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ROTATION AND ORIENTATION OF COSMIC DUST PARTICLES

by

A. Z. Dolginov

(USSR)

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SUMMARY

In view of discussing the passage of light through the outer space medium, various hypotheses are invoked to find the causes inducing the spinning and orientation od cosmic dust particles. These phenomena are examined in inter-stellar, as well as interplanetary space. The roles of solar wind protons and of gas flows are discussed. The behavior of cosmic dust particles in planetary atmospheres is also examined.

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1. Data on concentration and physical properties of cosmic dust are indispensable for the description of light passage through the outer space medium, the explanation of Zodiacal light, the construction of cosmogonic hypotheses and so forth. Observations show that when light traverses cosmic dust clouds, it is polarized and partially absorbed, particularly in the short-wave region of the spectrum. Light polarization is apparently due to the scattering of dust particles having a non-spherical shape or sharply anisotropic properties and oriented in outer space.

In most of the hypotheses explaining the orientation of dust particles it is postulated that they contain ferromagnetic atoms. When such a particles spins in the interstellar magnetic field, its angular moment is lined up along the lines of force. However, the alignment time is great, some 10^6 years. It is comparable with the time of dust cloud existence and is less than the characteristic times of gas' turbulent motion. Moreover, this hypothesis requires an anomalously large distribution of ferromagnetic substances.

In another hypothesis, that of Gold [2], the orientation is considered under the action of interstellar gas' supersonic flow. The total moment of a dust particle induced by atomic gas impacts is determined as $M = M_0 + M_1$, where M_0 is a moment from collision with chaotically moving atoms, and M_1 is

(*) VRASHCHENIYE I ORIENTATSIYA KOSMICHESKIKH PYLINOK

$\vec{M}_1 = \sum_n m\vec{r}_n \times \vec{v}$ is the moment from collisions with the directed flow; m is the mass of the atom, v is the flow velocity, $\vec{r}_n$ is the radius-vector from the center of the dust particle to the point of impact, Σ is the sum by all impacts. The quantity $\vec{M}_1$ is perpendicular to the flow, but it is very small, since the probability of impact on one side of the particle's center of gravity is equal to the probability of impact from the other side, while fluctuations were disregarded by Gold. This is why the sum with respect to n is equal by order of magnitude to one addend, i. e. to the moment obtained from a single atomic gas impact. The chaotic component $\vec{M}_0$ approaches the large equilibrium value

$$M_0 \to (3kTI)^{1/2},$$

where I is the moment of inertia of the dust particle and T is the temperature of the gas. Inasmuch as in those conditions no notable moment orientation can be expected, the Gold hypothesis failed to become widespread.

In all the above hypotheses no attention was given the fluctuation of the number of impacts of incident particles on various sides of dust particle's center of gravity. Meantime, this is the situation which precisely leads to a qualitatively new situation assuring a rapid orientation of dust particles' moments. We shall demonstrate that dust particles orient themselves under the action of corpuscular and light fluxes originating from the Sun and stars, and of gas flows in the outer space. Let us stress that dust particles orient themselves not only in the interstellar, but also in the interplanetary space and even in the atmosphere.

2. Let us consider a dust particle in interplanetary space. Proton flux of solar wind and Sun's light emission act upon it. Assume for the sake of simplicity that the dust particle is symmetrical relative to its center of gravity. Let $w_p t$ be the mean number of protons incident on the particle on one side from its center for the time t. The probability of hitting by a specific number of protons is given by Poisson distribution. The probability that for the time t n more protons will be incident on one side than on the other is

$$W_n = \sum_{N=0}^{\infty} [(N+n)!N!]^{-1} (w_p t)^{2N+n} \exp(2w_p t). \tag{1}$$

The root-mean-square value of the excess of the number of protons

$$(\overline{n^2})^{1/2} = \Big(\sum_n n^2 W_n\Big)^{1/2} = (2w_p t)^{1/2}$$

rises proportionally to the square root of flux's action time.

The average moment acquired by the dust particle during the time t as a result of the fluctuation of the number of protons hitting it is

$$\mathbf{M} = m[\vec{\rho}, \mathrm{v_p}]\,(2w_p t)^{1/2}, \tag{3}$$

where $\vec{v}_p$ is the mean velocity of protons, and $\vec{\rho}$ is the mean value of the impact parameter.

