Conditions of Disintegration of Asteroids from Observations of the Properties of the Zodiacal Light

V. G. Fesenkov

RECENT data[1–3] show that the zodiacal light is characterized by the scattering effect of dust particles in an interplanetary medium largely devoid of free electrons. In fact, its observable properties—its form, position in relation to the ecliptic, absolute brightness, color, polarization, and even its probable connection with the solar corona—can all be explained in terms of the dust hypothesis, that is, in terms of the scattering of solar light by fine particles. The presence in the solar system of a gaseous or even an electronic component cannot be demonstrated photometrically. Fine dust, however, cannot remain long in space, owing to the retarding action of solar radiation and corpuscular emission from the sun. For the first reason alone all such dust should be precipitated on the sun within the comparatively short period of about 100,000 years. Thus the composition of the material of the zodiacal light must be continuously renewed by the uninterrupted arrival of matter from the outside, and this very intensive process is the result of the gradual disintegration of asteroids. The same process is also accompanied by the separation of meteorites, as evidenced by the low values for the cosmic ages of such bodies determined from their He_3 content.[4, 5]

Starting from the distribution of asteroids according to the angles of inclination of their orbits, it is possible to calculate the isophotes of the zodiacal light and compare them with observations. This presents known difficulties, since the visible isophotes of the zodiacal light are affected by various components of the night glow of atmospheric and cosmic origin, and, moreover, by zodiacal twilight, i.e., the intensification of parts of the zodiacal light close to the horizon by considerably brighter parts lying directly below it, and, finally, by supplementary scattering in the troposphere.

The author's calculations[6] show that the effect of zodiacal twilight is small and incapable of introducing significant distortions into isophote observations; at the same time, the illumination of the troposphere by the zodiacal light itself is quite appreciable, owing to its considerable angular dimensions, and, furthermore, is not uniform with respect to azimuth.

This results not only in a certain increase in the observed brightness of the phenomenon, but also in a marked broadening of the characteristic isophotes. It is possible, moreover, that there are other factors working in the same direction. All these influences, however, are much less important when the axis of the zodiacal light is oriented vertically with respect to the horizon, which happens, for example, near the tropics about the equinoctial epoch. We made numerous observations of the zodiacal light in the Libyan Desert, south of Aswan, in October and November 1957, when, in the course of the same night, it was possible to observe this phenomenon normal to the horizon in the east before sunrise and much inclined in the west soon after nightfall. In this way we obtained graphic confirmation of the visible distortion of the isophotes as a function of the angle of inclination of the ecliptic to the horizon. This distortion is largely attributable to the forementioned causes.

Even when the zodiacal light is normal to the horizon, however, we find that the true isophotes are comparatively broad, though completely symmetrical with respect to the ecliptic. These isophotes, as obtained from the observations made in Egypt, are shown in Fig. 1.

On the other hand, theoretical isophotes can be calculated, if we assume that there is a definite law of distribution of the density of the dust in interplanetary space as a function of the distance from the sun, and a definite form of the indicatrix of scattering, and assume that the dust results from the disintegration of asteroids without a marked initial relative velocity.

It seems most natural to take the density distribution of the dust as inversely proportional to the distance from the sun, assuming stationary conditions. In order to calculate the disintegration of the asteroids, it is necessary to start from the known distribution of the angles of inclination of their orbits with respect to the plane of the ecliptic.[7] The indicatrixes of scattering of the dust material in interplanetary space are not known, but it is possible to show that their nature has little effect on the result.

We propose to take three quite different forms of the indicatrix of scattering: a simple spherical form, for which the calculations are easiest; a form typical of the terrestrial atmosphere, i.e., reflecting the properties of the Rayleigh and aerosol scattering of light, with an asymmetry equal to 5.6, represented by the expression

$$f(\vartheta) = 1 + 5.5(e^{-3\vartheta} - 0.009) + 0.55\cos^2\vartheta$$

and a purely aerosol form with very great asymmetry, equal to 12, obtained from the foregoing by suitable elimination of the Rayleigh scattering:

$$f_1(\vartheta) = 1 + 11.1(e^{-3\vartheta} - 0.009)$$

The results of calculating the corresponding isophotes of the zodiacal light for these three indicatrixes are given in Figs. 2, 3, and 4.

