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ZODIACAL LIGHT

N. B. DIVARI

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ACCORDING to a universal but not exclusive hypothesis, zodiacal light is due to scattering of solar radiation by a lens-like cloud of interplanetary dust stretching along the ecliptic. This explanation was suggested as far back as in 1683 by J. Cassini[1], who proposed the first scientific description of zodiacal light. Since Cassini's time, this hypothesis was elaborated on many times, although its general character has remained the same to this day. We shall attempt to show below that this hypothesis cannot be regarded as the only possible explanation of the known properties of zodiacal light, and we shall moreover indicate the facts contradicting this hypothesis.

In the analysis of observations of zodiacal light, it is necessary to approach the published results with great caution, bearing in mind that these observations are made very difficult by the low brightness of the zodiacal light, and by the fact that zodiacal light is observed against the background of the night sky, the brightness of which is comparable with that of zodiacal light. The zodiacal light is usually separated from the total observed radiation under definite assumptions concerning the brightness distribution of the atmospheric component of the night sky. The stellar component, as a rule, is taken into account by statistical means. It is very difficult to evaluate accurately the influence of absorption and scattering of zodiacal light by the lower layers of the earth's atmosphere.

Photoelectric observations of zodiacal light are carried out most frequently along almucantars that are close to the horizon, where the influence of the atmospheric glow and tropospheric extinction is large. The brightnesses of the zodiacal light outside the atmosphere is usually determined by starting from the far-from-true assumption that the atmospheric glow of the night sky is independent of the azimuth, and depends only on the zenith distance. The intensity of the atmospheric component in a given almucantar is then determined either from the brightness at points far from the ecliptic, or from the brightness of the sky at the pole, subsequently reduced to the given almucantar by a formula that presupposes knowledge of the height of the emission layers of the night sky. Such a method can lead to considerable errors. The effect of the troposphere on the brightness of the zodiacal light is significant, since the observations are made near the horizon. Inasmuch as the zodiacal light has appreciable angular dimensions, the Bouguer formula cannot be used in its usual form. V. G. Fesenkov[2] proposed, to make approximate allowance for the influence of the troposphere, a modified Bouguer formula, in which the transparency coefficient is increased by approximately 0.02, so as to take account of the zodiacal light scattered by the troposphere. Such an approximation can be more or less acceptable if the ecliptic is perpendicular to the horizon. However, as shown by Fesenkov[3], if the ecliptic is inclined to the horizon, the effect of the tropospheric component is not uniform along the almucantar and the use of the modified Bouguer formula can introduce errors that are much larger than the errors of modern photoelectric observations. It is very difficult, and perhaps impossible, to obtain at the present time the absolute brightnesses of the zodiacal light, free of errors connected with allowance for all the components of the night-sky glow and tropospheric extinction. Consequently, deductions concerning the nature of the zodiacal light can now be made only on the basis of thoroughly checked observation results, carried out in various locations on earth under ideal atmospheric conditions.

The authors of many papers have determined, on the basis of various observations of the zodiacal light, the structure of the interplanetary dust cloud responsible for the zodiacal light. In practically all of them, however, in order to compare their own deductions with the observation results, these authors make use of either one or at best two characteristic features of the phenomenon. The feature most frequently used for this purpose is the distribution of the brightness and of the polarization of the zodiacal light along the ecliptic. Other important features of the phenomenon are accordingly ignored. It is perfectly obvious that the use of only a single limited fraction of the known facts on the zodiacal light, without a suitable critical analysis, can lead to unfounded deductions regarding the nature of the scattering medium. Any theory of the zodiacal light must be based on all the information concerning the zodiacal light and explain all and not part of the observed facts. It is therefore appropriate to review critically the available observation results and to estimate their reliability and the possibility of constructing one hypothesis or another on the basis of the available observed facts.

1. POSITION OBSERVATIONS

Many observers have determined the position of the zodiacal light in the star sky. A large number of observations were made visually, without any instruments. The first observations of these kind were made by Fazio (see [4]) who pointed out the connection between the zodiacal light and the ecliptic, Cassini assumed that the axis of the zodiacal light coincided with the plane of the solar equator (see [5]). Visual estimates of the position of the zodiacal light were made by Jones[6], Marchand[7], Zakharov[8], Hoffmeister[9,10], Schonberg and Pich[11], Schmid[12], and others. The results of these observations are quite contradictory, so it is difficult to arrive at any definite conclusion. Thus, for example, Hoffmeister[9,10] believes that the axis of the zodiacal light follows exactly the large planets. According to Marchand[7], the axis of the zodiacal light is inclined 6–7° to the ecliptic, the ascension node longitude being 70°, and is thus close to the plane of the solar equator. Schmid[12] arrived at the conclusion that the position of the zodiacal light axis depends on the geographic latitude of the place of observation. In the tropics, the axis coincides with the ecliptic, and in medium latitudes it shifts to the north in the northern hemisphere and to the south in the southern one. From observations made by Zakharov[8] in Ashkhabad it follows that the axis of the zodiacal light does not have a permanent orientation relative to the ecliptic during the year, coinciding in September-October with the ecliptic, and being inclined to it 6–8° in the late spring. A similar conclusion, that the inclination of the zodiacal-light axis is not constant, was reached by Tupman at the end of the last century (see [13]). Schonberg and Pich[11] found that the zodiacal-light axis is not a great circle. The symmetry line of the zodiacal light is a small circle on the celestial sphere parallel to the ecliptic and shifted 1° to the north for an observer situated near the Tropic of Cancer, and 1° to the south for an observer located near the Tropic of Capricorn.

