Research Article

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Comets of the Marsden and Kracht groups

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Abstract: Perihelion distances of Marsden and Kracht group comets fall into the range $6R_S < q < 12R_S$ (the Meyer group comets also share the same perihelion interval). It is by several folds larger than the perihelion distance of the Kreutz group comets ($q < 2R_S$). Average circulation period for comets of the Marsden group is $\bar{P} = 5.5$ years and for the Kracht group is $\bar{P} = 5.3$ years. The Marsden and Kracht group comets share the same origin; as well as 96P (Machholz), object 196256 (2003 EH1), meteor showers the Daytime Arietids, Northern and Southern δ Aquariids, Quadrantids forming the Machholz interplanetary complex. This work offers computational movement simulation for comet-progenitor fragments. It is shown that the orbits of the representatives of the complex can be explained if the decay of the comet-progenitor for objects 96P and 196256 occurred ~9500 years ago. The following evolution direction has been demonstrated for the complex objects: progenitor comet – comet 96P – the Marsden group comets – the Kracht group comets – the Southern δ Aquariids. However, not all the complex objects will necessarily pass through every stage of the above as it can be preceded by the total disintegration of the object.

Keywords: comets orbits, sungrazers, comet 96P/Machholz, object 2003 EH1 (196256)

1 Introduction

The overwhelming majority of comets with small perihelion distances of $q < 0.1$ AU belong to the Kreutz group (89% from the Marsden & Williams comet catalogue (2008)). Apart from the Kreutz group among the sungrazers there are other groups with similar orbital elements: the Meyer group, the Kracht group and the Marsden group. There are also sporadic comets which do not belong to any of the groups mentioned.

The origin and evolution of the Marsden and Kracht comet groups were studied in the work by Sekanina & Chodas (2005). The authors believe that these families are dynamically connected with each other as well as with the periodic comet 96P (Machholz) and the Arietids, and Northern and Southern δ -Aquariids meteor showers. Babadzhanov & Obruchov (1992, 1993) mentioned connection between comet 96P (Machholz) and such meteor showers as the Daytime Arietids, Southern and Northern δ -Aquariids, as well as the Quadrantids, Ursids, α -Cetids, Carinids, κ -Velids. Abedin *et al* (2018) shows that meteor showers identified by Babadzhanov & Obruchov as α -Cetids, Ursids and Carinids, correspond to the Daytime λ -Taurids, November ι -Draconids or the December α -

Draconids and the θ -Carinids. Some of these meteor showers can be associated with comet C/1490 Y1 (Ki-Won *et al.*, 2009), asteroid 2003 EH1 (Babadzhanov *et al.*, 2008). The orbital elements of the objects that might be connected with the groups of Marsden and Kracht are presented in Table 1.

The study of Babadzhanov *et al.* (2017) based on the study of the orbital evolution of comet 96P and asteroid 2003 EH1 on the interval $[-14000, +14000]$ concludes that these objects have a common progenitor that decayed 9500 years ago. Abedin *et al* (2018) research shows that Jupiter captured predecessor of comet 96P about 20000 BCE and the Marsden comet group was formed by subsequent fragmentation of approximately 100-950 CE.

The problem of the origin of comets with extremely small perihelion distances were considered by Bailey *et al.* (1992), where it was shown that the sungrazers orbits originally had an inclination of about 90° and moderately small perihelion distance of 0-2 AU. Further, the effect of long-term secular perturbations led to a correlated change of the orbital elements of the comets – reduction of the inclination (or increase of retrograde orbits) and eccentricity increase, and, consequently, to reduction of the perihelion distance at a constant semimajor axis. This effect is known as the Kozai mechanism (Kozai, 1962).

The base of Halley cometary orbits (IAA RAS, <http://iaaras.ru/dept/lbss/halley/>) as published on 2013-03-13, updated with MPEC electronic circulars

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Table 1. Mean or osculating orbits elements members of Machholz interplanetary complex.

