SEARCH FOR NEW MEMBERS OF YOUNG ASTEROID FAMILIES

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The search for new members of young asteroid families is of interest for studying the formation history of these families. The paper examines 17 young families. Young families are characterized by strong clustering of both proper and osculating orbital elements. When searching for candidates for new members of young families, osculating orbital elements were analyzed. Kholshevnikov metrics were evaluated, the behavior of nodes and pericenters was analyzed, and low-velocity approaches were searched for. For all selected candidates, synthetic proper orbital elements were calculated using the OrbFit software package, based on which a conclusion was made about the asteroid's membership in the family. As a result, new members were found for eight young asteroid families.

Keywords: asteroid families, proper orbital elements, numerical modeling, Kholshevnikov metrics

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INTRODUCTION

In 1918, analyzing the distributions of proper values of semi-major axes, eccentricities, and inclinations of heliocentric asteroid orbits, Hirayama discovered the first examples of statistically significant concentrations (Hirayama, 1918). He introduced the term "asteroid families," suggesting that families represent collections of asteroids associated with parent bodies that disintegrated sometime in the past. He considered asteroid collisions as the source of these catastrophic events.

Currently, several other mechanisms of parent body destruction leading to the formation of asteroid families have been proposed: disruption of a rapidly rotating parent body (Pravec et al., 2010), secondary fission of bodies formed during disruption (Jacobson, Scheeres, 2011), crater-forming collision with an almost critically rotating parent asteroid (Vokrouhlický et al., 2017), cascade destruction of the family's parent body (Pravec et al., 2018).

Young asteroid families, whose age does not exceed several (up to 10) million years, are of particular interest to researchers. Conventionally, within this group of families, they distinguish very young ones - with an age of up to 2 million years (see, for example, Pravec et al., 2018) and extremely young ones - with an age of less than 1 million years (see, for example, Vokrouhlický et al., 2024). The study of the dynamic evolution of young families is of interest from the perspective of studying their formation history. It becomes possible, based on the results of numerical modeling, to establish the age of individual family members and their groups. The youth of the families and the proximity of their orbits allow, in particular, when preliminary searching for family members, to use five osculating elements (semimajor axis a , eccentricity e , inclination i , longitude of the ascending node Ω, argument of pericentre ω), and not be limited to three proper elements (semimajor axis a_p, eccentricity e_p, inclination i_p), as is customary for ordinary families. The current state of the problem of studying young asteroid families is presented in a number of works (see, for example, Pravec et al., 2018; Vokrouhlický et al., 2024).

In this paper, we plan to consider 17 young families in order to search for new members (see Table 1). Table 1 provides for each family: the number of asteroids, the values of positional osculating orbital elements a_{fam}, e_{fam}, i_{fam} of the main asteroid of the family and the range of variation of these elements for asteroids that are part of the family, according to the Asteroids Dynamic Site - AstDyS (https://newton.spacedys.com/astdys/). Orbital elements are given with precision to the fourth decimal place. If the modulus of the difference between the orbital elements of asteroids does not exceed 0.00005 in the corresponding units, a zero value is indicated. Obviously, this is most often realized for small families.

The search for candidates for new family members begins with the analysis of osculating orbital elements, based on which we evaluate Kholshevnikov metrics and check the possibility of node and pericenter approaches. Then for all candidates and family asteroids, we calculate synthetic proper orbital elements. The final conclusion about the candidates' membership in families is made based on the analysis of proper orbital elements.

Table 1. Positional osculating orbital elements of young asteroid families at epoch MJD 60200

Family of asteroids	Number of members	a_{fam}, AU	e_{fam}	i_{fam}, city
Adelaide	79	$2.2450^{+0.0040}_{-0.0006}$	$0.1017^{+0.0028}_{-0.0031}$	$5.9988^{+0.0655}_{-0.0000}$
Brugmansia	3	$2.6209^{+0.0007}_{-0.0015}$	$0.2187^{+0.0016}_{-0.0008}$	$1.6247^{+0.0019}_{-0.0022}$
Datura	92	$2.2346^{+0.0025}_{-0.0035}$	$0.2081^{+0.0029}_{-0.0032}$	$5.9863^{+0.0814}_{-0.1565}$
Emilkowal **s** ki	9	$2.6006^{+0.0000}_{-0.0014}$	$0.1503^{+0.0060}_{-0.0041}$	$17.7538^{+0.0168}_{-0.2824}$
Hobson	59	$2.5634^{+0.0029}_{-0.0026}$	$0.1834^{+0.0039}_{-0.0055}$	$4.3217^{+0.0111}_{-0.0179}$
Iochroma	5	$2.4442^{+0.0019}_{-0.0005}$	$0.1627^{+0.0000}_{-0.0039}$	$3.4214^{+0.0081}_{-0.0028}$
Irvine	4	$2.1675^{+0.0000}_{-0.0007}$	$0.0146^{+0.0004}_{-0.0000}$	$5.4046^{+0.0232}_{-0.0000}$
Kap'bos	5	$2.2507^{+0.0004}_{-0.0006}$	$0.0944^{+0.0004}_{-0.0100}$	$3.6916^{+0.0005}_{-0.0632}$
Lucascavin	3	$2.2809^{+0.0005}_{-0.0004}$	$0.1127^{+0.0000}_{-0.0012}$	$5.9805^{+0.0005}_{-0.0005}$
Mandragora	8	$3.0393^{+0.0178}_{-0.0066}$	$0.1975^{+0.0051}_{-0.0066}$	$0.5655^{+0.0343}_{-0.0173}$
Martes	6	$2.3783^{+0.0000}_{-0.0022}$	$0.2419^{+0.0024}_{-0.0000}$	$4.2829^{+0.0123}_{-0.0000}$
Nicandra	5	$2.6357^{+0.0007}_{-0.0014}$	$0.2442^{+0.0032}_{-0.0009}$	$3.6050^{+0.3225}_{-0.0000}$
Rampo	42	$2.3285^{+0.0013}_{-0.0014}$	$0.0952^{+0.0006}_{-0.0026}$	$6.0609^{+0.0410}_{-0.0260}$
Rozek	3	$1.9384^{+0.0000}_{-0.0010}$	$0.0886^{+0.0000}_{-0,0007}$	$19.9859^{+0.0000}_{-0.0589}$
Schulhof	12	$2.6109^{+0.0010}_{-0.0026}$	$0.1207^{+0.0051}_{-0.0015}$	$13.5351^{+0.1833}_{-0.0888}$
Wasserburg	8	$1.9452^{+0.0005}_{-0.0000}$	$0.0601^{+0.0004}_{-0.0002}$	$23.7143^{+0.0000}_{-0.0084}$
2002 PY38	3	$2.1961^{+0.0009}_{-0.0000}$	$0.1764^{+0.0002}_{-0.0004}$	$0.8889^{+0.0241}_{-0.0000}$

