What are Families of Minor Planets?

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ABSTRACT. This paper describes how the families of minor planets were discovered and how minor planets are classified into families and shows several evidences that at least some families were originated by collisions of minor planets. In fact for major families there are much more fainter minor planets than in other regions and when the families were discovered by Hirayama in 1918 only one sixth of the total numbered minor planets belonged to families whereas now more than one third of them belong to the families. It is also emphasized that the classification into the families is theory dependent and that any theory available now is not accurate enough to derive stable quantities for the families to study their origins as the families are usually bounded partly by mean motion and/or secular motion commensurability regions in the phase space.

1. Discoveries of Families

Families of minor planets were discovered by Kiyotsugu Hirayama(1918), who was a professor of astronomy, the University of Tokyo, 70 years ago, when only 790 minor planets were known, as he noticed several clusterings of minor planets with similar values of the semi-major axes, a, the eccentricities, e, and the inclinations, i. Soon he realized that when the poles of the orbital planes of the minor planets in one clustering were plotted on a plane they were distributed nearly along a circumference with the center almost coinciding with the pole of Jupiter's orbital plane. He also found that the points drawn on a plane for the eccentricities and the longitudes of the perihelions, ω, instead of the inclinations and the longitudes of the ascending nodes, Ω, were also distributed nearly along a circumference with larger scatterings.

According to the linear classical theory of the secular perturbations of minor planets by assuming that both the eccentricity and the inclination are very small, the equations for $\xi=e\cos\omega$ and $\eta=e\sin\omega$, as well as $p=\tan i\cos\Omega$ and $q=\tan i\sin\Omega$ are linear differential equations with solutions expressed by the sum of a free oscillation and forced ones due to the secular perturbations in the corresponding orbital elements of the disturbing planets. Then ξ and η as well as p and q vary with time along circumferences with centers moving more slowly due to the forced oscillations. The radii of the circumferences are called the proper eccentricity and the proper inclination which are the amplitudes of the free oscillations. The diagrams which Hirayama drew show that ξ, η as well as p, q for the minor planets in the clustering are distributed along trajectories expressing the secular perturbations, although the phases are different from each other due to small deviations in the secular motions, that is, the angular velocities

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of the circular motions.

Hirayama, therefore, concluded that since for the minor planets in the same clustering the semi-major axes, the proper inclinations and the proper eccentricities which are all stable quantities in the secular perturbation theory expressing averaged long-term behaviours of the motion take almost same values they had a common origin. And he called the clusterings as families of minor planets. By this way he identified five families, Themis, Eos, Coronis, Maria and Flora, and later he added the two families, Pallas and Phocaea(1923). Still they are the major families.

2. Identifications of Families

Groupings of minor planets into families were tried by several authors later on including Brouwer(1951). However, in fact the eccentricities and the inclinations for most of minor planets are not so small, and, therefore, the classical theory is not satisfactory to derive accurately stable quantities for them. Williams(1969) developed a new thory for secular perturbations and identified several more families according to his theory(1979). Kozai(1962 and 1979) modified the classical theory by introducing terms with integral multiples of $2g$ as arguments, where g is the argument of perihelion. Such terms are very important for minor planets with large eccentricities and inclinations.

For example, the inclination and the eccentricity of Pallas, the second minor planet discovered next to Ceres and a member of Pallas family, are $34.^\circ4$ and 0.234, respectively, and, therefore, are not at all small. By the theory of the author they change, respectively, between $28.^\circ7$ and $36.^\circ1$, and between 0.124 and 0.405 as periodic functions of twice the argument of perihelion. For any minor planet the variations of the eccentricity and the inclination with respect to the argument of perihelion can be estimated by assuming that all the disturbing planets move on the same plane along circular orbits, as under this assumption $\Theta=(1-e^2)^{1/2}\cos i$ is constant and the system of the equations of motion for the secular perturbations can be reduced to that of one degree of freedom.

