Contrib. Astron. Obs. Skalnaté Pleso **33**, 5 – 20, (2003)

Observed sizes of cometary nuclei

A summary

L. Neslušan

Astronomical Institute of the Slovak Academy of Sciences
059 60 Tatranská Lomnica, The Slovak Republic

Received: October 18, 2002

Abstract. The nuclear effective radii of both short-period (practically identical to the Jupiter-family) and long-period comets, as have been determined by many independent authors using several methods, are summarized. Despite the observational selection effects, it is possible to conclude that the observed nuclei of long-period (LP) comets are generally larger than their short-period (SP) counterparts. The average radius of SP-comet (LP-comet) nucleus is 2.3 km (8.9 km). The corresponding average mass of the nucleus is $2 \times 10^{14}.\rho/\rho_5$ kg ($1 \times 10^{16}.\rho/\rho_5$ kg), where ρ is the mean density of cometary nucleus and $\rho_5 = 500$ kg m^{-3}. Because of the determination uncertainty, the average radius can be a value from interval ranging from 2.1 to 2.7 km (from 7.4 to 9.2 km). The median radius of SP comets is less than about 2 km, whilst that of LP comets is larger than about 4 km. The slope index of cumulative distribution of the observed radii is rather uncertain due to very low-numerous samples of data available. It is probably a value ranging from 2.67 to 3.05 for SP comets and from 1.59 to 2.21 for LP comets.

Key words: comets – cometary nuclei

1. Introduction

Comets are the most populated minor bodies of the Solar System. Their distant cloud consists of 10^{12} to 10^{13} individual cometary nuclei (e.g. Wiegert and Tremaine, 1999). According to the generally accepted scenario of comet origin, the current population represents only a fragment of the original population once created in the proto-planetary disc. No more than a few per cent of cometesimals were finally placed into the distant reservoir during their early dynamical evolution (Safronov, 1972; Fernández, 1985). Moreover, external perturbers of a distant comet cloud have depleted it during existence of the Solar System. The original population was by a factor of 2 to 5 higher that the present population (Weissman, 1990). All this means that the proto-planetary disc once contained 10^{14} to 10^{15} cometary nuclei. If we assumed an older estimate of the typical mass of a cometary nucleus being 3.8×10^{13} kg (Weissman, 1990), then the original total mass of these bodies would have exceeded the total mass of planets in the disc.

Such a high total mass appeared as a problem in the classical scenario of comet origin and, thus, Stern and Weissman (2001) attempted to reduce the typical mass of a cometary nucleus and, consequently, the total mass. In their theoretical study they, however, proposed only a qualitative reduction of the typical mass, which is still needed to be confirmed by determinations of this quantity for real cometary nuclei. Anyway, a new estimate of the typical size of these nuclei, from which their typical mass can be derived, is important for a refinement of the theory of planet and comet common origin.

In the past two decades, a quite large set of sizes of cometary nuclei has been determined by several methods. In the present paper, we summarize the cometary-nucleus-size determinations and give new estimates of the typical size, from which the typical mass can be derived. The size is characterized by the equivalent (effective) radius, i.e. such a radius of sphere, in which the bulk volume is equal to the proper volume of a given cometary nucleus of an irregular shape. Possible uncertainties of the size determinations are appreciated, too. Based on the collected data, we also attempt to construct a cumulative distribution of the effective radii of cometary nuclei and to determine the slope index of the distribution.

2. Methods of size determinations

When a cometary nucleus approaches the Sun, gas and dust are released from its surface layer creating a huge cometary atmosphere, a coma. This atmosphere obscures the proper nucleus at the heliocentric distances where the comet is usually observed. Due to this phenomenon, the determination of the size of a bare cometary nucleus is very difficult. Several methods have been developed. First three methods were suggested by Konopleva and Shul'man (1972). These are based on three models of a cometary nucleus described by Shul'man (1972). The sizes of cometary nuclei summarized in Tables 1 and 2 were mostly determined by newer methods. They are labelled with a two-character abbreviation as described below.

The most obvious and oldest method of the determination of the size of a cometary nucleus is simply to observe a bare nucleus at large heliocentric distances (LD), where it is not obscurred by any coma. Unfortunately, the bare nucleus is relatively small and dark, therefore its brightness is extremly low at the large distances and big telescopes have to be used.

Within the method, several specific techniques can be distinguished. A minimum nuclear radius can be determined from an estimate of the size of active areas on the nucleus surface. In this way, Sanzovo et al. (2001) used the observed visual magnitudes (VM), which were converted into water release rates. These rates were then used to derive the nuclear surface areas and, subsequently, a corresponding nuclear (minimum) radius as well as gas mass loss. Instead of visual magnitudes, the active surface areas can also be derived from narrowband (NB) photometry observations (e.g. Schleicher and Osip, 2000) as well as broadband (BB) CCD imaging (Boehnhardt et al., 1999). The observations of comets at large heliocentric distances have recently started to be performed by the Hubble Space Telescope (HT).

