SEMI-EMPIRICAL MODELS OF UPPER ATMOSPHERIC AEROSOL COMPOSITION 2. DIFFUSION-SEDIMENTATION MODEL

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This paper presents the results of numerical calculations of the vertical profiles of the micrometeorite number density in the mass range from 10^{-17} to 10^{-8} g. Profiles of the atmospheric relative turbidity at wavelengths of 0.1 and 0.5 pm for the altitude range 30 to 110 km are also calculated. The effect of eddy diffusion is noticeable only for the smallest micrometeorites ($m \le 10^{-15}$ g) below 60 km.

In our previous study[1] we gave the general formulation of the problem of constructing a semi-empirical diffusion-sedimentation model of the concentration of primary particles of cosmic dust (micrometeorites) in the upper atmosphere. We also presented results from approximate calculations discounting the effect of diffusion, i. e. following a model of pure sedimentation. The present study presents results from computations employing the complete diffusion-sedimentation model that we have constructed.

The principal difference between our new approach and those previously described (Refs. 5, 6, 16, 18, and 21) is that it implements a detailed model of the influx of cosmic dust particles[11] within a wide mass range (10^{-17}–10^{4} g), taking into account the various mechanisms of their interaction with the terrestrial atmosphere as a function of individual particle mass and velocity.

MODEL OF THE INFLUX OF COSMIC DUST PARTICLES AND THEIR INTERACTION WITH THE ATMOSPHERE

Figure 1 presents the total time-averaged particle flux density in circumterrestrial space, obtained in Ref. 11 as a function of their mass $N(m)$. The complicated nature of the dependence of $N(m)$ is satisfactorily explained within the framework of the model of the formation of the interplanetary dust cloud.[9]

According to the most widely accepted contemporary ideas the principal sources of interplanetary space dust are disintegration of comet heads and collision of asteroids and large, meteorite - producing bodies. Within a wide mass range (10^{-17}–10^{-4} g) this source follows an near-power-law distribution

$$dP \sim m^{-s} dm \qquad (1)$$

Its exponent s decreases slightly roughly from 2.25 to 2, while the particle mass decreases from 10^{4} to 10^{-17} g.

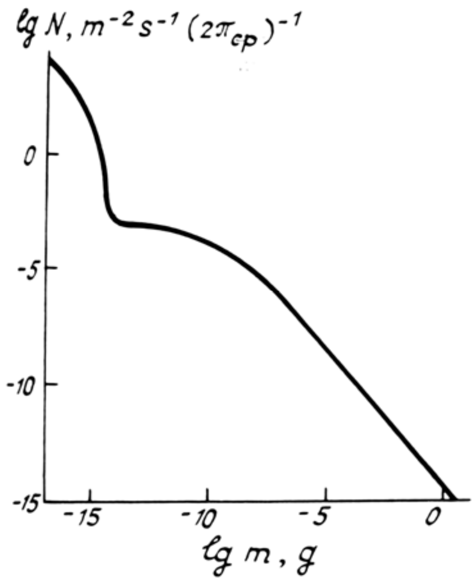

FIG. 1. Average model of the integral influx of cosmic dust.

The same distribution with an exponent of 2.25 also holds for particles with mass $m > 10^{-8}$ g in interplanetary space, which disappear mainly as a result of non-selective scavenging by planets. Particles in the mass range $10^{-11} < m < 10^{-8}$ g disappear mainly as a result of a gradual spiraling in to the Sun as a result of the effect of radioactive solar deceleration (the Pointing-Robertson effect). Such a deceleration is more strongly felt at lower m, for which reason the parameter s drops down to 1.6 for these particles. Particles in the range $10^{-14} < m < 10^{-11}$ g are practically absent in interplanetary space because they are pushed out of the solar system by solar radiation pressure. At $m < 10^{-14}$ g diffraction of the solar radiation around the particles becomes important, so that the effect of solar radiation pressure diminishes, and the number of particles quickly grows at lower masses.

