresholds were initially calculated for each of the criteria of the synthetic method. The threshold values were calculated using the individual meteoroid orbits and the calculated average orbit of the meteoroid stream. This approach is used to reduce the effect of meteoroid swarm scattering and to account for meteoroid emissions from the parent body. Next, a similar probabilistic approach is applied using the factor P individually for each criterion of the synthetic method. If the value calculated between the average orbit of the meteoroid stream and the orbit of the asteroid falls within the interval — threshold value of the criterion 2σ, then a high coupling factor P is assigned, if it falls within the interval — threshold value of the criterion $\pm 2\sigma$, then the average coupling factor P is assigned, if it falls within the interval — the threshold value of the criterion $\pm 3\sigma$, then the low coupling factor P is assigned. Next, the final coupling factor P is calculated as the product of the assigned coupling factors.

The values of the Tisserand constant relative to Jupiter were analyzed for the identified asteroids. As mentioned above, the Tisserand constant relative to Jupiter is a way to separate orbits into cometary and asteroid types. If the values of the Tisserand constant relative to Jupiter are less than 3, then it is assumed that the object is moving in a cometary orbit, if the value is about 3, then in a transitional orbit, i.e. such an object can be classified as both cometary and asteroid, if the value is greater than 3, then it is assumed that this object is an asteroid type. The analysis of the Tisserand constant relative to Jupiter was carried out in order to identify the cores of extinct comets or their fragments among identified asteroids. The values of the Tisserand constant relative to Jupiter T for asteroids identified with the April chi-Librids stream range from 2.5 to 3. According to the criteria for dividing orbits into cometary, asteroid and transitional orbits according to the Tisserand constant relative to Jupiter, it can be concluded that the movement of these asteroids occurs in orbits of cometary and transitional nature. The diameters D and the albedo α for the identified asteroids are unknown, so an additional calculation of the equivalent diameter was performed using three albedo values for dark (0.06), light (0.18) and bright objects (0.40). An analysis of the calculated data showed that the values of the equivalent diameter at the indicated albedo values are in the range from 0.14 to 0.37 km. The identified objects are small in size, which may indicate that these asteroids are fragments of a previously decayed cometary body [5].

For a more detailed study of the asteroids included in the group of parent bodies for the April chi-Librids meteoroid stream, their orbital evolution was studied for a time interval of 10,000 years. The integration of asteroid orbits was performed back and forth for 10,000 years, taking into account disturbances from the planets, the Sun and the influence of the Yarkovsky effect. An author's program written in Python was used using the REBOUND library, as this library allows you to simulate gravitational interactions in the Solar System and take into account the influence of additional forces, such as the Yarkovsky effect. The Yarkovsky effect manifests itself in the appearance of a reactive pulse due to the unevenly heated surface of a small body. The surface of a small body heats up only on one side during the day and cools down at night, giving the small body additional acceleration. The Yarkovsky effect is almost independent of the shape of a small body, so calculations can be performed for the shape of a conventionally spherical body. The influence of the Yarkovsky effect is manifested for all elements of the orbit, but most of all it manifests itself in changes in the values of the semi-major axis — it leads to secular perturbations of the semi-major axis of the object's orbit. There are diurnal and seasonal Yarkovsky effects. The diurnal Yarkovsky effect leads to both an increase and decrease in the values of the semi-major axis of the small body. The seasonal effect always leads to an increase in the values of the semi-major axis of the object. The diurnal effect is usually more extensive than the seasonal effect. This effect manifests itself in an additional shift in the position of a small body relative to its position in orbit. The effect of the effect causes asteroids to fall into the zone of resonance 1 : 3 with Jupiter, or into the zone of secular resonance, and are ejected from the Main Belt into the region of planetary motion.

Initially, the simulation was initialized — a simulation with the Sun and an asteroid was created, and planets of the Solar system were added. The IAS15 integrator was used, which is the default integrator in the REBOUND library and can integrate variational equations. The Everhart integrator IAS15 is a 15-th order integrator with adaptive control and the ability to select the time step size (this parameter controls the accuracy). The IAS15 integrator is a high-order unsymplectic integrator that can handle arbitrary forces as well as velocity-dependent forces. When integrating orbits over long time intervals, the Yarkovsky

