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Chemical abundances determined from meteor spectra – II. Evidence for enlarged sodium abundances in meteoroids

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ABSTRACT

The relative abundances of sodium in meteoroids have been estimated by averaging the composition of the radiating gas along the fireball path produced during their atmospheric entry. We used the method of thermal equilibrium for 13 fireballs produced by meteoroids mainly of cometary origin. The results show greater sodium abundances than those expected for interplanetary dust particles and chondritic meteorites, and interesting differences from the sodium abundance of 1P/Halley comet dust were also found.

Key words: astrochemistry – techniques: spectroscopic – comets: general – meteors, meteoroids.

1 INTRODUCTION

In a previous paper (Trigo-Rodríguez et al. 2003, hereafter Paper I), we discussed the use of meteor spectroscopy to determine the relative chemical abundances of the associated meteoroids. We followed the Borovička (1993) model to determine the physical parameters along the fireball path. The model assumes thermal equilibrium in the meteor head during the short time in which the intense radiation is produced, and is capable of reproducing the main characteristics of all meteor spectra. In Paper I, we applied this model to deduce the chemical abundances of Fe, Mg, Al, Ca, Ni, Co and Sr relative to Si in 13 fireballs. Here, we concentrate on the analysis and discussion of the Na/Si ratio results and on the comparison of the results with the typical abundances given for several primitive bodies. Most of the fireballs analysed were produced by periodic comets, as was deduced from the heliocentric orbits of the respective meteoroids (Ceplecha 1977). In consequence, the intrinsic interest arises from the study of the chemical abundances of matter that continuously reaches the terrestrial atmosphere from various cometary sources in the form of meteoroids.

Although sodium is not a major component in comets and meteorites, it is of strong cosmochemical interest. During the formation of the Solar system, volatile elements, such as sodium, were probably depleted from the inner protoplanetary disc due to intense solar radiation from the evolving Sun (Despois 1992). After that, rocky bodies formed in the inner Solar system suffered differentiation and degradation processes that probably also eroded volatile elements (Ehrenfreund et al. 1997). For these reasons, sodium abundances are expected to be higher in unprocessed bodies (i.e. comets) formed in the outer region of the disc. The extremely high volatility of compounds associated with this element is also exemplified in comets. This probably explains the formation of the recently discovered presence of a sodium tail in comets (Cremonese & Fulle 1997; Cremonese et al. 1997). These authors suggested two different ways by which cometary sodium tails could be produced: by coming from a near-nucleus region, probably by cometary degassing; and also via the breakup of Na-bearing molecules, ions or dust particles. To study sodium in comets, spectroscopists take advantage of the high efficiency of the sodium atom in resonant scattering of solar radiation, which makes this element detectable in cometary tails even when its column density is low. In a similar manner, we can study the presence of sodium in meteoroids by taking advantage of the fact that it is a very volatile element with a high luminous efficiency in the meteor paths.

Sodium is not only present in comets or meteoroids. It also appears in other Solar system bodies, such as Mercury, Io and the Moon, where it is used as a tracer of processes at work on their atmospheres. Sodium probably reaches these bodies from the constant entry of meteoroids. We therefore need a better understanding of the sodium fraction present in meteoroids and their parent bodies. One way to improve this knowledge is through meteor spectroscopy. Sodium abundances can be derived from meteor spectra because sodium emission lines are omnipresent and are usually some of the brightest lines visible in meteor spectra.

2 METHODOLOGY

The methodology followed for spectral interpretation is given in detail in Paper I. Briefly, we have analysed 15 meteor spectra belonging to 13 different fireballs registered at the Ondrejov Observatory

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between 1961 and 1989 (see table 1 in Paper I for details). All spectral records were obtained with fixed cameras equipped with prisms or diffraction gratings. Ten of them were obtained using a prism to scatter meteor light, and the others with a diffraction grating with 600 groove mm^{-1}. The focal length of the camera was 360 mm and the focal ratio 1 : 4.5. All spectra were taken on 18 × 24 cm^2 plates. The typical dispersion of prism spectra varies between 130 Å mm^{-1} at 4000 Å and 550 Å mm^{-1} at 6000 Å. The resolution of grating spectra is better, around 50 Å mm^{-1}, and is uniform across the whole spectral window, which covers 3600–6600 Å. The exposure time for all spectra was several hours on two different films: AGFA 100 and ORWO NP27 (ISO 400). The spectral plates were measured in detail using a two-axis densitometer at the Ondrejov Observatory. The camera plates were scanned along the diffraction hyperbola, since the meteor paths were often out of the optical axis of the camera (Ceplecha 1961). In order to obtain a detailed analysis, the densitometer included a rotation slot to keep the measured signal window parallel to the meteor path. The slot dimensions were adapted to each spectra according to the apparent size of the brightest lines. The spectra were scanned at least once per segment but often more frequently depending on the slot size. The wake was also measured between segments to determine the plate background and its influence on each spectrum. The position of the scans and the slot size were clearly defined on photographs to allow future identification, as is shown in Fig. 1 for the SPO3 spectrum. Scans were labelled with letters to allow the study of the chemical abundances along the meteor column. A detailed study for each spectrum is available in Trigo-Rodríguez (2002).

The measurements were carefully calibrated according to the relative spectral sensitivity of the spectrograph. The wavelength scale for each spectrum was determined by means of known lines in the spectrum following the usual procedure (Borovička 1993). Plate sensitivities were obtained in order to calibrate the real intensity of each line due to the fact that the plate response was different at each wavelength. The plate sensitivity of old plates taken on AGFA 100 was obtained by studying the bright and detailed spectra of the Polaris star that was recorded in the plate of the spectrum GEM. For the spectra taken on ORWO NP27, we assumed the same spectral sensitivity as obtained by Borovička (1993) analysing the Saturn spectrum on the plate of the Cechtice fireball. Both sensitivity curves were shown in fig. 4 of Paper I.

