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ON SOME MODELS OF ZODIACAL CLOUD

by

N. B. Divari

(USSR)

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ABSTRACT

(***)

Certain models of heliocentric cloud are considered. Starting from the distribution of orbit inclinations of dust particles, which are analogous to orbit distributions of comets, asteroids and meteors, the concentration $F(r, \phi)$ of a dust cloud is computed for each model as a function of the distance r from the Sun and of the heliocentric latitude ϕ. The functions $F(r, \phi)$, obtained for each model, were used for the calculation of brightness of zodiacal light.

Comparison of the so computed brightnesses with those observed shows that the distributions corresponding to asteroids, periodic comets, as well as to hyperbolic comets cannot be taken for the zodiacal cloud. Two models: the meteoric and the cometary, including both the periodic and hyperbolic orbits, assure a sufficiently good agreement with observations.

The calculated dependence of the degree of polarization on the distance from the Sun in the ecliptic is found to be sufficiently similar to that observed for all models. It should be noted that there are specific difficulties from the point of view of cosmogony linked with the explanation of zodiacal cloud existence at the expense of disintegration of periodical comets and meteors.

* * *

The investigations of zodiacal light, which according to generally-admitted representations is conditioned by the scattering of solar radiation on particles of the heliocentric dust cloud, provide the possibility of concluding on dust particle concentration in the interplanetary space. The concentration $n(r, \phi)$, searched for, as a function of heliocentric latitude ϕ and distance r from the Sun, may be determined by the brightness $B(\beta, \varepsilon)$ of zodiacal light

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(*) O NEKOTORYKH MODELYAKH ZODIAKAL'NOGO OBLAKA
(**) [This is a new periodical, having started with January 1967]
(***) [The original author's abstract is maintained with language improved].

from the integral equation

$$B(\beta, \varepsilon) = I_0 R^2 C (\pi\rho^2)_{cp}\, n(1.0) A \int_0^\infty \frac{f(\theta) F(r, \varphi)}{r^2} d\Delta. \qquad (1)$$

Here I_0 is the solar radiation flux at the distance of 1 a.u. from the Sun, R is the distance Earth-Sun, $Cf(\theta)$ is the scattering indicatrix, A is the albedo of dust particles, $(\pi\rho^2)_{cp}$ is the mean cross section of dust particles determined by the formula

$$(\pi\rho^2)_{cp} = \pi \int_{\rho_1}^{\rho_2} \rho^2 N(\rho)\, d\rho \Big/ \int_{\rho_1}^{\rho_2} N(\rho)\, d\rho, \qquad (2)$$

where $N(\rho)d\rho$ is the number of particles per cm^3 with radii between ρ and $\rho + d\rho$; ρ_1 and ρ_2 are respectively the minimum and maximum radii of scattering particles. The concentration $n(r,\phi)$ in (1) is represented in the form

$$n(r, \varphi) = n(1.0) F(r, \varphi), \qquad (3)$$

where n(1.0) is the concentration of dust particles in the ecliptic at the distance of 1 a.u. from the Sun. Inasmuch as the determination of function $F(r,\phi)$ from the integral equation (1) is quite difficult, this function is generally evaluated by way of assortment. Considering the various models of function $F(r,\phi)$, the brightnesses $B(\beta,\varepsilon)$ are computed by formula (1); they are compared with the values of brightness found from observations. At the same time, the coincidence of the course of the computed brightness of zodiacal light with the observed may serve as a criterion of validity of the selection of model $F(r,\phi)$.

When selecting the latter it is natural to start from certain assumptions on the possible sources of interplanetary space dust matter. Comets and asteroids were considered as such. As is shown by Fesenkov's calculations [1], the asteroid model of zodiacal light leads to a distribution of the brightness of zodiacal light differing from that observed. In his work [2] Fesenkov expressed the opinion that periodical comets cannot apparently ensure the observed distribution, and pointed to nonperiodic comets as the possible source of interplanetary space dust matter. In connection with this it appears interesting to conduct computations for concrete models and to compare the obtained brightnesses with those observed. At the same time it natural to consider besides the asteroid and cometary models, the meteoric model too.