Members of complex	q (AU)	e	P (year)	ω	Ω	i	L_{π}	B_{π}	References
Marsden group	0.048	0.984	5.30-6.10	$24^{\circ}.2$	79°	$26^{\circ}.5$	$100^{\circ}.9$	$10^{\circ}.5$	Knight 2008
Kracht group	0.045	0.984	4.81-5.81	58.8	43.8	13.4	101.9	11.4	Knight 2008
96P/1986 J2	0.12677	0.958012	5.25	14.534	94.501	59.988	101.9	12.6	Marsden & Williams 2008
96P (2017)	0.12395	0.959164	5.29	14.793	94.254	58.136	102.2	12.5	MPC 106348
(196256) 2003 EH1	0.17857	0.618723	5.52	171.361	282.979	70.838	100.1	8.2	MPCORB
C/1490 Y1	0.7376	1	...	129.84	295.89	51.65	79.3	37.0	Marsden & Williams 2008
Daytime Arietids	0.078	0.974	4.36	28.7	79.1	27.7	105.0	12.9	Jenniskens <i>et al.</i> 2016
Southern δ -Aquiriids	0.069	0.975	4.17	152.9	306.6	29.0	102.5	12.8	Jenniskens <i>et al.</i> 2016
Northern δ -Aquiriids	0.090	0.955	2.77	330.7	140.8	22.3	113.4	-10.7	Jenniskens <i>et al.</i> 2016
Quadrantids	0.979	0.657	4.74	171.4	283.3	71.2	100.5	8.1	Jenniskens <i>et al.</i> 2016
Daytime λ -Taurids	0.104	0.9337	1.97	210.8	1.7	23.2	210.42	-11.64	Brown <i>et al.</i> 2008
November ι -Draconids	0.973	0.734	6.89	194.7	254.4	72.9	78.81	-14.04	Jenniskens <i>et al.</i> 2016
December α -Draconids	0.983	0.603	3.90	177.4	254.8	71.8	73.99	2.47	Jenniskens <i>et al.</i> 2016
θ -Carinids	0.966	0.595	3.67	342.2	96	74.5	91.1	-17.13	Pokorný <i>et al.</i> 2017

(<http://www.minorplanetcenter.net/iau/mpec/>) of the Minor Planet Center. The catalog contains the orbital elements of comets with perihelion distances of $q < 0.1$ AU in apparition in 2010 (with minor gaps) and the elements of the orbits of some comets in the apparition in 2011-2013. The catalog and its processing results are presented below; they are given for the ecliptic and equinox J2000.0. The resulting catalog contains the orbital elements of 1983 apparitions of comets with perihelion distances of $q < 0.1$ AU.

2 Orbits elements of Marsden and Kracht group comets

Comets of the Marsden and Kracht groups can be related to each other by common descent (Sekanina & Chodas, 2005; Ohtsuka *et al.*, 2003), so further we will consider them together. These groups have the following features:

- perihelion distance of $6R_S < q < 12R_S$, where $R_S = 0.00465$ AU is the Sun radius (comets of the Meyer group perihelions are in the same interval of peri-

helion distances), which is several times larger than perihelion distances of the Kreutz group ($q < 2R_S$);

- similarity of the orbital elements within the group (Figures 1 and 2);
- the number of known members is much smaller than the Kreutz group (in our catalog there are $N = 34$ apparitions of the Marsden comets, and $N = 44$ of the Kracht comets);
- they often pass perihelion in pairs or clusters, which indicates that they have undergone recent fragmentation.

Figure 1 indicates dependences $\Omega - \omega$, $i - \omega$, $L_{\pi} - \omega$, $B_{\pi} - \omega$ for the Marsden group and Figure 2 indicates similar dependences for the Kracht group. The orbits elements of these comets vary within quite wide limits, which may indicate the fast dynamic evolution of the groups.

Proximity of longitude L_{π} and latitude B_{π} of perihelion *i.e.* the apsidal lines proximity states the common origin of the comet groups under consideration. For the Marsden and Kracht comet groups perihelion longitude L_{π} remains constant for different perihelion argument ω and perihelion latitude increases proportionately with ω . Dependence $B_{\pi} - \omega$ can be approximated by a linear function $B_{\pi} = a \cdot \omega + b$, where the ratios are the following for the

Figure 1. Orbits elements of Marsden group.