Several authors have worked out indirect methods of size determination, when a comet is in the zone of visibility, deeply embedded in its coma. An effective nuclear radius can be calculated by using the standard thermal model (TM) for slow rotators (e.g. Fernández et al., 2000). Another indirect method is a modelling of the remnant dust (RD) tail by means of the inverse dust tail model (Fulle et al., 1998). Churyumov et al. (1999) analyzed the equation of energy balance (EB) to obtain a sublimation rate for water (for comet C/1995 O1). This rate enables to estimate the size of active surface areas and derive a minimum radius of the comet. Utilizing the ISOCAM images, Jorda et al. (2000) derived the size and geometric albedo by combining thermal fluxes (TF) with visible fluxes, whereby the signal from the nucleus was measured by fitting the data with a model including the contribution from both the coma and the nucleus.

An estimate of the size of a cometary nucleus can be done on the basis of infrared (IR) observations, either by studying thermal emission from dust grains in a cometary coma (Sarmecanic et al., 1997) or from a photometric resolution of the nucleus in the thermal infrared (Lisse et al., 1999).

Except for the observations of a bare cometary nucleus at large heliocentric distances, this nucleus appears to be observable, relatively close to the Earth, at radio wavelengths. Several authors have thus derived the size of cometary nucleus from radio observations (RA).

A specific method of the cometary-nucleus-size determination was suggested and applied by Sekanina (1997b): from a detection, by the Hubble Space Telescope, of a satellite orbiting (SO) the nucleus.

Finally, we mention the most precise and reliable way of the determination of the nucleus size: from observations performed in situ with the help of cameras aboard cosmic spacecrafts (SC). So far, the nuclei of only two comets, 1P/Halley and 19P/Borelly, have been observed this way. This technique will, however, certainly happen a main source of our knowledge of cometary nuclei in the future.

3. Observed nuclear radii

The nuclear radii of short-period (SP, hereinafter) comets, as found by individual authors, are listed in Table 1. It turns out that all these comets belong to the subgroup of the Jupiter-family comets. We found only a single radius of a comet, which belongs to the Halley-type comets (1P/Halley itself). Thus, SP comets can practically be identified up to the Jupiter-family comets in the following. To be concise, we do not repeat the values collected by Tancredi et al. (2000) from various sources, unless the given value is included for purpose of its comparison with the corresponding value(s) found by other author(s). (65 of 105 values are skipped.) The method of determination of Tancredi et al.'s values is denoted as AM, since they typically converted the collected nuclear absolute magnitudes of comets, determined in many ways, into the corresponding radii.

The nuclear radii of long-period (LP, hereinafter) comets are listed in Table 2. To keep the table concise, we again do not repeat 11 values from the study by Svoreň (1987) and 5 values from the research by Meech and Hainaut (1997). All the skipped values of both SP and LP comets can easily be found in the tables published in refereed papers. And these are, of course, considered in all calculations and dependence constructions presented.

In both the tables, the radius of a given comet is, sometimes, determined by two or more independent methods, which, however, often give different results. To respect the uncertainty of the radius determination, we calculate the minimum, medium, and maximum average radii of both SP and LP comets. Thus, the values listed in Tables 1 and 2 are supplied into 6 specific files. The first (fourth) file contains the minimum values, the second (fifth) file contains the medium values, and the third (sixth) file contains the maximum values of the determined radii of all SP (LP) comets. The totals of 108 (20), 112 (19), and 115 (21) values of the radii of SP (LP) comets are considered, respectively.

The medium average radius of a given comet is calculated as the average value of all published values. If there is only known a lower (upper) estimate of the radius of a comet, then it figures only in the file containing the minimum (maximum) values. Having the above mentioned six files, the minimum, medium, and maximum average radii are calculated averaging all values in the first (fourth), second (fifth), and third (sixth) files, respectively, for the SP (LP) comets. The average radii as well as corresponding masses of cometary nuclei, assuming their mean density to be equal to 500 $\mathrm{kg\,m^{-3}}$, are given in Table 3.

4. Fitting the size distribution

The calculation of a simple average size of a cometary nucleus does not provide such subtle information on the cometary population as a determination of the distribution of cometary sizes (radii). So, we construct the cumulative distribution of observed cometary radii and fit a theoretical power law to this distribution. In terms of mathematics, the number of nuclei $N(R)$ with radii ranging from R to infinity can be given by

$$N(R) = B.R^{-s}, \tag{1}$$

where B is a constant of proportionality and s is a slope index.

From a statistical point of view, the samples of known radii of cometary nuclei available are unfortunately quite poor. Due to this fact, we obtain different results when the given range of observed values is divided into a different

Table 1. The nuclear radii of short-period comets. The methods of determination are described in Sect. 2 (one in the beginning of Sect. 3).