The absolute calibration of the spectra consisted basically in adjusting the flux arriving from the meteor using the equation:

$$F(\lambda) = Ac^{-1}(\lambda)[D(\lambda)]^p, \qquad (1)$$

where D is the measured opacity, p is the reciprocal slope of the characteristic curve, c is the spectral sensitivity function and F is the absolute energy flux. The absolute magnitude of the fireball is adjusted by changing the A value until the magnitude is in accordance with the measured magnitude of the fireball estimated from all-sky images. Unfortunately, the absolute magnitudes of some fireballs were not available, so the absolute calibration was not always possible. However, in Paper I and in the present work we consider relative elemental abundances, which are not seriously affected by the absolute calibration (Borovička 1993).

We used the empirical equation deduced from 6000 radio meteors by Verniani (1973) to relate the photometric magnitude and the geocentric velocity of the meteors with the mass of the incoming meteoroids:

$$0.92 \log m = 24.214 - 3.91 \log V_{\mathrm{g}} - 0.4 M_{\mathrm{v}}, \qquad (2)$$

where m is the meteoroid mass in grams, V_{g} is the geocentric velocity in cm s^{-1} and M_{v} is the meteor visual magnitude.

Results on the mass of the meteoroids producing the analysed spectra are given in Table 1. We have estimated that the mass uncertainty is *c.* 10 per cent for the fireballs with known absolute magnitude and *c.* 30 per cent when the absolute magnitude is not known (given between parentheses in Table 1).

To obtain the relative chemical composition of meteoroids, we used the geometrical model of the meteor developed by Borovička (1993). The radiating volume is treated as a prism with square base and elongated in the direction of the meteor flight. The prism length is b and the width is a. The model assumes for simplicity that the spectrograph only sees one side of that prism. The angle between the side of the prism and the observer was calculated for each fireball from the known meteor trajectory in space. The ratio b/a of the

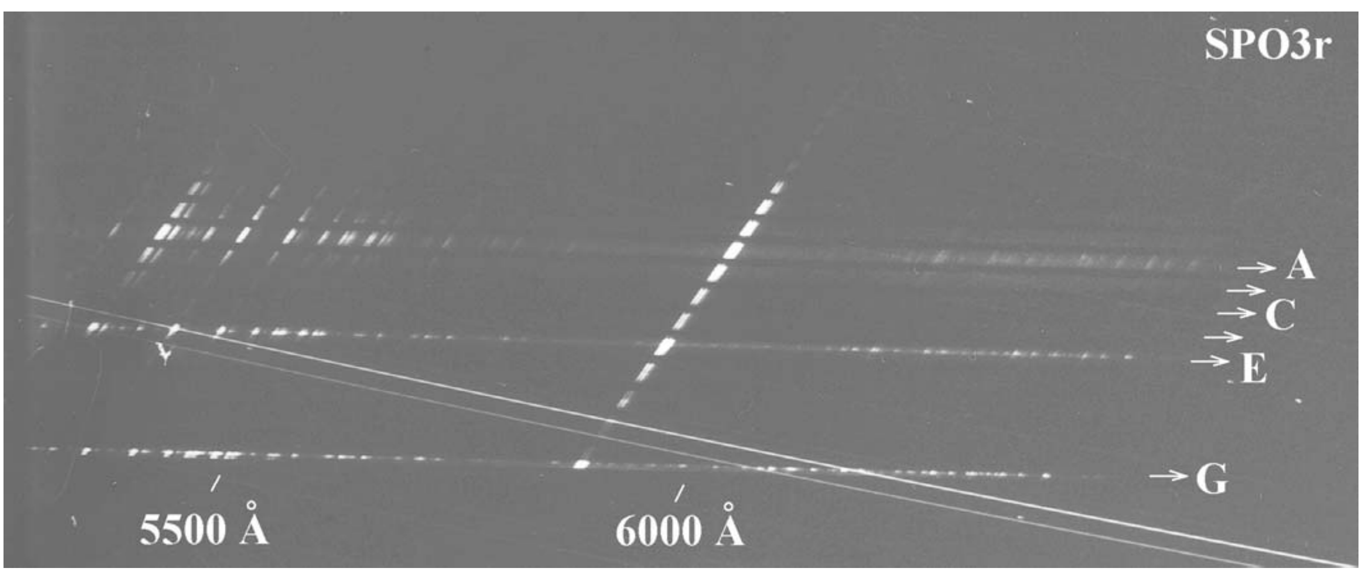

Figure 1. The first order of the SPO3r spectrum showing the spectral wavelengths and the different segments where the fireball was analysed. The sodium line doublet (multiplet 1) shows the brightest lines, clearly visible around 5900 Å.

Table 1. Averaged Na I/Fe I atomic ratio, Na/Fe ratio after correction for ionization, and Si/Fe ratio derived from the second component after correction for ionization, for various spectra. For low-velocity meteors the silicon line was not present in the second component. In these cases we assumed a typical chondritic ratio of Si/Fe = 1.16 given in parentheses (Anders & Grevesse 1989). M_v denotes the visual magnitude of the fireball. m denotes the estimated mass of the meteoroids. Values in parentheses are only approximate.