Figure 2. Orbits elements of Kracht group.

Marsden group: $a = 0.32 \pm 0.02$, $b = 2^\circ.64 \pm 0^\circ.62$, determination coefficient is $R^2 = 0.83$; for the Kracht group: $a = 0.15 \pm 0.03$, $b = 3^\circ.04 \pm 1^\circ.70$, $R^2 = 0.48$.

Comets with similar orbits were discovered within the Marsden and Kracht comet groups, which helped to identify them as different apparitions of the same comet. Table 2 and Table 3 present orbit elements of such comets. The last column in Table 2 and Table 3 present the sources where the data concerning comets identity and their orbital elements (mainly electronic circulars of the Minor Planet Center) were taken and non-gravitational parameters value from these sources, if known (in 10^{-8} AU/day²). The average value of the orbital period according to the Table 2 and Table 3 are $\bar{P} = 5.5$ years for the Marsden group and $\bar{P} = 5.3$ years for the Kracht group.

3 Orbital evolution of Marsden and Kracht group comets

According to the research by Sekanina & Chodas (2005) objects of the Machholz interplanetary complex had common ancestors, which were the fragments of the first generation of the progenitor comet. The fragments had a similar orbital evolution, but it takes them different time to reach the same state. Let us further consider possible options of orbital evolution of fragments of the first generation of the progenitor comet of the complex. Orbital evolution scenarios of these fragments depend essentially on the progenitor comet's orbit and the time of its destruction. The comet fragmentation can be of tidal or non-tidal na-

Table 2. The Marsden group comets, observed in several apparitions.

Comet	T_0	q (AU)	e	P (year)	ω (deg)	Ω (deg)	i (deg)	Osclation epoch	References and nongravitational parameters
C/2002 R1	2002 Sept. 2.53937	0.0483786	0.9842184	5.37	33.66510	69.91968	22.53272	2002 Sept. 3.0	MPEC 2008-B61
C/2008 A3	2008 Jan. 15.74887	0.0486856	0.9841271	5.37	33.91712	69.69445	22.39288	2008 Jan. 15.0	
P/1999 J6	1999 May 11.58181	0.0492535	0.9841653	5.49	21.90952	81.73717	26.66811	1999 May 22.0	MPEC 2010-J28
P/2004 V9	2004 Nov. 8.55843	0.0491728	0.9841398	5.46	22.01100	81.61896	26.61524	1999 May 22.0	$A_1 = +0.31$
P/2010 H3	2010 Apr. 19.89211	0.0475735	0.9846159	5.44	24.86064	78.34830	23.87902	1999 May 22.0	$A_2 = -0.89$
C/2002 R4	2002 Sept. 3.31301	0.0498480	0.9835970	5.30	22.32491	82.12393	28.74015	2002 Sept. 3.0	MPEC 2008-B49
C/2007 Y4	2007 Dec. 22.15262	0.0501562	0.9835057	5.30	22.46461	82.00956	28.57542	2007 Dec. 6.0	
C/2003 Q1	2003 Aug. 20.87668	0.0470844	0.9845160	5.30	25.59797	78.88665	24.70523	2003 Aug. 29.0	MPEC 2009-F81
C/2008 X6	2008 Dec. 7.58188	0.0458668	0.9848933	5.29	26.06056	78.50295	24.43332	2008 Nov. 30.0	
C/2003 Q6	2003 Aug. 26.48038	0.0469972	0.9845937	5.33	24.29133	78.95099	24.72208	2003 Aug. 29.0	MPEC 2009-F81
C/2008 Y11	2008 Dec. 22.26415	0.0455279	0.9850471	5.31	24.82137	78.50628	24.39686	2009 Jan. 9.0	
C/1999 U2	1999 Oct. 25.22593	0.0490396	0.9852970	6.09	21.80837	82.04805	27.10761	1999 Oct. 29.0	MPEC 2005-Y27
C/2005 W5	2005 Nov. 29.91210	0.0493181	0.9852269	6.10	21.96168	81.84466	26.91558	2005 Dec. 16.0	
C/2000 C4	2000 Feb. 5.16819	0.0477861	0.9851534	5.77	23.00778	80.69749	25.03921	2000 Jan. 17.0	MPEC 2005-W07
C/2005 W1	2005 Nov. 17.27636	0.0481354	0.9850600	5.78	23.18018	80.48244	24.85297	2005 Nov. 6.0	

Table 3. The Kracht group comets, observed in several apparitions.

