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Properties of meteoroids from different classes of parent bodies

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Abstract. Meteoroids observed to disintegrate in the terrestrial atmosphere can be directly linked to their parent bodies in case that they belong to certain meteor showers. We present a list of two dozens of parent bodies reliably associated with well recognized meteor showers. Among the parent bodies are long period comets, Halley-type comets, Jupiter family comets, comets of the inner solar system (such as 2P/Encke) and asteroids.

Physical and chemical properties of meteoroids coming from various parents are compared on the basis of meteor heights, decelerations, light curves and spectra. Jupiter family comets produce meteoroids with the lowest strength, namely porous aggregates of dust grains with bulk densities of about 0.3 g cm^{-3} or less. Halley type material is somewhat stronger and the material related to comet Encke is even stronger. In addition, small strong constituents, perhaps similar to carbonaceous chondrites, can be encountered within the normal cometary material. The strength of cometary material is also enhanced by long-term exposure to cosmic rays and by solar heating in the vicinity to the Sun ($r < 0.2$ AU). Both these processes lead to the loss of volatile sodium. Southern δ-Aquariids, Geminids and partly also Quadrantids were influenced by solar radiation. We argue that these showers, the asteroids associated with them ((3200) Phaethon and 2003 EH_1), and the whole interplanetary complexes they belong to are of cometary origin. The argument is supported by lower than chondritic Fe/Mg ratio found in Geminids as well as in Halley type comets. The typical property of stony meteoroids of asteroidal origin is the presence of internal cracks which cause that the incoming meteoroids are much weaker than the recovered meteorites.

Keywords. Meteors, meteoroids; comets: general; asteroids

1. Introduction

Meteoroids, by definition, are all bodies on heliocentric (or interstellar) orbits in the size range from several tens of microns to about 10 meters. Size is the only parameter which discriminates meteoroids from dust particles on one side and asteroids on the other side. The primary sources of meteoroids in the Solar System are comets and asteroids. Only a minority of meteoroids come from the solid surfaces of planets (e.g. Mars) and planetary satellites (e.g. Moon) or from the interstellar space. Since the dynamical lifetime of objects in the near-Earth space is of the order of 10 Myr only (Gladman *et al.* 2000; Foschini *et al.* 2000), no meteoroids could survive here from the beginning of the Solar System.

With the exception of the so called *cometary dust trails* (Davies *et al.* 1984; Sykes *et al.* 1986, 2004), meteoroids can be observed only as meteors in the planetary atmospheres. Earth-based meteor observations provide the orbits of an unbiased sample of meteoroids reaching the heliocentric distance of 1 AU. Physical properties (e.g. mechanical strength) and approximate composition of meteoroids can be also derived from meteor observations. This method provides an opportunity to study the properties of large variety of meteoroid parent bodies, in addition to the laboratory studies of meteorites, which is accessible only

Table 1. Long period and Halley-type comets with known meteoroid streams.

Comet	P [yr]	q [AU]	i [°]	Stream	Activity	Ref
		Long period				
C/1911 N1 Kiess	2500	0.684	148	Aurigids	O	[1]
C/1983 H1 IRAS-Araki-Alcock	963	0.991	73	η-Lyrids	AL	[2]
C/1861 G1 Thatcher	415	0.921	80	Lyrids	AM+O	[1]
C/1739 K1 (Zanotti)	unknown	0.674	124	Leonis Minorids	AL	[1]
		Halley-type				
C/1917 F1 Mellish	145	0.190	33	Dec. Monocerotids	AL	[1]
109P/Swift-Tuttle	133	0.960	113	Perseids	AH+O	[1]
1P/Halley	75.3	0.586	162	η-Aquariids	AH	[1]
				Orionids	AM+O	[1]
55P/Tempel-Tuttle	33.2	0.976	163	Leonids	AL+S	[1]
8P/Tuttle	13.5	0.997	55	Ursids	AL+O	[1,3]

for explanation see Table 3

for the strong part of meteoroid population, and still rare and expensive sample return missions. It is the main purpose of this review to discuss the physical and chemical properties of meteoroids of various parent bodies.

There are basically three processes which lead to the separation of meteoroids from their parent bodies. During the normal cometary activity near perihelion, the drag of vapors from evaporating ices takes away also the solid particles, dust and meteoroids (Whipple 1951). Secondly, a catastrophic disruption of comets produces not only secondary nuclei but also a large amount of dust and meteoroids (Jenniskens 2006). Finally, collisions among solar system bodies, in particular among asteroids, produces collisional fragments, including meteoroids (Nesvorný *et al.* 2003). In all cases, the separation velocities of meteoroids are much smaller than the orbital velocity. The orbits of young meteoroids are therefore very similar to the orbits of their parent bodies. If there is a range of orbital periods, then a meteoroid stream is formed in the next orbit. In this stage, it is relatively easy to link the meteoroid stream with its parent body. As time proceeds, various gravitational and non-gravitational forces lead to the dispersion of the stream and/or its separation from the parent body (see e.g. Vaubaillon *et al.* 2006).

