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DYNAMICAL EVOLUTION AND STATISTICS OF DAMOCLOIDS. 2.

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This paper presents a comparative analysis of two small-body populations: Damocloids and long-period comets, covering 171 and 1495 objects, respectively. It is established that, on average, Damocloids have larger perihelion distances. The inclination distributions are quite similar for both systems, with retrograde motion predominating. A striking difference is found in the comparison of perihelion concentration planes. Unlike long-period comets, the perihelia of Damocloids tend to concentrate more toward the ecliptic. In the distribution of MOID values of Damocloids and long-period comets relative to the orbits of the giant planets, excesses are observed in both groups, being more pronounced among Damocloids.

Keywords: damocloids – long-periodic comets – giant planets – statistics

1. INTRODUCTION

The present article is a logical continuation of the work [8], which analyzed the structure and evolutionary characteristics of the Damocloid population. These are minor bodies following comet-like orbits but lacking visible coma. The Tisserand parameter values relative to Jupiter, do not exceed two. The cited study examined the orbital evolution of 144 such objects. The results obtained in that work

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provide a basis for expanding the scope of the analysis of the Damocloid system and exploring new patterns within this population of small bodies.

2. OBJECTIVE OF THE STUDY AND DATA USED

Since most Damocloids originate from outer regions of the Solar System, it is natural to hypothesize their similarity to long-period comets. In other words, Damocloids may represent comets that have lost their volatile components and evolved into asteroid-like bodies. Their relatively large sizes might be explained by selection effects. If this scenario holds true, there should be significant similarities between Damocloids and LPCs in terms of their orbital characteristics (e.g., orientation of apsidal lines, perihelion concentration near particular points or planes on the celestial sphere-great circles on the celestial sphere aphelion and nodal distances, etc.). This question was partially addressed in a previous study, but that analysis was not exhaustive. Thus, this subject requires further investigation, which constitutes one of the objectives of the present paper.

Furthermore, the number of identified Damocloids has significantly increased in recent years, expanding the possibilities for deeper analysis. As of early 2025, the number of such bodies has reached 316, which is 2.2 times higher than during the period covered in study [8]. In this study, the authors aim to compare two minor-body populations: Damocloids and LPCs. A constraint on aphelion distances $Q>30$AU has been set for both small-body populations. It is reasonable to assume that objects with lower Q values are more strongly influenced by the gravitational perturbations of giant planets. The number of Damocloids meeting this criterion is 171. The compiled list begins 5335 Damocles (1991 DA) and ends with (2024 XN25). Additionally, a small number of rare objects with perihelion distances $q>10$ AU were excluded from further consideration to ensure the robustness of the analysis.

Regarding LPCs, three additional restrictions were applied:

1. Comets with perihelion distances $q<0.01$AU were excluded from the list.

2. If multiple LPCs have nearly identical orbits (twin comets) only one is included in the dataset. For example, comets C/1988 F1 and C/1988 J1 share almost identical orbits and are likely fragments of a common parent nucleus. In a comparative analysis, it is more reasonable to consider them as single entity. This effect is even more pronounced among short-perihelion comets, which are therefore entirely excluded from the statistical sample.

3. As with Damocloids, comets with $q>10$AU were also excluded from consideration. As previously noted, their numbers are extremely small, yet they could distort the statistical similarities or differences being investigated.

A review of the comet catalog [9] and MPEC data up to early 2025 resulted in a dataset of 1495 objects for comparative analysis. This list begins with comet C/-43 K1 and ends with C/2024 Y1.

3. FEATURES OF THE DISTRIBUTION OF APHELION DISTANCES OF DAMOCLOIDS

It is well known that the distribution of aphelion distances (Q) for long-period comets (LPC) in the trans-Neptunian region exhibits certain clustering and "gaps". This phenomenon has been recognized for a long time (see, for example, [4,5]) and has even been utilized in attempts to predict undiscovered planetary bodies in the Solar System. These clusters are particularly prominent in the ranges of 30–38 AU, 49–57 AU, 73–89 AU, 99–117 AU, and 160–180 AU. In this respect, the data for Damocloids independently or simultaneously raise interest. The authors analyzed the values of Q for 171 Damocloids and noted that only the clustering within the range of 101–120 AU, (18 objects), warrants further investigation, as the adjacent intervals contain

only 10 and 5 objects, respectively. No similar clustering or gaps are observed across the rest of the distance scale. Analysis and calculations showed that the aphelia of 8 out of the identified 17 Damocloids are concentrated within ±10° of the plane defined by parameters:

$$\mathrm{I_p} = 11^0.40 \cdot \Omega_p = 331^0.49 \tag{1}$$

Some data regarding these 8 Damocloids are provided in the left part of Table 1. The concentration of perihelia near this plane is statistically significant and unlikely to be accidental. A parallel analysis of long-period comets with Q ranging from 100 to 120 AU revealed a rather intriguing pattern. It turned out that the perihelia of 8 out of 27 such comets, observed up to early 2025 , are located within ±10° of the plane with the following parameters:

$$\mathrm{I_p} = 10^0 \cdot \Omega_\mathrm{p} = 358^0 \tag{2}$$

A list of these comets along with some of their data is presented in the right part of Table . Although this concentration is less pronounced than the previous one, the proximity of the parameters of the computed planes remains noteworthy.

The observed similarity between these two classes of minor bodies corresponding to the same Q range should be further investigated as new objects are discovered. It is possible that this similarity contains valuable information for theoretical searches of undiscovered planetary bodies.

Table 1. Parameters of 8 Damocloids and 8 LPCs relative to two planes

Some Damocloids parameters relatively to the plane (1)				Some comet parameters relatively to the plane (2)			
Damocloid	**q**	**e**	B'	**Long-period comets**	**q**	**e**	B'
(2000 AB229)	2.273	0.956	2.11	C/2005 O1	3.591	0.93	-9.95
(A/2020 B1)	1.748	0.967	-1.49	C/1995 Q2	1.889	0.967	-6.44
(2024 LY9)	9.679	0.839	-4.9	C/1964 N1	0.822	0.985	-4.21
(2024 RQ11)	2.675	0.954	-4.49	C/2013 PE67	1.847	0.967	-3.77
(A/2019 Q2)	1.258	0.979	-4.6	C/2020 Q1	1.315	0.978	-1.35
(2020 KX11)	3.244	0.947	2.1	153P/1661 C1	0.513	0.99	7.64
(2016 AT281)	2.688	0.956	-9.57	C/2007 D2	1.245	0.977	9.33
(2012 HD2)	2.534	0.959	-5.85	C/1941 B1	0.942	0.981	9.45

4. FEATURES OF THE DISTRIBUTION OF ORBITAL APSIDAL LINES

The peculiarities of the distribution of perihelion longitudes (and consequently, aphelion longitudes) have long formed the basis for various hypotheses in cometary cosmogony [4]. In this section, we primarily aim to determine the extent to which Damocloids resemble long-period comets (LPCs) in this regard. As is well known, the perihelion longitude of a comet or Damocloid is calculated using the formula:

$$\mathrm{L} = \Omega + \mathrm{atan}(\tan\omega\cos i)$$

where Ω, ω, and i are the angular orbital elements. However, in some studies, particularly in meteor astronomy, authors often use a simpler formula:

$$\pi = \Omega + \omega \tag{3}$$

Since we are only comparing two small-body systems, we will adopt the aforementioned formula (3). By dividing the range of possible values into 12 intervals, we counted the numbers of comets and Damocloids in each. After applying the appropriate normalization, we employed the Kolmogorov-Smirnov test to compare the perihelion distributions. [2, 10]. It turned out that the test statistic is 0.55 , and its significance is well below than the required 95% confidence level. This indicates that perihelion distributions of Damocloids and LPCs do not differ greatly. It is known that the perihelia of LPCs are concentrated around two planes (great circles on the celestial sphere), which have a mutual inclination of about 80° [6]. These planes are inclined relative to the ecliptic by 40.2° and 86.2°, respectively, with the concentration near the-latter being more pronounced. This observation has provided the basis of for the hypothesis of a large trans-Neptunian planet. Calculations conducted using the methodology described in [6] demonstrate that the perihelia or aphelia of Damocloids concentrate near a plane with the following parameters:

$$\mathrm{I_p} = 5^0.32; \Omega_\mathrm{p} = 342^0.36 \tag{4}$$

For instance, the orbits of 30 Damocloids have latitudes ranging from $-5°$ to $+5°$ relatively (4). This represents an initial marked difference from the long-period comets. There is one more characteristic of LPCs that can be tested in the Damocloid system. Such comets exhibit an excess of aphelia in the range of 250 to 400 AU [6]. Analysis of individual Q values for Damocloids demonstrates no distinct excess within this interval, although 9 values are concentrated between 280-360 AU. The optimal plane of perihelia for these selected 9 objects has the following parameters:

$$\mathrm{I_p} = 85^0.53 \cdot \Omega_\mathrm{m} = 78^0.14 \tag{5}$$

A rather weak similarity with long-period comets is observed here, as the two planes (the plane calculated in [6] and (5))have a mutual inclination of approximately 28°. However, the deviations of perihelia of these nine comets from plane (5) span a considerable range. With only three comets exhibiting deviations within ±10°. Therefore, it must be concluded that Damocloids significantly deviate from long-period comets in terms of perihelion distribution. Their perihelia tend to be more concentrated toward the ecliptic.