It is understood by cometary, asteroidal or meteoric models of zodiacal light, a dust cloud, of which the distribution of orbit inclinations of dust particles coincides with the distribution of orbits of respectively comets, asteroids and meteors. At the same time the distribution of orbits by other parameters is disregarded. The dependence of the concentration $F_1(\phi)$ of dust particles on the heliocentric latitude for the given distribution of orbits $\psi(i)$ by inclinations i may be computed by the formula derived by Fesenkov in the work [1] :

$$F_1(\varphi) = \int_{\varphi}^{\pi-\varphi} \frac{\psi(i)\,di}{\sqrt{\sin^2 i - \sin^2\varphi}}. \tag{4}$$

The dependence of the concentration on the distance may be taken in the form R^n/r^n, then

$$F_1(r, \varphi) = \frac{R^n}{r^n} \int_{\varphi}^{\pi-\varphi} \frac{\psi(i)\,di}{\sqrt{\sin^2 i - \sin^2\varphi}}. \tag{5}$$

We conducted calculations for several models of zodiacal cloud, i. e., for various distributions of $\psi(i)$ with n = 1.0 and 1.5. The characteristics of the models considered are compiled in Table 1 hereafter.

TABLE 1

Number of models	n	Distribution of orbits by inclinations	References
1	1.0	Periodical comets observed more than once	[3]
2	1.0	Periodical comets observed once	[3]
3	1.0	All periodical comets	[3]
4	1.0	All comets (periodical and nonperiodical	[3]
5	1.0	$\psi(i)$ = const	
6	1.0	Asteroids	[4]
7		Meteors	[5]
8	1.5	All comets (periodical and noperiodical)	[3]
9	1 to 1.5	All comets (periodical and noperiodical) n = 1.0 for r > 1.5; n=1.5 for r > 1.5	[3]
10	1.0	Nonperiodical comets	[3]

Besides the models indicated in Table 1, the model 11 is subsequently considered in detail; it was considered elsewhere [6] and it corresponds to the two-dimensional distribution $\psi(i, a)$ of meteoric orbits by inclinations i and major semiaxes a obtained in the work [7].

The distribution of dust matter concentration in interplanetary space and the brightness of zodiacal light for models 1, 2 and 3 were found to be close. This is why we do not talk below about models 1 and 2, but only of model 3. The obtained dependences of dust matter concentration, $F_1(\phi)$ on the heliocentric latitude ϕ for models 3, 4, 5, 7 and 10 are plotted in Fig.1. Attention is drawn by the closeness of the dependences for models 3 and 6 (particularly for $\phi > 15°$), and also for models 4, 5 and 7. If the dependence of concentration $F_1(\phi)$ on the heliocentric latitude ϕ is represented in the form

$$F_1(\varphi) = F_1(0)\,e^{-k_1 \sin\varphi}, \tag{6}$$

we shall obtain for the various models the following values of k_1:

MODEL	3	4	5	6	7	8	9	10
k_1	4.1	0.99	1.3	0.99	1.8	0.99	0.99	1.10

The brightness of zodiacal light $B(\beta,\varepsilon)$ at the point with the geocentric latitude β and longitude $\varepsilon = \Lambda - \Lambda_{\odot}$, counted from the Sun, was computed by the formula

$$B(\beta, \varepsilon) = I_0 RC(\pi\rho^2)_{cp} A \frac{n(1,0)}{\sin^{n+1}\gamma} \int_{\gamma}^{\pi} f(\theta) F_1(\varphi) \sin^n \theta \, d\theta, \tag{7}$$

which is obtained from (1) upon substitution

$$F(r, \varphi) = \frac{R^n}{r^n} F_1(\varphi); \quad \Delta = R \frac{\sin(\theta - \gamma)}{\sin\theta}; \quad \frac{1}{r} = \frac{1}{R} \frac{\sin\theta}{\sin\gamma}.$$