SEARCH FOR CANDIDATES FOR NEW MEMBERS OF YOUNG FAMILIES

To search for candidates for new members of young families, we used the catalog of osculating orbital elements of asteroids from the Asteroids Dynamic Site – AstDyS ((https://newton.spacedys.com/astdys/). The use of osculating orbital elements is justified because proper orbital elements are not known for all asteroids, and young asteroid families form tight clusters not only in the space of proper elements, but also in osculating orbital elements (see, for example, Vokrouhlický et al., 2024). Such clusters stand out both in the three-dimensional space of Keplerian positional orbital elements (a , e , i), and in the five-dimensional space (excluding the position of the body in orbit) of Keplerian orbital elements (a , e , i , Ω, ω). In this regard, to determine the distance between the orbits of family members and candidates, we used Kholshevnikov metrics ρ_5 and ρ_2

(Kholshevnikov et al., 2016; Kholshevnikov, Shchepalova, 2018; Kholshevnikov et al., 2020). The Kholshevnikov metric ρ_5 determines the distance between orbits in the space of positional Keplerian orbital elements. The metric ρ_2 - in five-dimensional space.

At the first step, the values of Kholshevnikov's metrics ρ_5 and ρ_2 were calculated between the candidate's orbit and the orbits of all family members, and the maximum values of metrics $(\rho_5)_{max}$ and $(\rho_2)_{max}$ were determined. The maximum values of metrics $(\rho_{5fam}$ and $(\rho_2)_{fam}$ between all possible pairs of orbits of known family asteroids were used as criteria. The orbits of candidates for new family members must simultaneously satisfy two conditions:

$$(\rho_5)_{max} \leq (\rho_5)_{fam} \text{ and } (\rho_2)_{max} \leq (\rho_2)_{fam} . \quad (1)$$

At the second step, to exclude random orbital proximity, numerical modeling of dynamic evolution into the past was performed for family members and selected candidates based on nominal orbits. The Mercury 6.2 package (Chambers, 1999) was used. Perturbations from the eight major planets and the dwarf planet Pluto were taken into account. The evolution of metrics ρ_5 and ρ_2 between the orbits of candidates and family members in osculating elements was analyzed. The criterion for the convergence of nodes and pericenters of candidate orbits (simultaneous zeroing of differences in longitudes of ascending nodes $\Delta\Omega$ and arguments of pericenters $\Delta\omega$) with the orbits of family members was checked. The search for low-velocity approaches (evolution of relative distances Δr and velocities Δv) of candidates and family members was performed. A necessary condition for a candidate to belong to a family is the proximity of the moments of the following events: 1) low-velocity approach of the candidate with one of the family asteroids; 2) reaching minimums of metrics ρ_5 and ρ_2 ; 3) convergence of nodes and pericenters ($\Delta\Omega \approx 0$, $\Delta\omega \approx 0$).

In the third step, the synthetic proper orbital elements were determined for the selected candidates (Knezevic, Milani, 2000; 2003; Knezevic et al., 2002). The OrbFit software package was used (Orbfit Consortium, 2011; http://adams.dm.unipi.it/orbfit/). The dynamical evolution modeling took into account perturbations from eight major planets and the dwarf planet Pluto, solar oblateness, and relativistic effects. The increased complexity compared to the second step of the perturbation force model is related to the need for a more detailed description of orbital evolution when determining proper orbital elements. The integration interval was 2 million years. This is a sufficiently long interval for effects associated with the stochastic properties of asteroid orbital evolution to manifest. In this regard, the largest Lyapunov exponent (LCE) was estimated for each asteroid. The initial epoch was MJD 60200 (13.09.2023). For each candidate, the proper elements a_p , e_p , i_p , mean motion n and proper frequencies of nodal *s* and pericenter *g* motion were obtained. The proper orbital elements for members of all considered young families are provided in the electronic supplement (see tables P1-P17 in (Perminov, 2024)).

