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Letter to the Editor

Thermal desorption of Na in meteoroids

Dependence on perihelion distance of meteor showers

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ABSTRACT

Context. The observed sodium abundance of meteoroids in meteor showers might differ from the original abundance because of processing in interplanetary space after ejections from their parent bodies. Among various processes, thermal alteration of alkali silicate is most likely the major process of Na depletion.
Aims. We clarify at which perihelion distances the thermal desorption alters the Na content of meteoroids that are observed as meteor showers.
Methods. We compile Na abundances of meteoroids in meteor showers at each perihelion distance and compare them to the sublimation temperatures of alkali silicates.
Results. Na abundances of meteoroids do not depend on their perihelion distances at $0.14 \leq q \leq 0.99$ AU. No Na depletion in these distances constrains the temperature of meteoroids at $q = 0.14$ AU to be lower than the sublimation temperature of alkali silicates ~900 K.
Conclusions. Meteoroid particles are characterized as large, compact, blackbody- like particles. On orbit with perihelion distances $q < 0.1$ AU, meteoroids would show evidence of thermal desorption of metals, in particular, Na.

Key words. meteors, meteoroids

1. Introduction

Sodium is a relatively abundant and moderately volatile element of meteoroids in meteor showers. Therefore, the abundance of Na in meteors is a good indicator for evolution of meteoroids during their residence in interplanetary space. Observed chemical abundances of meteoroids may be considerably altered from their original compositions by space weathering after ejections from their parent bodies.

Watanabe et al. (2003) carried out a spectroscopic monitor of comet 153P/Ikeya-Zhang at heliocentric distances between 0.5 and 0.8 AU. They found that the ratio of Na emission to continuum increased with decreasing heliocentric distance and suggested that thermal desorption from dust particles is the major mechanism for the variation of the Na emission/continuum ratio. Thermal desorption is produced by solar heating, which can sublimate Na-bearing materials in meteoroids and release Na. Subsequently, Furusho et al. (2005) found the same tendency of the Na emission for comet Hale-Bopp (C/1995 O1). If this is the case for all particles from any comets, we expect a correlation between the Na abundances of meteoroids and their perihelion distances.

Borovička et al. (2005) studied a correlation of orbital characteristics such as perihelion distance, aphelion, and Tisserand parameter with the Na-content of meteoroids in several meteor showers by analyzing the intensity ratios of Na I, Mg I, and Fe I emissions. They pointed out that meteoroids in orbit with perihelion distance smaller than 0.2 AU are Na-free. They attribute the Na-freeness of meteoroids to thermal desorption by solar heating. However, the intensity ratios do not directly reflect the elemental abundances of meteoroids but are merely the ratios of the emission intensities of neutral atoms. The intensity ratios depend not only on the abundances but also on the physical conditions such as the total mass of iron atoms and each velocity of meteor showers (Borovička 2001; Borovička et al. 2005; Koten et al. 2006). To study a possible effect of thermal desorption on the Na abundance, we concentrate on meteor showers for which the abundances have been derived by using electron densities. The present paper takes benefits from the great effort made in the last decade in obtaining chemical abundances in meteoroids of many meteor showers by using meteor spectroscopy (Kasuga et al. 2005a,b, 2006a,b; Borovička 1993; Borovička & Betlem 1997; Borovička et al. 1999; Trigo-Rodrìguez et al. 2003, 2004a, 2005).

In this letter, we compile the Na abundances of meteor showers to investigate the dependence of the Na abundances on the perihelion distances of meteoroids observed so far. We discuss thermal alteration and physical parameters of meteoroid particles by considering their sublimation temperatures.

2. Compilation of observational results

Figure 1 compiles the perihelion distances of meteoroid trails versus the abundance ratio Na/Mg in meteoroids derived so