Visual estimates of the position of the zodiacal-light axis have the major shortcoming that they do not take quantitative account of the effect of the extinction of the earth's atmosphere and of different components of the night-sky glow. The first to determine the position of the zodiacal-light axis on the basis of instrumental photometric observations were V. G. Fesenkov[13], who worked in 1913 in Meudon, and Nice (France). Table I lists the results obtained by different observers with instruments.

As can be seen from the presented data, the instrument observations, like the visual ones, do not lead to any one definite result. On the basis of these observations one can draw the rather indefinite conclusion that the axis of the zodiacal light is close to the ecliptic. The data listed in the table allows us to assume that the axis of the zodiacal light coincides with the ecliptic within approximately 2°. It is clear, however, that there are no grounds for a more accurate conclusion. At the present time we are justified to an equal degree in assuming in the theoretical analysis that the zodiacal-light axis coincides with the ecliptic or with the fixed Laplace plane, or else that it is shifted 1–2° parallel to the ecliptic, or finally that it is inclined to it by a small angle. Another deduction worthy of attention, based on visual estimates and not contradicting the instrument measurements, is that the zodiacal-light axis is parallel to the ecliptic but that the displacement depends on the latitude of the place of observation. Furuhata[26] concluded that the central line of the zodiacal light is close to the plane of the Taurids meteor shower. To make more precise the orientation of the symmetry plane of the zodiacal light relative to the ecliptic we need further and a better procedure for the reduction of the measurement data.

Table I

Author	Year of observation	Geographic latitude	Altitude	Method of observation	Result
Fesenkov[13]	1913	+44°	1500	Visual photometer	Shifted 2° to the north of the ecliptic
Fesenkov[13]	1913	+49	67	Visual photometer	Shifted 1° to the north
Elvey and Roach[14]	1936	+31	1890	Photoelectric photometer	Shifted 2° to the north
Brunner[15]	1931–1932	+47	1583	Visual photometer	Shifted 3–5° to the north
Divari[16]	1946–1950	+43	1450	Visual photometer	Shifted 1° to the north
Regener[17]	1953–1954	+35	2800	Photoelectric photometer	Coincides with ecliptic
Blackwell[18]	1955	–16	2750	Photographic method	Shifted 0.2° to the north
Blackwell and Ingham[19]	1958	–16°	5200	Photographic method	Inclined 1.5° to the ecliptic, longitude of ascending node 115°
Donitch[20, 21]	1946–1949	+23°		Photographic method	Inclined 2° to the ecliptic, longitude of ascending node 118°
Behr and Siedentopf[22]	1952	+46°	3576	Photoelectric measurements	Shifted 1–2° to the north
Peterson[23]	1959	+35	2800	Photoelectric measurements	Coincides with ecliptic (inclination 0.18 ± 1.1°)
Divari and Asaad[24]	1957	+24	200	Photoelectric measurements	Coincides with ecliptic or shifted 1° to the north
Divari and Krylova[25]	1958	+43	3000	Photoelectric measurements	Close to ecliptic but does not coincide with it.

II. BRIGHTNESS OF ZODIACAL LIGHT ALONG THE ECLIPTIC

The brightness of the zodiacal light was determined by many observers. Most of them published only the brightnesses along the ecliptic. The first instrumental measurements of this kind were made by V. G. Fesenkov. The values obtained by him, expressed in relative units, are listed in[13].

Table II contains some information on the published series of photoelectric measurements of the zodiacal-light brightness along the ecliptic, made at different times and in different places. Table III (upper numbers in each line) lists the values of the brightness of the zodiacal light along the ecliptic, expressed in the number of stars of tenth magnitude per square degree. The fifth column of Table II indicates which stars were used by the authors for this purpose. Inasmuch as the authors used different photometric systems (photographic, visual, photovisual), not all the brightnesses are comparable with one another. In order to compare the published data, we have reduced the brightnesses to a single system of units, namely units of 10^{-13} of the average brightness of the solar disc ($B_\odot$ units). These values are placed in the lower right corner of each box in Table III. In the reduction of the published brightnesses, we have assumed that the energy distribution in the spectrum of the zodiacal light coincides with the energy distribution in the spectrum of the sun (spectral class G2). The values assumed for the stellar magnitude of the sun are $m_{pv} = -26.76$[27] and $m_{ph} = -26.20$[28]. No difference was made here between the photovisual system (isophot wavelength 544 nm), the system V (isophot wavelength 553 nm), and the visual system (isophot wavelength 560 nm). The area of the solar disc was assumed equal to 0.223 deg^2. The last column of Table II gives the values of the conversion coefficient μ, by which the brightnesses expressed in the number of stars of tenth magnitude per square degree must be multiplied to obtain the brightnesses in units of 10^{-13} of the average solar-disc brightness.

As can be seen from the brightness values listed in Table III (in $B_\odot$ units), an appreciable difference exists in the absolute brightnesses of the zodiacal light measured by different observers. There is no doubt that some discrepancy is due to an inaccurate account of the influence of the extinction by the earth's atmosphere, which can be manifest, in particular, when ob-

Table II. Published photoelectric and photographic measurements of the brightness of the zodiacal light along the ecliptic in absolute units