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According to the physical theory of meteors[10,14] particles with $m > 10^{-8}$ g almost completely evaporate while decelerating in the atmosphere at an average entrance velocity $V = 30$ km/s. Particles with $m < 10^{-8}$ g lose most of their initial kinetic energy to thermal radiation, and, having decelerated at altitudes above 100 km, settle through the atmosphere as micrometeorites.

Thus, of the primary particles of cosmic dust only those with $m < 10^{-8}$ g, i. e. micrometeorites, can be present in the atmosphere in a suspended state. Since those particles that most effectively scatter solar radiation ($10^{-14} \le m \le 10^{-11}$ g) are practically absent from interplanetary space, we conclude that only micrometeorites of mass $m \le 10^{-14}$ g and $10^{-11} \le m \le 10^{-8}$ g can be present in the atmosphere.

Particles of cosmic origin in the atmosphere with $10^{-14} \le m \le 10^{-11}$ g, i. e., those which scatter light most effectively, can only be secondaries, i.e. products of meteoric vapor condensation or of coagulation (adhesion) of particles of mass $m \le 10^{-14}$ g. We do not consider condensation and coagulation processes in the present study.

The effective atmospheric sedimentation rate for micrometeorites is significantly affected by eddy diffusion, which we previously did not account for in Ref. 1.

Thus, we compute the vertical profile of primary cosmic aerosol particles for different particle masses and sizes, their source taken to be at $z \approx 100$ km and sink at $z = 0$, accounting for sedimentation and eddy diffusion. Molecular diffusion (i.e., Brownian motion of particles) can be neglected.

THE DIFFUSION-SEDIMENTATION MODEL

On the basis of the above assumptions the vertical profiles of the spectral aerosol size distribution $n(r, z)$ obey by the equation

$$\frac{d\Phi}{dz} = 0 \tag{2}$$

where

$$\Phi(r, z) = - D_T(z)\left[\frac{\partial n}{\partial z} + \frac{n}{H(z)}\right] - U_c(r, z)\, n(r, z) \tag{3}$$

Here r is the aerosol particle radius (we take them to be spherical); $\Phi(r, z)$ is the aerosol flux density; $D_T(z)$ is the eddy diffusion coefficient; $H(z)$ is the atmospheric scale height; and $U_C(r, z)$ is the aerosol sedimentation rate.

The boundary conditions have the form

$$\Phi(r, z)\Big|_{z=z_{max}} = \Phi_0(r); \quad n(r, z)\Big|_{z=z_{min}} = n_0(r) \tag{4}$$

where $\Phi_0(r)$ is the micrometeorite flux density at the atmospheric upper boundary, and $n_0(r)$ is their concentration at the bottom of the atmosphere.

The general solution of the problem posed by Eqs. (2)–(4) is

$$n(r, z) = \exp\left\{ - \int\limits_{z_{min}}^{z} \left[\frac{1}{H(z')} + \frac{U_s(r, z')}{D_T(z')} \right] dz' \right\} \times$$
$$\times \left[n(r_0) + \Phi_0(r) \int\limits_{z_{min}}^{z} \exp\left\{ \int\limits_{z_{min}}^{z'} \left[\frac{1}{H(z'')} + \right.\right.\right.$$
$$\left.\left.\left. + \frac{U_s(r, z'')}{D_T(z'')} \right] dz'' \right\} \frac{dz'}{D_T(z')} \right] \tag{5}$$

The rate of sedimentation can be described by the Stokes equation with an adjustment factor[4,20,24]

$$U_c(r, z) = \frac{2}{9}\,\frac{\rho_a g r^2}{\eta} \times$$
$$\times \left\{ 1 + \frac{l}{r}\left[1.257 + 0.4 \exp\left(- 1.1\, \frac{r}{l}\right)\right] \right\} \tag{6}$$

Here ρ_a is the aerosol material density; g is acceleration due to gravity; η is the air dynamic viscosity; l is the mean free path of the air molecules. Since the principal component of almost all stone meteorites is silicon dioxide (the overwhelming fraction of known fallen meteorites), we assume that all the aerosols of cosmic origin consist of quartz, which has a density $\rho_a = 2.5$ g/cm^3. Carbonaceous chondrites, to which the majority of meteoritic bodies entering the Earth's atmosphere belong,[12] have the same average density.