Estimates of the largest Lyapunov exponent LCE, obtained based on numerical modeling results, are on the order of 1-10 (million years)$^{-1}$, which corresponds to Lyapunov times of 0.1-1 million years. As is known, manifestations of chaos in the evolution of nodes and pericenters occur at intervals 2-3 orders of magnitude longer than chaos in orbital position, and for positional elements - at intervals 4-6 orders of magnitude longer (Kholshevnikov, Kuznetsov, 2007). Accordingly, over the interval of 2 million years, the behavior of asteroid orbits will have a regular character.

The final decision about the candidates belonging to families was made at the fourth step after comparing the values of the metric ρ_5, calculated based on the proper orbital elements. For asteroids - family members, the metrics ρ_5 were calculated for all possible pairs of asteroids and two maximum values were found: K_1 - among pairs that include the main asteroid of the family, and K_2 - among all pairs. For asteroids - candidates for family membership, the metrics ρ_5 were calculated for all possible pairs with family asteroids and two maximum values were found: L_1 - among pairs that include the main asteroid of the family, and L_2 - among all pairs. For new family members, one of two conditions must be met:

$$L_1 \leq K_1 \quad \text{or} \quad L_2 \leq K_2. \qquad (2)$$

Condition (2) allows for changes in the values of criteria K_1 and K_2 when including new asteroids in the family, which provides flexibility of the criterion when applied to real families. Meeting condition (2) guarantees that the candidate under consideration is a family member, but it may reject asteroids that belong to the family, especially in the case of a small family. Depending on the family formation mechanism and its age, the criteria values can be increased: αK_1 and βK_2 ($\alpha > 1$, $\beta > 1$). Refinement can be performed based on modeling results, which are planned to be carried out in the future. In this work, we are searching for new family members that fit within the range of variations of the proper orbital elements of known family members.

NEW MEMBERS OF YOUNG ASTEROID FAMILIES

In accordance with the methodology described in the previous section, the catalog of osculating elements of asteroid orbits from the AstDyS website for the epoch MJD 60200

(09/13/2023) was used to search for candidates for new members of these families. It contained information on 1.283.207 objects (including 629.007 numbered asteroids, 549.491 asteroids observed in several oppositions, and 104.709 asteroids observed in one opposition). Results of candidate selection among the Main Belt asteroids are shown in Table 2. The second column indicates the number of members in young families. The third column shows the number of candidates selected from the AstDyS catalog according to the range of osculating orbital elements from Table 1. The fourth column gives the number of candidates that satisfy conditions (1). The last column shows the number of candidates selected for determining proper orbital elements. Out of the 17 young asteroid families considered, candidates for new members were found for nine families.

At the third stage, the proper orbital elements were determined for the selected asteroids. We will present the results obtained from the analysis of the proper orbital elements of asteroids included in young families and candidates for new members. For each young family, a brief overview of the information is given, and the criteria assessments are given. K_1 and K_2 , maximum values of L_1 and L_2 for the metric ρ_5 for proper orbital elements of candidates selected in the first three steps of the methodology, and a conclusion about the presence of new family members is made.

Table 2. Number of candidates for new members of young asteroid families

Family of asteroids	Number of members	Selected candidates from the catalog	Number of candidates meeting conditions (1)	Selected candidates for determining proper elements
Adelaide	79	4	4	3
Brugmansia	3	1	1	1
Datura	92	0	—	—
Emilkowal **s** ki	9	15	13	11
Hobson	59	0	—	—
Iochroma	5	2	2	2
Irvine	4	0	—	—
Kap'bos	5	0	—	—
Lucascavin	3	0	—	—
Mandragora	8	16	16	11
Martes	6	0	—	—

Nicandra	5	7	7	7
Rampo	42	0	—	—
Rozek	3	2	2	2
Schulhof	12	47	44	25
Wasserburg	8	0	—	—
2002 PY38	3	12	12	11

Adelaide Family

The Adelaide family was discovered in 2019 by Novaković and Radović (2019) and contained only five objects. The family is located in the inner part of the Main Belt (a = 2.25 AU., i.e., e = 0.10, i = 5.99°). The age of the family is approximately 500 thousand years (Novaković, Radović, 2019), which makes it one of the very young families. In the works (Carruba et al., 2020; Vokrouhlický et al., 2021; 2024; Novaković et al., 2022), new family members were searched for. The Adelaide family is one of the largest among young families and contains 79 members (Vokrouhlický et al., 2024). Table 3 shows the criteria K_1 and K_2 and the maximum values L_1 and L_2 of the metric ρ_5 for candidates to the Adelaide family. The values K_1 and K_2 were obtained based on the proper orbital elements of 79 known family members (see Table S1 in (Perminov, 2024)). Of the three candidates, two asteroids – 2020 HG179 and 2020 BE131 – satisfy condition (2) and belong to the family. The number of members in the Adelaide asteroid family has increased to 81 (Table S1 in (Perminov, 2024)).