Author	Year of observation	Geographic latitude	Altitude, m	Brightness units used by the authors	$m_\odot$	μ
Elvey and Roach[14]	1935		1890	Tenth magnitude photographed per square degree	–26.20	$7.38\cdot10^{-16}$
Furuhata[24]	1948–49			Fifth magnitude stars, class A0, per square degree		
Behr and Siedentopf[22]	1952	+46°	3576	Stars having a brilliance of tenth magnitude per square degree in the given spectral interval	–26.76	$4.41\cdot10^{-16}$
Roach et al.[29]	1952–53	+36		Tenth magnitude stars, visual, class G0, per square degree	–26.76	$4.41\cdot10^{-16}$
Barbier[30]	1952–53	+44	650	Tenth magnitude stars, photographic, class G0, per square degree	–26.20	$7.38\cdot10^{-16}$
Regener[17]	1954	+35	2800	Tenth magnitude stars, photographic, class G0, per square degree	–26.20	$7.38\cdot10^{-16}$
Blackwell[18]	1955	+16	2743	10^{-13} of the average brightness of the solar disc		
Elasasser[31]	1956		1500	Stars having a brilliance of tenth magnitude per square degree in the given spectral interval	–26.27	$4.41\cdot10^{-16}$
Divari and Asaad[24]	1957	+24	200	Tenth magnitude stars, class G2, per square degree	–26.76	$4.41\cdot10^{-16}$
Ingham[32]	1958	–16	5200	10^{-13} of the average brightness of the solar disc		
Peterson[23]	1959	+35	2800	Tenth magnitude stars, photographic, class G0, per square degree	–26.76	$4.41\cdot10^{-16}$
Robley[33]	1961	+43	2850	10^{-13} of the average brightness of the solar disc		
Divari and Krylova[25]	1958	+43	3000	Tenth magnitude stars, photovisual, class G2, per square degree.	–26.76	$4.41\cdot10^{-16}$
Divari, Krylova, and Moroz[34]	1955	+43	1450	Tenth magnitude stars, photovisual, class G2, per square degree.	–26.76	$4.41\cdot10^{-16}$

servations made at different heights above sea level under different atmospheric conditions are compared. We cannot, however, exclude the possibility that the main cause of the discrepancy may be real fluctuations of the zodiacal-light brightness. This important question calls for a separate analysis.

For a theoretical analysis one can recommend the average values of the zodiacal-light brightness along the ecliptic, given in the next to the last line of Table III (in $B_{\odot}$ units). The last line of Table III contains the average brightnesses of the zodiacal light obtained from these values and expressed in the number of stars of tenth photovisual stellar magnitude of the solar spectral class (G2) per square degree.

The relative variation of the brightness of the zodiacal light along the ecliptic, as a function of the elongation ϵ, can be approximated sufficiently well by a power function $\sim \epsilon^{-k}$. Table IV lists the values of the

Table III. Brightnesses of zodiacal light along the ecliptic, expressed in two units

Authors	λ (nm)	$\varepsilon = \lvert \lambda_{\odot} - \lambda \rvert$								
		30°	35°	40°	45°	50°	60°	70°	80°	90°
[14]	450	— —	— —	912 6.73	740 5.46	618 4,56	436 3.22	322 2,45	261 1.93	213 1.57
[26], 7. II 1948	450	— —	2570 —	1360 —	— —	690 —	430 —	280 —	200 —	150 —
[26], 27. I 1949	450	— —	890 —	710 —	— —	440 —	280 —	210 —	140 —	100 —
[22]	543	— —	855 3.90	725 3.20	615 2,71	515 2,27	395 1.74	325 1,43	255 1,12	200 0.88
[29]	530	2330 10,3	1590 7.01	1184 5,22	945 4,17	755 3.33	498 2.20	371 1,64	297 1,31	247 1.09
[30]	440	— —	1075 7,93	700 5,17	530 3,91	420 3,10	255 1.88	200 1.48	143 1,06	110 0,81
[17]	450	1400 10,3	1000 7.38	750 5,53	590 4.35	480 3.54	320 2,36	— —	— —	— —
[18]	630	— 5,5	— 3,89	— 2,90	— 2,3	— 1,8	— —	— —	— —	— —
[31]	Visual region	1230 5,42	800 3,53	630 2,78	— —	420 1.85	270 1.19	180 0,79	130 0.57	110 0.48
[24]	414	— —	900 3,97	690 3,04	530 2.34	410 1,81	300 1,32	220 0,97	160 0.71	110 0.49
[24]	541	— —	— —	740 3,26	570 2,51	450 1.98	280 1.23	180 0,79	120 0.53	74 0,33
[24]	522	— —	— —	700 3,09	500 2,20	390 1,72	250 1,10	170 0,75	120 0,53	91 0,40
[32]	620	— 8,84	— 6.09	— 4,42	— 3,32	— 2,58	— 1.66	— 1,15	— —	— —
[23]	435	1660 7.32	1230 5,42	926 4,08	— —	697 3.07	380 1.67	291 1.29	246 1,08	223 0,98
[23]	542	1820 8.03	1150 5,07	875 3,86	— —	558 2,46	392 1.83	320 1,41	254 1.12	232 1,02
[23]	638	2020 8,91	1290 5,69	1010 4,45	— —	645 2,84	432 1.90	327 1.44	278 1,23	237 1,05
[33]	463	— —	— 8,9	— 5,40	— 3,95	— 3,02	— 2,24	— 1,89	— 1,73	— —
[33]	528	— —	— 10.0	— 6.05	— 4.45	— 3,60	— 2,69	— 2,16	— 1,80	— —
[33]	616	— —	— 9,4	— 6.30	— 4.75	— 3.75	— 2.60	— 2,07	— 1.70	— —
[25]	406	— —	— —	1140 5.03	690 3.04	535 2,36	350 1.54	220 0,97	150 0.66	— —
[25]	543	— —	— —	880 3.88	680 3,00	520 2,29	320 1.41	200 0.88	150 0.66	— —
[34]	460	— —	800 3,53	600 2,65	430 1.92	335 1,48	200 0,88	— —	— —	— —
[34]	520	— —	905 3,97	670 2.98	460 2,03	350 1,57	223 0.99	— —	— —	— —
Average, 10^{-13} $B_{\odot}$	—	8,45	5.98	4.29	3,38	2.66	1.78	1,38	1,11	0,83
Average, tenth magnitude, photovisual, G2	—	1920	1360	973	766	603	404	313	252	188