In this paper the numbered minor planets are classified into the eight families listed in Table 1 with the ranges of the three stable quantities, namely, the semi-major axis, the value of the inclination to Jupiter's orbital plane at $2g = 0^\circ$, i_{min}, which is the minimum value, and Θ. Hungaria family, which has only few bright members, is the only one which is added to those in Hirayama's papers in Table 1, where the numbers of member minor planets shown in Hirayama(1923) and Brouwer(1951) as well as that by the author(1988) using 3840 minor planets are listed also.

TABLE 1. Eight major families

Family	a(AU)	Θ	i_{min}	Number of Members (1988)	(1923)	(1951)	v (km.s^{-1})	Δv
Hungaria	1.84–1.98	0.880–0.950	$19.^\circ0$–$28.^\circ0$	39	(1)	(8)	22	0.40
Flora	2.15–2.30	0.950–1.000	00. 0–09. 6	602	63	125	20	0.34
Phocaea	2.28–2.44	0.850–0.920	20. 0–24. 0	64	11	21	20	0.34
Maria	2.52–2.57	0.950–0.980	13. 5–16. 0	41	14	17	19	0.09
Pallas	2.60–2.80	0.770–0.830	24. 0–31. 0	15	3	6	18	0.33
Coronis	2.83–2.92	0.994–1.000	01. 5–02. 6	126	20	33	18	0.14
Eos	2.99–3.04	0.974–0.986	09. 0–10. 7	193	27	58	17	0.07
Themis	3.07–3.22	0.976–1.000	00. 6–02. 5	228	32	53	17	0.20

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In Table 1 besides the ranges of the orbital parameters and the numbers of the members the velocity, v, and the scattering velocity, Δv, which are that for the circular motion with the mean value of the semi-major axes of the members and that producing the discrepancy of the semi-major axes, respectively, for each family are shown. The numbers in parenthesis for Hungaria family under (1923) and (1951) are estimated by the author by using the improved theory of the author(1962) whereas the numbers for Pallas family under (1923) and (1951) are the original ones in their papers by using the classical linear theory of the secular perturbations.

In Figure 1 a diagram showing the positions of i_{min} and a of the numbered minor planets is given for the range of a between 1.5 and 3.5AU(Astronomical Unit), the sizes of the points depending on Θ. In the Figure the eight families in Table 1 are clearly seen. Particularly, Maria, Coronis, Eos and Themis families are remarkable, as they are compact and dense. On the other hand, Hungaria, Flora, Phocaea and Pallas families are not so dense, however, they can be identified because of recognized boundaries where very few asteroids are found.

