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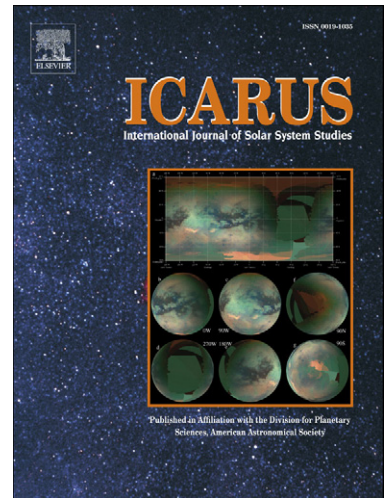
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**Quantitative model of the release of sodium from
meteoroids in the vicinity of the Sun:
Application to Geminids.**

David Čapek and Jiří Borovička

Astronomical Institute of the Academy of Sciences
25165 Ondřejov Observatory, Czech Republic

capek@asu.cas.cz, borovic@asu.cas.cz

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Editorial correspondence to:

David Čapek

Astronomical Institute of the Academy of Sciences

Fričova 298

251 65 Ondřejov

Czech Republic

E-mail adress: capek@asu.cas.cz

Abstract

A considerable depletion of sodium was observed in Geminid meteoroids. To explain this phenomenon, we developed a quantitative model of sodium loss from meteoroids due to solar heating. We found that sodium can be lost completely from Geminid meteoroids after several thousands of years when they are composed of grains with sizes up to $\sim 100\mu\text{m}$. The observed variations of sodium abundances in Geminid meteor spectra can be explained by differences in the grain sizes among these meteoroids. Sodium depletions are also to be expected for other meteoroid streams with perihelion distances smaller than $\sim 0.2\text{ AU}$.

In our model, the meteoroids were represented by spherical dust-balls of spherical grains with an interconnected pore space system. The grains have no porosity and contain usual minerals known from meteorites and IDP's, including small amount of Na-bearing minerals. We modeled the sequence of three consecutive processes for sodium loss in Geminid meteoroids: (i) solid-state diffusion of Na atoms from Na-bearing minerals to the surface of grains, (ii) thermal desorption from grain surfaces and (iii) diffusion through the pore system to the space. The unknown material parameters were approximated by terrestrial analogs; the solid-state diffusion of Na in the grains was approximated by the diffusion rates for albite and orthoclase.

Key words: meteors, interplanetary dust, mineralogy

1 Introduction

Sodium is a relatively volatile element. It can easily diffuse and escape from the source body when heated on orbit. For example, sodium tails of comets consist from Na atoms released from cometary dust particles (e.g. Rietmeijer, 1999; Leblanc et al., 2008) and the Mercury's surface material is depleted of sodium due to solar heating (e.g. Domingue et al., 2007).

Recently a similar phenomenon was observed in meteoroids. Borovička et al. (2005) studied relative intensities of the lines of Mg, Na and Fe in spectra of mainly sporadic meteors. They compared these measurements with theoretical line intensities for chondritic material. Substantial sodium depletion was found for some meteoroids on Halley type orbits and for almost all bodies on Sun-approaching orbits with perihelia smaller than $q \leq 0.2$ AU. Five Sun-approaching meteoroids were sporadic meteors, three belonged to the δ -Aquadrid stream. The loss of Na was explained by solar heating, analogously to the processes of Na depletion of Mercury's surface. The spectra of Geminid meteoroids ($q = 0.14$ AU) also showed Na depletion, but to a smaller extent and with large variations of sodium spectral line intensity from meteor to meteor. These variations were interpreted as a result of different age of Geminid meteoroids (Borovička et al., 2005).

Kasuga et al. (2006) compiled spectroscopy data for several meteor streams, and found no correlation of Na abundance with perihelion distance in the range 0.14 – 0.99 AU. They expected sodium depletion only for meteoroids with perihelion $q < 0.1$ AU, since the corresponding perihelion black body temperature is higher than sublimation temperature of sodalite.

The Geminids orbit the Sun on an eccentric orbit with perihelion 0.14 AU

and semimajor axis 1.357 AU. Borovička (2006) has published results of analysis of 89 Geminid meteor spectra. Sodium abundances were found to be $2 - 10\times$ lower than compared to its solar photosphere and CI chondrites abundances (Lodders, 2003). Escape of sodium due to solar heating near the perihelion was suggested as an explanation of this phenomenon. Three possible explanations were suggested for the large variations in sodium contents: (i) age differences among Geminid meteoroids, (ii) gradient of Na content in the surface layer of the parent body of the Geminid stream - (3200) Phaethon, (iii) heterogeneities in Phaethon-like material on millimeter scales.

Up to now, no quantitative study concerning the processes of sodium depletion in meteoroids has been made. The aim of this study is to develop a quantitative model describing the release of sodium from 1 mm–10 cm meteoroids due to solar heating and answer the following questions: (i) Which processes participate in the sodium release? Are these processes able to deplete sodium from its initially chondritic abundance to the observed abundances? (ii) What causes the large variations of Na abundance among different Geminid meteoroids? (iii) Can we expect sodium depletion for meteoroid streams other than Geminids and δ -Aquadrids?

2 Meteoroid structure

The behaviour of shower meteoroids in the Earth's atmosphere indicates that most of these bodies have low densities and high porosities. They were modeled as so-called dust-balls, i.e. conglomerates of large number of grains, which are poorly bonded together (e.g. Hawkes and Jones, 1975; Campbell-Brown and

Jones, 2003; Borovička et al., 2007). Geminid meteoroids are much stronger and of lower porosity compared to most meteoroids (Babadzhanov, 2002; Koten et al., 2004), possibly as a result of thermal alteration in the vicinity of the Sun (this implies different structure - especially higher porosity - in the past) or due to unusual (relative to most meteoroids) material properties of the parent body (Borovička et al., 2005; Kasuga et al., 2006; Licandro et al., 2007).

In the present study, we use a model for a Geminid meteoroid that is assumed to be a nearly spherical unit that consists of spherical grains. The grain mass distribution is described by a power law:

$$dn \propto m^{-s} dm, \quad (1)$$

where dn is the number of grains with masses in the infinitesimally small interval $(m, m + dm)$ and s is the mass-distribution index. The maximum and minimum grain masses are m_{\max} and m_{\min} . The grain masses are separated into bins $i = 0 \dots N$ with masses

$$m_i = m_{\max} q^i, \quad (2)$$

where $N = \log(m_{\min}/m_{\max})/\log q$ and q is the mass-sorting parameter. The number of grains with mass m_i is given by

$$n_i = m_i^{1-s} m / \sum_{j=0}^N m_j^{2-s}, \quad (3)$$

where m represents the total mass of the meteoroid.