comet	method	radius [km]	reference
1P	SC	4.58 (dimens.: $16 \times 8 \times 6$)	Möhlmann et al., 1986
	SC	5.65 (dimens.: $16 \times 10 \times 9$)	Wilhelm et al., 1986
2P	LD	2.9	Svoreň, 1987
	TM	2.4±0.3	Fernández et al., 2000
	AM	1.3	Tancredi et al., 2000
	VM	> 0.5	Sanzovo et al., 2001
4P	LD	4.4	Svoreň, 1987
	HT	1.77	Lamy et al., 2000
	AM	2.2	Tancredi et al., 2000
6P	AM	1.5	Tancredi et al., 2000
	LD	≤ 2.1	Lowry and Fitzsimmons, 2001
	VM	> 0.8	Sanzovo et al., 2001
7P	AM	1.5	Tancredi et al., 2000
	LD	2.6±0.1	Lowry and Fitzsimmons, 2001
9P	AM	2.3	Tancredi et al., 2000
	HT	3.1	Lamy et al., 2001a
	LD	2.4±0.1	Lowry and Fitzsimmons, 2001
10P	LD	2.3	Svoreň, 1987
	HT	4.60	Lamy et al., 2000
	AM	2.9	Tancredi et al., 2000
16P	LD	1.8	Svoreň, 1987
	AM	1.7	Tancredi et al., 2000
17P	HT	1.71	Lamy et al., 2000
	AM	2.0	Tancredi et al., 2000
19P	SC	length = 8	Soderblom et al., 2002
	AM	3.0	Tancredi et al., 2000
22P	HT	1.65−1.92	Lamy et al., 1996
	AM	1.8	Tancredi et al., 2000
	LD	1.8±0.1	Lowry and Fitzsimmons, 2001
	TM	1.67±0.18	Lamy et al., 2002
26P	BB	1.5	Boehnhardt et al., 1999
	AM	1.3	Tancredi et al., 2000
29P	HT	≈ 19.5	Feldman et al., 1996
	AM	13.2	Tancredi et al., 2000
31P	LD	4.3	Svoreň, 1987
	AM	3.2	Tancredi et al., 2000
32P	LD	6.3	Svoreň, 1987
	AM	2.5	Tancredi et al., 2000
36P	LD	4.8	Svoreň, 1987
	AM	2.3	Tancredi et al., 2000
37P	HT	0.81	Lamy et al., 2000
	LD	1.0	Licandro et al., 2000
	(AM	1.0	Tancredi et al., 2000)

39P	LD	3.5	Svoreň, 1987
	AM	9.1	Tancredi et al., 2000
44P	HT	1.63	Lamy et al., 2000
	AM	1.5	Tancredi et al., 2000
	LD	≤ 1.4	Lowry and Fitzsimmons, 2001
45P	HT	0.35	Lamy et al., 1996
	AM	0.5	Tancredi et al., 2000
46P	AM	0.7	Tancredi et al., 2000
	LD	0.555 ± 0.040	Boehnhardt et al., 2002
47P	LD	4.4	Svoreň, 1987
	AM	2.9	Tancredi et al., 2000
48P	AM	2.2	Tancredi et al., 2000
	LD	≤ 3.5	Lowry and Fitzsimmons, 2001
49P	AM	3.2	Tancredi et al., 2000
	LD	4.4 ± 0.1	Lowry and Fitzsimmons, 2001
50P	HT	0.95	Lamy et al., 2000
	AM	3.0	Tancredi et al., 2000
51P	AM	1.4	Tancredi et al., 2000
	LD	≤ 1.9	Lowry and Fitzsimmons, 2001
53P	LD	7.2	Svoreň, 1987
	AM	3.8	Tancredi et al., 2000
54P	LD	≤ 2.1	Lowry and Fitzsimmons, 2001
56P	LD	3.0	Svoreň, 1987
	AM	1.5	Tancredi et al., 2000
57P	AM	1.6	Tancredi et al., 2000
	LD	≤ 1.1	Lowry and Fitzsimmons, 2001
59P	LD	4.9	Svoreň, 1987
	HT	0.79	Lamy et al., 2000
63P	HT	1.46	Lamy et al., 2000
	LD	≤ 0.6	Lowry and Fitzsimmons, 2001
65P	LD	6.3	Svoreň, 1987
	LD	11.0	Licandro et al., 2000
	AM	4.8	Tancredi et al., 2000
	LD	≤ 8.8	Lowry and Fitzsimmons, 2001
71P	HT	0.68	Lamy et al., 2000
	AM	1.3	Tancredi et al., 2000
	LD	≤ 0.9	Lowry and Fitzsimmons, 2001
73P	BB	< 1.1	Boehnhardt et al., 1999
	AM	1.0	Tancredi et al., 2000
	LD	≤ 0.9	Lowry and Fitzsimmons, 2001
	VM	> 0.6	Sanzovo et al., 2001
74P	AM	6.0	Tancredi et al., 2000
	LD	≤ 12.7	Lowry and Fitzsimmons, 2001

79P	LD	≤ 1.5	Lowry and Fitzsimmons, 2001
81P	LD	2.87	Meech and Newburn, 1998
	AM	2.2	Tancredi et al., 2000
	VM	> 1.5	Sanzovo et al., 2001
84P	HT	0.90	Lamy et al., 2000
	AM	1.4	Tancredi et al., 2000
86P	AM	0.9	Tancredi et al., 2000
	LD	≤ 0.9	Lowry and Fitzsimmons, 2001
87P	AM	1.3	Tancredi et al., 2000
	LD	≤ 0.6	Lowry and Fitzsimmons, 2001
100P	AM	1.3	Tancredi et al., 2000
	LD	≤ 1.2	Lowry and Fitzsimmons, 2001
103P	TF	0.56	Jorda et al., 2000
	AM	3.8	Tancredi et al., 2000
	LD	≤ 5.9	Lowry and Fitzsimmons, 2001
106P	HT	0.94	Lamy et al., 2000
112P	HT	0.90	Lamy et al., 2000
	AM	0.7	Tancredi et al., 2000
114P	HT	0.78	Lamy et al., 2000
128P	AM	2.0	Tancredi et al., 2000
	LD	≤ 4.0	Lowry and Fitzsimmons, 2001
139P	LD	≤ 4.6	Lowry and Fitzsimmons, 2001
147P	HT	0.13	Lamy et al., 2001b
D/1960 S1	LD	14.8	Svoreň, 1987
the largest fragments of Shoemaker-Levy 9	HS	≈ 2	Sekanina, 1995
17 JF comets	LD	0.6−12.7 (mean ≈ 3)	Meech et al., 2000