2. Known parent bodies

It is likely that every active comet produces a meteoroid stream during perihelion passage. The common presence of cometary dust trails (Reach 2005) is an evidence of this process. Of course, the corresponding meteor shower can be observed only if at least a part of the stream intersects the orbit of the Earth. On the other hand, there are well recognized meteor showers with still unknown parent bodies (Vaubaillon *et al.* 2006). In Tables 1–3, we have compiled the known associations between meteoroid streams and their parent bodies. Only the associations which are certain or very likely are listed. Some other associations found in the literature (e.g. Hughes & Williams 2000) were omitted.

There are meteoroid streams related to almost all types of objects which cross the orbit of the Earth: long period comets ($P > 200$ years), Halley-type comets ($P < 200$ years, Tisserand parameter with respect to Jupiter, $T_J < 2$), Jupiter-family comets ($2 < T_J < 3$), Encke-type comets ($T_J > 3$), as well as objects classified according to their appearance as asteroids (which may also be dormant cometary nuclei). Tables 1–3 contain the current orbital period, P, perihelion distance, q, and inclination, i, of the parent bodies taken from

Table 2. Jupiter-family comets with known meteoroid streams.

Comet	P [yr]	q [AU]	i [°]	Stream	Activity	Ref
3D/Biela	6.65	0.879	13	Andromedids	S	[1]
7P/Pons-Winnecke	6.37	1.257	22	June Bootids	O	[1,4]
21P/Giacobini-Zinner	6.62	1.038	32	October Draconids	AL+S	[1]
26P/Grigg-Skjelerupp	5.11	0.997	21	π-Puppids	O	[5]
73P/Schwassmann-Wachmann 3	5.34	0.933	11	τ-Herculids	O	[1,6]
169P/NEAT	4.20	0.605	11	α-Capricornids	AL	[7]
Marsden group of comets	≈ 5.5	0.047	26	Daytime Arietids	AH	[7,8,9]
Kracht group of comets	≈ 5	0.045	13	S δ-Aquariids	AM	[9]
D/1819 W1 Blanpain = 2003 WY_{25}	5.10	0.892	9.1	December Phoenicids	AL+O	[1,10]

for explanation see Table 3

Table 3. Encke-type comets and asteroids with known meteoroid streams.

Object	P [yr]	q [AU]	i [°]	Stream	Activity	Ref
			Encke-type			
2P/Encke	3.3	0.339	12	Taurids	AM	[1]
				Daytime β-Taurids	AM	[1]
			Asteroids			
2003 EH_1	5.53	1.193	71	Quadrantids	AH	[11]
2005 UD	1.44	0.163	29	Daytime Sextantids	AM	[12]
(3200) Phaethon	1.43	0.140	22	Geminids	AH	[13,14]

Explanation to Tables 1–3: *Activity type:* AL – annual low (ZHR $\leqslant$ 10), AM – annual medium, AH – annual high (ZHR $>$ 50), O – occasional outbursts (ZHR $>$ 50), S – occasional storms (ZHR $>$ 1000); ZHR is zenithal hourly rate of meteors;
References: [1] Cook (1973), [2] Lyytinen & Jenniskens (2003), [3] Jenniskens *et al.* (2002), [4] Asher & Emel'yanenko (2002), [5] Vaubaillon & Colas (2005), [6] Wiegert *et al.* (2005), [7] Jenniskens (2006), [8] Gorbanev & Knyaz'kova (2003). [9] Sekanina & Chodas (2005), [10] Jenniskens & Lyytinen (2005), [11] Jenniskens (2004), [12] Ohtsuka *et al.* (2006), [13] Whipple (1983) [14] Williams & Wu (1993)

the JPL Small-Body Database (http://ssd.jpl.nasa.gov). Note that the current orbits may differ from the situation at the time when the meteoroid stream was formed. For example, the perihelion of comet 7P/Pons-Winnecke has moved far outside the Earth's orbit since 1825, when the meteoroid swarm, which collided with the Earth in 1998, was ejected (Asher & Emel'yanenko 2002).

Not all bodies listed in Tables 1–3 are independent. Numerical simulations have shown that the orbits of some comets, asteroids and meteoroid streams are related. Such groups are called interplanetary complexes. Table 4 lists three complexes most discussed in the literature. It is a common view that interplanetary complexes are products of disintegration of a common progenitor (grand parent), presumably a comet. Note, however, that in neither case such a scenario has been proved by a detailed study.

The Machholz complex consists of objects on currently different orbits but showing the same orbital evolution. Of particular interest is the small perihelion distance reached during the orbital evolution and exhibited currently by the Marsden and Kracht groups of comets ($q \sim 0.05$ AU), Southern δ-Aquariids ($q \sim 0.07$ AU), and Daytime Arietids ($q \sim 0.09$ AU). The most detailed discussion of the complex was published by Sekanina & Chodas (2005). The Phaethon-Geminid complex was recently extended by the discovery

Table 4. Interplanetary complexes

Complex	Member Bodies	Member Streams	Ref
Machholz complex	96P/Machholz Marsden group of sunskirting comets Kracht group of sunskirting comets 2003 EH_1 C/1490 Y1	 Daytime Arietids S δ-Aquariids Quadrantids	[1,2]
Phaethon-Geminid complex	(3200) Phaethon 2005 UD	Geminids Daytime Sextantids	[3]
Taurid complex	2P/Encke possibly a number of asteroids, in particular 2004 TG_{10}	Taurids (N and S) Piscids χ-Orionids Daytime β-Taurids Daytime ζ-Perseids	[4,5]