Table 3. Criteria K_1 and K_2, maximum values L_1 and L_2 of the metric ρ_5 for candidates to the Adelaide family

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Belongs to the family
K_1 = 0.00183 (AU)$^{1/2}$, K_2 = 0.00272 (AU)$^{1/2}$			
2015BP523	0.00227	0.00405	No
2020HG179	0.00047	0.00195	Yes
2020BE131	0.00081	0.00185	Yes

Brugmansia Family

The Brugmansia family is located in the middle part of the Main Belt (a = 2.62 AU, e., e = 0.22, i = 1.62°). The Brugmansia family, including three asteroids, was discovered in 2006 (Nesvorný, Vokrouhlický, 2006). In the work (Nesvorný et al., 2006), the age of the family was estimated to be 50-250 thousand years. The article (Pravec et al., 2018) confirmed the composition of the family consisting of three asteroids. In the work (Vasileva, Kuznetsov, 2022), it was shown that asteroid 2006 SK443 may belong to the Brugmansia family. This asteroid meets the requirements for family membership candidates and, as seen from Table 4, satisfies condition (2). Thus, the number of members in the Brugmansia family has increased to four (see Table P2 in (Perminov, 2024)).

Table 4. Criteria K_1 and K_2, maximum values L_1 and L_2 of metric ρ_5 for a candidate member of the Brugmansia family

Asteroid	L_1, (a.u.)$^{1/2}$	L_2, (a.u.)$^{1/2}$	Belongs to the family
K_1 = 0.00019 (a.u.)$^{1/2}$, K_2 = 0.00019 (a.u.)$^{1/2}$			
2006 SK443	0.00007	0.00013	Yes

Datura Family

The Datura family, consisting of seven asteroids, was identified in 2006 (Nesvorný et al., 2006; Nesvorný, Vokrouhlický, 2006). The family is located in the inner part of the Main Asteroid Belt (a = 2.23 a.u. i.e., e = 0.21, i = 5.99°). The initial age estimate of 450 ± 50 thousand years (Nesvorný et al., 2006) was later refined to 530 ± 20 thousand years (Vokrouhlický et al., 2009). In the work (Vokrouhlický et al., 2024), as of June 2023, 92 asteroids were assigned to the Datura family, and it is noted that two more asteroids, 2016 PL51 and 2022 RB57, observed in one opposition and having uncertainly determined orbital elements, may belong to the family. In the present work, no candidates for new members of the Datura family were found. The proper orbital elements of the Datura family asteroids are given in Table P3 in (Perminov, 2024). Estimates of the criteria values K_1 and K_2 for the Datura family are: K_1 = 0.00389 (AU)$^{1/2}$, K_2 = 0.00470 (AU)$^{1/2}$.

Emilkowalski Family

The young Emilkowalski asteroid family is located in the middle part of the Main Belt (a = 2.60 AU., e = 0.15, i = 17.75°). The Emilkowalski family was identified in 2006 (Nesvorný, Vokrouhlický, 2006) as a group of three asteroids: (14627) Emilkowalski, (126761) 2002 DW10, and (224559) 2005 WU179. The initial age estimate of the group was 220 ± 30 thousand years. In subsequent works (Pravec et al., 2018; Fatka et al., 2020), new members of this family were discovered, and the family composition increased to nine asteroids. The age estimates also increased. Modeling performed in works (Pravec et al., 2018; Fatka et al., 2020) shows that at least two breakup events of the parent asteroid of this family occurred over the past 5 million years, which is consistent with the scenario of cascading destruction of the parent body. The Emilkowalski family is a likely source of the dust band (Vokrouhlicky et al. 2008; Espy et al., 2009; Pravec et al., 2018), inclined to the ecliptic at 17° and detected by the IRAS infrared space observatory.

Table 5 shows the criteria K_1 and K_2 and the maximum values L_1 and L_2 of the metric ρ_5 for eleven candidates for membership in the Emilkowalski family. The values K_1 and K_2 were obtained based on the proper orbital elements of nine known family members (see Table S4 in (Perminov, 2024)). Four asteroids meet condition (2): 2015 WH29, 2016 CS377, 2017 UY114, and 2022 SA160. The number of members in the Emilkowalski asteroid family has increased to 13 (Table S4 in (Perminov, 2024)). After including new asteroids in the family, the criteria values changed: K_1 = 0.00050 (a. u.)$^{1/2}$, K_2 = 0.00062 (a. u.)$^{1/2}$, but there are no candidates in Table 4 that satisfy condition (2) with the new criteria values.

Table 5. Criteria K_1 and K_2, maximum values L_1 and L_2 of metric ρ_5 for candidates for membership in the Emilkowalski family

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Belongs to the family
K_1 = 0.00050 (AU)$^{1/2}$, K_2 = 0.00059 (AU)$^{1/2}$			
2006 UQ33	0.00438	0.00456	No
2009 UL13	0.00077	0.00088	No
2014 WE584	0.00097	0.00113	No
2015 WH29	0.00012	0.00062	Yes
2016 CS377	0.00021	0.00033	Yes
2017 UY114	0.00016	0.00035	Yes
2020 UZ20	0.00055	0.00068	No
2021 TU55	0.00079	0.00091	No

2019SV55	0.00141	0.00153	No
2019UN69	0.00849	0.00858	No
2022SA160	0.00023	0.00042	Yes