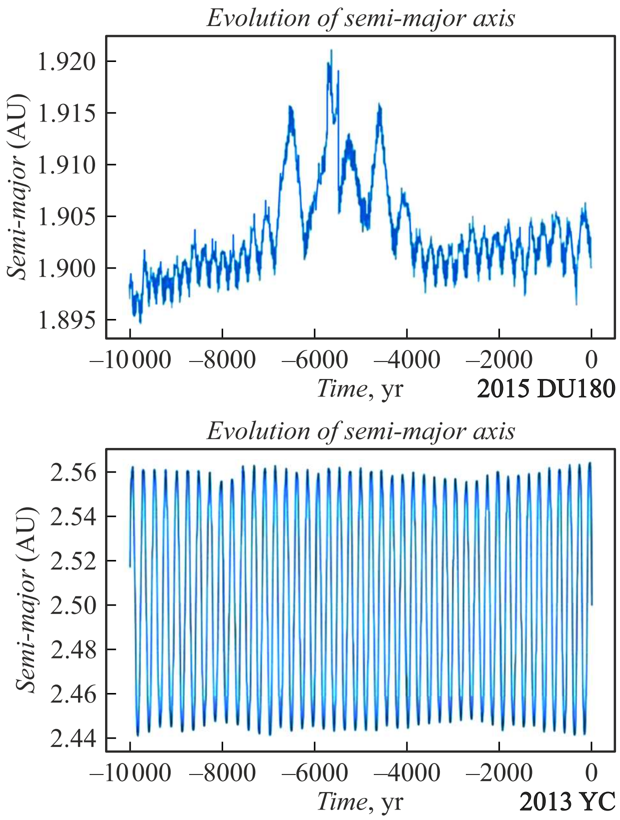

Figure 1. Time dependence of the semi-major axes of asteroids 2015 DU180, 2013 WM, 2013 YC, 2011 BT59 when integrating orbits back 10,000 years.

effect was taken into account, and it was implemented in a simplified model. Within the framework of this model, the Yarkovsky effect adds a small acceleration to the asteroid, only 10^{-15} m/s^2, which simulates the reactive force from the thermal radiation of the asteroid. Dependence graphs for each orbital element were constructed and analyzed for each identified asteroid depending on the time interval of 10,000 years.

To determine the evolution of the orbital elements (semi-major axis a (AU), perihelion distance q (AU), eccentricity e, inclination $i°$, perihelion argument $\omega°$, the longitude of the ascending node $\Omega°$), the evolutionary changes in the orbit of the near-Earth asteroids 2011 BT59, 2013 WM, 2013 YC, 2015 DU180 in the range of 10,000 years were calculated when integrating backward and forward. Fig. 1 shows the time dependences of the semi-major axis of the asteroids 2015 DU180, 2013 WM, 2013 YC, 2011 BT59 when integrated back 10,000 years. According to our research, the semi-major axes of the orbits of the identified asteroids lie in the range from 1.9 to 2.5 AU.

Analyzing the presented graphs, it can be noted that the semi-major axes of asteroid orbits undergo gravitational perturbations from the planets. Asteroid 2011 BT59 has a resonance 4 : 1 with Earth, 1 : 3 with Jupiter, 2 : 1 with Mars, 6 : 1 with Venus. Asteroid 2015 DU180 has a resonance 3 : 1 with Earth, 1 : 4 with Jupiter, 1 : 1 with Mars, 4 : 1 with Venus. Asteroid 2013 WM has a resonance 3 : 1 with Earth, 1 : 4 with Jupiter, 2 : 1 with Mars, 5 : 1 with Venus. Asteroid 2013 YC has a resonance 4 : 1 with Earth, 1 : 3 with Jupiter, 2 : 1 with Mars, 6 : 1 with Venus.

When asteroids come into resonance with planets, the eccentricities of the asteroids' orbits increase dramatically and, consequently, the perihelion distances decrease greatly. Asteroids are under the gravitational influence of large planets all the time, but Jupiter has the greatest influence on small bodies. When a body enters into resonance 3 : 1 with Jupiter, it can move in an orbit with a small eccentricity for a long time, and then sharply increase it to large values. This is because the asteroid has fallen into a zone of chaos. Chaos zones greatly change the nature of the movement of a small body. The resonance 3 : 1 with Jupiter adds irregular fluctuations to the eccentricity of the orbit from 0.1 to 0.4 on time scales of tens to hundreds of years. The consequence is that as the eccentricity increases, the perihelion distance decreases, thus making it possible for the object to cross the orbit of Mars. The influence of Mars and its chaos zone can increase the eccentricity to 0.9 or more. Under the influence of the chaos zone, the orbit changes, and the asteroid acquires the possibility of approaching Earth and Venus. If the perihelion distance decreases significantly, becomes less than the radius of the Sun, then the object becomes near-solar and may fall into