Spectrum	V_g (m s^{-1})	M_v	m (g)	Na I/Fe I ($\times 10^{-4}$)	Na/Fe ($\times 10^{-2}$)	Si/Fe
KCIGr	23	−8.5	(600)	4 ± 1	9.3 ± 2.1	(1.16)
AND	24	−9	4000	6 ± 2	50 ± 20	(1.16)
SPO2	27	(−5)	(56)	9 ± 2	13 ± 5	(1.16)
SPO3	29	(−7)	(9000)	9 ± 4	9 ± 5	(1.16)
SPO3r	29	(−7)	(9000)	7 ± 1	9.5 ± 1.4	(1.16)
GEMr	36	(−6)	(4)	5 ± 1	12 ± 4	(1.16)
SPO4	57	−6	2	7 ± 2	10 ± 4	1.07 ± 0.18
PER2	60	(−8)	(1)	7 ± 2	9 ± 5	1.4 ± 0.5
PER3	60	(−8)	(4)	4 ± 1	10 ± 3	1.2 ± 0.3
PER4	60	(−9)	(29)	5 ± 2	12 ± 3	1.03 ± 0.22
PER5	60	(−7)	(6)	5 ± 3	8 ± 4	1.15 ± 0.11
PER1	60	(−6)	(0.2)	8 ± 1	10 ± 1	1.19 ± 0.17
SPO1	67.8	−12	21	11 ± 6	13 ± 8	1.2 ± 0.3
LEO	71	−12	250	7 ± 2	10 ± 4	1.23 ± 0.24

meteor radiating head could not be determined from photographic observations due to low resolution and the fact that the meteor spectra moved too quickly along the plate in the exposure interval. Only an upper limit for a could be obtained from the width of the meteor trail on the photograph. Assuming thermal equilibrium, the brightness of the spectral lines was computed by adjusting four parameters: temperature T, column density of atoms N, damping constant Γ, and surface area P (Borovička 1993). The surface area registered by the spectrograph is

$$P = ab \sin\theta. \quad (3)$$

From this equation we estimate the approximate ratio b/a for the analysed photographs, finding values between 0.5 and 4. In consequence, we assumed the ratio $b/a = 2$ for all spectra, the same value as taken by Borovička (1993). We will discuss the influence of this assumption in the final results.

The procedure was to use software to reconstruct a synthetic spectrum that allowed determination of these four parameters from the observed brightness of lines. This is done by the least-squares method implemented on the Borovička (1993) software. As most lines in the spectrum are of neutral iron, Fe I is taken as a reference element to adjust the intensity of lines and temperature. When T, Γ and P have been estimated, the software allows the column density N of any element to be changed. To obtain chemical abundances, the degree of ionization of different elements has been considered taking into account the ratio of neutral, singly and doubly ionized atoms given by the Saha equation. A more detailed explanation of the full procedure and the related theory is given in the original paper by Borovička (1993).

3 RESULTS AND DISCUSSION

3.1 Determination of sodium abundance from meteor spectra

Meteor spectra consist of two components, each with a different temperature, as described by Borovička (1994) and also confirmed in Paper I. The typical temperature of the main component is 4500 K and that of the second component is 10 000 K. We have obtained the abundance ratio relative to silicon for several elements, among them sodium, by comparison of the synthetic and observed spectra along several points in the trajectory of the 13 fireballs (Paper I). In the spectra produced by high geocentric velocity meteors, we can obtain directly the silicon abundance from the second component of the spectra where Si II lines are very prominent. Unfortunately, for slow meteors it is not possible to determine the Si abundance from the spectra. For these meteors the second component is very faint and Si II lines are usually missing. In such cases we assumed a typical chondritic ratio of Si/Fe = 1.16 (Anders & Grevesse 1989).

Sodium lines are omnipresent in meteor spectra. Their low excitation potential (2.1 eV) makes it possible to observe the Na I doublet (multiplet 1) at 5893 Å easily, not only in fireball spectra but also in faint video meteors with lower column densities (Borovička, Stork & Bocek 1999; Abe et al. 2000). In Table 2 the characteristic lines of the brightest segments of meteor spectra have been normalized to the intensity of the Na doublet. In this way it becomes possible to compare the relative intensity of Na lines with respect to neutral and ionized calcium (Ca I–Ca II), magnesium (Mg I and Mg II), neutral iron (Fe I) and ionized silicon (Si II). Ionized calcium comes from both the main and the second component, whereas ionized magnesium and silicon lines belong to the high-temperature component. From Table 2 it is clear that meteor velocity is an important factor in the intensity of the second component of spectra. Meteoroids with low geocentric velocities generate meteors with a faint second component.

We note that the intensity of the lines of the sodium doublet, in general terms, fully agrees with the computed synthetic spectra. This shows that the assumed physical parameters of the model are realistic. However, to rule out the presence of an artificial effect in the detected sodium abundance in meteor spectra, we must consider the influence of two important factors. The first is the influence of the assumed geometrical ratio b/a of the radiating volume, bearing in mind that this ratio is variable and unknown along the fireball trajectory. The second factor is related to the presence of a sodium layer in the region of meteor ablation in the atmosphere (Plane 1991).

In order to evaluate the influence of the b/a ratio on the derived sodium abundance, we recomputed the Na abundance in the brightest segment of several spectra with representative geocentric velocities, taking different b/a ratios into account in these calculations. The results clearly show that the differences in Na abundance are smaller than the relative dispersion errors (see Table 3). In consequence, the geometry assumed for the radiating volume only slightly affects the determination of relative chemical abundances.

On the other hand, the presence of metal layers in the upper atmosphere is well known (Plane 1991; Rietmeijer 2002a,b). These layers are explained by the constant entry of meteoroids that suffer ablation around these regions. The consequence of this continuous process is the deposition of metals and their accumulation in layers, mainly in the mesosphere (Plane 1991). We have therefore estimated the sodium column density in the brightest and faintest segments belonging to some of the fireballs analysed here. The results are given in Table 4. From Table 4 it can be deduced that the fireballs analysed have a sodium column density more than seven orders of magnitude larger that that deduced from LIDAR techniques in the Na mesospheric layer (Plane 1991). An important consequence of this result is that the sodium abundance detected in fireballs must

Table 2. Maximum calibrated intensities for the main lines of the analysed spectra. For comparison, the intensity of other bright lines have been normalized to that of the sodium doublet (Na I-1) in all spectra. For each element, the degree of ionization and multiplet number are given at each line. M_v denotes the visual magnitude of the fireball. Values in parentheses are only approximate.