The meteoroid is further described by its porosity defined as $p = 1 - \rho_{\text{bulk}}/\rho_{\text{fg}}$, where ρ_{fg} is the mean density of the grains and ρ_{bulk} is the bulk density of the meteoroid. Mean pore size d_{pore} can be estimated as

$$d_{\text{pore}} = d_{\text{fg}} \left(\frac{\rho_{\text{fg}}}{\rho_{\text{bulk}}} - 1 \right)^{1/3} = d_{\text{fg}} \left(\frac{p}{1-p} \right)^{1/3}, \quad (4)$$

where $d_{\text{fg}} = \frac{2}{N} \sum_i n_i (3m_i/4\pi\rho_{\text{fg}})^{1/3}$ is the mean size of the grains.

Thus, there are several parameters that determine the structure of a meteoroid. The maximum and minimum grain masses m_{max} , m_{min} (or diameters d_{max} , d_{min}) and mass-distribution index s are collectively called *granularity* in the following text. The density of grains ρ_{fg} and bulk density of the meteoroid ρ_{bulk} (or porosity p) must be known for determination of the mean pore size.

Granularity can be estimated from the fragmentation behaviour of meteoroids in the atmosphere. Recently Borovička et al. (2007) applied the model of quasi-continuous release of constituent grains from a meteoroid during its flight through the atmosphere to the observed behaviour of 7 Draconid meteoroids. They found the grain sizes ranged from $16\mu\text{m}$ to $108\mu\text{m}$ and that the mass-distribution index s was between 1.8 and 2.7.

The grain sizes and mass-distribution index for Geminid meteoroids are unknown. We will use plausible values using observational evidence from interplanetary dust particles (IDPs). The grain sizes can possibly range from typical sizes of aggregate IDPs, $10-25\mu\text{m}$, to sizes of cluster IDPs, $100-500\mu\text{m}$, (Rietmeijer and Nuth, 2004). In our modeling, we will keep granularity of meteoroids as free parameter.

3 The temperature of the meteoroid

The temperature T is a key quantity, which affects the processes of the release of sodium that can be computed from the heat diffusion equation. The radially

symmetric heat diffusion problem was solved numerically by implicit Crank-Nicholson scheme for meteoroid diameters from 1 mm to 10 m with Phaethon (Bond) albedo $A = 0.11$ and emissivity $\epsilon = 0.89$. The temperature dependence of the heat capacity c_v was taken from Winter and Saari (1969) and the temperature dependence of the thermal conductivity K was adopted from Urquhart and Jakosky (1997).

It was found, that the temperature of Geminid meteoroids varies from 179 K at aphelion to 745 K at perihelion. If realistic values of thermal conductivity $K \geq 0.02 \text{ Wm}^{-1}\text{K}^{-1}$ are considered, then bodies smaller than $\simeq 10 \text{ cm}$ are isothermal. Their temperature can be estimated by the expression

$$T = \left(\frac{(1-A)\mathcal{E}_0}{4\epsilon\sigma_{\text{SB}}d^2} \right)^{1/4}, \quad (5)$$

where $\mathcal{E}_0 = 1366 \text{ W/m}^2$ is the solar constant at 1 AU and d is heliocentric distance in astronomical units and $\sigma_{\text{SB}} = 5.6697 \times 10^{-8} \text{ JK}^{-4}$ is Stephan-Boltzmann constant. A colder core forms inside Geminid meteoroids larger than $\sim 50 \text{ cm}$.

4 The release of sodium

Sodium represents an important component of the exosphere of Mercury and it was shown, that a large fraction was derived from the planet's surface. The processes of sodium release were extensively studied (e.g. the review of Domingue et al., 2007) and several phenomena were suggested to participate in sodium release: solid-state diffusion, regolith diffusion, thermal desorption, photon stimulated desorption, solar wind sputtering, etc. (e.g. Killen et al., 2004; Leblanc

and Johnson, 2003; Hunten and Sprague, 1997; Potter, 1995; Cintala, 1992; Sprague, 1992, 1990; Killen, 1989; Morgan et al., 1988; Cheng et al., 1987; Ip, 1986; McGrath et al., 1986).

In the presented model of sodium release from meteoroids we will not consider sputtering and photon stimulated desorption because they act only on the surface of the meteoroid and they are inefficient in comparison with thermal desorption which acts even inside the porous meteoroid. We will not consider regolith turnover or collisions with IDPs that denudes only the subsurface layer. The volume of resulting microcrater is evaporated and it leads to meteoroid size reduction, but not to the change of the sodium abundance in the remaining material.

Na atoms are contained in sodium-bearing minerals inside the grains. The escape of sodium consists from several steps:

1. Sodium diffuses from Na-bearing minerals through their crystal lattice and along grain boundaries to the surface of grains,
2. sodium is released from the grain surfaces to the pore system of the meteoroid by thermal desorption, and
3. sodium atoms diffuse through the pore system to the surface of the meteoroid and escape into the space.

4.1 Solid-state diffusion

The role of solid-state diffusion for the release of Na into the Mercury's exosphere was studied for example by Sprague (1990, 1992) and Killen (1989). Diffusion is a thermally activated process, by which atoms, ions or molecules migrate within

a medium in the absence of a bulk flow. The movement is generally caused by gradient of chemical potential (concentration), temperature gradient or both (Ganguly, 2002; Brady, 1995). Diffusion at high temperatures in solids occurs mainly by volume diffusion through crystalline lattice due to point defects, like vacant sites or interstitial ions and at lower temperatures by grain-boundary diffusion due to line and surface defects like grain boundaries or dislocations (Freer, 1981).

The diffusion flux \mathbf{J} ($\text{m}^{-2}\text{s}^{-1}$) of specific component follows the phenomenological Fick's law: $\mathbf{J} = -D\nabla c$, where c represents concentration (m^{-3}) and D is the diffusion coefficient of the component (m^2s^{-1}). If the solid is homogeneous and isotropic and diffusion coefficient is independent on position, the diffusion equation reads (Freer, 1981):

$$\frac{\partial c}{\partial t} = D\nabla^2 c. \quad (6)$$

The diffusion coefficient D varies over several orders of magnitude depending on temperature. The temperature dependence of the diffusion coefficient is described by the Arrhenius law:

$$D = D_0 \exp(-Q/RT), \quad (7)$$

where the pre-exponential factor D_0 corresponds to $D(T = \infty)$, Q is the activation energy (J mol^{-1}), R is the gas constant ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$) and T is the temperature (K). The compilations of experimentally determined values of D_0 and Q can be found in Freer (1981) and Brady (1995). The available diffusion data are listed in Table 1.

Since our intention is to compute the changes of sodium abundance during

much larger time scales than the orbital period is, it is useful to introduce the characteristic diffusion coefficient D_{ch} by averaging over time:

$$D_{\text{ch}} = \frac{1}{t'} \int_{t=0}^{t'} D(T(t)) dt \quad (8)$$

This quantity can be used for comparison of diffusion rates in case of temperature variations with time.