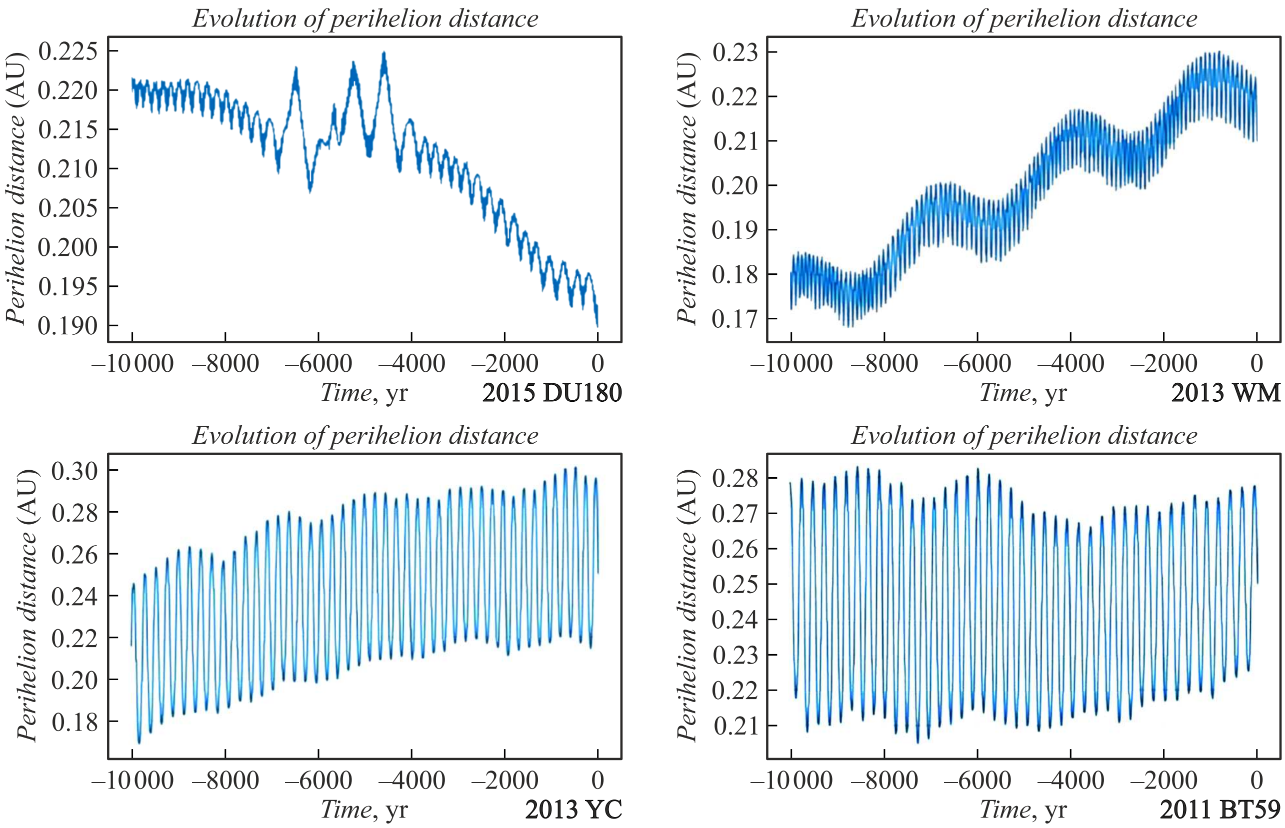

Figure 2. Dependence of perihelion distances q of asteroids 2015 DU180, 2013 WM, 2013 YC, 2011 BT59 on time when integrating orbits back 10,000 years.

the Sun. The effect of resonance with Jupiter 5 : 2 also causes a similar mechanism for changing the orbit of a small body. Another mechanism for increasing the eccentricity of the orbit is the presence of secular resonances. Secular resonances perturb the eccentricity of the orbit and the inclination of bodies with orbital periods of tens or hundreds of years. Thus, an increase in the eccentricity of the orbit of a small body entails a rapprochement with planets, and this, in turn, contributes to the migration of asteroids from the Main Belt into the space of planetary motion.

Fig. 2 shows the dependence of the perihelion distances q for asteroids 2015 DU180, 2013 WM, 2013 YC, 2011 BT59 on time when integrating orbits back 10,000 years. According to the analysis of graphs of the dependence of changes in the eccentricity and perihelion distance of asteroid orbits on time, it can be noted that asteroid objects experience orbital resonances, since there is a sharp increase in the eccentricities of the orbits and a sharp decrease in the perihelion distance. At some points in time, the perihelion distance reaches $q < 1$ AU when integrating the orbits of asteroids back 10,000 years, therefore, asteroids are influenced by the Sun, which affects the destruction of the surface and replenishment of asteroid matter meteoroid stream [6].