As can be seen from the figures, the most compressed isophotes are those given by the spherical indicatrix, while, as the asymmetry increases, there is a definite, though slight, broadening with respect to the ecliptic. In the same way, the distribution of brightness in the zodiacal light in the plane of the ecliptic is almost identical for the last two cases, as shown in Fig. 5.

Thus, the nature of the isophotes depends little on the form of the indicatrix of scattering and is completely determined by the distribution of the orbits of the dust particles with respect to their angles of inclination to the ecliptic.

We can state that under all conditions the theoretical isophotes of the zodiacal light will be more compressed with re-

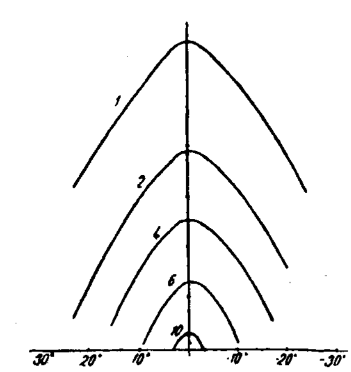

Fig. 1

Translated from Izvestiia Astrofizicheskogo Instituta Akademii Nauk Kazakhskoi SSR (Bulletin of the Astrophysical Institute of the Academy of Sciences of the Kazakh SSR) VIII, 3–12 (1959). Translated by Faraday Translations, New York.

spect to the ecliptic, if they are calculated starting from a known distribution of the inclinations of the asteroids' orbits.

In order to characterize the isophotes of the zodiacal light, they may be roughly imagined as isosceles triangles, normal to the horizon, with a definite ratio of base to height. For southern Egypt we get an average of 1.3 for the real isophotes, taking into account the necessary corrections, and only 0.56 for the theoretical, even for those corresponding to the greatest degree of asymmetry.

Thus, there is a considerable discrepancy between the forms of the observed and theoretical isophotes, apparently due solely to the conditions of formation of the zodiacal light, i.e., from our point of view, to the conditions associated with the gradual disintegration of asteroids.

We shall proceed from the hypothesis that the gradual disintegration of an asteroid can be likened to the uniform ejection in all directions of particles of matter with the same relative velocity. If this velocity is an appreciable fraction of the orbital velocity of the asteroid, there ought to be a