Spectrum	V_g (m s^{-1})	M_v	Ca II-1 3934/3968 Å		Ca I-2 4227 Å	Mg II-4 4481 Å	Mg I-2 5184 Å	Fe I-15 5372 Å	Na I-1 5890 Å	Si II-2 6347 Å
KCIGr	23	−8.5	0.08	0.02	0.06	0.08	0.47	0.15	1	–
AND	24	−9	0.02	0.01	0.01	0.16	0.62	0.01	1	(0.003)
SPO2	27	(−5)	0.01	0.005	0.001	0.15	0.32	0.09	1	–
SPO3	29	(−7)	2.78	2.85	0.97	0.25	0.82	0.80	1	0.15
SPO3r	29	(−7)	1.08	0.92	0.34	0.17	0.79	0.81	1	–
GEMr	36	(−6)	3.13	1.88	0.63	0.38	0.75	1.06	1	–
SPO4	57	−6	2.04	1.87	0.09	0.50	0.79	0.01	1	0.12
PER2	60	(−8)	270.3	294.7	0.33	0.72	1.20	0.27	1	0.67
PER3	60	(−8)	2.83	3.12	0.08	0.42	0.55	0.01	1	0.81
PER4	60	(−9)	2.60	2.91	0.28	0.61	0.92	0.01	1	0.83
PER5	60	(−7)	2.19	2.65	0.05	0.72	0.91	0.006	1	1.16
PER1	60	(−6)	2.33	1.17	0.07	0.52	0.73	0.03	1	2.17
SPO1	67.8	−12	3.22	1.82	0.91	0.95	0.81	0.13	1	4.88
LEO	71	−12	102.1	100.2	0.87	0.91	1.35	0.84	1	1.49

Table 3. Na/Si abundances for different shapes of the meteor head in selected spectra.

Spectrum	V_g (km s^{-1})	Segment	Dispersion error	Na/Si $b = 2a$	Na/Si $b = 4a$	Na/Si $b = 6a$
AND	24	B	0.04	0.100	0.092	0.088
SPO3	29	A	0.01	0.057	0.056	0.055
GEM	38	J	0.03	0.105	0.098	0.091
SPO4	57	A	0.04	0.125	0.117	0.110
PER1	60	A	0.02	0.076	0.068	0.061
LEO	72	A & N	0.02	0.071	0.069	0.064

Table 4. Na column density of neutral and ionized atoms in several spectra.

Source of Na	Segment labels Max.	Min.	V_g (km s^{-1})	Na column density (cm^{-3}) Max.	Min.
AND	A	H	24	7.5×10^{11}	1.3×10^{11}
SPO3	A	N	29	1.6×10^{12}	3.7×10^{11}
GEM	J	D	38	1.3×10^{11}	7.1×10^{10}
SPO4	A	Z	57	6.5×10^{11}	3.3×10^{11}
PER1	A	D	60	4.9×10^{11}	2.3×10^{11}
LEO	A	N	72	6.5×10^{11}	1.6×10^{11}
[Na] in the atmosphere (Plane 1991)			–	10^4	10^3

be real and is not an artefact related to the presence of this element in the upper terrestrial atmosphere.

We have thus obtained the sodium abundance, relative to silicon, for 13 fireballs in order to compare them with other objects in the Solar system on a cosmochemical basis. This study is particularly valuable since in recent years important differences have been reported in the sodium content in comets. For example, the sodium abundance measured in the dust of comet 1P/Halley was *c.* 5 times the cosmic value (Jessberger, Christoforidis & Kissel 1988a; Jessberger, Kissel & Rahe 1988b; Anders & Grevesse 1989). In contrast to this, the observations of comet Hale–Bopp's sodium tail showed that the amount of sodium causing this tail is less than *c.* 0.1 per cent of the cosmic abundance (Cremonese & Fulle 1997; Cremonese et al. 1997). From meteor spectroscopy we have analysed the sodium content in meteoroids coming from different comets. The relative sodium abundance can be derived from meteor spectra because their lines are well defined in all spectra and the results are not sensitive to the assumptions. In consequence we think that, in a similar way as for other chemical elements, the sodium abundances derived from meteor spectra are realistic and show the presence of an important content of this element in meteoroids.

The abundance of sodium was obtained in several segments of each fireball and averaged as explained in Paper I. The errors were estimated from the dispersion of the abundance in all segments analysed. In the present paper we decided to avoid the faintest segments where the sodium values have larger dispersion errors. The results are given in Fig. 2, where we have arranged fireball data as a function of the geocentric velocity of the incoming meteoroid. For the sake of comparison, the cut-off of the *x*-axis allows us to show the measured abundance in interplanetary dust particles (IDPs), 1P/Halley dust (Jessberger et al. 1988a) and CI and CM carbonaceous chondrites (Rietmeijer & Nuth 2000). Clearly the estimated sodium abundances in meteor spectra are larger than the values of the other samples of interplanetary matter. It is quite significant that particles coming from periodic comets, such as 109P/Swift–Tuttle (meteors PER1 and PER4) and 55P/Tempel–Tuttle (LEO), display sodium abundances that are twice those of comet 1P/Halley dust measured from the *Giotto* spacecraft, although a silicon anomaly in Halley dust could also contribute to the low abundance ratio of Na/Si taking into account the unusually high Si/Mg and low Fe/Mg ratios shown by this comet. Other meteoroids of our sample show similar values, although on some occasions the typical values for interplanetary samples are inside the error bars. Moreover, it is remarkable that the GEM meteoroid, associated with the Phaeton asteroid, has a significantly high sodium content in comparison to chondritic meteorites that may be considered representative of asteroid samples. This observation supports the suggested cometary origin of Phaeton, which in fact has an albedo and orbital parameters that may well correspond to an extinct or a dormant comet, as has been previously suggested by other sources (Halliday 1988; Gustafson 1989; Williams & Wu 1993).