number of equidistant intervals (bars in a corresponding bargraph). Under these circumstances, there is a task not only to fit a theoretical curve to the observed behaviour, but, at the same time, to construct the most appropriate distribution from the values available.

It is expected that the radii are distributed by a power law. The method of least squares is chosen to fit the power law to the observed dependence. To find out an optimally constructed distribution, we construct a set of distributions dividing the observed range of values into 3 to N equidistant intervals, where N is the number of values in a given sample. At the fitting the power-law curve to each division, we calculate the corresponding mean residual (sum of the least squares divided by the number of added terms), S_{res}. We regard as optimal the

Table 2. The nuclear radii of long-period comets. The methods of determination are described in Sect. 2.

C/1984 V1	VM	> 1.4	Sanzovo et al., 2001
C/1996 Q1	RD	< 0.35	Fulle et al., 1998
C/1995 O1	HT	35.5 ± 2	Sekanina, 1997a
	SO	≈ 35	Sekanina, 1997b
	HT	$13.5-21$	Weaver et al., 1997
	EB	$\approx 33; > 14.6$	Churyumov et al., 1999
	TF	56	Jorda et al., 2000
a satellite of			
C/1995 O1	SO	≈ 15	Sekanina, 1997b
C/1996 B2	IR	2.1 ± 0.4	Sarmecanic et al., 1997
	IR	2.4 ± 0.5	Lisse et al., 1999
	RA	2.7	Lisse et al., 1999
	NB	> 0.75	Schleicher and Osip, 2000
C/1999 S4			
before breakup	LD	> 0.44	Farnham et al., 2001
	RA	0.45	Altenhoff et al., 2002
C/2001 A2(B)	RA	< 3	Nolan et al., 2001

division with the minimum mean residual of an appropriate fit.

Not only a cumulative distribution, but the differential distribution (the number of radii in the interval from $R - \Delta R/2$ to $R + \Delta R/2$ versus R) has a power-law behaviour as well. We know that the power-law function has a monotonous, decreasing behaviour. In the differential distribution, one can, however, observe a steep increase of behaviour from the minimum abscissa value to a certain critical value (see an example in Fig. 2). Only for abscissa values higher than the critical value the behaviour is power-law like. A similar effect was detected in the differential mass distribution of meteors of most numerous meteor showers, Perseids and Geminids, in the photographic IAU MDC database (Slavkovský, 2002). The anomalous increase is caused by observational selection effects. The smallest observable comets (or meteors) are actually observed in a far less rate than larger bodies, therefore they are obviously underestimated in the data. It is then reasonable to skip the biased part of the data, within the increasing interval, before making the fitting procedure. We empirically found that the critical value, where the increase ends, does not significantly depend on the way of construction of an observed distribution (on what number of intervals is the entire range of values divided). An approximate critical value can be discernible from the plots. For the six used files (see Sect. 3), the appropriate critical values, $R_{crit.}$, are given in Table 3.

In Table 3, there are also given the optimal numbers of total range division, n, and the appropriate fits, i.e. constants of proportionality B and slope indices s, for the minimum, medium, and maximum estimates of radii of both SP and

Table 3. The observed radii of comets. In the first, second, and third datum column, there are given the listed quantities for minimum-, medium-, and maximum-value determinations of the radii, respectively. $R_{med.}$ – the median nuclear radius, $< R >$ – – the average nuclear radius, $< M >$ – the average mass corresponding to radius $< R >$, when the mean density of the nucleus equal to 500 kg m^{-3} is assumed, $R_{crit.}$ – the critical radius of nucleus, up to which the observational selection effects significantly bias the data (see Sect. 4), n – the number of division of the entire range of observed radii into the equidistant intervals in the construction of their cumulative distribution, B – the constant of proportionality in the fitting of a theoretical power law into the observed cumulative distribution, s – the slope index of the fitted curve, $S_{res.}$ – the mean residual at the fitting.

	short-period comets		
	minimum	medium	maximum
$R_{med.}$ [km]	1.6	1.8	1.9
$< R >$ [km]	2.1	2.3	2.7
$< M >$ [kg]	2×10^{14}	2×10^{14}	3×10^{14}
$R_{crit.}$ [km]	0.7	0.8	0.75
n	4	3	3
B	1104.	4300.	5278.
s	2.668 ± 0.011	3.042 ± 0.004	2.853 ± 0.002
$S_{res.}$	0.220	0.109	0.017

	long-period comets		
	minimum	medium	maximum
$R_{med.}$ [km]	4.3	4.5	4.0
$< R >$ [km]	7.4	8.9	9.2
$< M >$ [kg]	7×10^{15}	1×10^{16}	2×10^{16}
$R_{crit.}$ [km]	2	1.5	3
n	3	3	3
B	995.9	482.1	3714.
s	1.943 ± 0.005	1.593 ± 0.003	2.206 ± 0.007
$S_{res.}$	0.013	0.004	0.026

LP comets. The constructed cumulative distributions for the medium radii of the SP and LP comets are displayed, together with the appropriate fitted curves, in Fig. 1 (a) and (b), respectively.