In our model, we assumed that Na atoms initially diffuse through the crystal lattice of sodium-bearing minerals that form a minor component of the grain volume. Subsequently, Na diffuses through the rest of the grain, especially through the planar defects and mineral boundaries, to the surface of the grain. There are no data concerning mineralogy of Geminid meteoroids and we do not precisely know what is the grain composition and which sodium-bearing minerals could be present in the grains. It is reasonable to assume that the grains contain the usual components known from meteorites, IDP's or comet Wild, namely olivine, pyroxene, metal, sulfides etc., as well as a minority of sodium bearing minerals like plagioclase, alkali feldspar, Na-Al silicate glass, or roedderite (Rietmeijer, 2008). There are no measurements of sodium diffusion in this kind of cosmic material. Thus we had to estimate the value of diffusion coefficient of the whole grain on the basis of measurements of terrestrial materials (Table 1). We selected the following two measurements:

Orthoclase. The data of Foland (1974) for orthoclase Or_{94} was used as a limit for the slowest possible diffusion (reference “k” in Table 1). The resulting characteristic diffusion coefficient for meteoroids on Geminid orbits is $D_{\text{char}} = 1.3 \times 10^{-21} \text{ m}^2\text{s}^{-1}$. The value of D_{char} is roughly $10\times$ lower than other data for feldspars. The actual value of D_{char} is probably

higher than the experimentally determined limit of diffusion in orthoclase because there may be a lot of accessible channels such as grain boundaries, and line and surface defects of the crystal lattices inside the grain.

Albite. Another diffusion data is that of Bailey (1971) for albite (reference “j₁” in Table 1). The characteristic diffusion coefficient for Geminid meteoroids is $D_{\text{char}} = 1.4 \times 10^{-20} \text{ m}^2\text{s}^{-1}$, i.e. approximately 10× higher than for orthoclase. We considered it to be a more realistic value.

Since the extrapolation of experimentally determined values of D_0 and Q to temperatures different from the range of measurements is problematic (Freer, 1981), the diffusion data of Bailey (1971) for albite (reference “j₂” in Table 1) was used for the lower temperatures near aphelion in both cases. However, as temperature decreases at larger heliocentric distances, the diffusion coefficient drops by many orders of magnitude and the diffusion of sodium freezes (see Fig. 1). Thus, the efficient diffusion and release of sodium takes place only in a very short time interval during close approach of meteoroids to the Sun - typically during less than 6 weeks. For example, 3 weeks after the perihelion passage the diffusion coefficient for albite drops to 1/1000 of the characteristic diffusion coefficient D_{char} .

Fig. 1
Table 1

4.2 Release of sodium from grain surfaces

The importance of thermal desorption among the processes of releasing Na atoms from the surface of Mercury was shown for example by Leblanc and Johnson (2003) or Hunten and Sprague (1997). Thermal desorption (or thermal vaporization) is the only process of Na release from the grain surfaces in the

present model. According to Killen et al. (2004)¹, the thermal vaporization rate is given by

$$R_{\text{vap}} = \sigma f \nu_0 \exp(-U_b/k_B T), \quad (9)$$

where σ is surface number density of atoms, $f = (c_{\text{Na}}/c_{\text{all}})_{\text{surf}}$, that represents the fraction of Na atoms on the grain surface, ν_0 and U_b are the vibration frequency and binding energy of Na atoms, respectively, and $k_B = 1.381 \times 10^{-23} \text{ J K}^{-1}$ is the Boltzmann constant. The equation (9) serves as a boundary condition² at the surface of a spherical meteoroid grain:

$$D \nabla c_{\text{Na}} = -\sigma f \nu_0 \exp(-U_b/k_B T). \quad (10)$$

The following values were used: $\nu_0 = 10^{13} \text{ Hz}$, $U_b = 1.85 \text{ eV}$ (Yakshinskiy et al., 2000), and $\sigma = 7.5 \times 10^{18} \text{ m}^{-2}$ (lunar value, Heiken et al. (1991)). The resulting thermal vaporization rate from the surface is much higher than refilling of sodium by diffusion from the grain interior. The concentration of sodium on the grain surface therefore approaches zero. Numerical computations showed that the boundary condition (10) with these values, gives the same results as the assumption of zero sodium concentration on the grain surface.

$$c_{\text{surface}} = 0. \quad (11)$$

¹Killen et al. (2004) as well as Leblanc and Johnson (2003) gave positive binding energy U_b and term $\exp(U_b/k_B T)$ instead of $\exp(-U_b/k_B T)$, probably due to typographical error.

²This is so-called Fourier's surface condition (Woodward, 1901).

4.3 Diffusion in pore system of meteoroid

Sprague (1990) and Killen (1989) studied diffusion of sodium in lunar and Mercurian regolith. It was shown, that it is much faster, than solid-state diffusion. Diffusion in the pore system of a meteoroid can be described by the same formalism. It follows Eq. (6) with an appropriate diffusion coefficient, which depends on adsorption time τ and mean free path λ of Na atoms (which be set equal to the mean pore size d_{pore}). According to Sprague (1990), the diffusion coefficient is

$$D_{\text{pore}} = \lambda^2 / \tau, \quad (12)$$

and residence time for adsorption is

$$\tau = \tau_0 \exp(U_b / k_B T), \quad (13)$$

where $\tau_0 \simeq 10^{-13}$ s is a vibration time for Na in the van der Waals potential.

Let us now estimate how fast the pore diffusion is. For this purpose it is useful to introduce the diffusion time t_{dif} :

$$t_{\text{dif}} = L^2 / (4D_{\text{char}}), \quad (14)$$

where L is the diffusion length (Tajčmanová et al., 2007). In a fine-grained Geminid meteoroid, the speed of sodium diffusion in pores will be slower than in a coarse-grained Geminid meteoroid. Thus, let us suppose a fine-grained structure with grain sizes $d = 16 - 40 \mu\text{m}$, $s = 1.8 - 2.8$ and low porosity $p = 3\%$. Then, mean grain size is $d_{\text{fg}} = 18 \mu\text{m}$, mean pore size is $d_{\text{pore}} \simeq 6 \mu\text{m}$ (Eq. 4). We assume an ideal case with 100% pore connectivity and then:

$D_{\text{pore}} \simeq 360 \exp(21\,468/T) \text{ Wm}^{-1}\text{K}^{-1}$ and $D_{\text{char}} = 4.8 \times 10^{-13} \text{ Wm}^{-1}\text{K}^{-1}$. For meteoroids with diameters 10 cm, 1 cm and 1 mm, the diffusion times t_{dif} will be 1.3×10^9 s, 1.3×10^7 s and 1.3×10^5 s respectively.