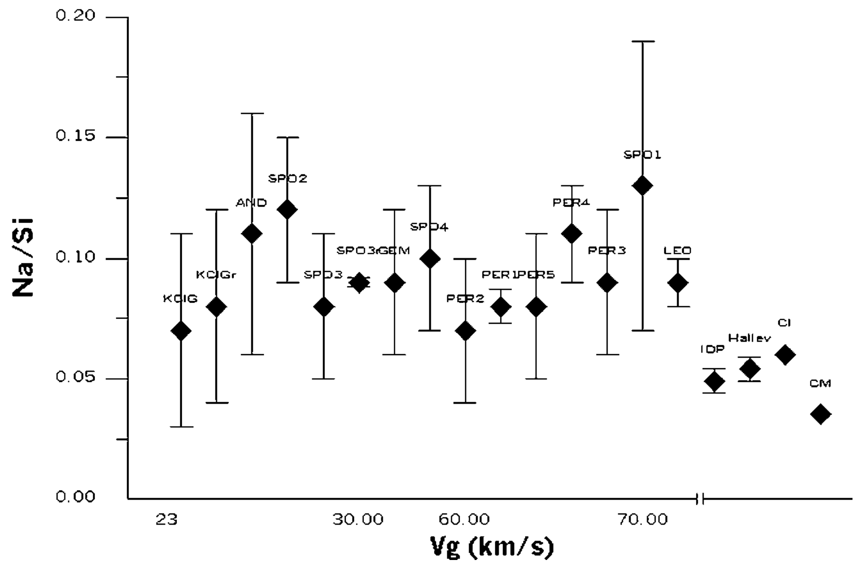

Figure 2. Relative chemical abundances of Na/Si for the analysed spectra. The spectra are ordered as a function of their geocentric velocity. The expected ratios for IDPs, CI and CM chondrites and 1P/Halley dust are included for comparison.

3.2 The hierarchical accretion of dust

In Paper I we provided evidence of the link between cometary meteoroids and IDPs. The only difference between the two definitions probably lies in the fact that IDPs survive atmospheric entry because they are smaller and are decelerated earlier than the melting temperature is reached. It is well known that IDPs in the geocentric velocity (v_g) range of 11 to ~20 km s^{-1} decelerate in the Earth's atmosphere at an altitude of between 100 and 80 km and only experience flash heating (Rietmeijer & Nuth 2000). This short heating event probably causes the loss of volatile elements such as sulphur and sodium. According to Rietmeijer (1999), sodium survives the flash heating in plagioclase ($NaAlSi_3O_8$–$CaAl_2Si_2O_8$), alkali feldspar [$(Na,K)AlSi_3O_8$] and layer silicate minerals present in aggregate IDPs. In spite of this, our results rather suggest that the amount of sodium measured in IDPs would not represent its original (pre-entry) abundance. The high-velocity meteoroids we analysed (all with $v_g > 25$ km s^{-1}) show that the sodium abundance is greater than that measured in IDPs. In fact, sodium lines in meteor spectra usually appear at high altitudes much earlier than the other observed elements, and it is also possible that an important amount of Na content is lost in a diffuse phase during the first stages of the ablation. Various mineral assemblages could be responsible for this sodium-rich diffuse phase, such as aqueous alteration-derived silicates and sulphates, which are well-known mineral phases present in CI and CM chondrites. The small grains or layers of these altered phases would be in this manner easily removed during ablation.

Considering the model of hierarchical dust accretion developed by Rietmeijer (2002b), the smallest grains slowly evolve into larger grains and, in doing so, trace elements in the oldest (smallest) dust are gradually concentrated. This process is well illustrated by analysing the presence of Na and K in IDPs (Rietmeijer 2002b). In fact, in amorphous Al-bearing silica materials, the smallest dust constituents of IDPs, Na and K are trace elements. However, the relatively younger clusters of IDPs contain discrete feldspar and plagioclase grains that are rich in sodium. The hierarchical dust accretion model of Rietmeijer (2002a) predicts that in unprocessed cometary debris the concentration of this chemical element will increase as the mass of the aggregates increases. In other words, the sodium content in most cometary meteors will be higher than in the collected IDPs and meteorites. Probably this difference denotes that meteorites are objects that may have had their sodium content altered during parent-body modification. Moreover, the differences observed in the sodium content between meteoroids producing meteor spectra and collected IDPs could also be a consequence of the fact that IDPs have probably been around in the Solar system for 100 000 yr or more, while comet dust, associated with dust trails or periodic meteor showers, is only several hundreds of years old (Hughes 1996; Greenberg 2000).

We have also evidenced the variation of relative sodium abundances along each one of the different fireball trajectories studied. Usually the volatilization of this chemical element occurs at the beginning of the meteor trajectory due to the high efficiency of volatilization of the mineral phases associated with this element. Fig. 3 shows, as an example, the evolution in the atmosphere of the LEO spectrum. From the spectroscopic analysis performed in this work, we are able to derive the temperature and relative abundances in the different regions of the fireball. Fig. 4 shows the temperature of the main component and the relative chemical abundance of sodium and other elements as a function of the meteor height. In this figure, the weakness of Na in the end part of the meteor (after the flare) can be clearly seen. Our data are complementary and consistent with recent video spectroscopy obtained by different teams (Borovička et al. 1999; Stork et al. 1999; Abe et al. 2000; Borovička & Jenniskens 2000; Borovička 2001) that reported the occurrence of an early release of sodium for an important number of cometary meteoroids and, particularly, the well studied and rich 1998 to 2000 Leonid returns. Usually these teams used image-intensified video cameras capable of registering fainter meteors than those included in our sample. Such systems are able to register meteors in the magnitude interval $-2 < M_v < +1$, which correspond to meteoroids in the mass range of $1 < m(\mathrm{g}) < 10^{-3}$, clearly below the masses given in Table 1 for our meteoroids, except for three Perseids and one Sporadic meteor.