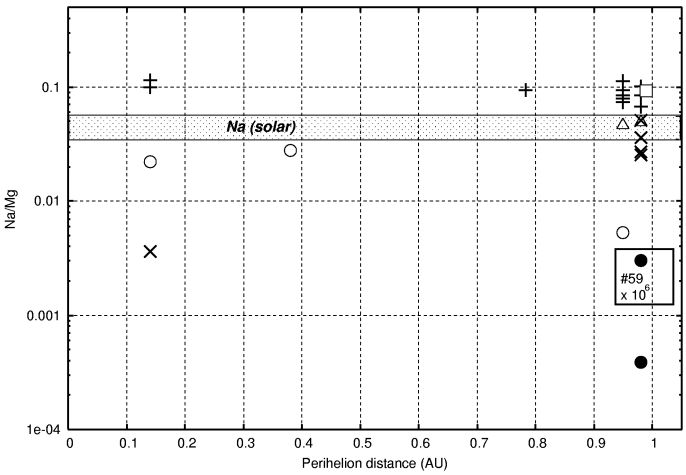

Fig. 1. Perihelion distance vs. Na/Mg ratios without indicating the errors of Kasuga et al. (2005b, 2006a) [×], Trigo-Rodrìguez et al. (2003, 2005) [+], Borovička & Betlem (1997); Borovička et al. (1999) [△], Nagasawa (1978) [•], Millman (1972) [□], Harvey (1973) [○] for Draconid (0.99 AU), Leonid (0.98 AU), Cygnid (0.98 AU), Perseid (0.95 AU), Andromedid (0.78 AU), Taurid (0.38 AU) and Geminid (0.14 AU). The shaded area shows the solar composition (Asplund et al. 2006). Leonid data: #59 of Nagasawa (1978) is shown as $\times 10^6$, because of its too small values (#59: 3.0×10^{-9}). Perihelion distance of Andromedid is obtained from Jenniskens & Lyytineen (2005).

far by using meteor spectroscopy (Kasuga et al. 2006a, 2005b; Trigo-Rodrìguez et al. 2003, 2005; Borovička & Betlem 1997; Borovička et al. 1999; Millman 1972; Harvey 1973; Nagasawa 1978). The solar abundances of Na and Mg are given by Asplund et al. (2006). The Na/Mg ratios for individual meteors are highly scattered around its solar ratio at any perihelion distance. We find no clear evidence for the depletion of Na with decreasing perihelion distance at $q \geq 0.14$ AU. It is worth noting that Halley's dust shows a large variation in its composition for each dust particle (Jessberger et al. 1988). Namely the composition of each cometary dust largely deviates from the solar, while the average composition of all the dust is the solar. We expect that the large variations in the Na abundances of meteoroids are the intrinsic nature of these meteoroids.

3. Meteoroid temperature

To assess the solar heating effect on the Na content in meteoroids during their orbital motion in interplanetary space, we plot in Fig. 2 the average Na/Mg abundance deduced using the data plotted in Fig. 1. Also indicated by a horizontal line and shaded area are a range of sublimation temperature of Na-bearing alkali silicates from 10^{-7} to 10^{-4} bar of total pressure; the former is sodalite ($Na_4(AlSiO_4)_3Cl$) and the latter is feldspar ($(Na, K)AlSi_3O_8$) (Lodders 2003; Field 1974; Rietmeijer et al. 1989; Fegley & Lewis 1980). We do not consider phyllosilicates produced by aqueous alteration because the present study focuses on the Na desorption by thermal alteration. Although Na resides partly in volatiles, its amount is negligibly small (Rietmeijer 1999). A blackbody has a temperature shown by a solid curve. For a reference, we show by dashed curve the temperature of 0.1 μm spherical grains composed of organic refractory whose optical constants are taken from Li & Greenberg (1997).

Figure 2 indicates that the Na abundances of meteoroids with perihelion distance $q \geq 0.14$ AU (Geminid, Taurid, Andromedid, Perseid, Cygnid, Leonid) are solar on average. Note that a blackbody temperature does not reach the sublimation temperature of Na-bearing silicates at perihelion distance $q \geq 0.1$ AU. At $q > 0.5$ AU, the temperature of meteoroids does not reach the sublimation temperature of alkali silicates even if they were submicron organic particles.