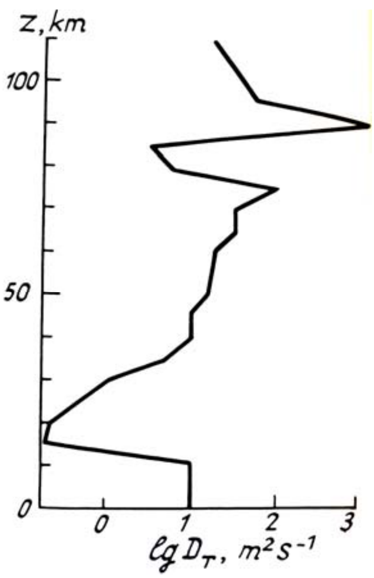

FIG. 2. Vertical profile of the eddy diffusion coefficient vertical component.

The profile of the vertical eddy diffusion coefficient in the stratosphere and mesosphere has still not received a thorough experimental study, for which reason various semi-empirical models are usually employed to describe it. Among several models of the vertical profile for $D_T(z)$ (Refs. 23 and 25) we choose as our basic profile the one presented in Fig. 2. The presence of a deep minimum of $D_T(z)$ in the region of the mesopause and of a sharp maximum close to our source (at 95 km) makes it possible to estimate the effect of the extrema in $D_T(z)$ on the generation of layers of either increased or decreased concentration of micrometeorites in the upper atmosphere. Test simulations were also conducted for several other vertical profiles.

AEROSOL SCATTERING OF LIGHT IN THE UPPER ATMOSPHERE.

The aerosol volume scattering coefficient for polydisperse particles with radii from r_1 to r_2 at an altitude z and wavelength λ can be written in the form

$$\sigma_a(z, \lambda) = \int_{r_1}^{r_2} K(r, k, \lambda)\, \pi r^2\, n(r, z)\, dr \tag{7}$$

where $K(r, k, \lambda)$ is the scattering efficiency for particles of radius r and refractive index k (for quartz $k = 1.5$).

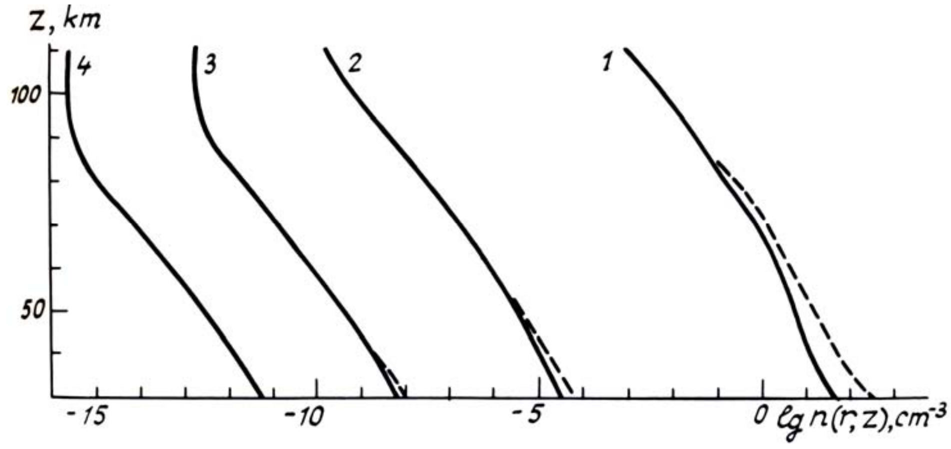

FIG. 3. Micrometeorite absolute concentration: Vertical profiles for various particle radii: 1 — 0.0098–0.0115 μm; 2 — 0.084–0.098 μm; 3 — 0.98–1.15 μm; 4 — 8.4–9.8 μm; dots — eddy diffusion neglected.

The scattering efficiency is calculated from the rather cumbersome formulas of Mie theory.[3,19] Results of such calculations for spherical quartz particles are presented in Refs. 3 and 19. Recalling that micrometeorites have a wide gap in their mass distribution (10^{-14}–10^{-11} g), i.e., in the range of the most efficient light scatterers, simple approximation formulas[1] may be employed for computing $K(r, k, \lambda)$.