Comet	T_0	q (AU)	e	P (year)	ω (deg)	Ω (deg)	i (deg)	Osclation epoch	References and nongravitational parameters
C/1996 X3	1996 Dec. 6.12338	0.0490795	0.9847883	5.80	51.39986	50.72645	13.61683	1996 Dec. 23.0	MPEC 2009-J14
C/2002 S7	2002 Sept. 21.06697	0.0482438	0.9850282	5.78	51.58326	50.56599	13.58602	2002 Sept. 3.0	$A_1 = 0.0000$
C/2008 N4	2008 July 4.38322	0.0481635	0.9850514	5.78	52.38575	49.82469	13.46737	2008 June 23.0	$A_2 = +0.0027$
P/2000 O3	2000 July 30.94952	0.0540632	0.9822358	5.31	48.95380	53.55488	14.73060	2000 Aug. 4.0	MPEC 2011-F14
P/2005 W4	2005 Nov. 23.49789	0.0546022	0.9820752	5.32	49.37076	53.10781	14.63204	2005 Nov. 6.0	$A_1 = +0.00$
P/2011 E1	2011 Mar. 9.83663	0.0533979	0.9824613	5.31	57.25585	44.78691	13.10849	2011 Mar. 20.0	$A_2 = 0.0076$
322P/1999 R1	1999 Sept. 5.51913	0.0563788	0.9776453	4.01	43.34320	5.38591	13.67849	1999 Sept. 19.0	MPEC 2007-S16
322P/2003 R5	2003 Sept. 8.81649	0.0568899	0.9774588	4.01	43.62425	5.09358	13.60425	2003 Aug. 29.0	
322P/2007 R5	2007 Sept. 11.31967	0.0537196	0.9786494	3.99	48.56551	0.04886	12.64000	2007 Sept. 17.0	www.aerith.net/comet/catalog/
322P/2011 R4	2011 Sept. 7.12120	0.0531692	0.9788550	3.99	48.70248	359.88377	12.66358	2011 Aug. 27.0	0322P/2011.html
C/2002 Q8	2002 Aug. 25.92003	0.0491639	0.9842545	5.52	50.31482	52.29189	13.39727	2002 Sept. 3.0	MPEC 2008-F32
C/2008 E4	2008 Mar. 3.01620	0.0494407	0.9841727	5.52	50.78177	51.86699	13.31853	2008 Feb. 24.0	
C/1996 E5	1996 Dec. 6.32757	0.0490155	0.9847988	5.79	50.97045	51.10871	13.66055	1996 Dec. 23.0	MPEC 2009-T27
C/2002 S5	2002 Sept. 19.31631	0.0481806	0.9850383	5.78	51.14815	50.95408	13.63032	2002 Sept. 3.0	
C/2002 S4	2002 Sept. 18.22443	0.0482623	0.9853318	5.97	51.48190	50.85505	13.66478	2002 Sept. 3.0	MPEC 2008-S67
C/2008 R7	2008 Sept. 6.59759	0.0479575	0.9854173	5.96	52.60267	49.80391	13.50307	2008 Sept. 11.0	
C/2002 S11	2002 Sept. 30.33199	0.0480460	0.9846440	5.53	51.04955	50.97938	13.63079	2002 Oct. 13.0	MPEC 2008-L29
C/2008 G6	2008 Apr. 13.47301	0.0481773	0.9846072	5.54	51.60594	50.47041	13.54265	2008 Apr. 4.0	

ture. In the first case, it could occur only near the orbit perihelion, in the second case – at any heliocentric distance. The convergence with the planets (primarily Jupiter), non-gravitational effects, relative speed of the fragments while separating influenced the speed of orbital evolution.