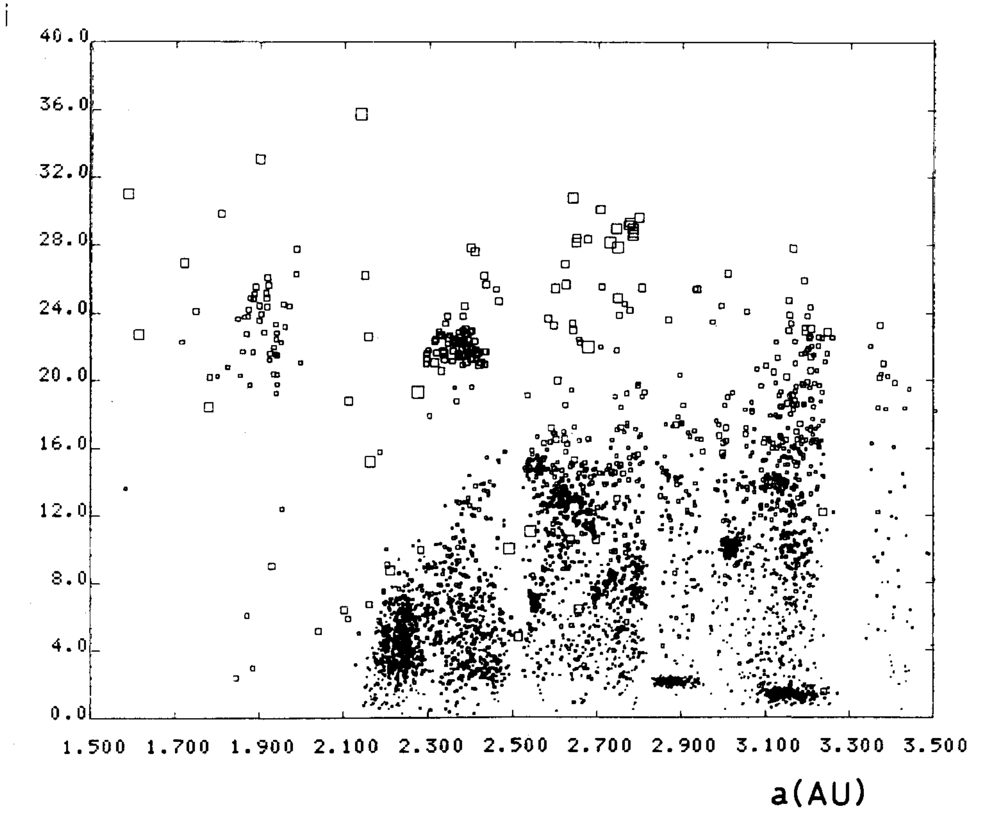

Figure 1. Diagram for the minimum values of the inclinations, i_{min}, and the semi-major axes, a, for numbered minor planets.

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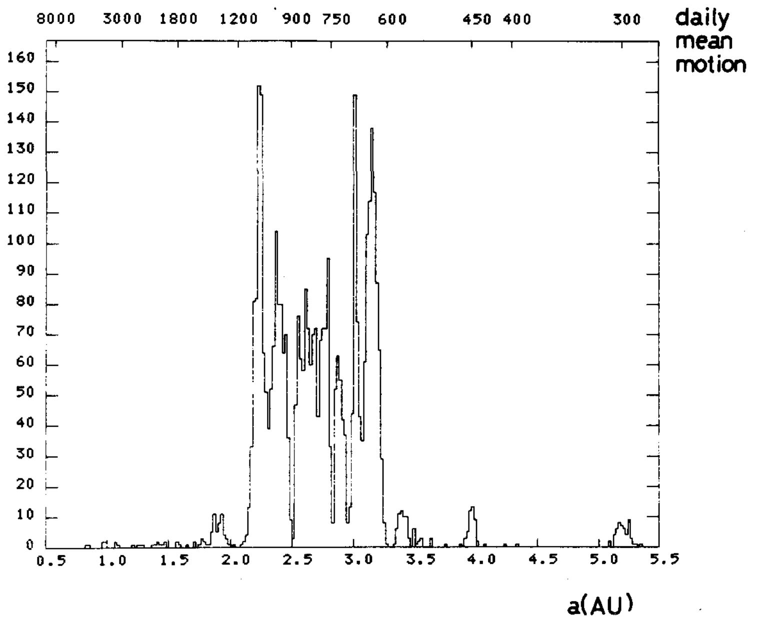

Figure 2. Number distribution with a for 3750 minor planets.