Although in our meteoroid sample the sodium abundances are quite similar, we must note that important heterogeneity has been

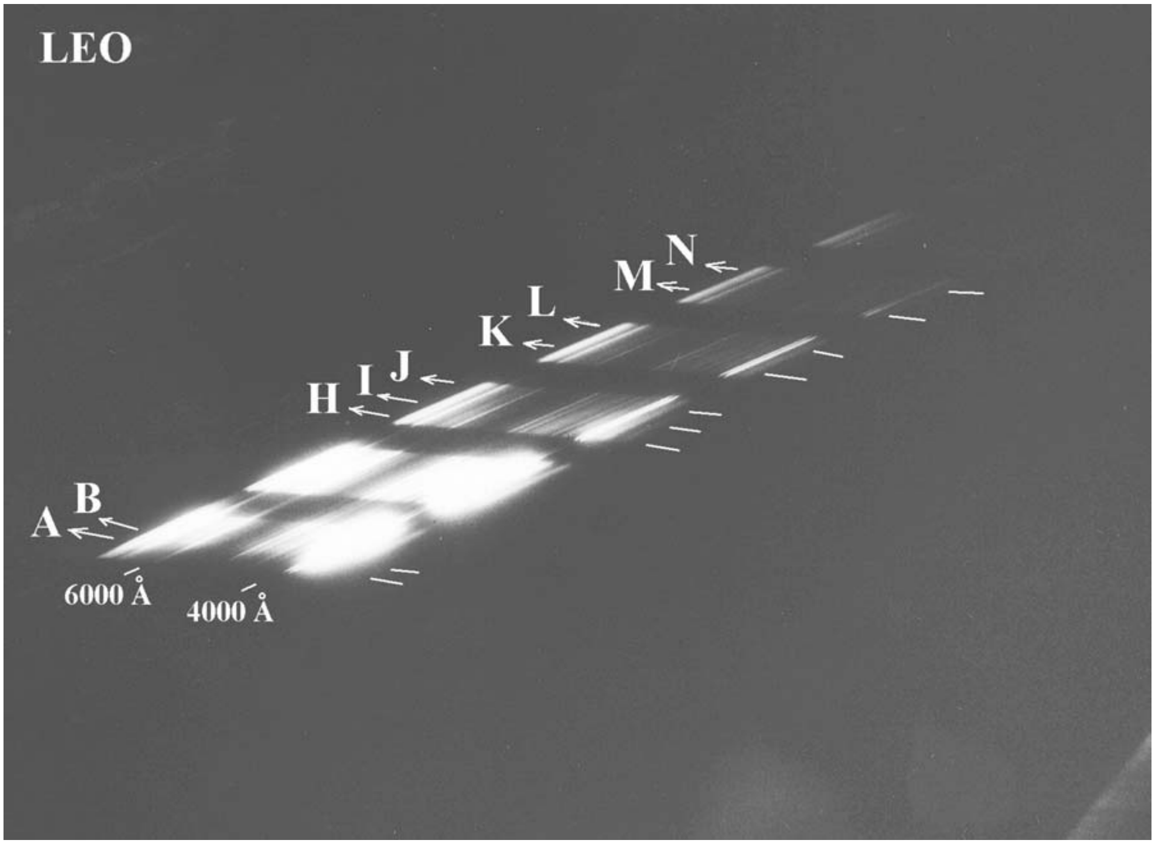

Figure 3. LEO spectrum showing the spectral wavelengths and the different segments where the fireball was analysed. Sodium emission shows luminosity changes along the fireball path. A bright flare between H and B scans saturated the brightest spectral lines and in consequence this region was not accessible for the study of the chemical abundances.

observed in larger meteoroids. Our results are also comparable to these previously obtained by several authors (Ceplecha 1964, 1965; Millman 1972; Harvey 1973; Nagasawa 1978; Borovička 1993; Borovička & Spurný 1996; Borovička & Betlem 1997). All these data on the relative abundances of the different elements existing in the literature, including the Na/Fe ratio, were previously compiled in Ceplecha et al. (1998). Several authors reported previously the appearance of fireballs where sodium lines were missing. For example, Halliday (1960) reported the spectra of a sporadic meteor around 50 g in mass where sodium lines were completely absent. According to the low velocity (13.2 km s^{-1}) and its orbit, this author suggested an asteroid origin. Also Spurný & Borovička (1999) reported the study of a unique fireball (Karltein, EN 010697) produced by an anomalous meteoroid in a retrograde orbit with a spectrum that was Na-free and Mg-poor despite its high geocentric velocity (69 km s^{-1}). Borovička (2001) also detected one of these anomalous Na-free meteoroids using video spectroscopy and also coming from a retrograde orbit similar to Karltein fireball.

3.3 1P/Halley dust abundances

Another important subject that can be discussed here is the observed difference between the sodium content in the meteoroids analysed here and the 1P/Halley composition analysed by the *Vega* and *Giotto* mass spectrometers (Kissel & Krueger 1987; Jessberger 1998a,b). In general the abundances from meteor spectra are greater than those measured for Halley dust (see Fig. 2). On analysing 1P/Halley particles, Fomenkova et al. (1992) noted three chemically distinct types of dust: CHON particles; particles rich in carbonaceous compounds and silicates; and mineral particles with Fe, Mg and Si as their main components. The organic CHON particles have not been recovered up till now in the terrestrial atmosphere, probably because of their fragility to solar radiation during their stay in the interplanetary medium or, as was suggested by Rietmeijer (2002a), due to their being fused during the flash heating that occurs on entry into the terrestrial atmosphere. Moreover, the *Halley* mass spectrometers detected only very small particles that have their mass equivalent to the so-called principal components (PCs) that are inside the matrix of IDPs. Neither PCs nor any other constituent (e.g. mineral grains) has chondritic element proportions (Rietmeijer 2002a). In consequence the measurements of *Giotto* spectrometers were biased towards small cometary particles poor in sodium. We think that this is the main reason that explains the low content of sodium in the Halley dust particles compared to our meteoroid sample.