Table IV. Values of the exponent k

Authors	λ, nm	ϵ	k	Authors	λ, nm	ϵ	k
Roach et. al[29]	530	30–60°	2.22	Elvey and Roach[14]	450	40–70	1.87
Regener[17]	450	30–60	2.12	Behr and Siedentopf[22]	543	35–60	1.48
Divari and Asaad[24]	414	35–60	2.4	Furuhata, 7.II 1948[26]	450	35–70	3.13
Divari and Asaad[24]	541	40–60	2.1	Furuhata, 27.I 1949	450	35–70	2.04
Nikol'skii[35]	540	32–55	2.5	Furuhata, 10.II 1945	720	35–70	2.59
Ingham[32]	620	20–70	2.4	Furuhata, 12.II 1947	720	30–70	1.25
Peterson[23]	435.5	25–60	2.22	Barbier [30]	440	35–70	2.65
Peterson[23]	542.5	25–60	2.19	Elsasser[31]	Visual region	30–60	1.46
Peterson[23]	638	25–60	2.19				
Divari and Krylova[25]	410	40–85	2.9	Robley[33]	463	35–65	2.33
Divari and Krylova[25]	540	40–80	2.5	Robley[33]	528	35–65	2.24
Divari, Krylova, and Moroz[34]	460	35–65	2.7	Robley[33]	616.5	35–65	2.30
Divari, Krylova, and Moroz[34]	520	35–65	2.5				

Remark. The last 11 values of k were calculated by us from the published brightnesses listed in Table III.

exponent k determined by different authors. As can be seen from Table IV, there are considerable discrepancies in the relative variation of the brightness along the ecliptic, as obtained from different observations. This may be due to errors in taking into account the influence of the transparency of the earth's atmosphere on the brightness of the zodiacal light. Unfortunately, there is still no universal theory of the influence of the earth's atmosphere on the brightness of the zodiacal light, and not all observers reduce their measurement data in accordance with a single scheme. The average value of the exponent k was found to be 2.26.

III. VARIATION OF BRIGHTNESS PERPENDICULAR TO THE ECLIPTIC

Unfortunately, very few measurements of the brightness of the zodiacal light perpendicular to the ecliptic have been published, inasmuch as most observers have confined themselves to measurements of the brightness along the ecliptic. As shown by V. G. Fesenkov[2], the observed zodiacal-light cone turns out to be much broader than that calculated theoretically under the assumption that the zodiacal light is due to scattering of the sunlight by particles of meteoric dust formed in interplanetary space by disintegration of asteroids. This conclusion was confirmed in [25], where it was shown that the dependence of the zodiacal-light brightness on the ecliptical latitude is given by a relation of the form

$$I = I_0 \exp[-k_1(\beta - \beta_0)^2],$$

where β_0 —latitude of the maximum of the brightness I_0 at a given elongation. The observations of 1958[25], showed k_1 to be 0.0039, while observations in 1955[34] yielded $k_1 = 0.00335$. For polarized radiation[34], $k_1 = 0.00275$.

Of great importance to the theory of zodiacal light is the question of how far from the ecliptic the zodiacal light extends over the celestial sphere. Although it is customary to assume that the zodiacal light extends over the entire sky, there exist data contradicting this notion. According to observations of Brunner[15], made in the Alps, the intensity of the night-sky ceases to vary with the ecliptic latitude when $\beta > 25°$. Photometric observations made by us in visual rays during the period from 1946 through 1950[36] have shown that at elongation larger than 90°, the intensity of the zodiacal light ceases to vary at ecliptic latitudes larger than 35° (1 on Fig. 1). On the basis of polarization observations, Furuhata[26] found that at an elongation of 45° there is no zodiacal light at latitudes larger than 60° or at least it does not exceed 1% of the total brightness of the night sky. The conclusion that there is practically no zodiacal light at large ecliptic latitudes is confirmed also by the fact that the degree of polarization of the night sky in these regions of the sky is close to zero. For example, according to Furuhata[20] the degree of polarization at the pole of the ecliptic is less than 0.3%. According to observations made in Egypt[24], the degree of polarization of the night sky far from the ecliptic turned out to be smaller than 1%.

Recently Saito[37] reached the conclusion that the zodiacal light extends over the entire sky, thus confirming the result of Van Rhijn[38]. The dependence of the brightness of the zodiacal light on the ecliptical latitude obtained by Saito and Van Rhijn for the elongation integral 120—180° is shown in Fig. 1. Saito obtained the brightness of the zodiacal light by a new method, consisting in determining the atmospheric component of the continuous spectrum of the night-sky glow at the wavelength λ 5,250 Å from the intensity of radiation of the night sky at the wavelength λ 5,577 Å.

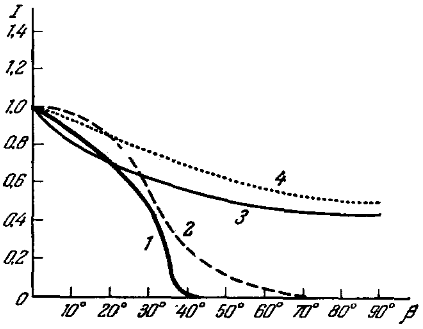

FIG. 1. Dependence of the brightness of the zodiacal light on the ecliptic latitude β at large elongations. 1 – Observations of Divari[33] for elongations larger than 90°; 2 – observations of Furuhata[26] for elongation at 45°; 3 – observations of Saito[37] for elongations 120 – 180°; 4 – observations of Van Rhijn[38] for elongations 120 – 150°.