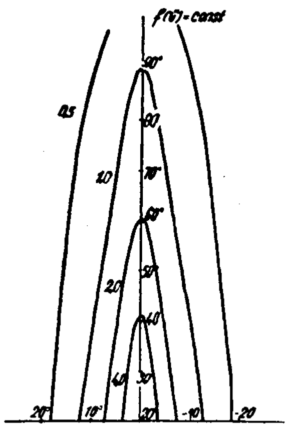

Fig. 2

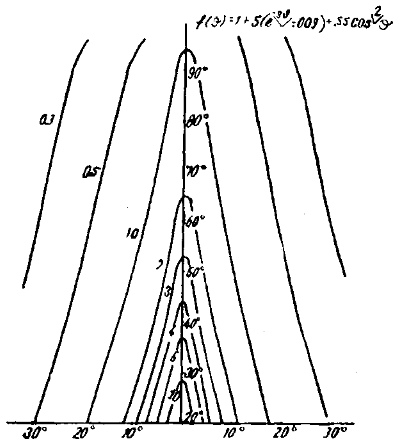

Fig. 3

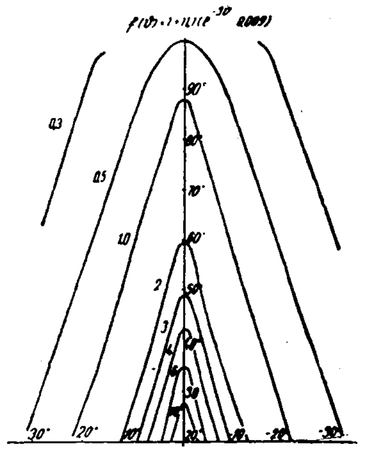

Fig. 4

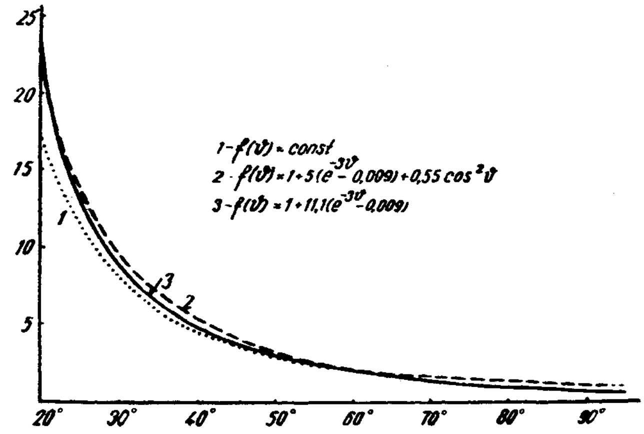

Fig. 5

sufficient dissemination of dust particles in space on both sides of the ecliptic and, hence, a corresponding broadening of the isophotes of the zodiacal light. As has already been shown,[7] these isophotes can be represented by the following simple expression:

$$I_{zl} = \int_0^\infty \frac{e^{-k_1 \frac{\Delta}{\gamma} \sin\beta} f(\vartheta) d\Delta}{r} \tag{1}$$

where r is the distance from the sun, Δ the distance from the observer, β the geocentric latitude, and k_1 a coefficient, defining the nature of the distribution of the dust particles in space as a function of the heliocentric angle φ with respect to the plane of the ecliptic:

$$\Phi(\varphi) \sim e^{-k_1 \sin\varphi / r}$$

After having determined this coefficient from (1), from an integral equation of the form

$$\Phi(\varphi) = \int_\varphi^{\pi/2} \frac{F(i)di}{\sqrt{\sin^2 i - \sin^2\varphi}}$$

we can then find the distribution function of the dust particles $F(i)$ as a function of the angle of inclination of their orbits i. This function is connected directly with the relative velocity of ejection during disintegration of the asteroid.

It is simpler, however, to proceed in the reverse order and first establish the dependence of the relative velocity of ejection of the dust particles on the distribution of their orbits with respect to the angles of inclination i. We shall denote by v the orbital velocity of the asteroid and by w the relative velocity of ejection of a dust particle from its surface, and write the ordinary equations for the area integrals:

$$y\frac{dx}{dt} - x\frac{dy}{dt} = C \cos i$$

$$z\frac{dy}{dt} - y\frac{dz}{dt} = C \sin\Omega \sin i$$

$$x\frac{dz}{dt} - z\frac{dx}{dt} = C \cos\Omega \sin i$$

where for the asteroid in question we can assume that $x = r$ and $y = z = 0$ (y axis in the direction of orbital motion). Obviously

$$\cos(x, w) = \sin\vartheta \cos\lambda$$

$$\cos(y, w) = \cos\vartheta$$

$$\cos(z, w) = \sin\vartheta \sin\lambda$$

if ϑ and λ are polar coordinates, defining the direction of the ejected particle, ϑ being analogous to the angular distance,

Table 1

$\cos\vartheta$	0.998	0.99	0.98	0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20
Δi	19.6	24.4	18.2	35.8	39.5	53.5	38.0	29.7	22.9	20.2	15.8	11.4
i	0.16	0.53	0.88	1.34	1.96	2.74	3.05	4.06	4.50	4.86	5.16	5.40
$\Delta P/\Delta i$	59.2	50.0	50.4	48.3	55.0	52.2	54.5	49.2	50.6	50.2	56.2	55.7

reckoned from the direction of the apex of the motion of the asteroid, and λ analogous to the length, reckoned from the orbital plane.

Furthermore

$$dx/dt = w\cos(x, w)$$
$$dy/dt = w\cos(y, w) + v$$
$$dz/dt = w\cos(z, w)$$

from which we find that

$$\tan i = -\frac{K\sin\vartheta\sin\lambda}{1 + K\cos\vartheta} \qquad (2)$$

where $K = w/v$ is the relative velocity of ejection, expressed as a fraction of the orbital velocity.

In general, the probability of the ejection of material from the surface of an asteroid is a certain function $f(\lambda, \vartheta)$ of ϑ, λ, and K. The number of dust particles, the orbits of which differ by angles of inclination i–$i + di$, may be represented by the expression

$$P \sim \int f(\vartheta, \lambda)\frac{\sin\vartheta d\vartheta d\lambda}{dt}$$

In the case of uniform ejection in all directions $f(\lambda, \vartheta) = \text{const}$, λ and ϑ being connected by relation (2). Let us determine on a representative sphere the curved line corresponding to a constant value of the angle of inclination [$i = \text{const}$, $\lambda = \varphi(i, \cos\vartheta)$]. In this case our integral can be written

$$P(i) = \int \frac{d\varphi(i, \cos\vartheta)}{di}\sin\vartheta d\vartheta$$

or

$$\frac{d}{di}\int_{\vartheta_1}^{\vartheta_2}\arcsin\left[\frac{\tan i(1 + K\cos\vartheta)}{K\sin\vartheta}\right]\sin\vartheta d\vartheta$$

where ϑ_2 and ϑ_1 are upper and lower limits corresponding to the real values of the angle λ.