The solid-state diffusion time for $18 \mu\text{m}$ grain with albitic characteristic diffusion coefficient is 1.4×10^9 s, which is comparable with diffusion time in pore system of 10 cm fine grained meteoroid. For smaller, more porous meteoroids, or more coarse-grained meteoroid, the diffusion of Na in the pore system is several orders of magnitude faster, than solid-state diffusion in grains.

Thus, we will assume, that sodium release is controlled by solid-state diffusion: as soon as a sodium atom is released from a grain, it reaches the meteoroid surface quickly and escapes into the space. This simplification is valid for Geminid meteoroids smaller than 10 cm. Most meteoroids in other streams are more porous than Geminid meteoroids and diffusion in their pore systems will be more effective.

5 Computation of sodium depletion

Since diffusion through pores is a fast process (Section 4.3), the depletion of sodium could be computed by modeling the diffusion from spherical grains directly to the space.

At first, the orbit, granularity and the diffusion data were chosen. Then, the temperature (5) along the orbit and the corresponding diffusion coefficients (7) as well as the characteristic diffusion coefficient (8) were determined. In the next step, the sodium content in the grains of each size was computed. The radially symmetric Eq. (6) with boundary condition (10) and constant initial

condition was solved analytically. Similarly as Woodward (1901), we obtained the expression for the sodium concentration $c_i(r, t)$ in a grain with radius R_i :

$$c_i(r, t) = 2c_i^0 \sum_{k=1}^{\infty} (-1)^{k+1} \frac{\sin(k\pi r/R_i)}{k\pi r/R_i} \exp\left(-D_{\text{char}} \frac{k^2\pi^2}{R_i^2} t\right), \quad (15)$$

where r is distance from the grain center, t is the time, c_i^0 is the initial concentration of sodium (m^{-3}). The sodium content \mathcal{C}_{R_i} in the grain is then given by:

$$\mathcal{C}_{R_i}(t) = \frac{8c_i^0 R_i^3}{\pi} \sum_{k=1}^{\infty} \frac{1}{k^2} \exp\left(-D_{\text{char}} \frac{k^2\pi^2}{R_i^2} t\right). \quad (16)$$

We assumed that initial sodium content c_i^0 does not depend on the grain size: $c_i^0 = c^0$. The sodium content \mathcal{C} in the whole meteoroid was determined by summation over all grains:

$$\mathcal{C}(t) = \sum_{i=0}^N n_i \mathcal{C}_{R_i}(t), \quad (17)$$

where n_i represents a number of grains with radius R_i . Instead of content \mathcal{C} , the ratio $\tilde{\mathcal{C}} = \mathcal{C}(t)/\mathcal{C}(0)$ (where $\mathcal{C}(0)$ denotes initial sodium content), which is a more useful parameter, was used. The ratio $\tilde{\mathcal{C}}$ will be called the “*relative sodium abundance*”, where no sodium depletion is characterized by $\tilde{\mathcal{C}} = 1$ and the loss of all sodium is described by $\tilde{\mathcal{C}} = 0$.

Let us assume, that only a fraction ξ of the grains contains sodium and this fraction is the same for all grain sizes. In this case, the relative sodium abundance is: $\tilde{\mathcal{C}} = \frac{\sum_{i=0}^N \xi n_i \mathcal{C}_{R_i}(t)}{\sum_{i=0}^N \xi n_i \mathcal{C}_{R_i}(0)} = \frac{\sum_{i=0}^N n_i \mathcal{C}_{R_i}(t)}{\sum_{i=0}^N n_i \mathcal{C}_{R_i}(0)}$. Thus we can see, that the relative sodium abundance $\tilde{\mathcal{C}}$ does not depend on ξ .

6 Results for Geminids

In order to evaluate possible sodium depletion in Geminid meteoroids, we first computed the escape of sodium from monolithic bodies (i.e. massive pieces of a rock without a pore system) on Geminid orbits.

Figure 2 shows the time $T_{1/10}$ as a function of the meteoroid diameter for the diffusion coefficients of orthoclase and albite (see Section 4.1). The quantity $T_{1/10}$ represents the time necessary to attain relative sodium abundance $\tilde{C} = 0.1$, i.e. escape of 90% of initial sodium content. Assuming an albite diffusion coefficient, meteoroids smaller than 200 – 100 μm will lose 90% of the initial sodium content after 1000–4000 years, which is the probable age of the Geminid stream (e.g. Ryabova, 2007; Beech, 2002; Williams and Wu, 1993; Gustafson, 1989). Using an orthoclase diffusion coefficient, 90% sodium loss occurs in bodies smaller than 30–60 μm . The results show that there will be no significant Na loss from monolithic Geminid meteoroids $\sim 1 - 10$ cm in diameter within the expected orbital lifetime of these bodies.

Fig. 2

Fig. 3

Fig. 4

In contrast to monolithic meteoroids, sodium escape from dust-ball meteoroids does not depend on diameter of meteoroids in the studied size range. It will depend on the granularity as a function of the grain sizes. The independence on meteoroid size is caused by almost instantaneous diffusion of Na through the pore system and the absence of the cold core due to small sizes of the spherical meteoroids in our model.

It is not clear yet, if Geminid meteoroids are monolithic or are composed of grains. To test the grain hypothesis, sodium depletion was computed for a wide variety of possible combinations of d_{\min} , d_{\max} and two distinct values of s . The maximum and minimum grain sizes varied from 10 μm to 1 mm, and the

mass-distribution index was 1.8 or 2.8. The diffusion coefficients for orthoclase and albite were used. The resulting \tilde{C} is shown in Fig. 3 and 4.

In general the rate of sodium depletion increases with decreasing sizes of the spherical grains in the model. Therefore, it also increases as a function of mass-distribution index s because a higher mass-distribution index s means that a larger fraction of the meteoroid mass is contained in the smallest grains. If $d_{\max}/d_{\min} \leq \sim 3$, the resulting \tilde{C} is almost the same for $s = 1.8$ and $s = 2.8$.

In summary, our model that includes solid-state diffusion, thermal desorption and diffusion through the pore system of meteoroid shows how considerable amounts of sodium can be lost from Geminid meteoroids without making unreasonable assumptions.

For example using the slow diffusion of orthoclase (see Fig. 3) and assuming that variations in granularity of Geminid meteoroids are similar to those observed for the Draconid meteoroids (Borovička et al., 2007), we see that sodium depletion will be $\tilde{C} \simeq 0.6$ in a 1000 years old coarse-grained meteoroid with $d_{\text{fg}} = 80 - 108 \mu\text{m}$. A fine-grained meteoroid in our model with $d_{\text{fg}} = 16 - 40 \mu\text{m}$ will be almost sodium free after more than 1000 years.