References: [1] Sekanina & Chodas (2005), [2] Jenniskens (2006), [3] Ohtsuka *et al.* (2006), [4] Babadzhanov (2001) [5] Porubčan *et al.* (2006),

of the asteroid 2005 UD (Ohtsuka *et al.* 2006). This relatively compact complex does not contain any active comet. The members also have small perihelion distance ($q = 0.14 - 0.16$ AU) and the orbital period is very short (1.4 yr). The Taurid complex is an extensive complex of meteoroid streams with low inclination and perihelia between 0.2 and 0.5 AU. The center of the stream is clearly related to comet 2P/Encke. The relation of other parts of the complex to about two dozens of Apollo asteroids has been proposed (Babadzhanov 2001; Porubčan *et al.* 2006). It is, however, possible that some coincidences are random, since the orbits are similar to those of asteroids evolving from the ν_6 resonance (Valsecchi *et al.* 1995).

We do not list as complex the comet D/1819 W1 Blanpain, its probable fragment 2003 WY_{25} (Jenniskens & Lyytinen 2005) and the December Phoenicid stream. The number of involved bodies and streams is not large enough to classify as a complex.

3. Asteroids as potential parent bodies

A number of near-Earth asteroids other than those listed in Table 3 have been proposed as parent bodies of observed meteors by various authors. They include asteroids (2101) Adonis (Babadzhanov 2003), (1620) Geographos (Ryabova 2002), and 2001 YB_5 (Meng *et al.* 2004) which have been associated with individual meteors found in meteor orbit databases or with rather doubtful minor showers. The problem for objects on typical asteroidal orbit is the generally low encounter velocity with the Earth. The potential meteors are faint, the shower radiant has a large area and unless the stream is very dense, it is difficult to distinguish individual meteors from sporadic background. At the present time, it is quite possible that the proposed associations are just chance coincidences.

Several links were proposed between meteorites of certain types and asteroids of certain taxonomic classes. These links are based on similar reflectance spectra and presumably similar mineralogical composition (see Burbine *et al.* 2002, for a detailed review). The direct orbital link is missing from two reasons. First, orbits of meteorites, except for nine cases (Trigo-Rodríguez *et al.* 2006), are unknown. Secondly, unlike the cometary streams which are only hundreds or thousand years old, the meteorites separated from their parent bodies millions of years ago. Their orbits were then modified chaotically under the influences of the Yarkovsky effect, orbital resonances and close encounters

Table 5. Orbital elements (J2000.0) of some fireballs of special interest

Fireball	a [AU]	q [AU]	i [°]	ω [°]	Ω [°]	Note	Ref
EN 041089	2.501 ±0.006	0.8310 ±0.0002	19.25 ±0.02	234.71 ±0.03	191.8631 ±0.0001	Probable diogenite	[1]
Karlštejn	3.49 ±0.09	1.0124 ±0.0001	137.90 ±0.05	174.60 ±0.07	71.5461 ±0.0001	Probable cometary crust	[2]
Příbram	2.401 ±0.002	0.78951 ±0.00006	10.482 ±0.004	241.750 ±0.013	17.79147 ±0.00001	Recovered H5 chondrite	[3]
Neuschwanstein	2.40 ±0.02	0.7929 ±0.0004	11.41 ±0.03	241.20 ±0.06	16.82664 ±0.00001	Recovered EL6 chondrite	[3]

References: [1] Borovička (1994), [2] Spurný & Borovička (1999b), [3] Spurný *et al.* (2003)

with terrestrial planets (Vokrouhlický & Farinella 2000). So, the preatmospheric orbit of an old meteoroid can be used to infer the character of its orbital evolution and the probable source region of the meteoroid but does not tell us the actual parent body.

The most firmly established asteroid-meteorite link is between the HED meteorites (howardites, eucrites, and diogenites) and the asteroid (4) Vesta and its family (Pieters *et al.* 2006). The fragments from the cratering on Vesta occupy the space up to the 3:1 resonance with Jupiter, which is the dynamical gateway to deliver bodies from the main belt to Earth-crossing orbits. No HED meteorite orbit is known, nevertheless, the spectrum of the fireball EN 041089 suggested diogenite composition (Borovička 1994). The orbit (see Table 5) indeed places the EN 041089 meteoroid exactly into the 3:1 resonance. The other proposed parent bodies include (8) Flora for L-chondrites, (6) Hebe for H-chondrites (Vokrouhlický & Farinella 2000), (3103) Eger for aubrites (Gaffey *et al.* 1992) and few others (Burbine *et al.* 2002).

4. Meteor data

Only the properties of meteorites can be studied in laboratory in detail. Since meteorites represent only the strongest part of the strongest meteoroids encountering the atmosphere, we would obviously like to know how do the meteoroids look before the atmospheric encounter and, even more desirably, how does the weaker cometary material look like. Meteor observations provide us at least a partial answer.