The connection between the two intensities for the night sky was established statistically from the observations themselves. An examination of the data shown in Fig. 1 indicates that the results of Saito do not contradict the conclusion that the zodiacal light remains constant for $\beta > 60°$. On the other hand, the small slope of the zodiacal-light brightness vs. ecliptic latitude curve, which cannot ensure a gradient sufficient to make the zodiacal band visible, raises doubts, particularly if we recognize that the total light flux of the night sky contains other more intense components. The latter pertains to an equal degree to the results of Van Rhijn. There is no doubt that the value obtained by Saito for the zodiacal component at the pole of the ecliptic, which exceeds 100 tenth-magnitude stars per square degree, needs a detailed verification, all the more since the color of this component, according to Saito's data, is close to the color of a class-K star, and not to the color of the sun.

As noted by V. G. Fesenkov[39], the zodiacal component at the pole of the ecliptic is negligibly small, causing the total observed degree of polarization in this point of the sky not to exceed 1–2%. Taking into account all the foregoing, we can assume that the available observations allow us to state with full justification that the zodiacal light does not extend over the entire sky, and is concentrated near the ecliptic.

IV. SPECTRUM OF ZODIACAL LIGHT

The first spectrum of the zodiacal light was obtained by Fath[40], who established the presence of absorption bands in the zodiacal light, so that the hypothesis could be advanced that the zodiacal light constitutes scattered sunlight. The same result was reached by a study of the spectra obtained by Eropkin and Kozyrev[41] and by Hoffmeister[42]. In 1932 Ramanathan[43] observed in the spectrum of the zodiacal light an intensification of the emission lines of the night sky. This result was confirmed by Karimov[44,45], Tikhov[46], and Karyagina[47]. However, the photoelectric observations of Roach et al[29] and of Divari and Asaad[48] enable us to assume with sufficient assurance that there is no intensification of the emission lines of the night sky in the zodiacal light. In addition, the spectra obtained by Fath[40], Hoffmeister[42], and Cabannes and Dufay[49] also confirm the conclusion that there is no intensification of the emission lines, and according to Eropkin and Kozyrev[41] and Hoffmeister[42], there was even observed in the zodiacal light an attenuation of the emission line λ 5577 Å. It is not clear as yet why some spectrograms show an intensification of the emission lines, which is not confirmed by photoelectric observations. It is possible that they are due to instrumental effects, connected with the very low resolution of the spectrographs usually employed to obtain the spectra of the zodiacal light; it may also be due to the random factor which enters when the intensity of an emission line that varies along the almucantar is averaged over the exposure time.

Of considerable interest in connection with the possible role of the electrons in the formation of zodiacal-light cones are the contours of the spectral lines of the zodiacal light. On the spectrograms obtained by Hoffmeister[42], the Fraunhofer lines G, h, H, and K are clearly separated in the Gegenschein spectrum, but are somewhat smeared in the zodiacal-light spectrum. An analysis of Hoffmeister's spectrum was made by Beckers[50], who reached the conclusion that only 0.4 of the intensity of the zodiacal light is due to scattering by solid dust particles, and the remainder is due to scattering by free electrons. It must be noted, however, that the result of Beckers cannot be regarded as in any way reliable, inasmuch as the Hoffmeister spectra which he employed were not intended for research of this type.

A spectral investigation of the Fraunhofer lines in the spectrum of the zodiacal light was made by Blackwell and Ingham[51], using the spectrum obtained in 1958 in the Bolivian Andes (Chacaltaya) with the aid of a diffraction spectrograph having a dispersion 38 Å/mm. The night-sky spectrum was first subtracted from the obtained spectrograms which were superpositions of the spectra of the zodiacal light, the night sky, and twilight. This was done by photoelectric comparison of the intensity of the zodiacal light and of the night-sky light in a wide region of the spectrum, with subsequent interpolation in order to obtain the relative fraction of the night sky intensity at each wavelength. The spectrum thus obtained was then rid of the emission lines of the twilight glow by comparison with the solar spectrum, taken from the Utrecht atlas. The spectrograms, from which the night and twilight sky spectra were thus eliminated, were then used to determine the depths of the Fraunhofer lines at the point of maximum absorption, and were compared with the depths of the corresponding lines of the solar spectrum. For seven selected Fraunhofer lines, the ratio of the depth of the zodiacal-light line to the depth of the solar-spectral line was in the mean 0.97. In addition, the ratios of the quantities

$$A = \frac{\left[\int I_\lambda \, d\lambda\right]_{\text{zod. light}}}{\left[\int I_\lambda \, d\lambda\right]_{\text{Sun}}}$$

were obtained for five lines from the zodiacal-light and solar spectra, which yielded on the average a value 1.04. Combining the results obtained by these two methods, Blackwell and Ingham obtained a final value 1.01 ± 0.10 for the ratio of the depth of the Fraunhofer lines in the spectra of the zodiacal light and of the sun. This value shows that the zodiacal spectrum does not exhibit smearing of the Fraunhofer lines, which could be caused by the scattering from free electrons.

However, Schmid and Elsasser[52] objected to the latter conclusion, believing that Blackwell and Ingham averaged the obtained ratios incorrectly. They indicate that since theoretically the ratios in question cannot exceed unity, it is necessary when averaging the measured ratios to discard those values which exceed unity by an amount equal to the probable error of one measurement. Using the same data as Blackwell and Ingham[51], they obtained a value of 0.95 ± 0.10 for the average ratio of the depth of the Fraunhofer line in the spectrum of the zodiacal light to the depth of the corresponding line in the solar spectrum; this differs slightly from the results of Blackwell and Ingham[51]. A major shortcoming of the procedure of Blackwell and Ingham is that they did not take into account the true distribution of the energy in the night-sky and stellar-background spectra superimposed on the spectrum of the zodiacal light. It is necessary to bear in mind here that the spectrum of the night sky differs from the spectrum of the zodiacal light. The same holds for the spectrum of the twilight sky, which was used by Blackwell and Ingham for a comparison with the solar spectrum. Photoelectric observations of the twilight radiation, made with interference filters[53], have shown that the spectrum of the twilight glow differs from the spectrum of the sun, and the absorption by ozone in the Chapuis band plays an appreciable role in the visible region.