Using diffusion rates of albite (see Fig. 4), the sodium escape is even faster. After a very short time (500 years), the relative sodium abundance decreases to the value $\tilde{C} \sim 0.2$ in a coarse-grained meteoroid in our model ($d_{\text{fg}} = 80 - 108 \mu\text{m}$). For higher ages, both, coarse- and fine- grained meteoroids will be almost sodium free. Assuming that the initial Geminid composition was chondritic, these diffusion data lead to the smaller sodium abundances than observed (Borovička et al., 2005) even for extremely short ages of < 500 years. Since the minimum ages of Geminid meteoroids are older, they have to be more coarse-grained than

Draconid meteoroids. If the maximum and minimum grain sizes are of the same order of magnitude, the predicted granularity of Geminid meteoroids would be $\approx 100 - 400 \mu\text{m}$. As to test our model the determination of the actual Geminid granularity from their fragmentation behaviour in the atmosphere will be critical.

7 Results for other meteoroid streams

To answer the question, which meteoroid streams can be expected to be depleted in sodium, we studied the dependence of \tilde{C} on their orbital parameters, in particular perihelion distance q and semimajor axis a . The results using the diffusion data for Na in orthoclase and albite and values for the granularity $d_{\text{fg}} = 80 - 108 \mu\text{m}$ and $d_{\text{fg}} = 16 - 40 \mu\text{m}$ are shown in Fig. 5 for an assumed 2000 years for the meteoroid stream. It can be seen, that the dependence on perihelion distance q , which controls the maximum meteoroid temperature, is the most important variable. Since the frequency of meteoroid reentries to the Sun is proportional to $a^{-2/3}$, the characteristic diffusion coefficient D_{eff} also decreases with increasing semimajor axis. Nevertheless, the dependence on a is less important than on q .

Fig. 5

We have selected several well-established cometary meteor showers with small perihelia from the working list of Jenniskens (2006) and computed the expected sodium depletion using our model. To reduce the number of free parameters, it was assumed, that meteoroids are composed from grains of uniform sizes: either $10 \mu\text{m}$, or $40 \mu\text{m}$ or $100 \mu\text{m}$. The diffusion data for albite were used. The sodium loss was characterized by the number of perihelion passages neces-

sary for the escape of a half of the initial sodium content (i.e. $\tilde{C} = 0.5$). The results are given in Table 2. The showers with perihelion distances $q \leq 0.1$ AU need only one perihelion passage if the grain size is $10 \mu\text{m}$, and less than several tens of passages if $d_{\text{fg}} = 100 \mu\text{m}$. Severe sodium depletion can be expected in these showers.

In case the perihelion distance is ≈ 0.2 AU or higher, the number of required perihelion passages is very high and sodium depletion can be expected only if meteoroids are composed of small grains. Sodium depletion will be very improbable in Dec. Monocerotids, because of their long orbital period.

Table 2
Fig. 6

In showers with intermediate perihelia, sodium depletion can be expected only if the streams are sufficiently old. The depletions in sodium as a function of the age and perihelion distance are shown in Fig. 6. For older meteoroid streams, the orbital evolution must be taken into account. Some meteoroid streams such as the Quadrantids (Koten et al., 2006) with a perihelion distance too high for the sodium to escape at present, could have approached the Sun more closely in the past causing sodium depletion.

8 Conclusions

We have conducted a modeling study of the release of sodium from Geminid meteoroids due to solar heating. It was found, that sodium can escape from meteoroids with diameters from 1 mm to 10 cm in a considerable amount only if they are not monolithic bodies (i.e. massive pieces of a rock without a pore system), but porous dust-balls composed from spherical grains. The main processes of the sodium release to the space are (i) solid-state diffusion from Na-bearing

minerals to the grain surfaces, (ii) thermal desorption to the meteoroid pore system and (iii) diffusion through the pore system and finally escape into the space.

Thermal desorption is so rapid, that Na concentrations at the grain surfaces is zero. Diffusion through the pore system is also very rapid. It can be approximated by an immediate release of sodium from the grain surfaces into the space. Both these processes are much faster in comparison with the solid-state diffusion. Solid-state diffusion therefore controls the sodium release from the meteoroid. It is a steep function of the temperature and occurs only near perihelion. The model showed, that the above mentioned processes are able to deplete sodium from Geminid meteoroids in the observed amounts, assuming that initial Na content corresponded to those of solar photosphere and CI chondrites. The unknown material parameters were approximated by terrestrial analogs (e.g. the diffusion coefficient of the whole grains was approximated by the values for albite or orthoclase). In the grain size range studied sodium depletion does not depend on meteoroid size.

We suggest that the large variations of sodium abundance observed in Geminids are caused by their variable granularity (i.e. distribution of grain sizes). If the range of Draconid granularities (Borovička et al., 2007) is assumed together with the slow diffusion data for Na in orthoclase (Foland, 1974) and ages of 1000-4000 years, the predicted sodium abundance variations agree well with the observed values. The faster diffusion of Na in albite Bailey (1971) gives appropriate sodium abundance variations only for more coarse-grained dust-balls ($d_{fg} = 100 - 400 \mu\text{m}$).

Sodium depletion critically depends on perihelion distance q , which controls

the maximum temperature of meteoroids. Large sodium depletion can be expected for meteoroid streams with $q \leq 0.1$ AU. If the perihelion distance is between 0.1 – 0.2 AU, higher number of perihelion passages is needed for significant sodium depletion. For $q > 0.2$, sodium depletion is unlikely. There is also dependence on semimajor axis, since meteoroids with longer orbital periods need longer time for sodium depletion.