Here γ is the elongation from the Sun, θ is the angle of scattering at the point of scattering, Δ is the distance of the scattering elements from the observer (see Fig.2). Besides brightness the degree of field polarization was also computed by the formula (function $F_1(\phi)$ is so normalized that $F_1(0) = 1$)

$$P(\beta, \varepsilon) = \frac{B_P(\beta, \varepsilon)}{B(\beta, \varepsilon)}, \tag{8}$$

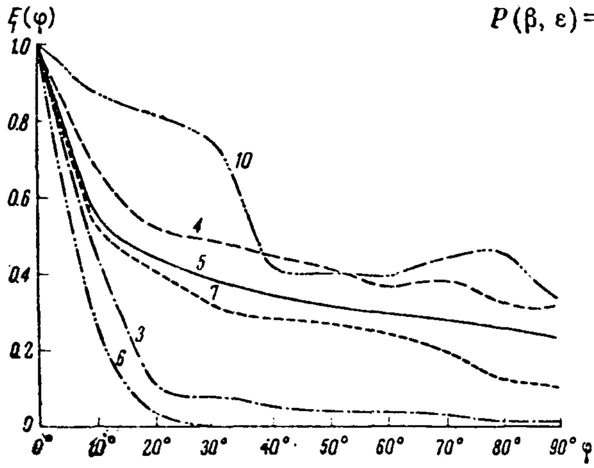

Fig.1. Dependence of dust concentration $F_1(\phi)$ on heliocentric latitude ϕ, computed for various models. The numerals correspond to the numbers of models.

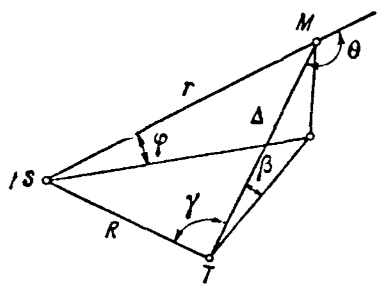

Fig.2. Sketch showing the angles and the disposition of the scattering element M relative to the Earth (T) and the Sun (S).

where $B_P(\beta\ \varepsilon)$ is the polarized component of zodiacal light brightness. It is determined by the formula

$$B_P(\beta, \varepsilon) = I_0 RC(\pi\rho^2)_{cp} A \frac{n(1.0)}{\sin^{n+1}\gamma} \int_{\gamma}^{\pi} p(\theta) f(\theta) F_1(\varphi) \sin^n \theta \, d\theta. \tag{9}$$

Here p(θ) is a function determining the degree of polarization of solar radiation scattered by interplanetary dust. It was taken in the form obtained in [8] after the observations by E. V. Pyaskovskaya-Fesenkova [9].

The brightness distributions of zodiacal light computed by formula (7) for nine models were compared with the observed distribution found by L. Smith, F. E. Roach and R. W. Owen [10], and also with the distribution obtained in the work [11]. The results of work [10] are characteristic by the fact that the value of zodiacal light brightness found in it for the pole of ecliptic (100 stars 10 st. magn. per sq.degree) is close to the value found in other works [12 –16] by photometric as well as by polarization measurements. The brightnesses of zodiacal light found in [11] correspond to the brightnesses of cones relative to background which is obtained by measured sky brightnesses at points remote from the cones after subtracting from these brightnesses all the known components, except for the zodiacal light component. The values of brightness and polarization of zodiacal light utilized by us are free from the influence of the terrestrial atmosphere.

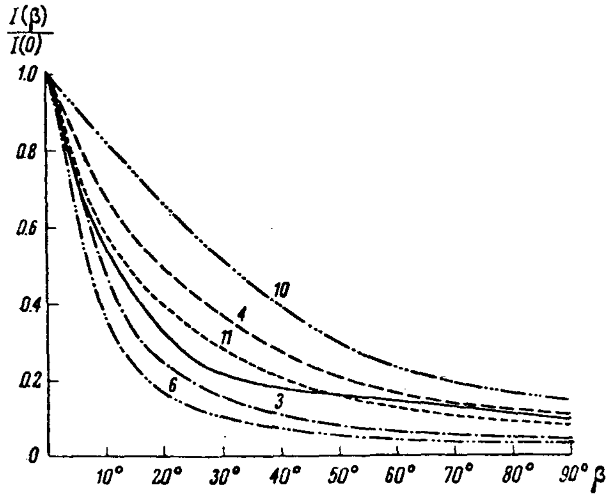

Fig.3. Dependence of the brightness of zodiacal light on the geocentric latitude β, computed for various models for $\varepsilon = 40°$. The numerals are the numbers of models. The solid line represents the observed dependence after the work [10].

