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ROTATION AND ORIENTATION OF COSMIC DUST GRAINS

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1. Data on the concentration and physical properties of cosmic dust are necessary for describing the passage of light through the cosmic medium, for explaining zodiacal light, for constructing cosmogonic hypotheses, and so on. Observations show that light, passing through clouds of cosmic dust, is polarized and partially absorbed, especially in the short-wavelength region of the spectrum. The polarization of light is evidently caused by scattering by dust grains that have a nonspherical shape or sharply anisotropic properties and are oriented in space.

In most hypotheses explaining the orientation of dust grains, it is assumed that the grains rotate under the action of impacts by the surrounding gas atoms, and some mechanism is indicated for orienting their angular momentum. The axes of the dust grains, in turn, are oriented with respect to the moment and thereby with respect to the external medium.

In the most widespread hypothesis—that of Davis and Greenstein (^1)—it is assumed that the dust grains contain ferromagnetic atoms. When such a dust grain rotates in an interstellar magnetic field, its angular momentum is aligned along the lines of force. However, the alignment time is large, $\sim 10^6$ years. It is comparable with the lifetime of dust clouds and is less than the characteristic times of turbulent motion of the gas. In addition, this hypothesis requires an anomalously high abundance of ferromagnetic substances.

In another hypothesis—that of Gold (^2)—orientation under the action of a supersonic stream of interstellar gas is considered. The total moment of a dust grain, produced by impacts of gas atoms, is defined as $\mathbf{M} = \mathbf{M}_0 + \mathbf{M}_1$, where $\mathbf{M}_0$ is the moment due to collisions with chaotically moving atoms, and $\mathbf{M}_1 = \sum_n m\mathbf{r}_n \times \mathbf{v}$ is due to collisions with the directed stream. Here m is the mass of the atoms, $\mathbf{v}$ is the stream velocity, $\mathbf{r}_n$ is the radius vector from the center of the dust grain to the point of impact, and $\sum_n$ is the sum over all impacts. The quantity $\mathbf{M}_1$ is perpendicular to the stream, but is very small, since the probability of an impact on one side of the center of gravity of the dust grain is equal to the probability of an impact on the other side, and fluctuations were not taken into account by Gold. Therefore the sum over n is, in order of magnitude, equal to one term, i.e., to the moment obtained from a single impact of a gas atom. The chaotic component $\mathbf{M}_0$ tends to the large equilibrium value $M_0 \to (3kTI)^{1/2}$, where I is the moment of inertia of the dust grain and T is the temperature of the gas. Since under such conditions one cannot expect a noticeable orientation of the moment, Gold' s hypothesis did not become widespread.

In all the proposed hypotheses, fluctuations in the number of impacts of incident particles on different sides of the center of gravity of the dust grain were not taken into account. Meanwhile, it is precisely this phenomenon that leads to a qualitatively new situation, ensuring rapid orientation of the moments of dust grains. We shall show that dust grains are oriented under the action of corpuscular and light fluxes coming from the Sun and the stars, and of gas fluxes in cosmic space. We emphasize that dust grains are oriented not only in interstellar, but also in interplanetary space and even in the atmospheres of planets.

2. Let us consider a dust grain in interplanetary space. It is acted upon by the flux of solar-wind protons and by the light radiation of the Sun. For simplicity, let us assume that the dust grain is symmetric with respect to its center of gravity. Let $w_p t$ be the mean number of protons falling on the dust grain on one side of its center during the time t. The probability that a given number of protons will strike is given by the Poisson distribution. The probability that, on one side during the time t, n more protons will fall than on the other is equal to

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

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

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

increases in proportion to the square root of the time during which the flux acts.

The mean moment acquired by the dust grain during the time t as a result of fluctuations in the number of protons striking it is equal to

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

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

Let us consider a homogeneous dust grain with dimensions $B = C$ along two axes and $A = \gamma B$ along the third axis, where $\gamma \gtrless 1$. The motion of such a dust grain is composed of rotation about the axis A and precession about the direction $\mathbf{M}$. If the dust grain is elongated ($\gamma > 1$), then the component of the angular momentum about the short axis is the largest, since it corresponds to the largest value of the mean impact parameter $\rho_A = \gamma B/4$. The angle between the axis A and the direction of the angular momentum is determined by the known formulas for the motion of a symmetric top,

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

The angular velocities of rotation of the dust grain about the axis A and of its precession about M are, respectively,

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

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 grain.