Hobson Family

The Hobson family is located in the middle part of the Main Belt (a = 2.56 AU. i.e., e = 0.18, i = 4.32°). Initially, this family was discovered by Pravec and Vokrouhlický (2009), however, they were not certain that asteroid (18777) Hobson belongs to it. In their work, the largest asteroid of the family was (57738) 2001 UZ160. Rosaev and Plávalová (2016) proved that (18777) Hobson belongs to the family. Thus, this family contains two large asteroids (18777) Hobson and (57738) 2001 UZ160, similar in size. The age of the family is estimated at 365 ± 67 thousand years (Rosaev, Plávalová, 2018), the upper age limit does not exceed 500 thousand years (Pravec, Vokrouhlický, 2009). The work (Pravec et al., 2018) refuted the formation of the family through rotational fission. In the work (Kuznetsov et al., 2020), a new, twelfth member of the Hobson family – 2017 SQ83 was discovered, which is not in the list presented in the work (Rosaev, Plávalová, 2018). In the work (Vokrouhlický et al., 2024), a list of 60 asteroids belonging to the Hobson family was published. This list includes asteroid 2019 NB193, which is not in the catalogs of the Minor Planet Center (https://www.minorplanetcenter.net/iau/MPCORB/MPCORB.DAT), AstDyS, and in the Small-Body Database (https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html). No new candidates for membership in the Hobson family were discovered in this work. We calculated the proper orbital elements for 59 asteroids of the Hobson family, excluding asteroid 2019 NB193 (see Table P5 in (Perminov, 2024)). Estimates of the criteria values K_1 and K_2 for the Hobson family are: K_1 = 0.00099 (AU)$^{1/2}$, K_2 = 0.00140 (AU)$^{1/2}$.

Iochroma Family

The Iochroma family is located in the inner part of the Main Belt (a = 2.44 AU, e = 0.16, i = 3.42°). The Iochroma family was identified in the work (Pravec, Vokrouhlický, 2009) as a cluster of five asteroids in the Nysa family. In the work (Pravec et al., 2018), the composition of the Iochroma family of five asteroids was confirmed and two age estimates for the family were given: 190^{+200}_{-100} and 140^{+130}_{-70} thousand years. The semi-major axes of the orbits of asteroids in the Iochroma family are bounded by two three-body resonances: 3J-1M-3 with Jupiter and Mars and 5J-3S-2 with Jupiter and

Saturn (Rosaev, 2022). Table 6 shows the criteria K_1 and K_2 and the maximum values L_1 and L_2 of the metric ρ_5 for two candidates for membership in the Iochroma family. The values K_1 and K_2 were obtained based on the proper orbital elements of the five known family members (see Table P6 in (Perminov, 2024)). Both candidates do not satisfy condition (2).

Table 6. Criteria K_1 and K_2, maximum values L_1 and L_2 of the metric ρ_5 for candidates for membership in the Iochroma family

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Member of the family
	K_1 = 0.00011 (AU)$^{1/2}$,	K_2 = 0.00013 (AU)$^{1/2}$	
2016 BG138	0.00012	0.00015	No
2016 UT3	0.00018	0.00022	No

Irvine Family

The Irvine family, located in the inner part of the Main Belt (a = 2.17 AU, e., e = 0.01, i = 5.40°), was discovered by Pravec and Vokrouhlický (2009). The family consists of four asteroids. The age estimate of the family 1790^{+460}_{-350} thousand years was obtained by Pravec et al. (2018), using the method of convergence of clones in secular angles. In this work, no candidates for new members of the Irvine family were found. We calculated the proper orbital elements for four asteroids of the Irvine family (see Table A7 in (Perminov, 2024)). Estimates of the values of criteria K_1 and K_2 for the Irvine family are: K_1 = 0.00064 (AU) e.)$^{1/2}$, K_2 = 0.00064 (AU)$^{1/2}$.

Kap'bos Family

The Kap'bos family is located in the inner part of the Main Belt (a = 2.25 AU, e., e = 0.09, i = 3.69°). The Kap'bos family was identified after the discovery of a third asteroid (Pravec et al., 2018) close to the tight pair (11842) Kap'bos – (228747) 2002 VH3, discovered by Pravec and Vokrouhlický (2009). The Kap'bos family is a compact cluster within the more extensive Flora family (Pravec et al., 2018). In 2020, two more asteroids belonging to the Kap'bos family were discovered: (349108) 2007 GD18 and (445874) 2012 TS255 (Fatka et al., 2020). Thus, the Kap'bos family includes five asteroids. In this work, no candidates for new members of the Kap'bos family were found. We found the proper orbital elements for five asteroids of the Kap'bos family (see Table A8 in (Perminov, 2024)). Estimates of the values of criteria K_1 and K_2 for the Kap'bos family are: $K_1 = 0.00042$ (AU)$^{1/2}$, $K_2 = 0.00042$ (AU)$^{1/2}$.

Lucascavin Family

The Lucascavin family is located in the inner part of the Main Belt ($a = 2.28$ AU e., $e = 0.11$, $i = 5.98°$). The Lucascavin family was discovered in 2006 by Nesvorný and Vokrouhlický (2006). Estimates of the family's age: 300-800 thousand years (Nesvorný, Vokrouhlický, 2006) or 500-1000 thousand years (Pravec et al., 2018). The family consists of only three asteroids and could have formed as a result of rotational fission of the parent body (Pravec et al., 2018). This formation scenario suggests that a large number of small fragments will not be found in the family (Vokrouhlický et al., 2024). In the present work, no candidates for new members of the Lucascavin family were found. We calculated proper orbital elements for the three asteroids of the Lucascavin family (see Table S9 in (Perminov, 2024)). Estimates of the criteria values K_1 and K_2 for the Lucascavin family are: $K_1 = 0.000054$ (AU) e.)$^{1/2}$, $K_2 = 0.000061$ (AU)$^{1/2}$.