As a result of this work, a multifactorial study of asteroids genetically related to the April chi-Librids meteoroid stream was conducted (see the table). Multifactorial research involves the analysis of orbital and taxonomic parameters, analysis based on the values of the Tisserand constant in order to detect small bodies moving in cometary-type orbits and transitional orbits, as well as to identify kinship relationships within a group of identified parent bodies. Kinship relationships were tested in groups of parent bodies using the classical D criteria of Southworth–Hawkins and Asher. Southworth–Hawkins criterion can change significantly upwards over time, since the longitude of the ascending node Ω and the argument of perihelion ω change over time. Thus, the Southworth–Hawkins criterion should be used carefully over long time intervals, as the longitude of the ascending node Ω and the argument of perihelion ω can change significantly. Therefore, another criterion is used — the Asher criterion. The Asher criterion depends only on three elements of the orbits, so it does not have such a strong dependence on time parameters. Threshold value $D < 0.2$ was used for D criteria of Southworth–Hawkins and Asher. It was found that the identified asteroids by the values of the Tisserand constant are predominantly objects of cometary and transitional nature, since they have values of the Tisserand constant less than 3, for asteroids 2011 BT59, 2013 YC, and exactly 3, for asteroid 2013 WM. And asteroid 2015 DU180 is clearly an asteroid object, since it has a constant $T = 3.17$. An analysis using the additional Southworth–Hawkins and Asher criteria showed that these asteroids have a connection within their identified group and the threshold value for them does not exceed $D < 0.2$.

According to the table, there is insufficient data on the diameters of asteroids and their albedo. Using optical observations, the diameters can only be calculated approximately based on the asteroid's absolute magnitude H and albedo α. Therefore, when determining the diameter in this way, you need to understand that these are only estimates of the size. The absolute stellar magnitude H is an estimate of the average brightness. This value is found when the apparent magnitude is used for observations at different phase angles at different distances from the Sun and Earth. The shape of the asteroid is unknown, so it is assumed to be spherical. Albedo α refers to the asteroid's reflectivity, and it is usually also unknown. There is a relationship between the taxonomic type of an asteroid and its albedo, but the taxonomic class is also generally unknown. Taking into account all the above factors, we calculated the diameters of the asteroids using the formula of the equivalent diameter [7]. The equivalent diameter formula uses the relationship between the diameter of D in km, the absolute magnitude of H and the albedo value of α. The albedo values for these asteroids are unknown, so calculations were performed for three average albedo values α. The albedo was assumed to be 0.06 for dark asteroids, $\alpha = 0.18$ for light asteroids, and 0.40 for bright asteroids. For those asteroids for which the sizes are unknown, namely for asteroids 2013 YC, 2011 BT59, 2013 WM, the equivalent diameter values were calculated at three different albedo values. Analyzing the data on the approach to the Earth, it can be noted that all objects from the identified asteroids approach the Earth at minimal distances, therefore, they are potentially dangerous.

The change in the orbits of asteroids from due to the presence of orbital resonances with planets for identified asteroids is discussed. Orbital resonances are calculated as the ratio of the periods of rotation of an asteroid and a planet, i.e. an asteroid and a planet are in resonance when the ratio of their periods is close to the ratio of integers. When resonating with planets near the orbits of asteroids, the eccentricities of the orbits increase significantly and sharply and, consequently, the perihelion distances decrease significantly, which can be noted in the graphs constructed in the work. According to the analysis of graphs of time dependence of the eccentricity and perihelion distances of asteroids, it can be noted that asteroid objects are subject to orbital resonances. At some points in time, the perihelion distance reaches $q < 1\,\mathrm{AU}$ when integrating the orbits of asteroids back 10,000 years, therefore, asteroids are influenced by the Sun, which affects the destruction of the surface and replenishment of asteroid matter meteoroid stream. The multifactorial, orbital, and long-term time-interval analysis of the evolution of orbits shows that the asteroids identified with the stream 2015 DU180, 2013 WM, 2013 YC, 2011 BT59, according to their characteristics, most likely satisfy the concept held by the authors that the asteroids identified with the stream are extinct fragments of a previously decayed cometary body.

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Conflict of interest

The authors declare that they have no conflict of interest.

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