The integral represented by this expression can easily be evaluated by a numerical method. We have done this for two different values of the constant K, namely, $K = 0.1$ and $K = 1.0$.

The computational procedure reduces to the construction of the curves $\lambda = \varphi(i, \cos\vartheta)$. Values of λ in degrees are plotted along the ordinate axis and $\cos\vartheta$ from -1 to $+1$ along the abscissa. Then the trapezoid method is used to evaluate the area lying between these curves and the coordinate axes corresponding to $i = 0$, and the differences in area are taken for the corresponding adjacent curves. These differences are then divided by the corresponding interval in the angle of inclination. Finally, it should be noted that the maximum possible value of i:

$$\max i = \arctan\frac{K}{\sqrt{1 - K^2}}$$

is $i_{\max} = 5.74°$ in the first case ($K = 0.1$) and $i_{\max} = 90°$ in the second.

The results of the calculations, expressed in arbitrary units, are given in Table 1.

The computation of this table is not altogether accurate, since the method used to evaluate the lower limit of $\cos\vartheta$ was only approximate. Nevertheless, it is clear that the orbital distribution function of the ejected particles is constant over the whole of the region of possible motion.

In the same way we can calculate the distribution function of the orbits with respect to the angles of inclination to the ecliptic for $K = 1$, when the relative velocity of ejection is equal to the orbital velocity. The results of such calculations are given in Table 2.

As can be seen from Table 2, this distribution function slowly but steadily decreases with increase in the angle of inclination. In smoothed form it can be represented as shown in Table 3.

The next step is to calculate the effect of these functions on the distribution with respect to angles of inclination of the entire complex of dust material in the solar system. Let us assume, for example, as is often stated, that the distribution of asteroid orbits with respect to inclinations is a function $f(i)$ represented by a curve, the ordinates of which decrease with increase in i. Let us suppose that every point on such a curve spreads in a manner dependent on the nature of $\varphi(i)$, that is, turns into a homogeneous spot, if $\varphi(i)$ is constant, or into a nonhomogeneous one, if this function decreases with increase in i.

The total effect that can be expected for any value of i is given by the integral

$$N(i) = c\int f(\xi)\varphi(\xi - i)d\xi \qquad (3)$$

Table 2

$\tan i$	0.1	0.2	0.3	0.4	0.5	0.6	0.7
$\cos\vartheta$	0.980	0.923	0.835	0.724	0.600	0.474	0.343
Δi	5.72	5.60	5.38	5.10	4.77	4.40	4.03
i	2.8	8.5	14.0	19.2	24.2	28.8	33.0
$\Delta P/\Delta i$	32.3	30.6	30.4	29.0	29.5	26.9	24.7
$\tan i$	0.8	1.0	1.2	1.6	2.0	4.0	...
$\cos\vartheta$	0.118	0.000	−0.181	−0.428	−0.600	−0.882	−1.000
Δi	3.66	6.34	5.20	7.80	5.43	12.53	14.04
i	36.8	41.8	47.6	54.1	60.7	69.7	83.0
$\Delta P/\Delta i$	25.3	24.5	21.2	17.9	16.8	10.3	3.9

Table 3

i, deg	0	5	10	15	20	25	30	35	40
$\varphi(i)$	1.0	0.998	0.993	0.978	0.952	0.917	0.865	0.823	0.765
i, deg	45	50	55	60	65	70	75	80	90
$\varphi(i)$	0.710	0.646	0.587	0.522	6.442	0.339	0.258	0.174	0

Table 4

i, deg	0	5	10	15	20	25	30	35
$f(i)$	1.00	0.977	0.872	0.537	0.248	0.091	0.021	0.0062

Table 5

$K = 0.1$								
i, deg	0	5	10	15	20	25	30	35
$N(i)$	1.00	0.967	0.827	0.542	0.264	0.111	0.037	0.0087
$K = 1$								
i, deg	0	10	20	30	40	50	60	
$N(i)$	1.00	0.986	0.943	0.866	0.767	0.647	0.506	...