Mandragora Family

The Mandragora family is located in the outer part of the Main Belt ($a = 3.04$ AU e., $e = 0.19$, $i = 0.56°$). The Mandragora family, which includes eight asteroids, was identified in the work (Pravec et al., 2018). In the same work, it was concluded that the formation of this family through rotational fission is impossible. Table 7 shows the criteria K_1 and K_2 and the maximum values of L_1 and L_2 for the metric ρ_5 for eleven candidates for membership in the Mandragora family. The values of K_1 and K_2 were obtained based on the proper orbital elements of eight known family members (see Table S10 in (Perminov, 2024)). The orbits of four asteroids satisfy condition (2): (43239) 2000 AK238, (391017) 2005 SX208, (459310) 2012 GZ32, (514734) 2007 BJ41. As a result, the number of known members of the Mandragora asteroid family increased to 12 (Table S10 in (Perminov, 2024)).

Table 7. Criteria K_1 and K_2, maximum values L_1 and L_2 of metric ρ_5 for candidates to the Mandragora family

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Belongs to the family
$K_1 = 0.00054$ (AU)$^{1/2}$, $K_2 = 0.00104$ (AU)$^{1/2}$			

(43239) 2000 AK238	0.00029	0.00081	Yes
(204960) 4713 P-L	0.00556	0.00606	No
(265395) 2004 TM4	0.00182	0.00230	No
(327558) 2006 CE52	0.00187	0.00236	No
(373667) 2002 QX88	0.00087	0.00136	No
(391017) 2005 SX208	0.00053	0.00100	Yes
(412122) 2013 GQ30	0.00180	0.00228	No
(459310) 2012 GZ32	0.00018	0.00011	Yes
(490713) 2010 RY26	0.02229	0.02275	No
(514734) 2007 BJ41	0.00035	0.00083	Yes
2008HP40	0.00076	0.00125	No

Martes Family

The Martes family is located in the inner part of the Main Belt (a = 2.38 AU e., e = 0.24, i = 4.28°). In 2022, in the work (Novaković et al., 2022), an asteroid close to the tight pair (5026) Martes – 2005 WW113 (Vokrouhlický, Nesvorný, 2008) was found. In the work (Vokrouhlický et al., 2024), three more family members were found. The Martes family is a tight cluster within the large Erigone family. The family is very young; according to one estimate, the age of the pair (5026) Martes – 2005 WW113 is 18 ±1 thousand years (Pravec et al., 2019). In the present work, no candidates for new members of the Martes family were found. We found proper orbital elements for six asteroids of the Martes family (see Table A11 in (Perminov, 2024)). Estimates of the criteria K_1 and K_2 for the Martes family are: K_1 = 0.00048 (a. e.)$^{1/2}$, K_2 = 0.00065 (a. e.)$^{1/2}$.

Nicandra Family

The Nicandra family is located in the middle part of the Main Belt (a = 2.64 a. e., e = 0.24, i = 3.60°). The Nicandra family consisting of five asteroids was identified in the work (Pravec et al., 2018). In the same work, an estimate of the family's age 870^{+170}_{-30} thousand years was obtained. Table 8 shows the criteria K_1 and K_2 and the maximum values of L_1 and L_2 for the ρ_5 metric for seven candidates for membership in the Nicandra family. The values of K_1 and K_2 were obtained based on the proper orbital elements of five known family members (see Table A12 in (Perminov, 2024)). The orbits of all candidates satisfy condition (2). As a result, the number of known members of the Nicandra asteroid family increased to 12 (Table A12 in (Perminov, 2024)). After including new asteroids in the family, the criteria values changed: $K_1 = 0.00031$ (a. e.)$^{1/2}$, $K_2 = 0.00042$ (a. e.)$^{1/2}$.

Table 8. Criteria K_1 and K_2, maximum values L_1 and L_2 of the metric ρ_5 for candidates to the Nicandra family

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Belongs to the family
	$K_1 = 0.00031$ (AU)$^{1/2}$,	$K_2 = 0.00031$ (AU)$^{1/2}$	
2006 ST295	0.000093	0.00037	Yes
2007 RC364	0.00028	0.00028	Yes
2007 TM252	0.00019	0.000199	Yes
2016 SV22	0.00018	0.00018	Yes
2020 SN11	0.00012	0.00042	Yes
2021 RK120	0.000065	0.00029	Yes
2021 RY71	0.00016	0.00039	Yes

Rampo Family

The Rampo family is located in the inner part of the Main Belt (a = 2.33 AU, e = 0.09, i = 6.06°). The Rampo family was identified in the work (Pravec, Vokrouhlický, 2009). In the same paper, an age estimate of 0.5-1.1 million years was given. In subsequent works (Pravec et al. 2018; Kuznetsov et al., 2020; Novaković et al., 2022; Vokrouhlický et al., 2024), new family members were found. Currently, the Rampo family includes 42 asteroids (Vokrouhlický et al., 2024). In the present work, no candidates for new members of the Rampo family were found. We found proper orbital elements for 42 asteroids of the Rampo family (see Table A13 in (Perminov, 2024)). The estimated values of the criteria K_1 and K_2 for the Rampo family are: $K_1 = 0.00056$ (AU)$^{1/2}$, $K_2 = 0.00086$ (AU)$^{1/2}$.