Shown in Figures 3 and 4 is the course of zodiacal light brightness as a function of heliocentric latitude β for $\varepsilon = 40°$ and 90°, obtained for the models 3, 4, 6, 10 and 11, alongside with the course of the dependence found from observations of the work [10]. As may be seen from these graphs, the observed course of brightness perpendicularly to the ecliptic does not correspond either to asteroidal model 6, or to model 3 for periodical comets. The course of brightness obtained for these models at $\varepsilon = 40°$ was even found to be steeper than the course found in the work [11], in which the brightness of cones was determined relative to background. Thus the distribution of interplanetary dust cannot contribute either to distribution of periodical comets or asteroids, fact to which Fesenkov has already pointed [2]. However, the observed brightness distribution of zodiacal light does not correspond to nonperiodical comets either (model 10), which give a very slow drop of brightness in the direction toward the ecliptic pole.

A sufficiently good agreement with the observations is assured by the meteoric model 11, obtained by the two-dimensional distribution $\psi(i, a)$, and the cometary model 4, accounting for all comets, periodical as well as nonperiodical. At the same time, for $\varepsilon = 40°$ the meteoric model corresponds better to observations than the cometary, while for $\varepsilon = 90°$ it corresponds somewhat worse to the cometary model for $\beta < 50°$ and somewhat better for $\beta > 50°$.

As to course of the brightness as a function of ε, it is not dependent on orbit distribution by inclination and, besides the scattering indicatrix, it is mainly determined by dust concentration as a function distance r, i. e., in our case by the value of n. We compiled in Table 2 the relative values of brightness at $\beta = 0$ for models at $n = 1.0$ and $n = 1.5$, and also for the variable n (model 9) together with the observed values of brightness found in the works [10] and [17].

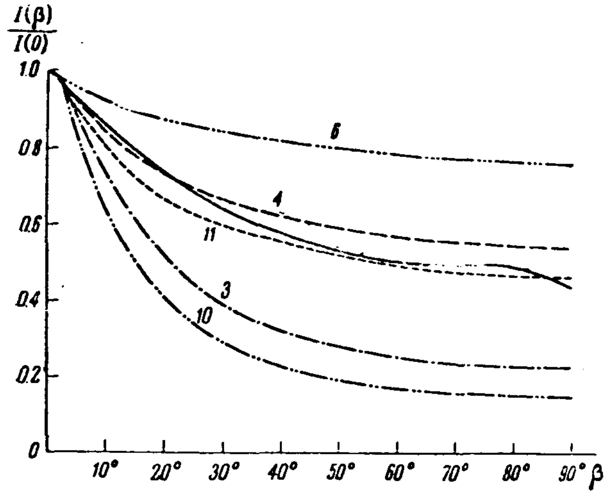

Fig.4. Brightness of zodiacal light as a function of geocentric latitude computed for various models with $\varepsilon = 90°$. The numerals correspond to the numbers of models (Nos. 6 and 10 should be in - verted). The solid line represents the observed dependence according to [10].