Physical studies of meteoroids are based on investigation of meteor heights, atmospheric deceleration, light curves, and spectra. The methods have been explained in detail in my previous review (Borovička 2006a), where also references to original work can be found. In the first approximation, physical properties of most meteoroids (excluding perhaps the iron meteoroids) can be well characterized by an one-dimensional parameter. The parameter expresses the degree of meteoroid fragility or, more exactly, mechanical strength. The classical classification of bolides into four types, I, II, IIIA, and IIIB, corresponds to increasing ability of meteoroids to disintegrate during the atmospheric entry by fragmentation. From I to IIIB, meteoroid mechanical strength and bulk density decreases, while porosity and fragility increases.

The signs which can be used to recognize and quantify meteoroid fragility are:

(*a*) In case of bright meteors caused by large meteoroids (> 1 cm),

- end height increases with increasing fragility (for a given velocity and mass);
- apparent ablation coefficient is large for more fragile bodies; and

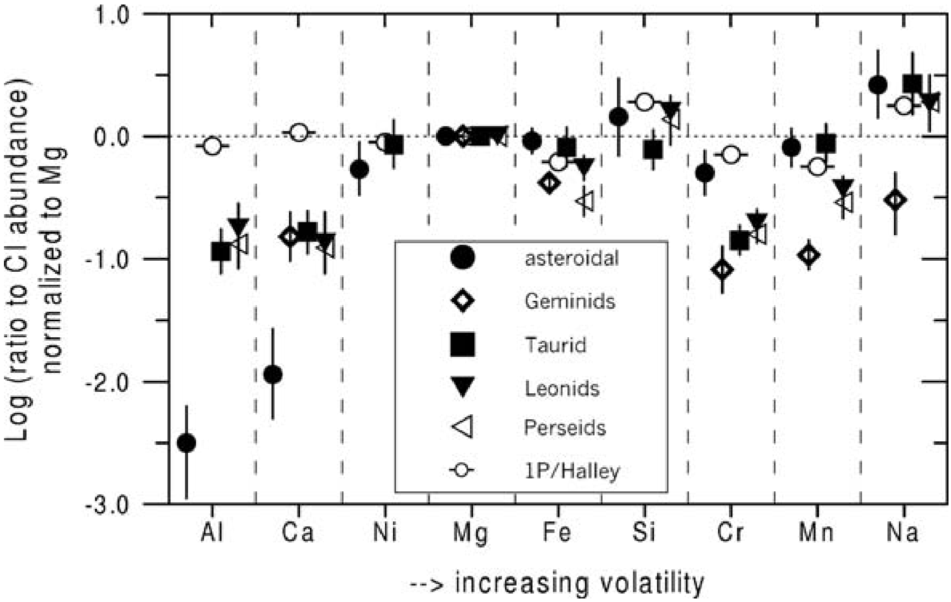

Figure 1. Abundances of eight elements relative to Mg in radiating plasma of selected fireballs as derived from photographic spectra. The abundances are shown as deviation from CI carbonaceous chondrite element-to-Mg ratio taken from Lodders (2003). The composition of Halley comet dust as determined by Jessberger *et al.* (1988) from the VEGA-1 spacecraft flyby is shown for comparison. The fireball data include the asteroidal fireball EN 270200 (Borovička 2006b), one Taurid fireball (this work), and an average of two Geminids (Borovička 2006c), three Leonids, and five Perseids (both from Borovička 2005).

- dynamic pressure causing meteoroid fragmentation in flight is smaller for more fragile bodies.

(*b*) In case of faint meteors,

- beginning height is larger (and increases with mass for a given shower) for more fragile bodies;
- light curves are symmetrical or skewed to the beginning for bodies which are subject to early disruption; and
- sodium may be released preferentially at the beginning of the luminous trajectory, if the body is disrupted very early.

Several authors attempted to compute meteoroid bulk densities from meteor data. Such task is very difficult and the results are model dependent. There is, nevertheless, an agreement that Geminids contain the meteoroids with highest density of all showers (Babadzhanov 2002; Bellot Rubio *et al.* 2002). Other meteoroids with relatively high density are δ-Aquariids and Quadrantids (Babadzhanov 2002).

Approximate chemical composition of meteoroids can be inferred from meteor spectra. In case of sufficiently rich spectra of bright meteors, the spectra can be modeled assuming thermal equilibrium and abundances of observable elements can be determined. In case of not-so-good but more numerous spectra of faint meteors, line intensities (mainly of Na, Mg, and Fe) can be mutually compared and the sample evaluated statistically.