Integrator RADAU (Everhart, 1974) of the fifteenth order was used to simulate movements of fragments of the comet. Perturbations of all large planets were taken into account. The input specifications of the model in addition to the orbital elements of the comet are the speed of separation V_{sep} and values of non-gravitational parameters A_1, A_2, A_3 . Radial a_1 , transversal a_2 and normal a_3 components of non-gravitational acceleration

$$a_i = A_i g(r), \quad i = 1, 2, 3.$$

The influence of non-gravitational effects was based on the Marsden model (Marsden *et al.*, 1973). The empirically established formula (Marsden *et al.*, 1973) for the stream of sublimating substances from the surface of the comet depending on the heliocentric distance

$$\begin{aligned} Z(r) &= Z_0 g(r), \\ g(r) &= \alpha \left(\frac{r}{r_0} \right)^{-m} \left[1 + \left(\frac{r}{r_0} \right)^n \right]^{-k}, \end{aligned} \quad (1)$$

where r_0 is the heliocentric distance at which the ratio of the solar energy expended for sublimation of ice to the re-emitted surface of the cometary nucleus is 0.023, α is the normalization coefficient corresponding $g(1) = 1$, Z_0 being the number of molecules sublimating per second from the surface unit at the heliocentric distance of 1 AU. For water ice $r_0 = 2.808$ a.e., $m = 2.15$, $n = 5.093$, $k = 4.6142$, $\alpha = 0.111262$ (Marsden *et al.*, 1973). Formula (1) assumes an isothermal model of water ice sublimation, according to which the temperature on the comet surface is the same everywhere and depends only on the heliocentric distance.

Table 4. Orbital elements of comet 96P/Machholz 1 and 196256 at 7415 BCE (J2000.0) by Babadzhanov *et al.* (2017).

Object	e	q (AU)	i	ω	Ω
96P/Machholz	0.795	0.622	65°.82	13°.28	98°.56
196256	0.798	0.615	65.03	15.55	97.78
mean	0.7965	0.6185	65.425	14.415	98.17

Table 4 contains data from the study of Babadzhanov *et al.* (2017) elements of orbits of objects 96P and 2003 EH1 in 7415 BCE, *i.e.* at the most probable, in their opinion, moment of disintegration of the parent comet. As the

elements of the orbits of the parent comet, the average values (the last line of Table 4) of the orbital elements 96P and 2003 EH1 were taken. It is assumed that the fragmentation of the parent comet occurred in perihelion, the maximum fragmentation rate is $V_{sep} = 5$ m/s (Kalinicheva, 2017). The catalog of elements of cometary orbits (Marsden & Williams, 2008) contains the following data on the significance of non-gravitational acceleration parameters for comet 96P: in the appearances of 1986, 1991 in 1996: $A_1 = 0.01 \cdot 10^{-8}$ AU/day², $A_2 = -0.0002 \cdot 10^{-8}$ AU/day². The known non-gravitational parameters for the Marsden and Kracht groups comets are shown in Table 2 and Table 3. While modeling the fragments motion the following non-gravitational parameters were adopted: non-gravitational parameters are normally distributed with mean values $A_1 = A_2 = A_3 = 0$, average squared displacement $\sigma(A_1) = \sigma(A_2) = 0.1 \cdot 10^{-8}$ AU/day², $\sigma(A_3) = 0.001 \cdot 10^{-8}$ AU/day². The evolution of the orbits of a hundred resulting model fragments was investigated in the interval of 9425 years, integration of the equations of motion ceased if the heliocentric distance of the fragment was no more than 0.0046 AU.

The angular elements of the orbits of model fragments for 2009 are shown in Figure 3. For comparison, Figure 3 shows the real elements of objects' orbits from Table 3. The

Figure 3. Angle elements of the orbits: black circles are model fragments for 2009; red crosshairs are fragments whose heliocentric distances were less than 0.0046 AU until 2009 (in this case, the angular elements of the orbits are given at the time corresponding to the heliocentric distance of $r = 0.0046$ AU); blue squares are objects of the Machholz interplanetary complex (Table 3).