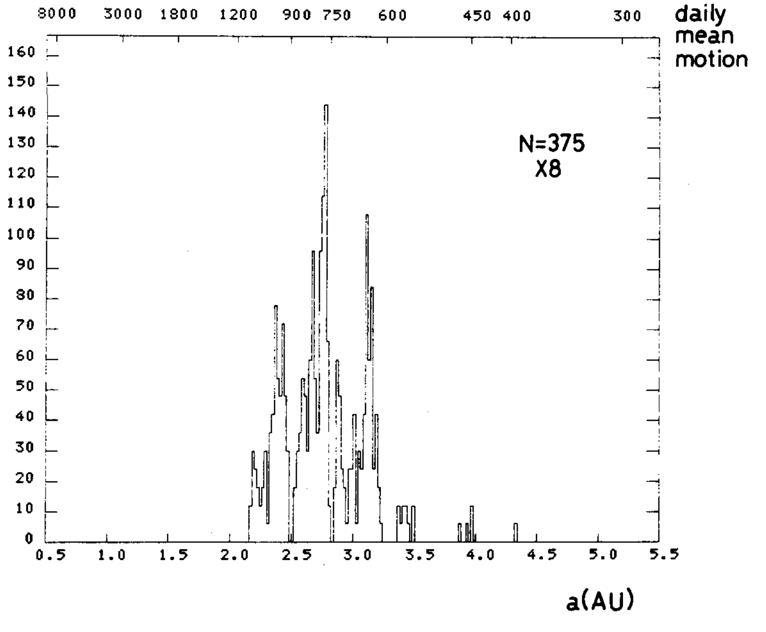

Figure 3. Number distribution with a for 375 minor planets.

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3. Characteristics of Families

Other remarkable characteristics of the positions of the families in the figures are that almost all the families are bounded at least partly by so-called commensurable regions, either of mean motions with Jupiter or of secular motions of the longitudes of the perihelion or the node, where there are very few minor planets. For example, the left and upper boundaries of Flora and the lower boundaries of Phocaea and Pallas families correspond to secular commensurable regions as Williams(1969) pointed out.

As any secular perturbation theory does not hold for such mean motion and secular motion commensurable cases more general secular perturbation theories are needed to identify families and to derive more stable quantities to find out their origins, although to formulate such general theories is very difficult.

In Figure 2 and 3 number distributions of the numbered minor planets for the number up to 3750 and 375, respectively, are shown, although the numbers are multipled by 8 in Figure 3 for the 375 minor planets. It is noticed that generally in Figure 3 only bright minor plnets are included and here the highest peak is at 2.77AU, which is predicted by Bode's law. However, in Figure 2 there are other higher peaks, which correspond to positions of the major families. This means that there are much more fainter minor planets in the major families.

The same conclusion can be reached by comparing the numbers of member minor planets by Hirayama(1923) and that by the author as although the total number of the minor planets used in this paper is five times as large as that by Hirayama(1923) the ratio for the numbers for Flora family is roughly ten. Now more than one third of the numbered minor planets are members of the eight families, although in 1918 only one sixth were members. This means that nearly a half of newly discovered minor planets in the past 30 years belong to the families.

In Figure 4 brightness distributions for $B(1,0)$ (a kind of absolute magnitude in blue color) of minor planets belonging to the eight families as well as Trojan and Hilda groups and also those in some regions with semi-major axes similar to those of major families for comparison. The figure in the parenthesis in each diagram shows the number to be added to $B(1,0)$ to derive averaged apparent magnitudes at opposition.

These diagrams also show that there are much more fainter minor planets in the major families, particularly, for Flora family, which contains more than 600 members and the largest family and for which as the geocentric distance at opposition is small many fainter and smaller minor planets have been observed. And it is expected that when many fainter minor planets will be observed in future much more members will be added to Coronis, Eos and Themis families, for which as their distances from the earth are large even at oppositions fainter minor planets have not yet been discovered. Diagrams for non-member minor planets with the ranges of the semi-major axes similar to those for Coronis, Eos and Themis families and that outside of Flora family clearly show that there are more brighter minor planets and not so much fainter ones than those for corresponding family member minor planets.

In fact for Hungaria, Flora and Phocaea families there are only a few minor planets which are brighter than 12th magnitude in $B(1,0)$ and for Coronis, Eos and Themis families brighter than 10th magnitude. It must be noticed here that IRAS observed an enormous amount of micron-sized particles with orbits similar to those of the members of Eos and Themis families(Dermott et al, 1984).