Figure 1 shows relative elemental abundances in radiating plasma of several fireballs of different origin. In order to present an homogeneous dataset, only the data obtained recently by me with a uniform method have been included. Unfortunately, the plasma composition does not reflect directly the meteoroid composition. The low abundances of Al and Ca are caused by incomplete evaporation of meteoric matter during the atmospheric flight. The Al and Ca data for the asteroidal fireball are consistent with a ∼ 90% evaporation of chondritic body (Borovička 2006b). The generally low abundances of Cr are not well understood and may be at least partly caused by another effect during ablation. The most important aspects in Fig. 1 are the differences in Fe abundances and the depletion of volatiles in Geminids. These facts will be discussed in the relevant sections. Figure 2 presents a comparison of the observed Mg, Na, and Fe line intensity ratios in

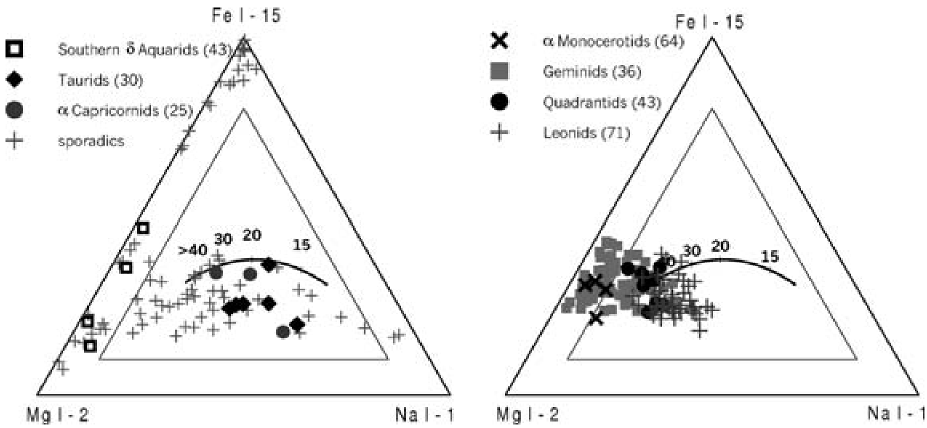

Figure 2. Comparison of brightness of three spectral lines – Mg I (multiplet 2), Na I (multiplet 1), and Fe I (multiplet 15) – in video spectra of faint meteors of seven showers and sporadic meteors. The thick curve shows the expected positions of meteors of chondritic composition and various velocities. The Na line is expected to be brighter in slower meteors (< 40 km s^{-1}), because of lower plasma temperature. The shower velocities in km s^{-1} are given in the legend in parenthesis. According to Borovička *et al.* (2005), Koten *et al.* (2006), and Borovička (2006c).

faint sporadic and shower meteors observed by video techniques. The thing to remember is that there is much larger diversity in composition among sporadic meteoroids in this size range (few millimeters) than among larger meteoroids. Shower meteoroids are better confined but there is real scatter even among meteoroids of the same shower. Differences between showers also exist. Southern δ-Aquariids do not contain Na and there is significant Na depletion in most Geminids and α-Monocerotids and partly also in Quadrantids. Most shower meteoroids have lower than chondritic Fe/Mg ratio.

5. Properties of meteoroids

In this section we will summarize the physical and chemical properties of meteoroids of various origin, without going into too much detail. At the moment we have only limited information on meteoroids from the long period comets in Table 1. Most of them are Lyrids. They do not show obvious differences from meteoroids of Halley-type comets, which is understandable because the 200 yr distinction period is quite arbitrary. Long period cometets are therefore not discussed here separately.

5.1. *Halley-type comets*

Halley-type comets are represented by well-studied meteor showers Perseids and Leonids (see Table 1). The data show that typical Halley-type cometary material has very low strength (< 0.05 MPa), low density ($\leqslant 1$ g cm^{-3}) and high porosity. Individual meteoroids are most likely irregular aggregates of dust grains. Small meteoroids often disintegrate into the constituents grains early during the atmospheric entry, producing meteors with nearly symmetrical light curves (Beech & Murray 2003; Koten *et al.* 2004).

Meteor beginning heights increase with meteoroid mass in Leonid and Perseid showers, indicating that the ablation (mostly by sputtering) starts very early (Koten *et al.* 2004). Early ablation is supported by volatility of some meteoroid components. Large meteoroids do not break-up at the beginning but often disintegrate catastrophically at lower heights, leading to quick evaporation of the grains and to spectacular meteor flares (Spurný *et al.* 2000a; Borovička & Jenniskens 2000). There are also evidences of spontaneous fragmentation of meteoroids in the interplanetary space (Watanabe *et al.* 2003).

The diversity of light curve shapes (Beech & Murray 2003; Koten *et al.* 2004) and the various degree of early evaporation of sodium in faint Leonid meteors (Borovička *et al.* 1999) indicate that there are differences in shape, structure and possibly also composition of mm-sized meteoroids even within one meteor shower. In addition, Perseids seem to be somewhat stronger on average than Leonids. This indication follows from the average light curve shape of faint meteors (Koten *et al.* 2004), from the comparison of end heights of Perseids (Spurný 1995) and Leonids (Spurný *et al.* 2000a), and from the meteoroid density estimates (Babadzhanov 2002).

Chemically, the Halley-type material is depleted in Fe relative to Mg in comparison with the composition of CI chondrites (Borovička 2005; Borovička *et al.* 2005, see also Figs. 1 and 2). Also the abundances of Cr and Mn seem to be lower, while Si and Na are enhanced. The same results were obtained by the *in situ* mass spectroscopy of comet 1P/Halley dust onboard the VEGA-1 spacecraft (Jessberger *et al.* 1988). Although the differences from the CI composition in the VEGA-1 experiment have been originally attributed to inaccurately known ion yields in the mass spectrometers, meteor data show that they are probably real.