If $\varphi(i)$ is constant, so that $\varphi(i) = \text{const}$, if $-a \leqslant i \leqslant a$, and $\varphi(i) = 0$, if $|i| \geqslant a$, then

$$N(i) = \int_{i-a}^{i+a} f(\xi)d\xi$$

For the value of $f(i)$ we shall take the distribution of the asteroids with respect to the inclination of their orbits, as given, for example, in Ref. 8, which in smoothed form is represented by the relative curve shown in Table 4.

Evaluating integral (3) for the two cases mentioned, we find the relative total distribution of inclinations in the complex of the orbits of dust particles originating in asteroids, as shown in Table 5.

Having obtained this distribution for dust particles (Fig. 6) derived from asteroids in accordance with the scheme described, we can finally calculate the corresponding theoretical isophotes of the zodiacal light and compare them with those observed. The result is fairly clear. When $K = 0.1$ there is no appreciable difference from the previous isophotes corresponding to the case $K = 0$. The theoretical form of the zodiacal light is represented by almost the same compressed system of isophotes. On the other hand, when $K = 1$ the calculated isophotes ought to be broader.

Thus, observations can evidently be represented by a certain intermediate value, in all probability equal to 0.4–0.5 for a relative velocity of ejection expressed in units of orbital velocity of the asteroid. Since at an average distance from the sun the orbital velocity of the asteroids is roughly 20 km/sec, the necessary velocity of scattering of the dust making up the material responsible for the zodiacal light ought to be rather high, of the order of 5 to 10 km/sec.

A more rigorous approach to the solution of this problem might be made as follows. From the approximate equality

$$e^{-k_1(\sin\varphi_1 - \sin\varphi_2)} \int_0^1 \frac{dx e^{-k \arccos(x \cos\varphi_1)}}{\sqrt{1-x^2}} : \int_0^1 \frac{dx e^{-k \arccos(x \cos\varphi_2)}}{\sqrt{1-x^2}}$$

where $x = \cos i/\cos\varphi$, it is possible to establish a relation between K and K_1. Thus, for example, when $K = 0.2$ we shall have $K_1 = 9$, and when $K = 0.1$, K_1 will be approximately halved.

The coefficient K characterizes the distribution $f(i)$ of the orbits of the asteroids with respect to the angles of inclination of the ecliptic, and K_1 enters directly into the expression determining the isophotes of the zodiacal light.

There is no direct need, however, for rather awkward calculations of this kind. The foregoing purely qualitative conclusions with respect to the initial velocity of the dust particles escaping from asteroids are fairly obvious. It is not possible, however, for such considerable velocities to result from collisions between asteroids; their relative velocity is itself rather low, since asteroids all move in the same direction.

Thus, the observed width of the isophotes of the zodiacal light evidently must be explained by the fact that the dust material responsible for it is composed not only of dust derived from asteroids but also from the periodic comets, which are characterized by a much broader distribution of orbits with respect to angles of inclination to the ecliptic. Another alternative is that, in addition to the relatively large asteroids with which we are familiar, there is another group of smaller bodies with a wider range of distribution of orbits with respect to angles of inclination. In any event, the observed form of the zodiacal light suggests that it originates in a complex of bodies sufficiently widely distributed with respect to the ecliptic, but having no relation to the solar equator. In order to characterize this complex as effectively as possible, it is necessary to establish the brightness of the zodiacal component at the pole of the ecliptic, after eliminating all the other components. This will be the next problem for students of the zodiacal light.

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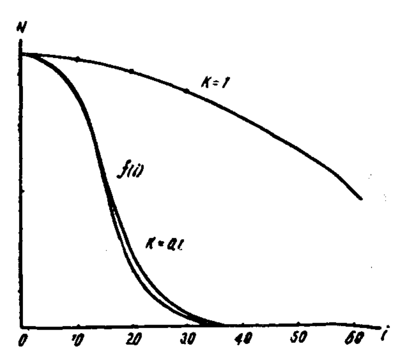

Fig. 6

Reviewer's Comment

The zodiacal light is a cone of light that may be seen over the horizon when the sun is depressed more than about 18° below the horizon. Blackwell and Ingham[1] have published a photograph of the phenomenon.