The observed relative course of brightness of zodiacal light at the ecliptic obtained in [10] differs little from that obtained in [17]. The dependence of dust concentration on the distance r from the Sun, taken in the form $\bar{R}^n / r^n$, corresponds better to observations at $n = 1.0$, than at $n = 1.5$. The combined model 9 ($n = 1.5$ for $r > 1.5$ and $n = 1.0$ for $r \leqslant 1.5$) differs little from the model $n = 1.0$ for $\varepsilon < 90°$, which is conditioned by the fact that for $\varepsilon < 90°$ the brightness of zodiacal light is determined mainly by the part of the zodiacal cloud that lies inside the Earth's orbit. As to the degree of polarization, its course along the ecliptic is obtained identical for all models, and sufficiently close to the experimentally observed. In directions perpendicular to the ecliptic, the degree of polarization varies differently for the various models; however, these differences are insignificant. Taking this into account alongside with the fact that the degree of polarization far from the ecliptic is insufficiently well known, inasmuch as there are very few of the respective measurements, there is no basis at present for a detailed comparison of the observed and computed course of the degree of polarization in directions perpendicular to the ecliptic. Moreover, one should bear in mind that the degrees of polarization computed for all models are strongly dependent upon the function $p(\theta)$, which is obtained by atmospheric aerosols, and not by interplanetary particles, and thus can not correspond to reality.

TABLE 2

ε	30°	35°	40°	45°	50°	60°	70°	80°	90°	100°	120°	140°	160°
$n = 1.0$	10.0	7.3	5.5	4.3	3.4	2.2	1.6	1.2	1.0	0.84	0.65	0.55	0.50
$n = 1.5$	14.6	10.3	7.6	5.6	4.3	2.8	1.7	1.3	1.0	0.83	0.62	0.51	0.46
model 9	10.6	7.7	5.8	4.5	3.5	2.3	1.6	1.2	1.0	0.83	0.63	0.52	0.47
[10]	9.3	6.4	4.7	3.8	3.0	2.0	1.5	1.2	1.0	0.88	0.74	0.70	0.70
[17]	10.2	7.2	5.2	4.1	3.2	2.2	1.7	1.3	1.0	—	—	—	—

The comparison of the different models just made shows that the best agreement with the observed distribution of zodiacal light is obtained for the meteoric model and for the cometary one, which takes into account all comets, periodical as well as nonperiodical, with dust concentration dependence on the distance r having the form R/r. The cometary model 4 is constructed on the condition that identical weight be attributed to all comets, i. e., it is postulated that all comets contribute identically to the distribution of interplanetary dust concentration.

It is necessary to take notice here that from the cosmogonic point of view there arise specific difficulties in the explanation of the existence of a zodiacal cloud by its filling at the expense of disintegration of nonperiodical comets. For example, Harwit [18] reached the conclusion that the dust, emitted by nonperiodical comets, cannot compensate the losses of dust on account of the Poynting-Robertson effect, inasmuch as the tiny particles ejected by these comets will have hyperbolic velocities relative to the Sun and thus will have to leave the solar system. According to his calculations, only short-period comets and asteroids may be sources of tiny dust susceptible to remain within the solar system. However, the rate of dust formation from short-period comets, constituting only about 0.07 t/sec, is small by comparison with the rate of dust loss at the expense of the Poynting-Robertson effect, which is $\sim$ 1 t/sec. Therefore, short-period comets must be rejected as sources of interplanetary dust from both the cosmogonic as well as observational viewpoints. It may be seen therefrom that the recourse to comets as possible sources of interplanetary dust is met with substantial difficulties. Taking into account the results of the conducted comparison of various models, one may reach the conclusion that the only source of zodiacal cloud replenishment by tiny dust may be in meteoroids. However, a series of questions then remain, which require detailed consideration, and therefore the meteoric model may now be viewed only as possible.

Asteroids could assure a sufficient rate of zodiacal cloud replenishment by tiny dust; however, they provide a distribution of zodiacal light not corresponding to observations. In connection with this the accounting of the conribution of the circumterrestrial dust cloud to the brightness of zodiacal light is of interest. The combination of dust arising from asteroids with the dust of the circumterrestrial cloud may assure a sufficiently good distribution of brightness of zodiacal light, inasmuch as the superimposition of light scattered by the circumterrestrial dust cloud will lead to the widening of isophots obtained by the asteroidal model.

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VOLT TECHNICAL CORPORATION
1145 19th St.NW
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