5.1.1. *Strong constituents*

There are evidences that quite strong constituents are embedded within the generally weak Halley-type material. At least in two cases, small Leonid fragments separated from much larger original bodies and were observed to continue well below the position of the main flare (Spurný *et al.* 2000b; Borovička & Jenniskens 2000). In the latter case, a mm-sized particle penetrated to the height of 56 km before being ablated, and survived dynamic pressure up to 2 MPa without fragmentation. The spectrum did not suggest any significant difference in chemical composition from the original meteoroid. The particle was therefore not a calcium-aluminum rich inclusion, for example. Possibly, it may have been material similar to carbonaceous chondrites. Note that Gounelle *et al.* (2006) argued for cometary origin of the CI Orgueil meteorite, based on the entry speed of the fireball.

5.1.2. *Probable cometary crust material*

Most sporadic meteoroids on Halley-type orbits show similar properties to Leonids and Perseids. However, a quite different material was also found on such orbits. The material is characterized by significantly larger strength (~ 1 MPa) and the lack of sodium within it. A typical example is the Karlštejn fireball (Spurný & Borovička 1999a, b; see Table 5 for orbital elements). Such material is quite rare among cm-sized bodies but was found to comprise about 10% of mm-sized sporadic meteoroids (Borovička *et al.* 2005). This type of material is not present within the showers of active comets. However, the α-Monocerotids – meteoroids of a long period shower with unknown parent body – have somewhat similar properties. They are stronger than Perseids (Jenniskens *et al.* 1997) and have lower content of sodium (Fig. 2).

It is likely that this material represents fragments of primordial cometary crust. The compaction and loss of volatile Na were produced by cosmic ray irradiation during long time residence of comets in the Oort cloud. We can speculate that α-Monocerotids were ejected from near surface layers of a long period comet during one of its first approaches to the Sun.

5.2. *Jupiter family comets*

The meteoroids from Jupiter family comets are even softer then those of Halley-type comets. The October Draconids are a prototype of the most fragile material entering the Earth's atmosphere. The likely bulk density is about 0.3 g cm^{-3} (see the discussion in Borovička 2006a). Recent observations at the Ondřejov Observatory (Borovička *et al.*, in preparation) have shown that small Draconids disintegrate under the dynamic pressures less than 1 kPa. Their strength is therefore comparable to the strength of fresh snow. The results of the Deep Impact experiment yielded even lower strength (< 65 Pa) of the surface layers of comet 9P/Tempel 1 (A'Hearn *et al.* 2005). The Fe/Mg ratio in the Jupiter family meteoroids was not firmly established yet.

5.3. *Taurid complex*

Taurid meteoroids are of medium strength on average, they are stronger than Halley-type and Jupiter family cometary material. Nevertheless, very weak material can also be encountered within the complex – for example the Šumava fireball (Borovička & Spurný 1996) was a χ-Orionid. The Fe/Mg ratio seems to be nearly chondritic, at least in some meteoroids (Fig. 1). On the other hand, some faint Taurids show low Fe/Mg (Fig. 2). The Taurid complex is therefore not homogenous. In any case, Taurid meteoroids suggest that comet Encke is physically distinct from Jupiter family comets and may have either different origin or different evolutionary history. The difference was, however, not due by solar heating, since Taurids do not show any hint of Na loss.

5.4. *Phaethon-Geminid complex*

Geminid meteoroids are known to be the strongest of all meteor showers (e.g. Spurný 1993). Their bulk density is about 3 g cm^{-3} (Ceplecha & McCrosky 1992; Babadzhanov 2002). They are severely depleted in Na and also in other volatiles like Mn (Figs. 1 and 2; Borovička 2006c). Unlike other meteor showers, Geminid meteor beginning height does not increase with meteoroid mass (Koten *et al.* 2004). All these distinct properties of Geminids are likely a consequence of their low perihelion distance of 0.14 AU. At 0.14 AU, the meteoroids are heated by solar radiation to about 700 K. Borovička *et al.* (2005) have found all small sporadic meteoroids with perihelia less than 0.2 AU completely depleted in Na and compacted. The Na depletion in Geminids is not complete and varies from meteoroid to meteoroid. Geminids therefore seem to be younger than most sporadic meteoroids. The variations in Na content suggest that the meteoroids are of various ages, i.e. they were released from Phaethon at various times in the past (Borovička 2006c). Alternatively, they may come from various depths inside Phaethon.

In our interpretation, the high strength of Geminids is not an evidence of their asteroidal origin. The Fe/Mg ratio is similar to Halley type cometary material (Fig. 1) and suggests cometary origin of the Geminids, Phaethon, and other members of the complex.

5.5. *Machholz complex*

Quadrantids and Southern δ-Aquariids, the two night time showers of the Machholz complex, have currently quite different orbits but show the same orbital evolution and may have evolved from a common progenitor (Sekanina & Chodas 2005). Southern δ-Aquariids have extremely low perihelion distance of 0.07 AU. They are completely Na-free and compacted (Fig. 2; Borovička *et al.* 2005), in accordance with the low perihelion.

At 0.07 AU, the meteoroid temperature reaches 1000 K. Southern δ-Aquariids are old enough to have lost all sodium by thermal desorption.