5. Discussion

Looking at Table 3, which gives a summary of the collected determinations of cometary radii in Tables 1 and 2, we can state the following facts.

The radii of observed SP-comet bare nuclei span from 130 m (147P) to 19.5 km (29P by HT method; see Sect. 2), those of LP-comet bare nuclei span from

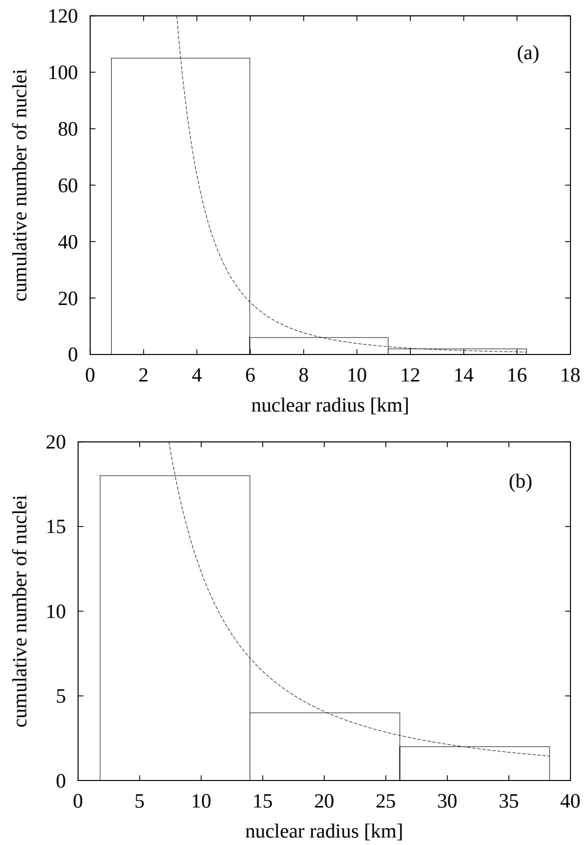

Figure 1. The cumulative distribution of the medium average radii of short-period (a) and long-period (b) comets. The number of divisions of the entire observed range of values is optimalized (see Sect. 4). The solid curve represents the fitted power law.

a value lower than 350 m (C/1996 Q1) to 56 km (C/1995 O1 by TF method). The dispersion of values estimated by independent authors and several different methods is often very large, up to a factor of 6.8 in the case of 103P. Some radii are determined quite well, e.g. four mutually consistent values found for the comet 22P. Using the input data with the minimum, medium, and maximum estimated radii (files described in Sect. 3), the median nuclear radii of observed SP comets are 1.6, 1.8, and 1.9 km, respectively. The median nuclear radii of LP comets are 4.3, 4.5, and 4.0 km, respectively. The median value of the maximum observed radii, 4.0 km, is paradoxically lower than the median values of the minimum and medium observed radii, 4.3 and 4.5 km. This is caused by the presence of several low upper limits of a size in the maximum-radii file. The

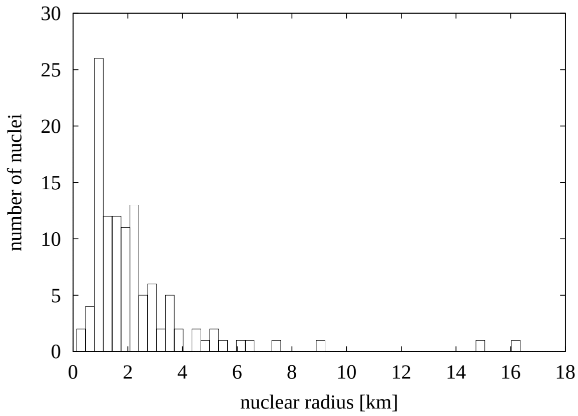

Figure 2. The differential distribution of the medium average radii of short-period comets constructed for the number of division of the entire observed range of values $n = 50$. With respect to the expected power-law distribution (a monotonously decreasing function), we can see a deficit of comets with the radii smaller than about 0.7 km (two leftmost bars) due to observational selection effects.

corresponding minimum and medium values are missing in minimum-radii and medium-radii files (see Sect. 3).

The average nuclear radii of observed SP comets are 2.1, 2.3, and 2.7 km, for minimum, medium, and maximum observed radii, respectively. In the case of LP comets, the average nuclear radii are 7.4, 8.9, and 9.2 km, respectively. For an illustration, the average masses, $< M >$, corresponding to the average radii, $< R >$, if the mean density of a cometary nucleus $\rho_5 = 500$ kg m^{-3}, are 2×10^{14}, 2×10^{14}, and 3×10^{14} kg in the case of SP-comet nuclei, and 7×10^{15}, 1×10^{16}, and 2×10^{16} kg in the case of LP-comet nuclei for the minimum, medium, and maximum estimates of radii, respectively. We do not know well the mean density of a cometary nucleus. An acceptable range of its proper value spans from about 200 to 1000 kg m^{-3}. For a value ρ different from value ρ_5 adopted here, the corresponding mass has to be corrected by a factor of ρ/ρ_5.