4. Discussion

No apparent depletion of Na for meteoroids with perihelion distance $q \geq 0.14$ AU indicates that the temperature of meteoroids at $q = 0.14$ AU must be below the sublimation temperature of alkali silicates (see Fig. 2). Here, Na-bearing alkali silicate in meteoroids is most likely in the form of sodalite rather than plagioclase feldspar, because Na in Halley's dust shows a strong correlation with Cl (Jessberger et al. 1988). Therefore, sodalite gives essentially an upper limit on the temperature, at which Na in meteoroids starts suffering from sublimation. The sublimation temperature of sodalite is approximately 20% higher than the blackbody temperature at $q = 0.14$ AU. As a result, we find that the temperature ratio of meteoroids to a blackbody lies in the range of 1.0–1.2. To speculate a realistic temperature of meteoroids, we compare it with the superheat S of dust particles in cometary trails, S being the ratio of the observed color temperature $T_{\rm color}$ to the blackbody temperature $T_{\rm BB}$. Superheat derived from observations of several cometary dust trails ranges from 1.0 to 1.3 (Sykes & Walker 1992; Kraemer et al. 2005). This is consistent with our constraints on the range of temperatures that meteoroids would have. This implies that meteoroid's temperature is closer to the blackbody temperature than the temperature of sub-micron organic particles and that the size of meteoroids is likely larger than infrared wavelengths. Observations of cometary dust trails reveal that trail particles have small β-values of 10^{-5} to 10^{-3}, β being the ratio of solar radiation pressure to solar gravity (Ishiguro et al. 2002, 2003). This small β-values for trail particles are consistent with those values inferred for Leonid meteoroids (Trigo-Rodrìguez et al. 2002, 2004b). This allows us to draw a picture that trails and meteoroids consist of relatively compact aggregates, because highly fluffy aggregates do not attain such small β-values (see Kimura et al. 2002 for β-values of fluffy aggregates). We conclude that the temperature and structure of meteoroids are well characterized by the properties of relatively compact agglomerates of blackbody-like grains.

Diversity of Na content in Geminids ($q \sim 0.14$ AU) may show the primitiveness of Geminids meteoroids and, in turn, of its parent body: (3200) Phaethon. Green et al. (1985) and Birkett et al. (1987) considered Phaethon to have a rocky-asteroid surface rather than having a cometary appearance. However, as noted by Hsieh & Jewitt (2005), Phaethon might have had a cometary activity that was extinguished after exhaustion of volatile icy materials in its surface layer. Phaethon has the orbital period of ~1.5 yr and ejected Geminids meteoroids more than 1000 years ago (Williams & Wu 1993). The dust mantle on the surfaces of short period comets is expected to consist of relatively compact aggregate particles after sublimation of volatile materials (Kolokolova et al. 2006). During the frequent revolution of (3200) Phaethon in a short period, blackbody-like compact dust aggregates accumulating at the surface of Phaethon may have halted its cometary activity.

For Geminids, no Na depletion is seen on average from the abundance ratios as shown in Fig. 2. On the contrary, systematic Na depletion is reported from observations of the intensity ratios (Borovička 2001; Borovička et al. 2005). Borovička et al. (1999) remarked that submillimeter-sized particles have low Na