Quadrantids, with perihelion distance of 0.98 AU, do not go any close to the Sun. Orbital simulations, however, show that the perihelion distance was low ($\sim$ 0.1 AU) 1000–2000 years ago (Porubčan & Kornoš 2005). The narrow width of the core of the stream and the relatively recent appearance of the shower on terrestrial skies, nevertheless, indicate that the core is only 200–500 years old (Jenniskens 2004; Wiegert & Brown 2005). Physical and chemical properties of Quadrantid meteoroids – the strength and Na content – were found to be intermediate between Leonids and Geminids (Koten *et al.* 2006, see also Fig. 2). There is therefore evidence on moderate influence by solar radiation at low perihelia. Since the stream is so young, the material alternation must have occurred near the surface of the parent body, most likely 2003 EH_1.

In this interpretation, asteroid 2003 EH_1 was active few hundred years ago when it produced the core of the Quadrantid stream. The meteoroids were released from near surface layers. A cometary splitting, which would produce meteoroids from deep interior of the body, is not consistent with the solar alternation of the Quadrantid material. On the other hand, 2003 EH_1 itself is likely a product of earlier fragmentation of the Machholz complex parent comet.

Outer portions of the Quadrantid stream are several thousands years old (Wiegert & Brown 2005). That material can be expected to be more influenced by solar radiation, unfortunately, we do not have physical data on meteors from that part of the stream.

5.6. *Asteroidal streams*

The search for meteoroid streams associated with asteroids is an evergreen topic in meteor science. The major streams Geminids and Quadrantids are associated with asteroids that very likely exhibited cometary activity in the past. Regular non-cometary asteroids may form meteoroid streams by their mutual collisions. Since asteroid collisions in near-Earth region are rare events, such streams, if any, are expected to be old, disperse and hard to detect. An interesting observation in this respect is the close orbital correspondence (see Table 5) of Příbram and Neuschwanstein meteorites, two of nine meteorites with known orbit (Spurný *et al.* 2003). The meteorites are, however, of different types – Příbram is an ordinary chondrite (H5) and Neuschwanstein is enstatite chondrite (EL6). If they are part of a larger meteoroid stream, they challenge our understanding of asteroid structure, stream formation and evolution. Pauls & Gladman (2005), nevertheless, concluded on statistical basis that the orbital closeness of both meteorites can be explained by chance coincidence.

5.7. *Sporadic meteoroids*

Actual parent bodies of sporadic meteors are not known. Nevertheless, we can compare physical and orbital properties of sporadic bodies and still get some information about source regions of different types of material. Figure 3 shows the distribution of semimajor axes and eccentricities of different types of fireballs (Shrbený 2005). The graph gives an idea of orbits of sporadic meteoroids in the size range from several cm to about a meter, which intersect Earth's orbit. There is no significant difference between the orbits of fireballs of types I and II, i.e. stony and carbonaceous bodies. Both groups have a peak at $a \sim 2.3$ AU and $e \sim 0.7$, indicating the origin in the inner asteroid belt. The fragile meteoroids of types IIIA and IIIB have flatter distribution of semimajor axes (axes larger than 5 AU are not shown in Fig 3). The most interesting aspects is the bimodal distributions of eccentricities of the soft cometary material IIIB. While the IIIA meteoroids tend to have large eccentricities, IIIB's have a secondary peak at $e \sim 0.7$. This