Rozek Family

The Rozek family is located in the inner part of the Main Belt (a = 1.94 AU i.e., e = 0.09, i = 19.98°). Vokrouhlický and Nesvorný in 2008 discovered a very close pair (63440) 2001 MD30 – (331933) 2004 TV14 (Vokrouhlický, Nesvorný, 2008). In 2019, Pravec reported on the possible proximity of asteroid 2008 VS46 to this pair (Pravec et al., 2019). Studies by Fatka et al. (2020) confirmed that asteroids (63440) 2001 MD30, (331933) 2004 TV14, and 2008 VS46 belong to the same family. Table 9 shows the criteria K_1 and K_2 and the maximum values L_1 and L_2 of the metric ρ_5 for two candidates for membership in the Rozek family. The values of K_1 and K_2 were obtained based on the proper orbital elements of the three known family members (see Table S14 in (Perminov, 2024)). The orbits of all candidates satisfy condition (2). As a result, the number of known members of the Rozek asteroid family increased to five (see Table S14 in (Perminov, 2024)). After including new asteroids in the family, the criteria values changed: $K_1 = 0.00034$ (AU)$^{1/2}$, $K_2 = 0.00061$ (AU)$^{1/2}$.

Table 9. Criteria K_1 and K_2, maximum values L_1 and L_2 of the metric ρ_5 for candidates for membership in the Rozek family

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Member of the family
	$K_1 = 0.00034$ (AU)$^{1/2}$, $K_2 = 0.00035$ (AU)$^{1/2}$		
2009 WQ62	0.00015	0.00021	Yes
2015 MF32	0.00029	0.00061	Yes

Schulhof family

The Schulhof family is located in the middle part of the Main Belt ($a = 2.61$ AU, e, $e = 0.12$, $i = 13.53°$). Initially, a cluster associated with asteroid (81337) 2000 GP36 was identified, consisting of four objects (Pravec, Vokrouhlický, 2009). Later it was shown that this cluster is part of the larger Schulhof family (Vokrouhlický, Nesvorný, 2011), which includes eight asteroids. In the work (Vokrouhlický et al., 2016), the family includes 12 asteroids, and its age is estimated at 800±200 thousand years. Table 10 shows the criteria K_1 and K_2 and the maximum values of L_1 and L_2 for the metric ρ_5 for 25 candidates for membership in the Schulhof family. The values of K_1 and K_2 were obtained based on the proper orbital elements of 12 known family members (see Table S15 in (Perminov, 2024)). The orbit of only one asteroid 2015 RN272 does not satisfy condition (2). As a result, the number of known members of the Schulhof asteroid family increased to 36 (Table S15 in (Perminov, 2024)). After including new asteroids in the family, the criteria values changed: $K_1 = 0.00033$ (AU)$^{1/2}$, $K_2 = 0.00064$ (AU)$^{1/2}$, but candidate 2015 RN272 still does not satisfy condition (2) with the new criteria.

Table 10. Criteria K_1 and K_2, maximum values L_1 and L_2 of metric ρ_5 for candidates to the Schulhof family members

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Belongs to the family
K_1 = 0.00033 (AU)$^{1/2}$, K_2 = 0.00061 (AU)$^{1/2}$			
(538410) 2016 DO32	0.00033	0.00059	Yes
(583004) 2016 CD342	0.00032	0.00064	Yes
(583246) 2016 FB8	0.00026	0.00053	Yes
(583459) 2016 GY245	0.00021	0.00047	Yes
(633027) 2009 BV194	0.00018	0.00044	Yes
(658039) 2017 FC76	0.00017	0.00036	Yes
(676281) 2016 EH195	0.00020	0.00045	Yes
2001 BB85	0.00012	0.00039	Yes
2005 EB352	0.00012	0.00039	Yes
2008 FF47	0.00016	0.00034	Yes
2012 FW85	0.00010	0.00032	Yes
2013 EQ37	0.00026	0.00058	Yes
2013 GV46	0.00020	0.00042	Yes
2015 GB17	0.000064	0.00032	Yes
2015 HB205	0.000092	0.00032	Yes
2015 RD144	0.00032	0.00060	Yes
2015 RN272	0.00036	0.00067	No
2016 DE45	0.00029	0.00049	Yes
2016 DY45	0.00025	0.00039	Yes
2016 EF9	0.00021	0.00042	Yes
2016 ES280	0.000093	0.00033	Yes
2016 FT28	0.00023	0.00050	Yes
2018 FK55	0.000086	0.00032	Yes
2019 FD26	0.00014	0.00031	Yes
2022 EU8	0.00026	0.00052	Yes

Wasserburg Family

The Wasserburg family is located in the inner part of the Main Belt (a = 1.95 AU. i.e., e = 0.06, i = 23.71°). Before the discovery of the Wasserburg family, a young close pair (4765) Wasserburg – 2001 XO105 (Vokrouhlický, Nesvorný, 2008) was known, with an age of more than 90 thousand years (Pravec et al., 2010). Subsequent studies showed that the pair is accompanied by other asteroids on very close orbits (Pravec et al., 2019; Novaković et al., 2022; Vokrouhlický et al., 2024). The Wasserburg family is classified as a very young family. The Wasserburg family could have originated from a powerful crater-forming event on the parent asteroid (4765) Wasserburg (Vokrouhlický et al., 2024). Currently, the Wasserburg family includes eight asteroids (Vokrouhlický et al., 2024). In the present work, no candidates for new members of the Wasserburg family were found. We found proper orbital elements for all asteroids of the Wasserburg family (see Table A16 in (Perminov, 2024)). The estimated values of criteria K_1 and K_2 for the Wasserburg family are: K_1 = 0.00018 (a. u.)$^{1/2}$, K_2 = 0.00018 (a. u.)$^{1/2}$.