Figure 4. Evolution of elements of orbits of model fragments with initial parameters: $q = 0.125$ AU, $e = 0.958$, $i = 60^\circ.0$, $\omega = 14^\circ.5$, $\Omega = 94^\circ.5$, $V_{sep\ max} = 3$ m/s, $\bar{A}_1 = \bar{A}_2 = \bar{A}_3 = 0$, $\sigma(A_1) = \sigma(A_2) = \sigma(A_3) = 0.1 \cdot 10^{-8}$ AU/day².

orbit of comet C/1490 Y1 can hardly be explained within the framework of the proposed model. This may be due to the fact that comet C/1490 Y1 has no common ancestors with the rest of the objects from Table 3, or the orbit of this comet is determined with a large error. The orbit of the Daytime λ -Taurids meteor shower is also not described by the proposed model. The states, characteristic of all other objects of the comet of the Machholz complex (Table 1) were achievable under the conditions of the presented model.

Part of the model fragments to the end of the integration interval were lost as a result of approaching the Sun by a distance less than its radius (the crosses in Figure 4). These fragments at the time when their heliocentric distance became $r \leq 0.0046$ AU had a perihelion argument of $170^\circ < \omega < 10^\circ$ and a predominantly small inclination of orbits $i < 30^\circ$. In the indicated interval of the peri-

lion argument ω and the inclination i , only the Northern δ -Aquiriids shower is currently known.

If dwarf comets of the Kreutz group, because of the extremely small perihelion distance in their orbit, live no more than one revolution (Kalinicheva, 2017), then the lifetime of the comets of the Marsden and Kracht groups can be much larger than one revolution. Nevertheless, the lifetime of the comets of these groups is extremely limited due to close and frequent passage near the Sun. Consequently, the comets of the Marsden and Kracht groups are the second or subsequent generations of the comet-progenitor. Suppose that the formation of comets of the Marsden and Kracht groups occurred as a result of the subsequent fragmentation of the comet nucleus, which had elements of orbits close to the elements of the 96P orbit: $q = 0.125$ AU, $e = 0.958$, $i = 60^\circ.0$, $\omega = 14^\circ.5$, $\Omega = 94^\circ.5$. Suppose that the fragmentation was of a tidal nature and occurred at perihelion.

Figure 4 shows changes in the orbital elements (inclination i , perihelion distance q and longitude of the ascending node Ω) of fifty model fragments in the interval of 600 years after fragmentation. From Figure 4b we see that the fragments reach a minimum inclination i in 10° - 15° approximately in 380-450 years after the beginning of integration. Simultaneously with the decrease in the inclination i , a decrease in the perihelion distance q is also observed to about 0.03-0.04 AU, as well as a decrease in the longitude of the ascending node Ω . Perihelion distance $q = 0.04$ AU is achieved in 250-350 years after the start of integration.

According to Figure 4 state, characteristic for the orbits of the Marsden group of comets, is reached in 250-300 years after the beginning of integration, for the orbits of the comets of the Kracht group – in 350-450 years, for the objects of the meteor shower Southern δ -Aquiriids – in 450-500 years. Thus, the direction of the orbital evolution of the comets of the Marsden and Kracht groups is the following: the comet-progenitor, then comet 96P, then comets of the Marsden group, then comets of the Kracht group. Objects that are in the later stages of orbital evolution have consistently passed states characterized by elements of the orbits of those representatives of the complex that are located to the left of this list. However, this does not mean that all objects in the complex will consistently pass all the listed states, since complete disintegration of the object may occur earlier.

4 Conclusion

The comets of the Marsden and Kracht groups were formed as a result of several processes of fragmentation of the progenitor comet. In addition to these, other objects were formed in these processes: comet 96P/Machholz, asteroid 196256 (2003 EH1), several meteor showers. The model, involving the appearance of fragments of the first generation about 9500 years ago, makes it possible to obtain states characteristic of the currently observed objects of the Machholz complex. In addition, this model allows to identify objects that can also be representatives of this complex.

The comets of the Marsden and Kracht groups are not fragments of the first generation; they formed as a result of subsequent fragmentation processes. As a result of frequent and close passage near the Sun, the lifetime of these comets is extremely limited. If the orbit of the predecessor of the Marsden and Kracht groups was close to the orbit of comet 96P, then the formation of these groups took place ~300-400 years ago.

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