Let us consider a uniform dust particle with dimensions B = C along two axes and A = γB along the third axis, where $\gamma \gtrless 1$. The motion of such a dust particle is composed of spinning around axis $\vec{A}$ and precession about the direction $\vec{M}$. If the particle is stretched ($\gamma > 1$), the component of the torque around the short axis is greatest, for the highest value of the mean impact parameter $\rho_A = \gamma B / 4$ corresponds to it. The angle between the axis $\vec{A}$ and the direction of the moment is determined by the well known formulas of motion of a symmetrical tip-top.

$$\cos\theta = M_A / M = (1 + 2\gamma^2)^{-1/2}. \tag{4}$$

The angular velocity of particle spinning about axis $\vec{A}$ and its precession around $\vec{M}$ are respectively equal to

$$\omega_A = \frac{M_A}{I_A} = \frac{3mv_p}{2\gamma B^4\delta}(2w_p t)^{1/2}, \quad \omega_{np} = \frac{M}{I_B} = \frac{3mv_p}{\gamma B^4\delta}\,\frac{(1+2\gamma^2)^{1/2}}{1+\gamma^2}\,(2w_p t)^{1/2}, \tag{5}$$

where $I_A = \gamma B^5\delta / 6$, $I_B = I_C = \gamma(1+\gamma^2)B^5\delta / 12$ are the moments of inertia and δ is the density of the dust particle.

The flux of solar wind protons at the distance r from the Sun is $J_p = nv_p$, where $n = Q/v_p r^2$ is the concentration of protons. The probability for one of these protons of hitting the particle is $2w_p = J_p S$, where S is the projection of particle's surface on a plane perpendicular to the flux. Thus,

$$\mathbf{M} = m[\vec{\rho}, \mathbf{v}_p]\,(J_p S t)^{1/2}. \tag{6}$$

For solar wind protons (with energy $\sim$ 1 kev) the dust particle is practically a blackbody. The data on light scattering and polarization point to the fact that the shape of cosmic dust particles is far from spherical and that their dimensions are most probably $\sim 10^{-4} - 10^{-5}$cm. Meteor data attest to the fact that the density values of dust particles have a wide range from 0.05 to 8 $g\cdot cm^{-3}$.

Assuming for example $B = 10^{-4}$ cm, $\rho = 5\cdot10^{-5}$ cm, $S \approx 10^{-8}$ cm, $\gamma = 2$, $\delta = 1$ g cm^{-3} at the distance of 1 a.u. = 1.5 10^{13} cm for average values $n = 5\ cm^{-3}$, $v_p = 3\cdot10^7\ cm\cdot sec^{-1}$, we shall obtain a torque $M \approx 3.10^{-21}\sqrt{t}$; the corresponding angular velocities will be $\omega_A \approx \omega_{pr} \approx 0.6\sqrt{t}$ $rad\cdot sec^{-1}$. Therefore, the angular velocity of a dust particle attains 0.6 $rad\cdot sec^{-1}$ as early as in the course of the first second of its sojourn in the flux; in 24 hours it reaches 200 $rad\cdot sec^{-1}$ and in the course of one year $\sim 3\ 10^3$ $rad\cdot sec^{-1}$. If the dimensions of the dust particle are $\sim 10^{-5}$ cm, its angular velocity is approximately 100 times greater than that indicated; however, such tiny dust particles are wiped out by radial pressure from the solar system.

The rotation of dust particles may be induced not only by a directed flux of protons, but also by a flux of photons arriving from the Sun. In this case we shall have, analogously to (6)

$$\mathbf{M} = \frac{h\nu}{c}[\rho, \mathbf{n}]\,(J_\gamma S t)^{1/2}, \quad \mathbf{k} = k\mathbf{n}; \tag{7}$$

$h\nu$ is the mean energy of photons and J_γ is their flux at the distance $\underline{r}$ from the Sun. Considering an identical dust particle as in the preceding case, and taking into account that the bulk of the solar wind is near the energy range $h\nu \approx 1$ ev while at the distance r = 1 a.u. the emission flux is $\sim 2.10^{17}$ photons//cm^2·sec, we shall obtain $M \approx 1.2\cdot10^{-22}\sqrt{t}$, i. e. the effect from the light flux is by one order smaller than that from the solar wind. However, at range from the Sun, where corpuscular stream loses its directed velocity, the light flux may become the main factor inducing the spinning of dust particles.

4. It is evident that all the preceding reasonings, with the exception of quantitative estimates, are also related to dust particles near stars, in the interstellar space and in gas-dust nebuale. Numerous data are available on gas flow in nebulae, but there is no basis to consider that gas and dust are there in equilibrium. External factors, such as light pressure, magnetic field, flux intrusion from without and so forth, influence in different fashion the gas and dust components of nebulae, and one is led to believe that the motion of gas relative to dust takes place all the time. Analogously to solar wind, gas flows also result in particle spinning. Alongside with the directed motion, gas particles participate in chaotic, thermal motion, which results in the appearance of an isotropic component of dust particle torque. The ratio of this component to that perpendicular to the flux is proportional to the quantity $(v_T / v)^{3/2}$, according to (6), where v is the directed and v_T is the chaotic velocity of gas particles. For $v \gg v_T$, the moment settles perpendicularly to the flow. At long diatnace from stars the light flux ($J_\gamma \sim 10^9$ photons/cm^2 sec) cannot create a notable orientation of dust particles' torques since the disorientation at collisions with interstellar gas particles is more effective than the orientation by light.