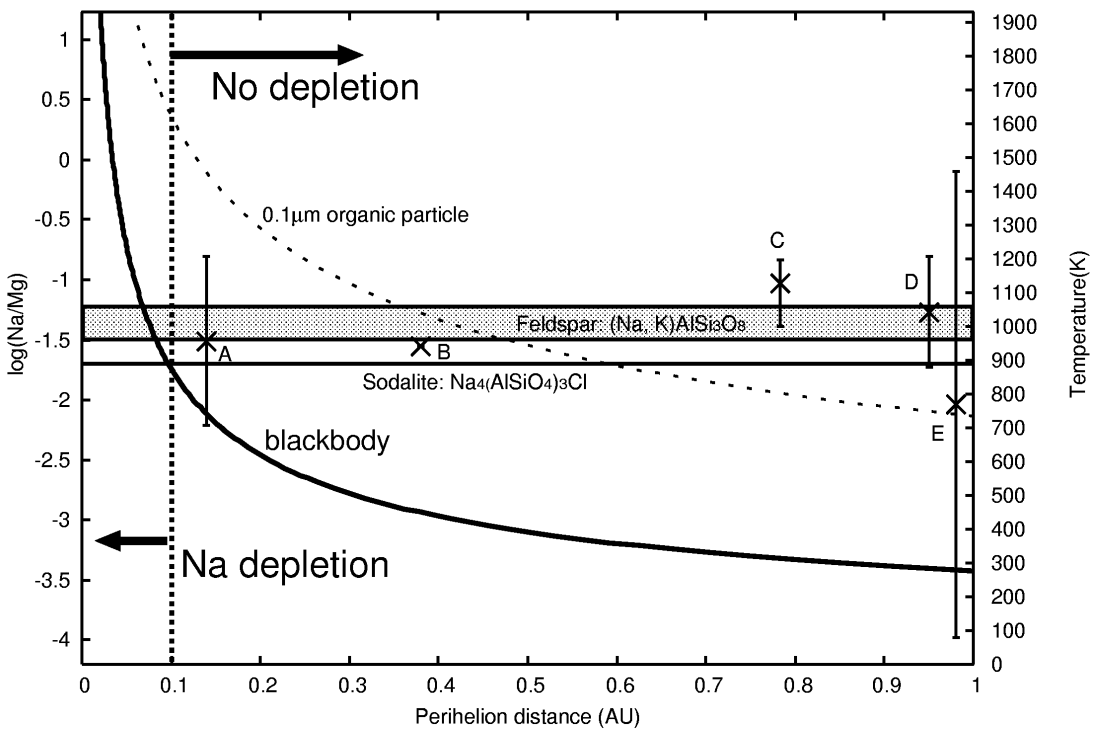

Fig. 2. Temperatures of dust particle as a function of the perihelion distance. Also plotted are the averaged Na/Mg ratios deduced from data in Fig. 1. Sublimation temperature of sodalite is shown by the horizontal line (the right axis). The stripe band shows solar Na/Mg ratio (the left axis) and sublimation temperature of feldspar (the right axis). The perihelion distances of meteor showers are $q \sim 0.14$ AU (A) for Geminid, 0.38 AU (B) for Taurid, 0.78 AU (C) for Andromedid, 0.95 AU (D) for Perseid, 0.98-0.99 AU (E) for Leonid, Cygnid and Draconid. The Na/Mg ratio at $q = 0.38$ AU (B) is determined by one Taurid data (Harvey 1973). The error of Andromedid is the standard deviation between the derived abundances along the meteor trajectory (Trigo-Rodrìguez et al. 2003).

content. Trigo-Rodrìguez et al. (2005) suggested that the Na content depends on the particle mass. If these are the cases, other elements would also be depleted. Whether such a small-particle effect is at work is an open question. Here, we have to admit that the Na abundance of Geminids we derived has a large uncertainty statistically, because the number of Geminids meteoroids used is only four. Therefore, we might have missed to observe a possible tendency of slight Na depletion if it exists. If Na were released partially from meteoroids at $q \sim 0.14$ AU, the possible Na depletion would be related to non-thermal effects such as electron and photon stimulated desorption (sputtering) as seen in Mercury and Moon (Madey et al. 1998). To clarify whether such space weathering is in effect at $q \sim 0.14$ AU, we need further observations of Geminids with a correct estimate of an electron density which allow us to derive its Na abundance.

Babadzhanov (2002) reported that Geminids ($q \sim 0.14$ AU) and δ-Aquarid ($q \sim 0.07$ AU) have bulk densities $\rho = 2.9 \pm 0.6$ g/cm^3 and $\rho = 2.4 \pm 0.6$ g/cm^3 much higher than other cometary meteoroids such as Leonids ($q \sim 1$ AU) of $\rho = 0.4 \pm 0.1$ g/cm^3. This might indicate that parent bodies possibly have different densities and composition. We suggest that meteoroids at $q \leq 0.14$ AU would have suffered from compaction during anisotropic sublimation of volatile materials (see Mukai & Fechtig 1983). This packing effect may be linked to the sublimation of organic refractories rather than to the sublimation of Na-bearing silicates. A laboratory experiment on sublimation of organic refractory materials shows that the organics sublimated completely at temperatures above 553 K (Nakano et al. 2003). Therefore, we expect that the temperatures of meteoroids at $q = 0.14$ AU is high enough to induce the packing effect on fluffy aggregates by sublimation of organic refractories.

For meteoroids with $q \leq 0.1$ AU, a blackbody temperature exceeds the sublimation temperature of alkali silicate. If the temperature of meteoroids is approximately a blackbody temperature, Na in meteoroids should be lost by sublimation. Looking at Fig. 14 of Borovička et al. (2005) derived from the intensity ratios, we find that all meteoroids with $q \leq 0.1$ AU have Na-free properties. In fact, δ-Aquarid meteors in orbits with perihelion distance $q \sim 0.07$ AU are Na-free. For sporadic meteors with extremely small perihelion distance (~0.03 AU), not only Na but also Mg and Fe are depleted, although their intrinsic compositions are unknown. These findings are consistent with our conclusion that meteoroids have a nearly blackbody temperature.

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