Pallas family is the only one which has a very bright and large member, Pallas. However, it does not contain many fainter members. In fact the increase of the numbers compared with those by Hirayama(1923) and Brouwer(1951) is partly due to the theories adopted to derive the proper elements. The improved theory can identify more members

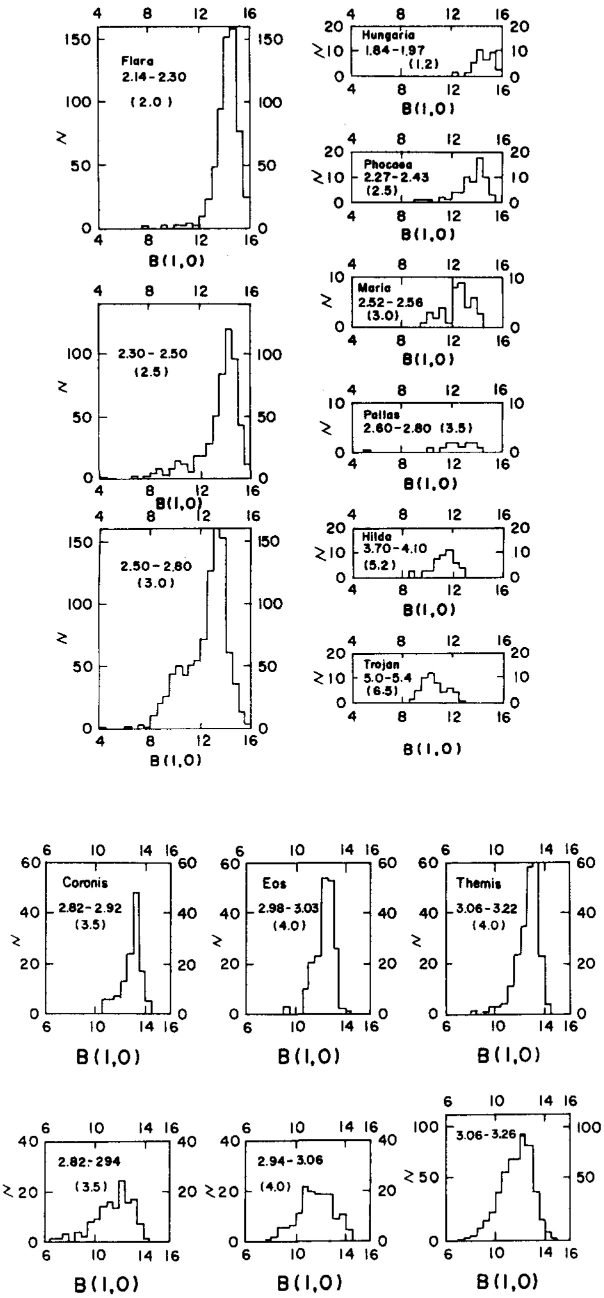

Figure 4. Brightness distributions for families and others.

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by taking into account the variations of the orbital elements with twice the argument of perihelion. Maria faimly has a peculiar brightness distribution which consists of a brighter and a fainter parts. It is expected for the two families more members will be discovered if high latitude sky will be surveyed systematically.

The brightness distributions for Hilda and Trojan groups are shown to find out any similarity to those of the families and it seems to the author that for Hilda group the diagram is not so different from those of some families showing some evidences of possible collisions.

4. Conclusions

In conclusion every data suggest that at least some of the families listed here were created by collisions among minor planets and, therefore, much more smaller particles produced during the formation of the families are expected to exist in interplanetary space. Still it seems to the author that since almost all the major families exist near mean motion and/or secular motion commensurable regions some resonance forces triggered the collisions and have kept the families in their present regions.

The author would like to stress, again, that any secular perturbation theories are not suffcient enough to produce very stable quantities for member minor planets of the families, and, therefore, it is very difficult to compute, for example, the original scattering velocity for each member after the possible collision accurately from the orbital data we have now. The scattering velocities in Table 1 which are computed from the present range of the semi–major axes of the member minor planets may not express the original scattering velocity, as the range of the semi–major axes are for most cases determined by mean motion commensurability zones.

Therefore, nothing can be said about the origin of the families very definitely now. Also it must be pointed out that even though collisions created the families listed here they cannot produce any meteorites found on the Earth. However, the author would like to mention that some of the craters on Mars were due to meteorites produced by the collisions which created Hungaria, Phocaea and Pallas families, as the perihelions of minor planets of the three families can approach to the orbit of Mars.

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