If we take the foregoing remarks into account, then the result of Blackwell and Ingham[51] cannot be regarded as sufficiently accurate for further deductions concerning the nature of the matter of the zodiacal light. Nonetheless, this result shows that within the limits of the observational and data-reduction accuracy the ratio of the depth of the Fraunhofer lines in the spectra of the zodiacal light to the spectrum of the sun is close to unity, i.e., the zodiacal spectrum does not exhibit noticeable smearing of the Fraunhofer lines of the solar spectrum.

Shcheglov[54], using an electron-optical converter combined with a Fabry-Perot etalon, observed in zodiacal light an intensification of H_α emission. He found that the H_α emission of the sky (λ6563) depends on the ecliptical latitude and on the elongation from the sun in such a way, that as the elongation varies from 90 to 180° the intensity along the ecliptic decreases to approximately $1/5$. Perpendicular to the ecliptic, when the latitude changes from 0 to 90° the intensity decreases by approximately six times. According to the measurements of Shcheglov, the H_α emission line has no traces of noticeable broadening or displacement as a result of the Doppler effect, i.e., this line is emitted by hydrogen atoms whose radial velocity component does not exceed 2–3 km/sec.

Measurements of the contour of the H_α absorption line λ4861, made in the Bolivian Andes (Chacaltaya) with the aid of a high resolution diffraction spectrograph used in combination with a Fabry-Perot etalon, have enabled James[55] to establish that in the evening zodiacal light one observes a Doppler shift towards the blue, but there is no noticeable smearing of the line. A red shift is observed in the morning zodiacal light, but much less reliably than the evening blue shift.

V. COLOR OF THE ZODIACAL LIGHT

The color of the zodiacal light is usually determined by photoelectric observations, which make it possible to determine the ratio of the intensities of the zodiacal light in two sections of the spectrum and to compare them with the corresponding ratio for sunlight, or to obtain directly the color exponent of the zodiacal light. Table V lists the published values of the color index of the zodiacal light or the value of $2.5 \log (I_g/I_b)$, where I_g and I_b are the intensities of the zodiacal light in the green and in the blue, respectively. The third column of the table lists the values of the color exponent of the sun, while the fourth column gives the values of the difference Δ of the color exponents of the zodiacal light and of the sun, a difference equal to $2.5 \log (I_g/I_b)$, if the observed brightnesses I_g and I_b are expressed in units of solar-disc brightness. The last column of the table gives the effective wavelengths of the spectral intervals used to obtain the intensity ratio.

The results of Divari and Asaad[24] and of Divari and Krylova[25] show that the zodiacal light is somewhat bluer than the sun. This agrees with the result of Karyagina[56], who showed with the aid of spectrographic observations that the color of the zodiacal light is somewhat bluer than the color of the sun. However, the results of Behr and Siedentopf[22], Peterson[23], Robley[33] and also of Divari, Krylova, and Moroz[36] contradict this conclusion. According to these observations, the zodiacal light is somewhat redder than the sun. It is possible that these discrepancies are connected with errors in accounting for the selective transparency of the atmosphere, as pointed out in [24]. Behr and Siedentopf[22] do not regard

Table V. Values of the color index of the zodiacal light

Authors	$C.I._{zod.}$	$C.I._{\odot}$	Δ	λ_b/λ_g
Behr and Siedentopf[22]	0.63	0,43	+0.20	444/542
Divari and Asaad[24]	0.35	0.45	—0.10	414/541
Nikol'skii[35]	0.56	?	?	414/540
Peterson[23]	0,48	0,45	+0.03	435/543
Divari and Krylova[25]	0.47	0,63	—0.16	406/543
Robley * [33]	—	—	+0.16	463/528
Divari, Krylova, and Moroz[34]	—	—	+0.14	460/520

*Calculated by myself from data in Table V of [33].

their own determination of the color exponent as reliable, inasmuch as their standardization in the blue region was not insufficiently reliable. The mean difference between the color exponents of the zodiacal light and of the sun, in accordance with the six sets of data given in Table V, is equal to 0.04 magnitude, showing that the color of the zodiacal light practically coincides with the color of the sun. This agrees with the old photoelectric observations of Elvey and Rudnik (cited [57]) and also with the spectrographic measurements of Eropkin and Kozyrev[41] and Karimov[44], who showed that the distribution of energy in the spectrum of the zodiacal light is close to the distribution in the spectrum of the sun.

By examining the zodiacal light at large ecliptic latitudes, Saito[37] determined that the color of this light is close to the color of a star of class K. This result, however, being in sharp contradiction to the measurements made by other authors, cannot be accepted and is possibly the consequence of an insufficiently complete elimination of the component of the night sky glow, which is noticeably redder than the sun[58].

Thus, photometric and spectrographic observations of the zodiacal light enable us to conclude that the color of the zodiacal light is close to that of the sun. This conclusion, however, must be regarded only as a first approximation, and it is desirable to make more exact and specially formulated observations in order to ascertain the finer features of the distribution of energy in the spectrum of the zodiacal light.