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$D_0(\text{m}^2\text{s}^{-1})$	$Q(\text{kJ mol}^{-1})$	$T_{\min}(\text{K})$	$T_{\max}(\text{K})$	$D_{\text{char}}(\text{m}^2\text{s}^{-1})$	ref.
analcite $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$					
1.4×10^{-5}	71.	298	326	1.1×10^{-12}	115
2.35×10^{-9}	48.	273	323	9.7×10^{-15}	113
rhyolitic, albitic, orthoclastic and basaltic glasses and obsidians					
5.00×10^{-7}	41.8	1018	1258	6.2×10^{-12}	148
5.30×10^{-7}	56.4	623	1068	5.0×10^{-13}	a
8.00×10^{-7}	79.4	623	1068	1.5×10^{-14}	a
1.29×10^{-6}	84.5	413	1123	1.0×10^{-14}	b
2.11×10^{-6}	89.9	918	1103	6.7×10^{-15}	155
4.40×10^{-6}	95.7	630	758	5.3×10^{-15}	c
4.40×10^{-6}	95.7	973	1073	5.3×10^{-15}	d
quartz SiO_2					
7.1×10^{-7}	48.	873	1073	2.9×10^{-12}	e
6.8×10^{-5}	84.4	573	843	5.5×10^{-13}	99
3.8×10^{-6}	102.4	673	1273	1.5×10^{-15}	f
4.0×10^{-6}	113.	873	1063	2.7×10^{-16}	100
3.6×10^{-7}	100.	573	773	2.1×10^{-16}	g
sodalite $\text{Na}_8(\text{Al}_6\text{Si}_6\text{O}_{24})\text{Cl}_2$					
1.2×10^{-6}	114	723	1123	6.8×10^{-17}	125
6.6×10^{-4}	177.7	853	948	1.0×10^{-18}	c
nepheline $\text{NaAlSi}_3\text{O}_8$					
6.0×10^{-9}	99.3	849	1073	3.9×10^{-18}	70
1.2×10^{-6}	142.1	849	1073	6.4×10^{-19}	c
albite $\text{NaAlSi}_3\text{O}_8$					
2.31×10^{-10}	79.4	473	873	4.3×10^{-18}	h
6.0×10^{-10}	96.0	1123	1213	6.8×10^{-19}	70
1.25×10^{-5}	176.	573	1073	2.5×10^{-20}	i
1.22×10^{-7}	149.	1123	1213	2.1×10^{-20}	c
5.3×10^{-8}	146.5	573	868	1.4×10^{-20}	j ₁
5.70×10^{-7}	175.6	573	1073	1.2×10^{-21}	69
1.0×10^{-22}	12.6	298	348	4.8×10^{-25}	j ₂
orthoclase KAlSi_3O_8					
8.90×10^{-4}	220.0	773	1073	1.3×10^{-21}	k
3.0×10^{-5}	213.0	1018	1324	1.4×10^{-22}	67

Table 1: Experimental self-diffusion data of Na for various minerals and glasses. The data was adopted mainly from compilation of Freer (1981) and Brady (1995). D_0 and Q represents preexponential factor and activation energy in Eq. (7), T_{\min} and T_{\max} are minimum and maximum temperature of the experiment, D_{char} is characteristic diffusion coefficient for Geminid meteor stream orbit. Numbers in column “ref” denote the references in Freer (1981) and letters denote: a) Jambon and Carron (1976), b) Jambon (1982), c) Sippel (1963), d) Magaritz and Hofmann (1978), e) Frischat (1970), f) Rybach and Laves (1967), g) Verhoogen (1952), h) Lin and Yund (1972), i) Yund (1983), j) Bailey (1971), k) Foland (1974).

meteor shower name	a (AU)	q (AU)	P (yr)	N_{rev}		
				10 μm	40 μm	100 μm
Daytime Arietids	1.67	0.1	2.15	1	5	30
Northern δ -Aquariids	2.536	0.071	4.03	1	1	2
Southern δ -Aquariids	3.107	0.087	5.47	1	2	10
Southern ι -Aquariids	2.676	0.190	4.37	261	4162	3×10^4
(Dec.) Monocerotids	50.7	0.193	361	267	4259	3×10^4
Geminids	1.357	0.14	1.58	8	120	750

Table 2: The number of revolutions N_{rev} , which are necessary for the escape of one half of the total sodium content from meteoroids of various streams. The grain diameters $d_{\text{fg}} = 10 \mu\text{m}$, $40 \mu\text{m}$, and $100 \mu\text{m}$ were assumed. Note that ten times larger grains need hundred times more revolutions. Orbital data were taken from Jenniskens (2006) and the diffusion data of albite (Bailey, 1971) were used.

Fig. 1 The dependence of diffusion coefficient of Na on temperature (left) and time (right) for different diffusion data and the Geminid orbit. The dashed curve corresponds to the limit of slowest diffusion (orthoclase), the solid one corresponds to albite. Diffusion of Na in albite and orthoclase freezes approximately 3 weeks after perihelion passage due to the steep dependence of D on temperature.

Fig. 2 Time $T_{1/10}$ necessary to attain relative sodium abundance $\tilde{C} = 0.1$ for monolithic spherical Geminid meteoroid as a function of diameter for diffusion data of orthoclase and albite. The dashed time interval corresponds to frequently quoted ages of the Geminid meteoroid stream.

Fig. 3 Relative sodium abundance \tilde{C} for porous dust-ball Geminid meteoroid with characteristic diffusion coefficient $D_{\text{char}} = 1.3 \times 10^{-21} \text{ m}^2/\text{s}$ (orthoclase, Foland, 1974) as a function of granularity. The isolines denote the \tilde{C} value. The left column was computed for the mass-distribution index $s = 1.8$; the right column is for $s = 2.8$. Three different ages of Geminid meteoroids were assumed: 4000 years (a,d), 2000 years (b,e) and 1000 years (c,f). The symbols correspond to the granularities of Draconid meteoroids (Borovička et al., 2007); the square represents the fine-grained body with $d_{\text{fg}} = 16 - 40 \mu\text{m}$ and the triangle represents the coarse-grained body with $d_{\text{fg}} = 80 - 108 \mu\text{m}$. The results are independent on meteoroid size in the studied size range (1 mm - 10 cm).

Fig. 4 Relative sodium abundance \tilde{C} for porous dust-ball Geminid meteoroid with characteristic diffusion coefficient $D_{\text{char}} = 1.4 \times 10^{-20} \text{ m}^2/\text{s}$ (albite, Bailey, 1971) as a function of granularity. See Fig. 3 for the description.

Fig. 5 Relative sodium abundance \tilde{C} for a porous meteoroid 2000 years old as a function of semimajor axis a and perihelion distance q . The isolines denote the \tilde{C} value. The size range of grains and the diffusion data are given in each plot. The diamond symbol denotes the orbit of Geminid meteoroid stream and the triangle denotes the orbit of the δ -Aquarid meteoroid stream.

Fig. 6 Relative sodium abundance \tilde{C} for a porous dust-ball meteoroid as a function of the age and the perihelion distance. The isolines denote the \tilde{C} value. Diffusion data for orthoclase with $d_{\text{fg}} = 80 - 108 \mu\text{m}$ (a) and diffusion data for albite with $d_{\text{fg}} = 16 - 40 \mu\text{m}$ were used. Semimajor axis $a = 2.5 \text{ AU}$ was assumed.

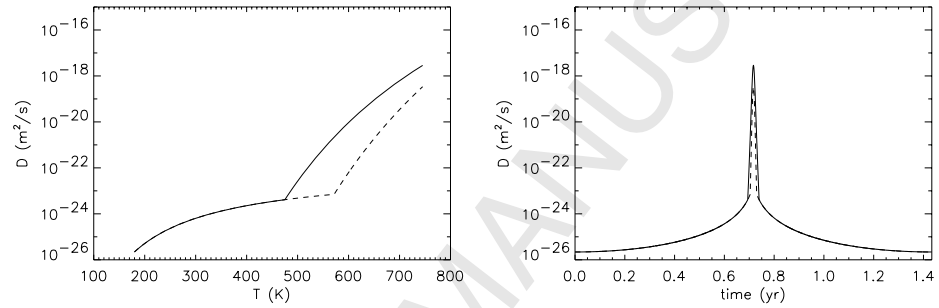


Figure 1: The dependence of diffusion coefficient of Na on temperature (left) and time (right) for different diffusion data and the Geminid orbit. The dashed curve corresponds to the limit of slowest diffusion (orthoclase) and the solid one corresponds to albite. Diffusion of Na in albite and orthoclase freezes approximately 3 weeks after perihelion passage due to the steep dependence of D on temperature.