Since the value of $\sigma_a(z, \lambda)$ varies significantly with height (approximately exponentially), the parameter more convenient for identifying aerosol layers in the atmosphere is the coefficient of relative atmospheric turbidity σ_a/σ_b , where $\sigma_b(z, \lambda)$ is the volume coefficient of Rayleigh scattering due to air molecules. The vertical profile of the atmospheric relative turbidity has been studied by many authors employing various techniques for this purpose.[4–7,11,15,16,20]

RESULTS OF NUMERICAL CALCULATIONS

Figure 3 presents the vertical profiles that have computed of the absolute aerosol concentrations for particle masses of about 10^{-17}, 10^{-14}, 10^{-11}, and 10^{-8} g. It can be seen from this figure that accounting for eddy diffusion significantly affects the computational results for the finest particles (those with $m \le 10^{-15}$ g) only, at altitudes $z \le 60$ km.

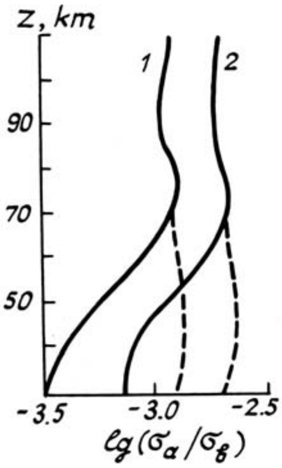

FIG. 4. Vertical profiles of the atmospheric turbidity coefficient at wavelengths: 1 — 0.1 μm, 2 — 0.5 μm. Dots — eddy diffusion neglected.

That effect may be neglected for larger particles ($m \geq 10^{-14}$ g), over the entire considered altitude range ($30 < z < 110$ km). The presence of sharp extrema at 85 and 95 km does not lead to the formation at these heights of layers with either markedly increased or decreased aerosol concentrations. Similar results were obtained for all the other vertical profiles $D_T(z)$ given in Refs. 12 and 13.

Figure 4 presents the vertical profile of the relative atmospheric turbidity coefficient σ_a/σ_b for the wavelengths 0.1 and 0.5 μm; the profile of σ_a/σ_b obtained from the pure sedimentation model is shown by dots. At both wavelengths the effect of eddy diffusion is manifested only below $z \leq 10$ km. At all altitudes the atmospheric relative turbidity coefficient $\sigma_a/\sigma_b \ll 1$.

CONCLUSIONS.

1. As can be seen from Fig. 4, the cosmic dust particles (micrometeorites) precipitating through the atmospheric cannot by themselves generate any noticeable upper atmospheric turbidity, since at every altitude $\sigma_a/\sigma_b \ll 1$. The model of average micrometeorite influx we assumed for our purposes is close to the available minimal estimates. Moreover, the highest available estimates of this influx do not exceed the value assumed in our model by more than an order of magnitude, so that, had we used them, the above conclusion would still hold.

2. The principal input to light scattering by micrometeorites is produced by particles in the mass range 10^{-16}– 10^{-14} g, for which the total cosmic dust influx to the Earth atmosphere is responsible for around 20%. The efficiency of light scattering by such particles (per unit mass) is significantly less than by particles of mass 10^{-t3}–10^{-12} g, which are the most effective in scattering light.

3. There are comparatively few particles of mass 10^{-13}–10^{-12} g in interplanetary space (they are pushed out of the Solar system by light pressure). However, they may be generated in the upper atmosphere by processes of coagulation of smaller particles or as a result of condensation of meteoritic vapor onto the finest particles of mass 10^{-17}–10^{-16} g. The concentration of the latter in the upper atmosphere is quite high. Since a large particle of cosmic dust entering the atmosphere is mostly evaporated, the process of condensation of such evaporated matter may, in principle, lead to a significant increase in the upper atmospheric turbidity. A large contribution may also be produced by coagulation of the finest micrometeorites of mass below 10^{-16} g, which produce more than 20% of the total cosmic dust influx.

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