Sodium has also been observed by means of spectroscopy in several cometary comae throughout the last century. Comets Mrkos, Ikeya–Seki, Seki–Lines, Bennett, Kohoutek, West, Halley and Hale–Bopp are clear examples (Nguyen-Huu-Doan 1960; Spinrad & Miner 1968; Rahe, McCracken & Donn 1976; Oppenheimer 1980; Combi, Disanti & Fink 1997; Cremonese & Fulle 1997). Unfortunately, dust particles from these comets did not intercept the Earth and it is not possible to study meteors from these sources, with the exception of 1P/Halley, which produces the Eta Aquarids and Orionid meteor streams that are only poorly studied by meteor

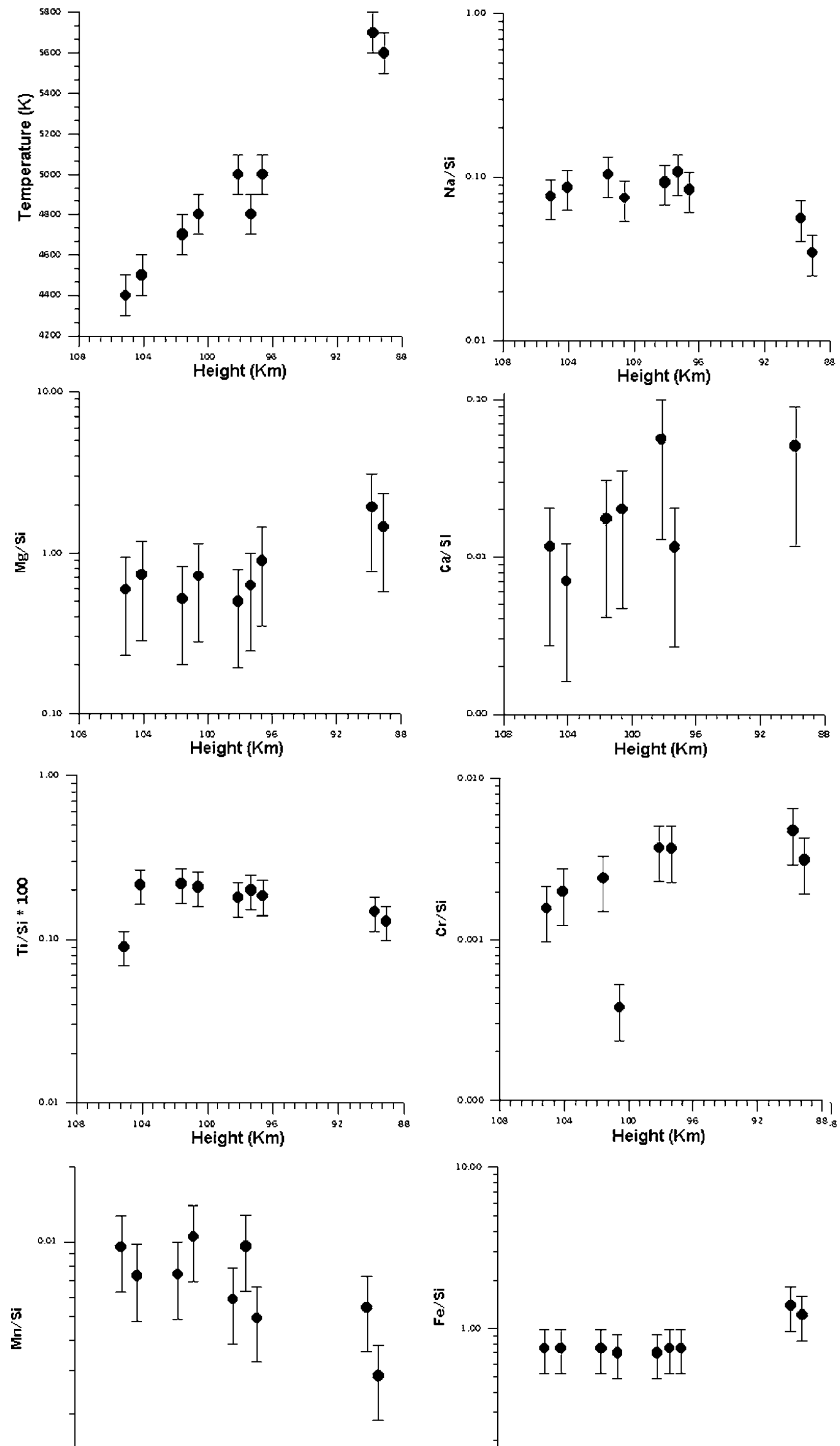

Figure 4. Temperature of the main component and relative chemical abundances as a function of meteor height for the LEO spectrum. We note that, despite the higher temperature in the end part, the sodium content is lower due to its being volatilized previously.

spectroscopy (Halliday 1987). From among the spectra analysed, we have derived the relative chemical abundances for five Perseids meteors produced by meteoroids coming from comet 109P/Swift–Tuttle. By averaging these abundances for a typical Perseid meteoroid, we can compare its abundances in relation to IDPs or CI chondrites (Fig. 5), which again demonstrates the value of meteor spectroscopy in providing additional information on matter coming from other comets. Qualitative data from cometary spectroscopy also supports the relatively high sodium content present in cometary meteoroids. For example, Hale–Bopp meteoroids probably