VI. POLARIZATION OF THE ZODIACAL LIGHT

Measurements of the variation of the degree of polarization of radiation of the zodiacal light along the ecliptic were first made by Dufay[59] by a photographic method. Photoelectric observations were made by

Table VI. Degree of polarization of zodiacal light along the ecliptic

Authors \ ε	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°	105°	120°	135°
Dufay[59]	—	—	0.125	—	0.125	—	0.13	—	0.15	—	0.13	0.10	0.06	0.04	0.025	—	—	—
Furuhata[26]	—	—	—	—	0.15	0.18	0.20	0.21	0.21	0.20	0.19	0.18	0.17	0.15	0.13	—	—	—
Behr and Siedentopf[22]	—	—	—	0.23	0.23	0.22	0.22	0.21	0.19	0.17	0.14	0.13	0.12	0.12	0.11	—	—	—
Blackwell[18]	0.09	0.14	0.19	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Divari and Asaad[24]	—	—	0.15	0.16	0.17	0.18	0.20	0.22	0.22	0.22	0.21	0.20	0.18	0.16	0.13	—	—	—
Elsasser[31]	—	—	0.20	—	0.29	—	0.31	—	0.33	—	0.36	—	0.35	—	0.36	—	—	—
Nikol'skii[35]	—	—	0.14	0.19	0.18	0.16	0.13	0.10	0.08	—	—	—	—	—	—	—	—	—
Blackwell, Ingham[19]	—	—	0.22	0.27	0.29	0.31	0.31	0.32	0.32	0.32	0.32	—	—	—	—	—	—	—
Peterson[23] (blue)	—	—	—	—	—	—	—	—	0.22	—	—	0.17	—	—	0.15	0.13	0.12	0.12
Peterson[23] (green)	—	—	—	—	—	—	—	—	0.23	—	—	0.21	—	—	0.20	0.165	0.16	0.15
Robley[33]	—	—	—	0.10	0.13	0.14	0.16	—	0.19	—	—	0.22	—	—	—	—	—	—
Divari, Krylova, Moroz[34] (blue)	—	—	0.14	0.17	0.17	0.20	0.21	0.22	0.24	—	—	—	—	—	—	—	—	—
Divari, Krylova, Moroz[34] (green)	—	—	0.16	0.17	0.21	0.22	0.23	0.22	0.23	0.23	—	—	—	—	—	—	—	—
Average (smoothed)	0.08	0.13	0.16	0.18	0.20	0.22	0.23	0.24	0.25	0.24	0.23	0.22	0.21	0.20	0.19	0.16	0.15	0.14

many workers to determine the degree of polarization of the zodiacal light. Table VI lists some of the results.

As can be seen from Table VI, there are considerable discrepancies in the absolute values of the degree of polarization. For example, the measured values of the polarization at an elongation $\epsilon = 60°$ fluctuate from 0.08[35] to 0.36[31], the average of all observation being 0.22. Such large differences are due to the difficulties in correctly separating the components of the zodiacal light from the total night-sky radiation. Since zodiacal light measurements yield the total light flux, including the night sky radiation, which is practically unpolarized[60], the observed degree of polarization turns out to be smaller than the degree of polarization of the zodiacal light. Thus, according to the analysis of Weinberg[61], the observed degree of polarization of the total radiation separated by an interference filter centered about 530 nm is equal to 0.16 at an elongation $\epsilon = 60°$, and the degree of polarization of the zodiacal light in the same region is 0.28. The broader the spectral band of the filter used for the observations, the less is the observed degree of polarization, since a broad-band filter passes a large fraction of unpolarized radiation from the night sky. For example, under the same conditions, at $\epsilon = 60°$, the observed polarization in the white light was found to be merely 0.04 in place of 0.16 as measured with a narrow filter.

From the data of Table VI it is obvious, first, that the monotonic decrease in the degree of polarization with increasing elongation, obtained by Behr and Siedentopf and by Nikol'skiĭ at elongations larger than 35°, does not agree with all the values obtained by others, and must be regarded as erroneous. We can apparently consider it established that the degree of polarization increases when the elongation increases from 30 to 60—70°. In the 50—70° region the degree of polarization changes little. At elongations larger than 70°, the variation of the degree of polarization, as observed by Dufay[59], Furuhata[26], Divari and Asaad[24], and Peterson[23] decreases little with increasing elongation. However, according to the observations of Elsasser at an elongation of 70—90°, the degree of polarization remains practically unchanged. For elongations larger than 90°, there is only one measurement, made by Peterson[23], which shows that the degree of polarization decreases noticeably in the 90—135° region. According to measurements by Blackwell[18], carried out from an altitude of 2700 meters, the degree of polarization increases with increasing elongation in the elongation region 20—30°.

The last line of Table IV gives the average smoothed values of the degree of polarization. The measurements of [22] and [35] were excluded from the average, since they give a relative variation that contradicts all the other observations. The average does not include, likewise, the observations of Dufay[59], since they pertain to a broad section of the spectrum (the photographic region of the spectrum), and therefore lead apparently to low values of the degree of polarization, particularly at large elongations. The averaged values of the degree of polarization were obtained without account of the possible dependence of the degree of polarization on the wavelength, for there is not enough observational material to be able to introduce this refinement at present. Figure 2 shows the dependence of the degree of polarization of the zodiacal light on the elongation for the ecliptic, which at present can be assumed to be the most probable result of the published data by different authors.

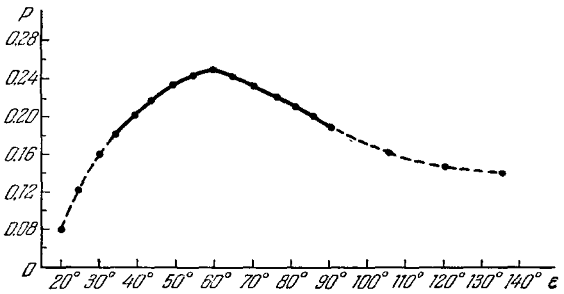

FIG. 2. Average dependence of the degree of polarization on the elongation for the ecliptic.