5. COMPARISON OF TWO SYSTEMS BY PERIHELION DISTANCES

Calculations show that the Damocloids from the compiled list have the following $\mathrm{q_{ast}}$ values and their standard deviation σ :

$$\mathrm{q_{ass}} = 3.262; \sigma = 1.821$$

Similar calculations for long-period comets yield:

$$g_{\mathrm{axit}} = 2.296; \sigma = 1.962$$

The normalized difference between these values is:

$$\mathrm{T} = (3.262 - 2.296)/\left(1.821^2/171 - 1.962^2/1495\right)^{0.5} = 6.52$$

and its statistical significance exceeds 0.99 [2]. Therefore, based on the qavr parameter, Damocloids exhibit a more than significant advantage over long-period comets. However, it remains unclear how observational selection effects influence this distribution. Clearly, comets having smaller heliocentric distances exhibit greater activity and are easier to detect. Another factor potentially affecting the observed distributions of Damocloids and LPCs is evolutionary in nature. It may be assumed that Damocloids with relatively smaller perihelion distances have depleted their volatile components over long evolutionary timescales, transforming into meteoroid streams. In contrast, observed LPCs likely have undergone fewer passages through the inner Solar System.

6. COMPARISON OF THE ORBITAL INCLINATIONS OF THE TWO SYSTEMS OF CELESTIAL BODIES

The distribution of orbital inclinations for LPCs from the compiled list is shown in Figure 1. The number of prograde and retrograde orbits is 735 and 760, respectively.

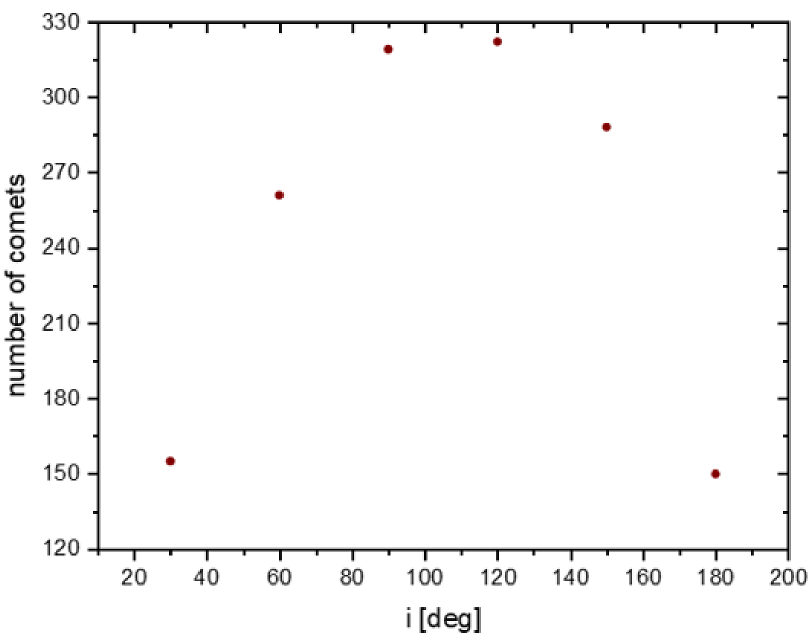

Fig. 1. Distribution of orbital inclinations for 1495 long-period comets.

A dominance of retrograde orbits over prograde ones (102 versus 69) is also observed among Damocloids (Fig. 2). Moreover, this effect is even more pronounced for Damocloids than in the case of LPCs. Overall, these two distributions are similar to each other. The only observable divergence occurs near 50°.