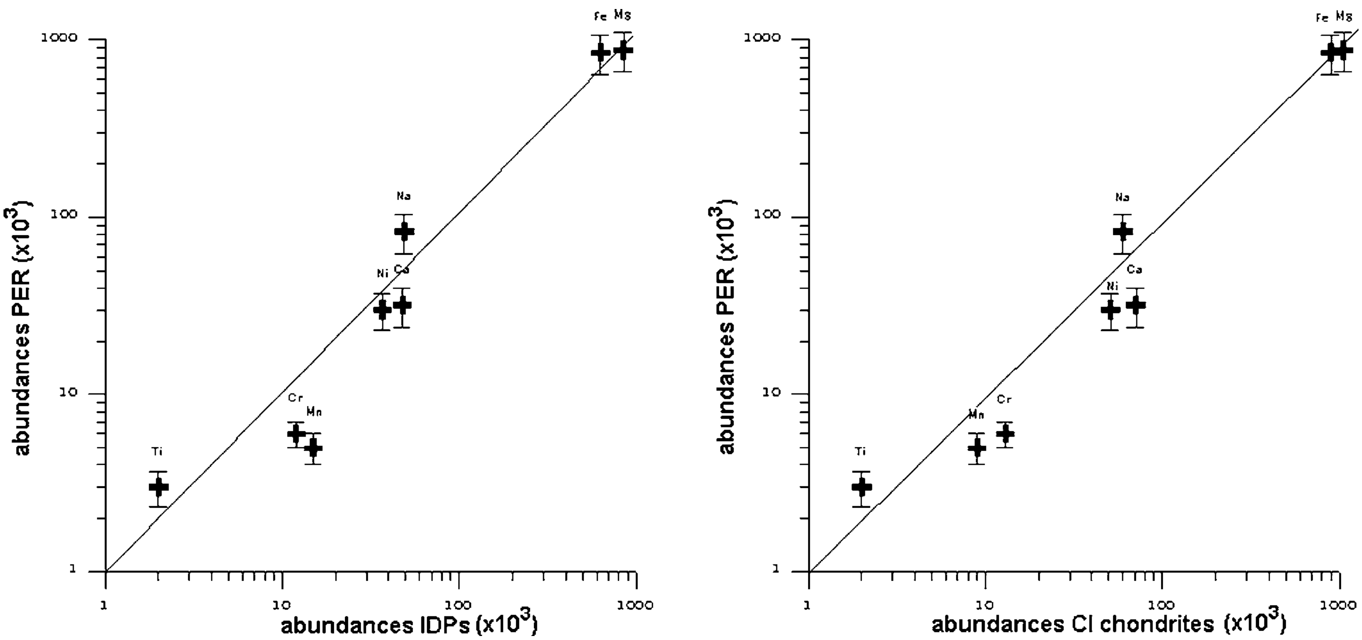

Figure 5. Five of the analysed spectra were produced by Perseids (meteoroids from comet 109P/Swift–Tuttle). By averaging the relative chemical abundances relative to silicon of these particles derived from meteor spectroscopy, they can be compared with the typical abundances of CI chondrites (right) and IDPs (left).

have a high sodium content since Cremonese & Fulle (1997) found two well-defined sodium tails. One narrow sodium tail of comet Hale–Bopp was explained by these authors as being due to a molecular process released from the comet nucleus. Another more diffuse sodium tail was proposed by these authors to be associated with the release of sodium atoms from dust particles (Rietmeijer 1999). Wilson, Baumgardner & Mendillo (1998) pointed out a diffuse sodium tail that was almost superimposed on the Hale–Bopp dust tail even several millions of kilometres away from the nucleus. Its morphology is consistent with a source of dust release produced by high-energy collisions between particles and the solar wind.

4 CONCLUSIONS

Meteor spectroscopy constitutes a valuable tool for the determination of relative sodium abundances in meteoroids. We have obtained evidence for a high content of sodium in meteoroids reaching the Earth compared to other samples of interplanetary materials analysed in laboratories. This clearly shows how meteor spectra can be used to determine chemical abundances in meteoroids without the need to collect them. We want to remark that, as we deduced the relative chemical abundances by averaging the different abundances measured at different heights, our dispersion values shown as error bars are probably larger than the real error introduced in the determination of abundances. We have shown that a detailed and averaged measurement along the meteor trail is an excellent way to study the process of differential ablation and to obtain relative chemical abundances with indicative limits for the dispersion of the mean values deduced from the meteor column.

We have confirmed the importance of differential ablation in the release of sodium from meteoroids. Ablation of Na-containing phases seems to occur suddenly in the upper part of the meteor's trajectory, which is in accordance with the results obtained by video spectroscopy (Borovička et al. 1999; Stork et al. 1999; Abe et al. 2000; Borovička & Jenniskens 2000; Borovička 2001) and LIDAR techniques (von Zahn 2001).

The overabundance of sodium reported here has important consequences because it shows that this element is lost very easily in the upper atmosphere during the atmospheric interaction. We also note that a part of the sodium content could be lost in the interplanetary medium. In fact, the 1ong-lasting characteristic trains and the differences observed in the photometric curves of young meteoroid material in comparison to annual meteoroids of the same shower (Trigo-Rodríguez 1992) could be associated directly to the different Na content, probably stored in some volatile compound which is easiest to be eroded in the interplanetary medium. As was proposed by Baggaley (1975), long-lived 1uminosity of meteor trains can involve the store of recombination energy of free atmospheric oxygen with sodium atoms continuously catalyzing the transformation of atomic oxygen to molecular oxygen by NaO formation, so that the dissociation energy of O_2 is converted into sodium light with the aid of the atmospheric species O_3 and O_2. Determination of a possible relationship between exposure times in the interplanetary medium determined for young Leonid meteoroids in basis to orbital modelling (Betlem et al. 2000; Trigo-Rodríguez et al. 2002) and the relative sodium abundances of young members of the stream as well as those characteristic of annual Leonid members is in progress. In fact, our observations suggest that *Giotto* measurements of 1P/Halley dust cannot be considered to be representative of cometary dust. The most probable reason for the relative absence of sodium in 1P/Halley dust is that the *Giotto* mass spectrometers detected only very small particles that have a mass equivalent to the principal components (PCs) in the matrix of IDPs. In consequence, the *Giotto* measurements were biased towards small cometary particles, which are not representative of other cometary particles reaching the Earth. Finally, our results have been seen to support the hierarchical dust accretion model proposed by Rietmeijer (2002a).

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