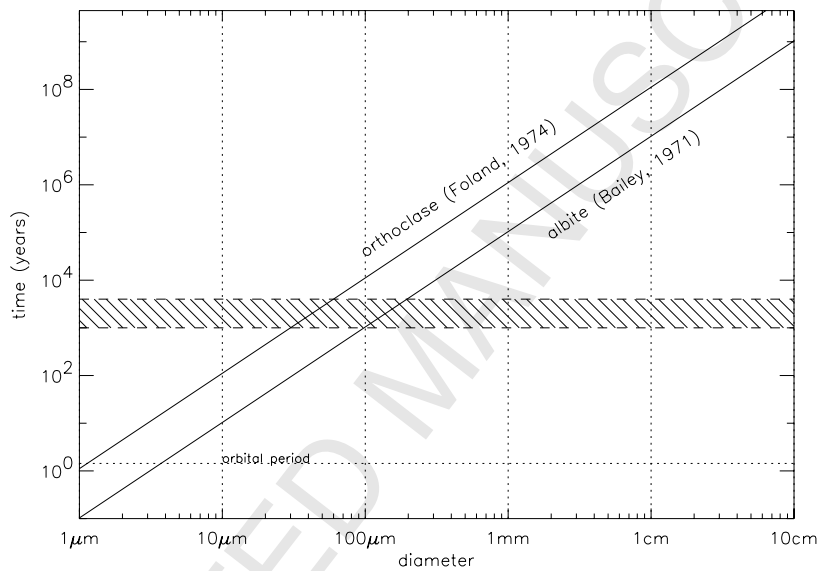


Figure 2: Time $T_{1/10}$ necessary to attain relative sodium abundance $\tilde{C} = 0.1$ for monolithic spherical Geminid meteoroid as a function of diameter for diffusion data of orthoclase and albite. The dashed time interval corresponds to frequently quoted ages of the Geminid meteoroid stream.

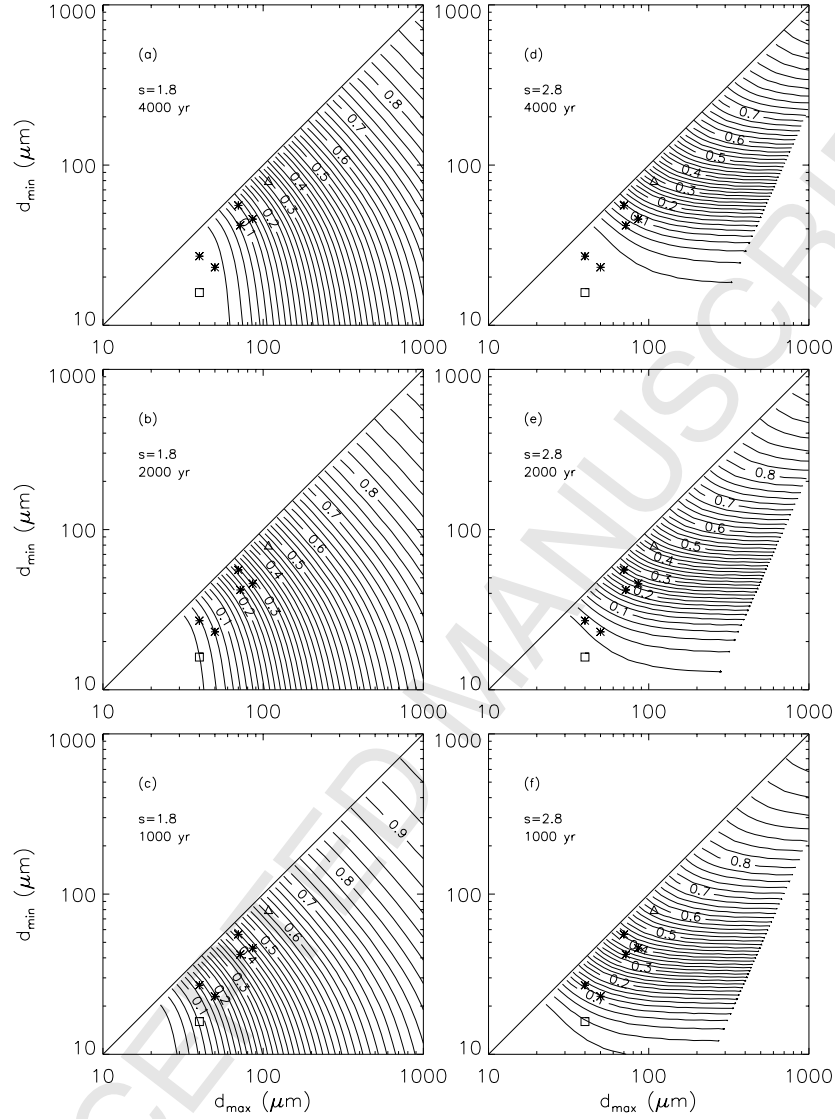


Figure 3: Relative sodium abundance \tilde{C} for porous dust-ball Geminid meteoroid with characteristic diffusion coefficient $D_{\text{char}} = 1.3 \times 10^{-21} \text{ m}^2/\text{s}$ (orthoclase, Foland, 1974) as a function of granularity. The isolines denote the \tilde{C} value. The left column was computed for the mass-distribution index $s = 1.8$; the right column is for $s = 2.8$. Three different ages of Geminid meteoroids were assumed: 4000 years (a,d), 2000 years (b,e) and 1000 years (c,f). The symbols correspond to the granularities of Draconid meteoroids (Borovička et al., 2007); the square represents the fine-grained body with $d_{\text{fg}} = 16 - 40 \mu\text{m}$ and the triangle represents the coarse-grained body with $d_{\text{fg}} = 80 - 108 \mu\text{m}$. The results are independent on meteoroid size in the studied size range (1 mm - 10 cm).