Assuming the minimum estimated mean density of a cometary nucleus $\rho = 200$ kg m^{-3} and a number of about 10^{12} cometary nuclei in the comet cloud, the total mass of the entire cometary population at present, derived from the observations of nuclear sizes, is at least 3×10^{27} kg, i.e. ≈ 500 M$_\oplus$ (Earth masses). This does not support the reduction of the total mass due to the collisional evolution (fragmentation) of planetesimals, in the period of their ejection, which was suggested by Stern and Weissman (2001). According to the latter, the original total mass, being by a factor of 2 to 5 larger than the current total mass (Weissman, 1990), did not exceed ≈ 3.5 M$_\oplus$.

As mentioned in Sect. 1, the relatively high total mass of the cometary population represents an energy problem within the classical scenario of comet ejections by the giant planets. This problem appears to be even worse taking into account the fact that the original total mass had to be by a factor of 2 to 5 higher than the current total mass. Because of the energy limitation, only a fragment of all cometary nuclei in the cloud, having the total mass less or comparable to the sum of masses of ejecting planets, could originate in the giant-planet region of the Solar System. A major part of the nuclei had to come into the distant comet cloud from elsewhere.

The uncertainty of the radius determination causes quite large differences in the slope index, s, as obtained using minimum, medium, and maximum determined radii (corresponding input-data files). The dispersion due to this uncertainty is significantly larger than the internal determination error ($1\,\sigma$). Despite this circumstance, we can distinguish between the cumulative distribution of SP-comet nuclei with $2.668 \leq s \leq 3.042$ and LP-comet nuclei with $1.593 \leq s \leq 2.206$.

The slope index s between ≈ 2.7 and ≈ 3.0 for SP comets appears to be in contradiction with $s = 0.88$ found by Fernández et al. (1999) for the Jupiter-family-comet radii representing a major part of all known SP-comet radii. A larger value, $s = 1.40$, was found by Weissman and Lowry (2001) for the cumulative distribution of the radii of the Jupiter-family and Halley-type comets. We suggest that the large differences are caused by considerably different divisions of the entire observed range of radii into the intervals by various authors. For example, if we divide the range of observed medium radii of SP comets into 10 intervals, instead of the optimal $n = 3$ (Table 3), s decreases to 1.83. Dividing the range into 50 intervals, it further decreases to 1.39, and for 100 intervals, we find $s = 1.35$. Here, the mean residual is however much larger, $S_{res.} = 14.8$, than that at the optimal division, where it does not exceed 0.220.

It seems that the radii of LP comets are, in average, larger than those of SP comets. Selection effects can affect, in a different way, the number of the smallest members of both groups. The SP comets repeat their returns to the Sun and, so, to the Earth, therefore the chance of their discovery and nuclear-size determination is significantly higher than that of the LP comets. An imprint of the selection effects is apparent from the fact that there have been determined 5 times more nuclear sizes of SP comets than those of LP comets. Consequently, we can expect a relatively larger number of known small SP comets than their LP counterparts, which can be discovered and measured only during a single perihelion passage. This could explain why the minimum observed radii of SP comets are lower than the minimum observed radii of LP comets.

However, if the maximum radii of SP comets were actually comparable or larger than the maximum radii of LP comets, then we would observe it. No selection effect can favour the discoveries and further observations of the biggest LP comets in comparison with the biggest SP comets. Therefore, the observed prevalence of the biggest nuclei of LP comets can be regarded as a real fact.

The latter indicates that the typical size of an LP-comet nucleus is larger than that of an SP-comet nucleus. Actually, this is also supported by median values of both populations of comets: the median values of an SP-comet nucleus are smaller than about 2 km, whilst those of an LP-comet nucleus are larger than about 4 km. Another support comes from the analysis of the distribution of cometary radii which shows that the slope of the distribution for LP comets is significantly lower (a value from interval 1.59 to 2.21; see Table 3) than the slope for SP comets (a value from interval 2.67 to 3.04). Thus, taking into account the relatively more moderate decrease of the size of LP-comet nuclei, from the biggest to smaller nuclei, we have to obtain a relatively higher average size.

A smaller typical size of an SP-comet nucleus can be a result of a more frequent splitting of SP comets revolving around the Sun and being objects of thermal shocks more often per a time unit. Whilst a major part of LP comets are probably the original planetesimals, a prevailing part of SP comets can be the fragments of few progenitors (possibly a single progenitor only) as suggested by Pittich and Rickman (1994).

6. Conclusions

(1) We found the typical (average) effective radius of a bare nucleus of observed SP comets (which are practically identical to the Jupiter-family comets in our sample) to be about 2.3 km. The corresponding mass is about $2 \times 10^{14}.\rho/\rho_5$ kg, where ρ is the assumed mean density of cometary nuclei and $\rho_5 = 500$ $\mathrm{kg\,m^{-3}}$.

(2) The typical (average) effective radius of a bare nucleus of observed LP comets is found to be larger than that of SP comets. It is about 8.9 km. The corresponding mass is about $1 \times 10^{16}.\rho/\rho_5$ kg.