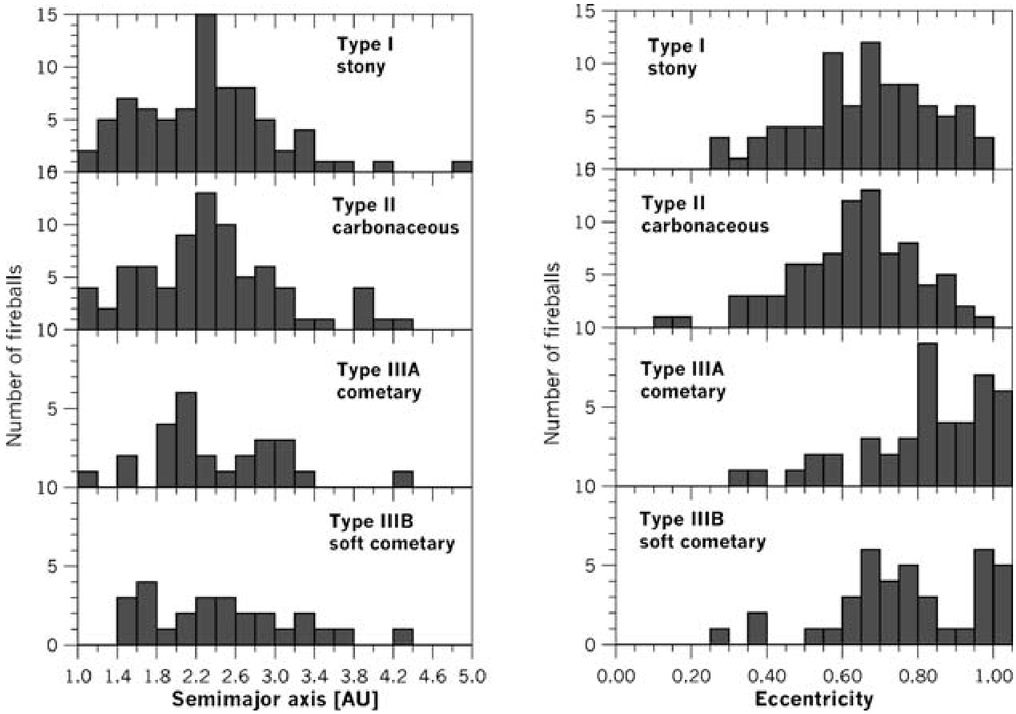

Figure 3. Distribution of semimajor axes (left) and eccentricities (right) of sporadic fireballs of four strength categories. Fireballs with $a > 5$ AU or $a < 1$ AU are not shown in the left graph. According to Shrbený (2005).

peak is clearly related to Jupiter family comets. The observation of sporadic meteoroids therefore confirm the softness of Jupiter family comets.

We should note that the picture would be different for smaller meteoroids. As noted already by Ceplecha (1988), stony bodies are almost absent among mm-sized meteoroids. The spectroscopic survey (Borovička *et al.* 2005) surprisingly revealed that iron type material prevails among the few small meteoroids on typically asteroidal orbits. Since large stony meteoroids are delivered form the main belt to the Earth with the help of the Yarkovsky effect (Vokrouhlický & Farinella 2000), which is inefficient for mm-sized bodies, the absence of small stones near the Earth can be understood. The reason for the presence of irons is, however, not clear.

5.8. *Properties of stony meteoroids*

Meteoroids of type I are related to stony meteorites. Stony meteorites are compact objects of high strength. Incoming meteoroids, on the other hand, easily fragment in the atmosphere under dynamic pressures two orders of magnitude smaller than the strength of meteorites (Petrovic 2001, Popova *et al.*, in preparation). This is valid both for cm-sized (Ceplecha *et al.* 1993) and meter sized bodies (Borovička *et al.* 1998; Borovička & Kalenda 2003). The typical property of stony meteoroids is therefore presence of various internal cracks, which cause structural weakness of the body. Recovered meteorites then represent the most compact part of incoming bodies. Of course, there are large differences between individual bodies but only rarely the incoming meteoroid does not break up under the loading pressure of a few MPa.

6. Summary

We have demonstrated that the analysis of meteor data can reveal differences in physical structure and chemical composition of various Small Bodies in the Solar System (comets and asteroids). The results presented here should be, nevertheless, considered in some sense as preliminary. The analysis of more data in the future is expected to provide larger statistical sample and more firmly established results.

The emerging picture shows that the cometary dust is fragile, porous, and irregular conglomerate of individual dust grains. The fragility varies among different types of comets. Jupiter family comets are composed from the most porous and fragile material. The bulk density is about 0.3 g cm^{-3} (or even less) and the strength of small meteoroids does not exceed 1 kPa. Although this type of material is present also in Halley type comets, typical Halley type material is markedly stronger with probable densities of about 0.8 g cm^{-3}. The material related to comet Encke is even stronger on average. Comet Encke has therefore either different origin or different evolutionary history than Jupiter family comets.

Comets, however, contain also much stronger constituents than is the typical cometary material. Millimeter sized particles of the strength of at least 2 MPa were found to be embedded in larger ($\sim$ 10 cm) Leonid meteoroids. The strength of these particles may be comparable to the strength of carbonaceous chondrites. In any case, cometary material is inhomogeneous, certainly on mm-scale, and perhaps on larger scales as well.

Meteor spectroscopy suggests that the Fe/Mg ratio in comets, at least in Halley type comets, is lower than chondritic. This conclusion is in conflict with widespread belief that cometary abundances of non-volatile elements are identical to solar photosphere and CI chondrites. There are, however, other suggestions that this is not the case: the mass spectroscopy of comet Halley dust and the infrared spectroscopy of comet Hale-Bopp (Jessberger *et al.* 1988; Hanner *et al.* 1999). If confirmed, the low Fe/Mg ratio in cometary dust will deserve further studies.

Cometary material can be significantly reprocessed by space environment. The thermal solar radiation in the vicinity to the Sun (< 0.2 AU) and long term exposure to cosmic rays in the Oort cloud have similar effects. They lead to the depletion of more volatile elements, namely Na, and to general compaction of the dust. In consequence, two populations of strong and Na-free meteoroids exist in the Solar System: the Sun approaching meteoroids and the remnants of cometary primordial crust.

The solar heating is responsible for the peculiar properties of Geminid meteoroids. Despite of their strength, we consider Geminids to be of cometary origin, based on their Fe/Mg ratio and also on their presence within an interplanetary complex. The situation is similar with Quadrantids. Both (3200) Phaethon and 2003 EH_1 are products of cometary fragmentation, exhibited cometary activity in the past and now are extinct or dormant.

Asteroidal fragments of centimeter to meter size contain many internal cracks. Their bulk strength is much lower than the strength of recovered meteorites. The meteoroid strength lies typically in the range 0.1 – 5 MPa. There is no clear dependence of the strength on meteoroid mass. It can be expected that small asteroids, even if they are not rubble piles, have low bulk strength.

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