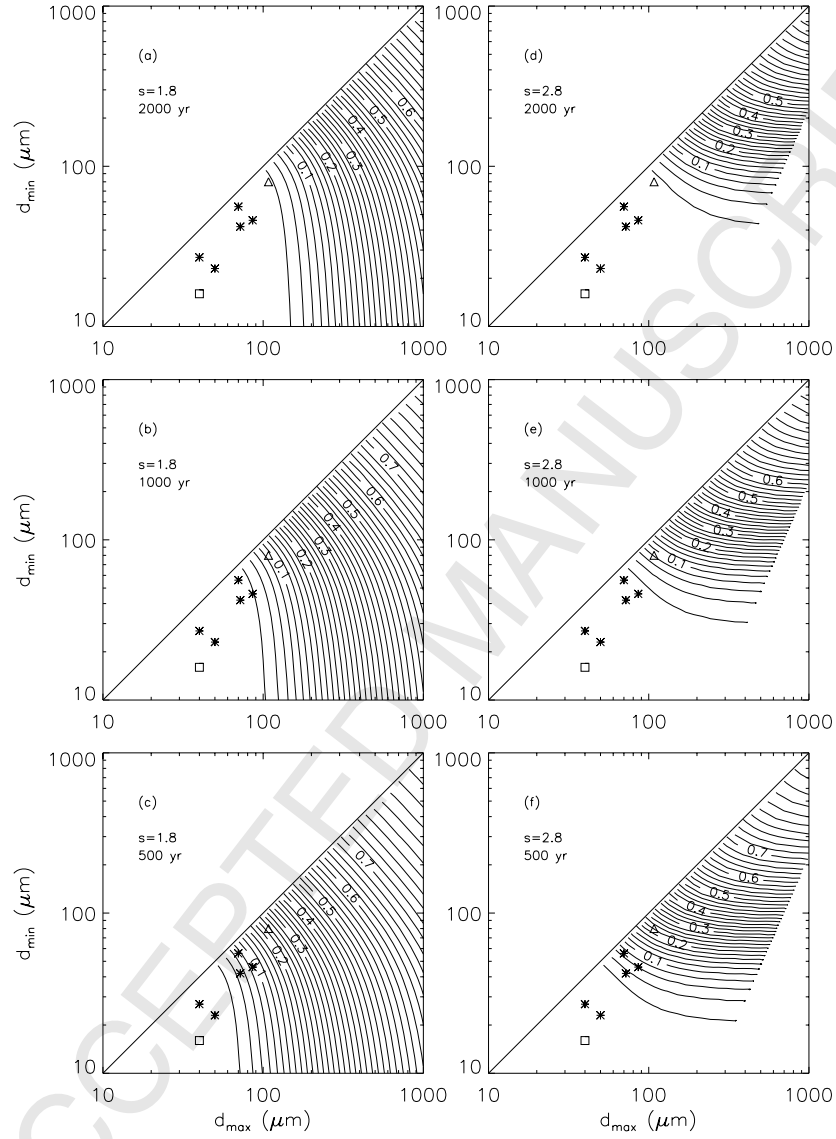


Figure 4: Relative sodium abundance \tilde{C} for porous dust-ball Geminid meteoroid with characteristic diffusion coefficient $D_{\text{char}} = 1.4 \times 10^{-20} \text{ m}^2/\text{s}$ (albite, Bailey, 1971) as a function of granularity. See Fig. 3 for the description.

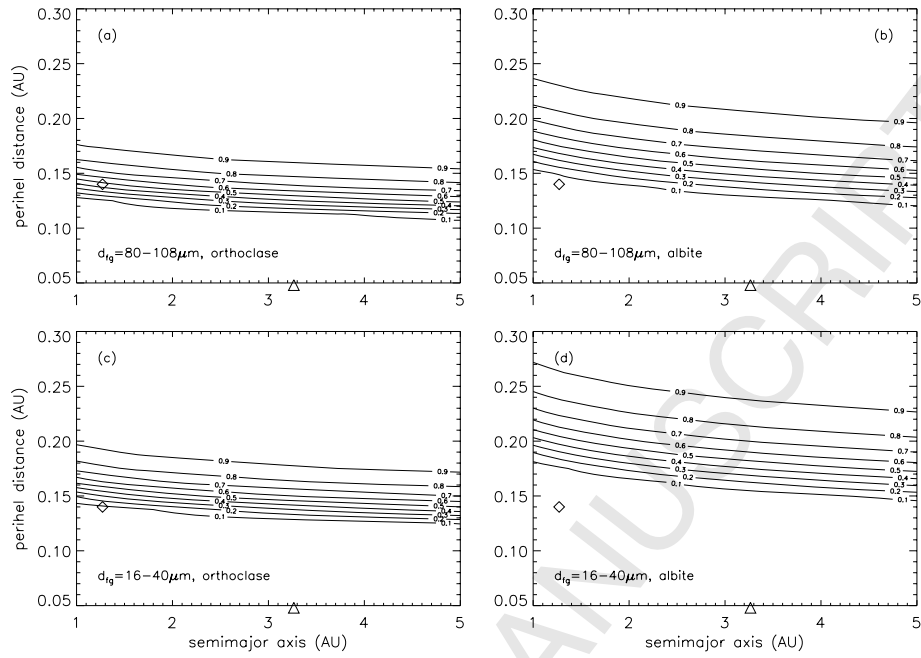


Figure 5: Relative sodium abundance \tilde{C} for a porous meteoroid 2000 years old as a function of semimajor axis a and perihelion distance q . The isolines denote the \tilde{C} value. The size range of grains and the diffusion data are given in each plot. The diamond symbol denotes the orbit of Geminid meteoroid stream and the triangle denotes the orbit of the δ -Aquadrid meteoroid stream.

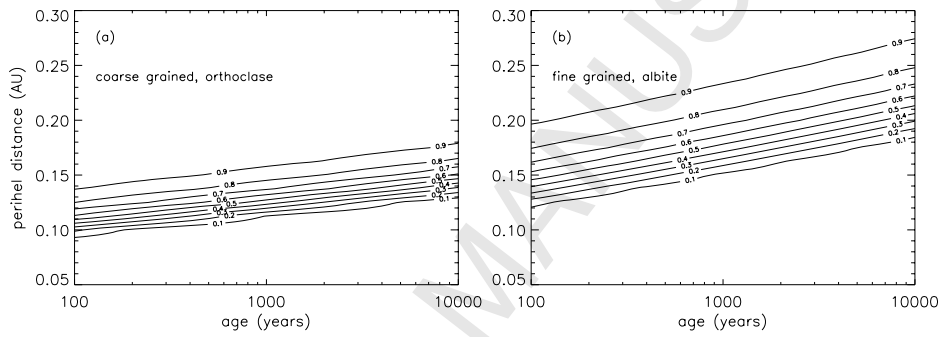


Figure 6: Relative sodium abundance \tilde{C} for a porous dust-ball meteoroid as a function of the age and the perihelion distance. The isolines denote the \tilde{C} value. Diffusion data for orthoclase with $d_{fg} = 80 - 108 \mu\text{m}$ (a) and diffusion data for albite with $d_{fg} = 16 - 40 \mu\text{m}$ were used. Semimajor axis $a = 2.5 \text{ AU}$ was assumed.