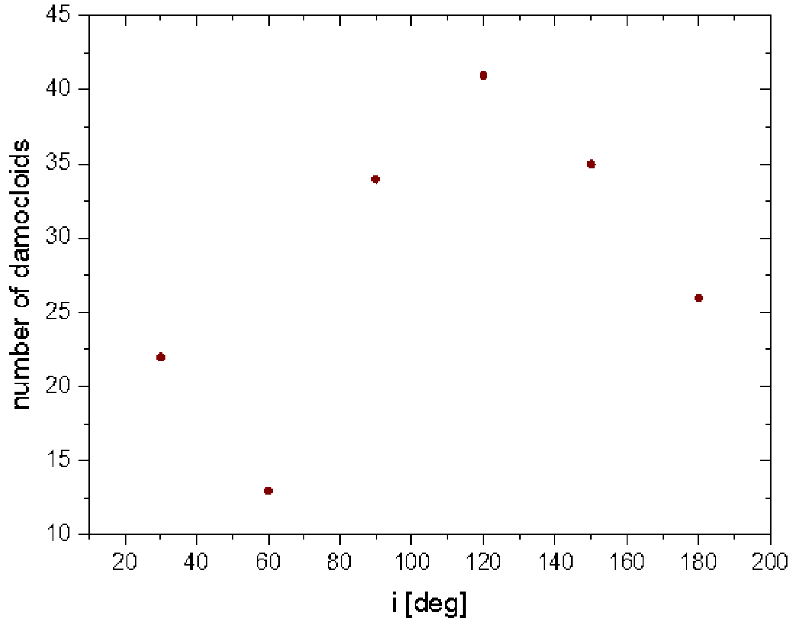

Fig. 2. Distribution of orbital inclinations for 1495 long-period comets.

7. DISTRIBUTION OF MOID VALUES FOR DAMOCLOIDS.

Numerous studies have been devoted to investigating the MOID values of long-period comets. However, the most significant numerical characteristics in this area were obtained in [7]. The results from the cited work indicate that the distribution of MOID values for Damocloids relative to the orbits of the giant planets exhibits significant excesses in the low-value range (1.4–1.7 times above the norm), which cannot be explained by random deviations. This implies that a portion of these objects is dynamically linked to the giant planets. In this regard, Damocloids also attract considerable interest. Using algorithms described in [1, 11, 12], we conducted a MOID analysis for 171 Damocloid orbits. Simultaneously, similar calculations were performed for the orbits of long-period comets, since their number increased significantly after publication [8] (1495 versus 1360). Below, we present comparative results for Damocloids and giant planets examined individually within the framework of the research problem:

7.1. Case of Jupiter:

The number of MOID values (ρ) not exceeding 0.322 AU (where ρ is the planetary sphere of influence) is 206 , i.e., 13.8%. The number of Damocloids with similar characteristics is 26 , i.e., 15.2%. When employing threshold values of ρ equal to 0.286 AU and 0.01 AU , the prevalence of Damocloids over LPCs is 1.28 and 15 times, respectively.

7.2. Case of Saturn:

Here, the number of suitable values ($\rho = 0.364\mathrm{AU}$) is 18 , i.e., 10.5% for Damocloids. For LPCs, the corresponding number is 135 (9%). By adjusting the ρ threshold to 0.32 AU , the prevalence of Damocloids increases to 1.66 times.

7.3. Case of Uranus ($\rho = 0.346\mathrm{AU}$) :

The number of Damocloids is 8 (5%), compared to 61 LPCs (4.1%). Reducing the ρ threshold to 0.32 AU yields a Damocloid predominance to 1.30 times.

7.4. Case of Neptune ($\rho = 0.58\mathrm{AU}$)

:

The number of relevant Damocloids is 10(5.8%), and for LPCs, it is 68(4.5%). In this case, Damocloids exhibit a superiority factor of 1.29 .

Thus, in all examined cases, Damocloids dominate LPCs according to this indicator. However, their dominance becomes even more significant if the threshold values are adjusted within reasonable limits.

8. CONCLUSIONS

Damocloids have statistically significantly larger perihelion distances compared to long-period comets.

Unlike long-period comets, Damocloids tend to cluster their orbital perihelia near the ecliptic; however, the perihelion longitudes of Damocloids do not differ from those of LPCs.

Based on their orbital characteristics, Damocloids appear to have undergone considerably more passages through the inner Solar System, particularly within the occupied by giant planets, compared to LPCs.

Dynamical parameters of Damocloids are less effective than those of LPCs for theoretical searches of undiscovered planets in the Solar System. However, the local maxima observed in the 100–120 AU range in both systems constitute an exception, as they are also accompanied by concentrations of aphelia near two planes with similar parameters.

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