(3) The characteristic median effective radii of SP and LP cometary nuclei are 1.8 and 4.5 km, respectively, supporting the idea that the effective nuclei of LP comets are larger than their SP counterparts.

(4) If the comet cloud currently contains about 10^{12} cometary nuclei and we adopt $\rho = \rho_5$, then the typical cloud's mass is 1×10^{28} kg (0.005 $M_\odot$). Such a high total mass requires other sources of the cloud's comets, not only their ejection from the region of giant planets.

(5) Due to an observational bias, the smallest observable comets (of radii below ≈ 0.8 km in the case of SP comets and below ≈ 2 km in the case of LP comets) are obviously observed in a lower rate than the comets of moderate and large sizes. This affects the found average radii, shifting them a little to higher than actual values.

(6) In the currently available data, there is no support for a suggestion that the typical radius (typical mass) of an SP-comet nucleus is lower than ≈ 2 km ($\approx 1 \times 10^{14}.\rho/\rho_5$ kg) or that the typical radius (typical mass) of an LP-comet nucleus is lower than ≈ 7 km ($\approx 7 \times 10^{15}.\rho/\rho_5$ kg). Assuming the minimum

estimated mean density of a cometary nucleus $\rho = 200$ kg m^{-3} and the number of about 10^{12} cometary nuclei in the comet reservoir, it follows that the total mass of the entire cometary population at present cannot be lower than 3×10^{27} kg (0.0014 $M_{\odot}$).

(7) The slope index of the cumulative distribution of the effective radii of SP-comet nuclei (Jupiter-family cometary nuclei, in fact) is a value from range $2.67 \leq s \leq 3.04$. It considerably differs from the values found by other authors, which are, however, mutually considerably controversial, too. The analogous index for LP-comet nuclei is a value from the range $1.59 \leq s \leq 2.21$. The uncertainty in determination of the index appears due to a very low-numerous samples of determined cometary radii available. Only poor statistics can be done.

Acknowledgements. This work was supported by VEGA – the Slovak Grant Agency for Science, grant No. 1023.

References

Altenhoff, W.J., Bertoldi, F., Menten, K.M., Sievers, A., Thum, C., Kreysa, E.: 2002, *Astron. Astrophys.* **391**, 353

Boehnhardt, H., Delahodde, C., Sekiguchi, T., Tozzi, G.P., Amestica, R., Hainaut, O., Spyromilio, J., Tarenghi, M., West, R.M., Schulz, R., Schwehm, G.: 2002, *Astron. Astrophys.* **387**, 1107

Boehnhardt, H., Rainer, N., Birkle, K., Schwehm, G.: 1999, *Astron. Astrophys.* **341**, 912

Churyumov, K.I., Kruchynenko, V.G., Makarchuk, R.V.: 1999, in *Evolution and Source Regions of Asteroids and Comets, Proc. IAU Coll. 173*, ed.: J. Svoreň, E. M. Pittich, and H. Rickman, Astron. Inst. Slovak Acad. Sci., Tatranská Lomnica, p. 371

Farnham, T.L., Schleicher, D.G., Woodney, L.M., Birch, P.V., Eberhardy, C.A., Levy, L.: 2001, *Science* **292**, 1348

Feldman, P.D., McPhate, J.B., Weaver, H.A., Tozzi, G.-P., A'Hearn, M.F.: 1996, *Bull. American Astron. Soc.* **DPS meeting #28**, #08.08

Fernández, J.A.: 1985, in *Dynamics of Comets: Their Origin and Evolution*, ed.: A. Carusi and G. B. Valsecchi, Reidel, Dordrecht, p. 45

Fernández, J.A., Tancredi, G., Rickman, H., Licandro, J.: 1999, *Astron. Astrophys.* **352**, 327

Fernández, Y.R., Lisse, C.M., Ulrich, K.H., Peschke, S.B., Weaver, H.A., A'Hearn, M.F., Lamy, P.P., Livengood, T.A., Kostiuk, T.: 2000, *Icarus* **147**, 145

Fulle, M., Mikuz, H., Nonino, M., Bosio, S.: 1998, *Icarus* **134**, 235

Jorda, L., Lamy, P., Groussin, O., Toth, I., A'Hearn, M.F., Peschke, S.: 2000, in *ISO Beyond Point Sources: Sources of Extended Infrared Emission, September 14-17, 1999, ISO Data Centre, Villafranca del Castillo, Madrid*, eds. R. J. Laureijs, K. Leech, and M. F. Kessler, ESA-SP 455, p. 61

Konopleva, V.P., Shul'man, L.M.: 1972, in *The Motion, Evolution of Orbits, and Origin of Comets, Proc. IAU Sump. No. 45*, ed.: G. A. Chebotarev et al., Reidel, Dordrecht, p. 277

Lamy, P.L., A'Hearn, M.F., Toth, I., Weaver, H.A.: 1996, *Bull. American Astron. Soc.* **DPS meeting #28**, #08.04

Lamy, P.L., Toth, I., A'Hearn, M.F., Weaver, H.A., Weissman, P.R.: 2001a, *Icarus* **154**, 337

Lamy, P.L., Toth, I., Jorda, L., Groussin, O., A'Hearn, M.F., Weaver, H.A.: 2002, *Icarus* **156**, 442