The flux of solar-wind protons at a distance r from the Sun is equal to $J_p = nv_p$, where $n = Q/v_p r^2$ is the proton concentration. The probability of one of the protons striking the dust grain is $2w_p = J_p S$, where S is the projection of the surface of the dust grain onto 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 ~ 1 keV) the dust grain is practically a black body. Data on the scattering and polarization of light indicate that the shape of cosmic dust grains is far from spherical, and the most probable sizes are $\sim 10^{-4}$–10^{-5} cm. Meteor data indicate a large scatter in the values of dust-grain density, from 0.05 to 8 $\text{g}\cdot\text{cm}^{-3}$.

Taking, for example, $B = 10^{-4}$ cm, $\rho = 5\cdot 10^{-5}$ cm, $S \approx 10^{-8}$ cm, $\gamma = 2$, $\delta = 1\ \text{g}\cdot\text{cm}^{-3}$ at a distance $r = 1$ AU $= 1.5\cdot 10^{13}$ cm, with mean values $n = 5\ \text{cm}^{-3}$, $v_p = 3\cdot 10^7\ \text{cm}\cdot\text{sec}^{-1}$, we obtain an angular momentum $M \approx 3\cdot 10^{-21}\sqrt{t}$, and the corresponding angular velocities $\omega_A \approx \omega_{\text{pr}} \approx 0.6\sqrt{t}\ \text{rad}\cdot\text{sec}^{-1}$. Thus, already during the first second of the dust grain' s stay in the flux its angular velocity reaches 0.6 $\text{rad}\cdot\text{sec}^{-1}$, in a day 200 $\text{rad}\cdot\text{sec}^{-1}$, and in

per year, $\sim 3\cdot 10^3\ \text{rad}\cdot\text{sec}^{-1}$. If the dimensions of a dust particle are $\sim 10^{-5}$ cm, its angular velocity is approximately 100 times greater than that indicated, but such small dust particles are swept out of the Solar System by radiation pressure.

3. The rotation of dust particles may be caused not only by a directed flux of protons, but also by a flux of photons coming from the Sun. In this case, analogously to (6), we obtain

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

$h\nu$ is the mean energy of the photons, and J_γ is their flux at a distance r from the Sun. Considering the same dust particle as in the preceding case, and taking into account that the main part of the solar spectrum lies near the energy $h\nu \approx 1$ eV, while the radiation flux at a distance $r = 1$ a.u. is $\sim 2 \cdot 10^{17}$ photons/cm$^2 \cdot$ sec, we obtain $M \approx 1.2 \cdot 10^{-22}\sqrt{t}$, i.e., the effect of the light flux is an order of magnitude smaller than the effect of the solar wind. However, far from the Sun, where the corpuscular flux loses its directed velocity, the light flux may become the principal factor causing the rotation of dust particles.

4. Obviously, all the preceding considerations, apart from the quantitative estimates, also apply to dust particles near stars, in interstellar space, and in gas–dust nebulae. There is much data on the motions of gas in nebulae, but there is no basis for assuming that the gas and dust there are in equilibrium. External factors (light pressure, magnetic fields, intrusion of fluxes from outside, etc.) affect the gaseous and dusty components of a nebula differently, and one may think that motion of the gas relative to the dust is always present. Gas fluxes, in analogy with the solar wind, set dust particles into rotation. Gas particles, along with directed motion, participate in chaotic thermal motion, which leads to the appearance of an isotropic component of the moment of rotation of the dust particles. The ratio of this component to the component perpendicular to the flux is, according to (6), proportional to the quantity $(v_\mathrm{T}/v)^{3/2}$, where v is the directed velocity and v_T is the chaotic velocity of the gas particles. For $v \gg v_\mathrm{T}$, the moment is established perpendicular to the flux. Far from the stars, the light flux ($J_\gamma \sim 10^9$ photons/cm$^2 \cdot$ sec) cannot create a noticeable orientation of the moments of rotation of dust particles, since disorientation in collisions with particles of the interstellar gas is more effective than orientation by light.