The basis of the paper by Fesenkov is the realization that the zodiacal light is due almost solely to the scattering of sunlight by dust particles in interplanetary space. This was the original theory of the zodiacal light which remained unchallenged for more than two centuries until 1953, when Behr and Siedentopf suggested that approximately half of the total brightness may be due to scattering of sunlight by free electrons in interplanetary space; the electron density required by this theory is about 600 cm^{-3} at 1 au from the sun. Fesenkov demonstrated (see his Refs. 1 and 3) that this theory of electron scattering is probably not true by showing that the polarization of the zodiacal light may be accounted for by scattering by dust. However, Fesenkvo does not mention that Rossi and associates at Harvard[2] have measured directly the ion density in interplanetary space at 1 au from the sun and shown it to be so much lower than the 600 cm^{-3} required by Behr and Siedentopf's theory that the contribution from electron scattering must be quite insignificant. Similar Russian investigations[3, 4] have yielded the same result. Furthermore, he does not mention the work of Blackwell and Ingham,[5] who obtained a similar result from spectrophotometric observations of the zodiacal light from a very high mountain station.

Fesenkov then considers the maintenance of the interplanetary dust cloud. The dust particles are drawn into the sun by the Poynting-Robertson effect, a phenomenon considered in some detail by Wyatt and Whipple.[6] The dust cloud is consumed at such a rate that it must be continually replenished, and Fesenkov considers the theory that the fresh dust arises from the disintegration of asteroids. He shows in an elegant way that no theory based on the properties of asteroid orbits can explain the large observed width of the isophotes of the zodiacal light, and he therefore concludes that the dust probably originates in the disintegration of comets, the orbits of which often have high inclinations to the ecliptic. However, he does not mention that comets may move in a direction opposite to that of the planets. Hence it will be of interest to see, from spectroscopic observation, whether the interplanetary dust cloud does in fact orbit in one direction only (corresponding to the disintegration of asteroids) or in both directions (corresponding to the disintegration of comets).

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Measurement of the Absorbed Radiation Dose on the Third Soviet Satellite Spaceship

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The third Soviet satellite spacecraft, launched on December 1, 1961 [sic] 1960 into an orbit with perigee 187 km, apogee 265 km, and angle of inclination to the plane of the Equator 65°, carried radiometric equipment of the kind used on the second satellite spacecraft.[1] This consisted of two scintillation counters and one gas-discharge counter, and differed from that used on the second spacecraft in the following ways:

1) Instead of two gas-discharge counters operating alternately there was a single counter in continuous operation, thus increasing the amount of information received.

2) The sensitivity of the channel measuring the energy release in the Na I (T1) crystal was increased by more than an order of magnitude.

3) The high voltage batteries for the photomultiplier and the gas-discharge counters were replaced by semiconductor voltage transformers.

The measurements made on the second spacecraft enabled investigators to establish the radiation distribution and to measure the absorbed dose at a height of 320 km above the earth's surface.[2] The trajectory of the third spacecraft, which averaged 100 km lower, made it possible to locate the lower boundaries of the radiation belts with greater precision.

Fig. 1 shows the readings of the radiometric counters on the third spacecraft for most of its trajectory. The picture differs only slightly from that observed during the flight of the second spacecraft. Superimposed on the maximum counts due to the latitude effect of cosmic rays are peaks created by the passage of the spacecraft through sections of the radiation belts. The geographical positions of these sections of the belts were about the same as the positions obtained on the second spacecraft,[2, 3] but the intensity of the bremsstrahlung from electrons in the outer radiation belt was lower—by $2\frac{1}{2}$ times on the average in the northern hemisphere and by 30% in the southern. The value of the average energy release of bremsstrahlung in the Na I (T1) crystal, determined as in Ref. 1, was 2×10^5 ev per quantum.

The intensity of bremsstrahlung declined markedly in the region of the Brazilian magnetic anomaly. The intensity of the proton component in this region also decreased by almost an order of magnitude.

The geographical distribution of the strength of the absorbed dose, determined on the basis of the energy release in the Na I (T1) crystal (Fig 2), was almost exactly the same as the distribution obtained on the second spacecraft. A slight difference is evident in the South Atlantic region alone.

The average strength of the absorbed dose was 6.9 mrad

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