The orienting action of the flow will cease when the dust particle will acquire its velocity. The standard estimates of concentration and temperature in the neutral hydrogen in interstellar space (in the HI zone) correspond to $n_H \approx 10$ cm^{-3}, $T \approx 100°$ K, i.e. to the thermal velocity $v_T \approx 1{,}5\cdot10^5$ cm/sec. The motion of fluxes in the zone HI (for example, as a result of hydrogen carrying as zone H II expands) takes place with velocities $v_0 > 10^6$ cm/sec. The velocity of a carried particle is determined by the equation

$$m_g\dot{v} = \varkappa n_H m S(v_0 - v)^2,$$

where κ is the accomodation factor, $m_g = \gamma B^3\delta$ is the mass of the dust particle, $S = \gamma B^2$ is its area turned toward the flux, δ is the density. The velocity $\underline{v}$ will be attained in the time $\tau_p = m_g v[v_0(v_0 - v)\varkappa n m S]^{-1}$. For dust particle with $\delta = 3$ g·cm^{-3}, $B = 5.10^{-5}$ cm and κ 1, the velocity $v \approx 0{,}8\,v_0$ will be attained in 10^6 years. During that time the dust particle will succeed in acquiring the mean angular velocity perpendicular to the flow, $\omega_{pr} = 3.10^5$ sec^{-1}.

Orientation disruption of dust particles may take place not only on account of collisions with chaotically moving atoms or with one another, but also as a consequence of precession in the magnetic field. If a dust particle with dimensions $B = 5\ 10^{-5}$ cm has a 0.03 v potential, the velocity of its precession in a magnetic field with $H = 10^{-5}$ oe will be $\Omega = 10^{-11}$ sec^{-1}, i. e. its orientation will be disrupted by about 1000 years.

We shall not compute here the parameters characterizing the polarization of light scattered by oriented particles, though this question calls for a more thorough consideration than the one made in the works [1 - 3]. The results of the latter may be utilized for the estimates of polarization. Note that the orientation of dust particles in interplanetary space must be taken into account when interpreting the polarization observations of comets, Zodiacal light and gegenschein.

5. In the Earth's and planetary atmospheres dust particles are under the action of wind. For the altitudes where the mean free path of molecules is much greater than the size of particles, wind induces spinning and orientation of dust particles' moments in the same way, as described above. In the dense layers of the atmosphere, where the mean free path is small, dust particles rapidly acquire the velocity of the wind and are carried with it. This phenomenon is immaterial for cosmic dust particles, for the time required for their carrying by solar wind or gas flows is very long. In the dense atmosphere entrainment time by the wind is short, while the spin deceleration is great. This is why no stationary spinning occurs. Nevertheless, orientation may arise in the presence of wind velocity gradient in a direction perpendicular to the flow, whereupon in the given case what is oriented is not the angular moment but directly the axis of the dust particle. To describe this case we may take advantage of the well known results about the orientation of stretched molecules in the flow [4]. The number of dust particles, whose axes form an angle ϑ with the direction of' the flow, is determined by the expression

$$N(\vartheta) = N_0\left[1 + \frac{\pi\eta l^3}{16kT}\frac{\partial v_z}{\partial y}\sin 2\vartheta\right]. \tag{8}$$

It was assumed when deriving (8) that all dust particles are identical and have the shape of thin rods with length l, while the gas flow is directed along the axis z and has a velocity gradient $(\partial v_z/\partial y)$ along the axis y. Here η is gas' viscosity factor, T is its temperature and k is the Boltzmann constant. The direction of dust particles' prevailing orientation forms an angle of 45° with the direction of the flow. For not too small atmospheric dust particles ($l \gtrsim 10^{-3}$ cm the degree of orientation may be not too small. For example, in lower air layers at $T \approx 3\cdot 10^2$ °K $\eta \approx 2\cdot 10^{-4}$, $(\partial v_z/\partial y) \approx 0{,}1$ and $l \approx 10^{-3}$ cm we shall obtain an orientation ~ 10 percent.

**** THE END ****

The Ioffe Institute of Physical Engineering of the USSR Academy of Sc.

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REFERENCES

1. L. DAVIS, J. GREENSTEIN. Astrophys. J. 114, 206, 1951.
2. T. Gold. Monthly Notices Roy Astronom. Soc., 112, 215, 1952
3. J. M. GREENBERG, G. SHAH. Astrophys. J. 145, 63, 1966.
4. YA. I. FRENKEL' Kineticheskaya teotiya zhidkosti (Kinetic Theory of Fluids) AN SSSR, 1945.