The orienting action of the flux will cease when the dust particle acquires its velocity. The usual estimates of the concentration and temperature of neutral hydrogen in interstellar space (in the H I zone) correspond to $n_\mathrm{H} \approx 10$ cm^{-3}, $T \approx 100^\circ$ K, i.e., the thermal velocity is $v_\mathrm{T} \approx 1.5 \cdot 10^5$ cm/sec. Motion of fluxes in the H I zone (for example, as a result of the entrainment of hydrogen during the expansion of an H II zone) occurs with velocities $v_0 > 10^6$ cm/sec. The velocity of the entrained dust particle is determined by the equation $m_g \dot{v} = \varkappa n_\mathrm{H} m S(v_0 - v)^2$, where $\varkappa$ is the accommodation coefficient, $m_g = \gamma B^3 \delta$ is the mass of the dust particle, $S = \gamma B^2$ is its area facing the flux, and δ is the density. The velocity v will be attained in the time $\tau_p = m_g v [v_0(v_0 - v)\varkappa n m S]^{-1}$. For a dust particle with $\delta = 3$ g $\cdot$ cm^{-3}, $B = 5 \cdot 10^{-5}$ cm, and $\varkappa \approx 1$, the velocity $v \approx 0.8 v_0$ will be attained in 10^6 years. During this time the dust particle will have time to acquire a mean angular velocity, perpendicular to the flux, $\omega_\mathrm{pr} = 3 \cdot 10^5$ sec^{-1}.

Disruption of the orientation of dust particles may occur not only as a result of collisions with chaotically moving atoms or with one another, but also as a result of precession in a magnetic field. If a dust particle with dimensions $B = 5 \cdot 10^{-5}$ cm has a potential of 0.03 V, then in a magnetic field with $H = 10^{-5}$ oersted the rate of its precession will be $\Omega = 10^{-11}$ sec^{-1}, i.e., its orientation will be disrupted in approximately 1000 years.

We shall not here calculate the parameters characterizing the polarization of light scattered by oriented dust particles, although this question

requires a more complete treatment than has been given in papers (1-3). The results of these papers can be used for estimates of polarization. Let us note that the orientation of dust particles in interplanetary space must be taken into account in interpreting polarization observations of comets, zodiacal light, and gegenschein.

5. In the atmospheres of the Earth and the planets, dust particles are acted upon by the wind. At those altitudes where the mean free path of the molecules is much greater than the sizes of the dust particles, the wind causes rotation and orientation of the moments of the dust particles in the same way as described above. In the dense layers of the atmosphere, where the mean free path is small, the dust particles rapidly acquire the wind velocity and are carried along with it. This phenomenon is immaterial for cosmic dust particles, since the time required for their entrainment by the solar wind or by gas streams is very large. In a dense atmosphere the entrainment time by the wind is small, and the braking of rotation is large. Therefore no stationary rotation arises. Orientation, nevertheless, may arise in the presence of a gradient of the wind velocity in the direction transverse to the flow; in this case it is not the angular momentum that is oriented, but directly the axis of the dust particle. To describe this case one may use the known results on the orientation of elongated molecules in a flow (4). The number of dust particles whose axes make an angle ϑ with the direction of the flow is determined by the expression

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

In deriving (8) it was assumed that all dust particles are identical and have the form of thin rods of length l, while the gas flow is directed along the z axis and has a velocity gradient $(\partial v_z / \partial y)$ along the y axis. Here η is the coefficient of viscosity of the gas, T its temperature, and k Boltzmann' s constant. The direction of preferential orientation of the dust particles makes 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 considerable. For example, in the lower layers of air, 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 obtain an orientation of $\sim 10\%$.

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Note: Figure translations are in progress. See original paper for figures.