2002 PY38 Family

The 2002 PY38 family is located in the inner part of the Main Belt (a = 2.20 a. u., e = 0.18, i = 0.89°). The family was discovered in 2020 and consisted of three asteroids: (338073) 2002 PY38, (529915) 2012 TZ97, 2016 SQ14 (Kuznetsov et al., 2020). The age of the family does not exceed 100 thousand years (Kuznetsov et al., 2020). Table 11 shows the criteria K_1 and K_2 and the maximum values L_1 and L_2 of the metric ρ_5 for eleven candidates for membership in the 2002 PY38 family. The values of K_1 and K_2 were obtained based on the proper orbital elements of twelve known family members (see Table A17 in (Perminov, 2024)). Only one candidate 2015 TO83 satisfies condition (2). As a result, the number of known members of the 2002 PY38 asteroid family increased to four (Table A17 in (Perminov, 2024)).

Table 11. Criteria K_1 and K_2, maximum values L_1 and L_2 of metric ρ_5 for candidates to members of family 2002 PY38

Asteroid	L_1, (AU)$^{1/2}$	L_2, (AU)$^{1/2}$	Member of family
K_1 = 0.000078 (AU)$^{1/2}$, K_2 = 0.000078 (AU)$^{1/2}$			
2001 KY82	0.000196	0.000196	No

2002 FD44	0.000144	0.000144	No
2006 UL238	0.000316	0.000333	No
2010 RV167	0.000611	0.000643	No
2013 VC79	0.000155	0.000156	No
2015 RA194	0.000211	0.000280	No
2015 TO83	0.000078	0.000078	Yes
2019 OU6	0.000552	0.000626	No
2019 SL111	0.000716	0.000716	No
2021 NV62	0.000603	0.000622	No
2022 OQ48	0.000513	0.000517	No

The discovery of new family members provides an opportunity to update data on the ranges of osculating orbital elements shown in Table 1. Table 12 shows the positional osculating orbital elements of the main asteroids of families and their ranges of variation for families in which new members were found. In the future, information about osculating (Table 11) and proper orbital elements (Tables P1-P17 in (Perminov, 2024)) will be used to search for new members of young families.

Table 12. Positional osculating orbital elements of young asteroid families, taking into account new members discovered in this work, at epoch MJD 60200

Asteroid family	Number of members	a_{fam}, AU	e_{fam}	i_{fam}, city
Adelaide	81	$2.2450^{+0.0040}_{-0.0012}$	$0.1017^{+0.0028}_{-0.0031}$	$5.9988^{+0.0655}_{-0.0146}$
Brugmansia	4	$2.6209^{+0.0007}_{-0.0015}$	$0.2187^{+0.0034}_{-0.0008}$	$1.6247^{+0.0019}_{-0.0022}$
Emilkowalski	13	$2.6006^{+0.0000}_{-0.0014}$	$0.1503^{+0.0060}_{-0.0041}$	$17.7538^{+0.0168}_{-0.2824}$
Mandragora	12	$3.0393^{+0.0178}_{-0.0086}$	$0.1975^{+0.0485}_{-0.0066}$	$0.5655^{+0.4088}_{-0.0173}$
Nicandra	12	$2.6357^{+0.0007}_{-0.0018}$	$0.2442^{+0.0032}_{-0.0011}$	$3.6050^{+0.4525}_{-0.0866}$
Rozek	5	$1.9384^{+0.0004}_{-0.0010}$	$0.0886^{+0.0003}_{-0,0007}$	$19.9859^{+0.0586}_{-0.0589}$
Schulhof	36	$2.6109^{+0.0010}_{-0.0037}$	$0.1207^{+0.0051}_{-0.0035}$	$13.5351^{+0.2765}_{-0.0990}$
2002 PY38	4	$2.1961^{+0.0009}_{-0.0000}$	$0.1764^{+0.0002}_{-0.0004}$	$0.8889^{+0.0312}_{-0.0000}$

CONCLUSION

The method presented in this work for finding new members of young asteroid pairs using Kholshevnikov metrics for osculating and proper orbital elements has proven its effectiveness. The method allowed finding new members in eight of the seventeen young families considered in the article. The existence of the young family 2002 PY38 was confirmed and a new asteroid belonging to the family was found. The ranges of positional osculating orbital elements (Tables 1 and 12) and estimates of criteria K_1 and K_2 (Tables S1-S17 in (Perminov, 2024)) will be in demand in the future when searching for new family members.

The homogeneous sets of proper orbital elements of family asteroids obtained during the study will be used in further research on the structure and dynamic configuration of families, assessing the influence of both mean motion and secular resonances on it.

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