Lamy, P.L., Toth, I., Weaver, H.A., Delahodde, C., Jorda, L., A'Hearn, M.F.: 2000, *Bull. American Astron. Soc.* **DPS meeting #32**, #36.04

Lamy, P.L., Toth, I., Weaver, H.A., Delahodde, C.E., Jorda, L., A'Hearn, M.F.: 2001b, *Bull. American Astron. Soc.* **DPS meeting #33**, #31.01

Licandro, J., Tancredi, G., Lindgren, M., Rickman, H., Hutton, G.R.: 2000, *Icarus* **147**, 161

Lisse, C.M., Fernández, Y.R., Kundu, A., A'Hearn, M.F., Dayal, A., Deutsch, L.K., Fazio, G.G., Hora, J.L., Hoffmann, W.F.: 1999, *Icarus* **140**, 189

Lowry, S.C., Fitzsimmons, A.: 2001, *Astron. Astrophys.* **365**, 204

Meech, K.J., Hainaut, O.R.: 1997, *Bull. American Astron. Soc.* **DPS meeting #29**, #25.11

Meech, K.J., Hainaut, O.R., Marsden, B.G.: 2000, in *Minor Bodies in the Outer Solar System, Proc. of ESO Workshop held at Garching, Germany, 2-5 November 1998*, ed.: A. Fitzsimmons, D. Jewitt, and R. M. West, Springer-Verlag, Berlin – New York, p. 75

Meech, K.J., Newburn, R.L.: 1998, *Bull. American Astron. Soc.* **DPS meeting #30**, #42.03

Möhlmann, D., Mangoldt, T., Börner, H., Rubbert, B., Danz, M., Weidlich, U., Elter, G.: 1986, in *Proc. 20th ESLAB Symp. on the Exploration of Halley's Comet. Vol. 2: Dust and Nucleus*, ESA SP-250, p. 339

Nolan, M.C., Howell, E.S., Harmon, J.K., Campbell, D.B., Margot, J.-L., Giorgini, J.D.: 2001, *Bull. American Astron. Soc.* **DPS meeting #33**, #43.02

Pittich, E.M., Rickman, H.: 1994, *Astron. Astrophys.* **281**, 579

Safronov, V.S.: 1972, in *The Motion, Evolution of Orbits, and Origin of Comets, Proc. IAU Sump. No. 45*, ed.: G. A. Chebotarev et al., Reidel, Dordrecht, p. 329

Sanzovo, G.C., de Almeida, A.A., Misra, A., Miguel Torres, R., Boice, D.C., Huebner, W.F.: 2001, *Mon. Not. R. Astron. Soc.* **326**, 852

Sarmecanic, J., Fomenkova, M., Jones, B., Lavezzi, T.: 1997, *Astrophys. J. Lett.* **483**, L69

Schleicher, D.G., Osip, D.J.: 2000, *Bull. American Astron. Soc.* **DPS meeting #32**, #40.07

Sekanina, Z.: 1995, *Astron. Astrophys.* **304**, 296

Sekanina, Z.: 1997a, *Earth, Moon, Planets* **77**, 147

Sekanina, Z.: 1997b, *Earth, Moon, Planets* **77**, 155

Slavkovský, M.: 2002, *Rozdelenie hmotností fotografických meteorov hlavných rojov. Diplomová práca*, Prírodovedecká fak., Univ. P. J. Šafárika, Košice

Soderblom, L.A., Becker, T.L., Bennett, G., Boice, D.C., Britt, D.T., Brown, R.H., Buratti, B.J., Isbell, C., Giese, B., Hare, T., Hicks, M.D., Howington-Kraus, E., Kirk, R.L., Lee, M., Nelson, R.M., Oberst, J., Owen, T.C., Rayman, M.D., Sandel, B.R., Stern, S.A., Thomas, N., Yelle, R.V.: 2002, *Science* **296**, 1087

Stern, S.A., Weissman, P.R.: 2001, *Nature* **409**, 589

Shul'man, L.M.: 1972, in *The Motion, Evolution of Orbits, and Origin of Comets, Proc. IAU Sump. No. 45*, ed.: G. A. Chebotarev et al., Reidel, Dordrecht, p. 271

Svoreň, J.: 1987, in *Proc. of the Symp. on the Diversity and Similarity of Comets*, ESA SP-278, p. 707

Tancredi, G., Fernández, J.A., Rickman, H., Licandro, J.: 2000, *Astron. Astrophys., Suppl. Ser.* **146**, 73

Weaver, H.A., Feldman, P.D., A'Hearn, M.F., Arpigny, C.: 1997, *Science* **275**, 1900

Weissman, P.R.: 1990, *Nature* **344**, 825

Weissman, P.R., Lowry, S.C.: 2001, *Bull. American Astron. Soc.* **DPS meeting #33**, #31.04

Wiegert, P., Tremaine, S.: 1999, *Icarus* **137**, 84

Wilhelm, K., Cosmovici, C.B., Delamere, W.A., Huebner, W.F., Keller, H.U., Reitsema, H., Schmidt, H.U., Whipple, F.L.: 1986, in *Proc. 20th ESLAB Symp. on the Exploration of Halley's Comet. Vol. 2: Dust and Nucleus*, ESA SP-250, p. 367