Measurements of the degree of polarization of the zodiacal light outside the ecliptic are carried out rarely. For the region of ecliptical latitudes $-15° \le \beta \le 25°$, the values of the degree of polarization of the zodiacal light are given in [34].

The orientation of the polarization vector was investigated by Fesenkov[62], using measurements which he made in the Lybian Desert. It turned out that the polarization vector in the case when the ecliptic is in a vertical position, is directed along the vertical to the sun. However, when the ecliptic is inclined, the direction of the polarization vector does not coincide with the direction to the sun, and deviates towards the vertical. This strange effect calls for a special verification.

VII. ZODIACAL LIGHT AND SOLAR CORONA

The assumption of the connection between the zodiacal light and the solar corona is based on the theory of Grotrian, according to which the solar corona consists of two components: electronic (K-corona) and dust (F-corona). If the F-component of the corona and the zodiacal light are due to scattering of the solar radiation by solid dust particles in interplanetary space, then a continuous transition from the solar corona to the zodiacal light would be natural. This concept was first developed by Allen[63] and Van de Hulst[64]. It was subsequently supported by the investigations of Rense, Jackson, and Todd[65], Roach and von Biesbroeck[66], and Blackwell and Ingham[19]. Observations of the zodiacal light are usually carried out at elongations $\epsilon > 30°$. Classical observations of the corona include a region of several solar radii from the center of the solar disc, and can be represented by the Van de Hulst model[67], which spans a region up to $10R_\odot$ (2.7°) from the center of the solar disc. Michard, Dollfus, Pecker, Laffinner, and d'Azambuja[68] measured, from observations of the solar eclipse of 25 February 1952 in Khartoum, the intensity of the corona up to a distance of $28R_\odot$ (7.5°) and the polarization up to $10R_\odot$ (2.7°). Rense, Jackson, and Todd[65] investigated the region between 5.5° ($21R_\odot$) and 13° ($47.5R_\odot$) using the observations of the eclipse of 25 February 1952 from an airplane flying at 9,750 meters. Blackwell[69] measured the intensity of the outer corona in the region from $6R_\odot$ to $55R_\odot$ (14.7°) and the polarization from $6R_\odot$ to $20R_\odot$ (5.3°) from an altitude of 13,000 meters during the time of the eclipse of the sun on 30 June 1954.

Figure 3 shows on a logarithmic scale the brightnesses of the outer corona and of the zodiacal light in units of 10^{-13} of the average brightness of the solar disc. As can be seen from the plot, there are considerable discrepancies between the brightnesses of the outer corona, measured by different observers. Extrapolating the brightness variation curves, obtained from the observations of Michard and his co-authors[68] and Rense and his co-authors[65], we can see that none of these curves can be regarded as a continuation of the curve for the zodiacal-light brightness. Blackwell's curve[69], which lies between the two former ones, is a perfectly good continuation of the curve of the zodiacal-light brightness. However, on the internal (solar) side, Blackwell's curve is not an exact continuation of the curves of Van de Hulst for the solar corona, although it is parallel to the corresponding section of the Van de Hulst curve for both the F-corona and for the (F+K)-corona. In order to join the curves of Blackwell and Van de Hulst, Ingham[32] was forced to modify somewhat the Van de Hulst curve, taking it for the maximum of the solar activity, although Blackwell's curve was obtained during the minimum of solar activity, since the minimal Van de Hulst corona model corresponds less to Blackwell's observations than the maximal model.

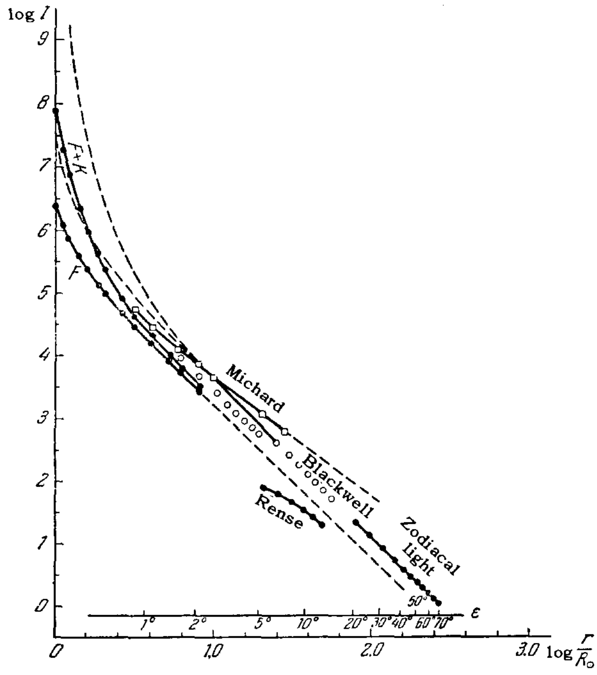

FIG. 3. Brightness of the outer corona, as obtained by different investigators, and the average brightness of the zodiacal light.

Extrapolation of the Van de Hulst curve into the region of the zodiacal light gives much lower brightnesses than the brightness of the zodiacal light. On the other hand, when extrapolating the zodiacal-light brightness curve towards that of the sun, the brightness values obtained exceed greatly the brightness of either the F- or the (K+F)-corona. (We have extrapolated the zodiacal curve in such a way as to make it congruent to the curve for the F- and for the (K+F)-coronas, respectively, in the regions close to the sun.) Since the classical observations of the corona extend approximately to 3° and reliable observations of the zodiacal light begin with a distance of 30° from the center of the solar disc, it is clear that the joining of the brightness curves of the zodiacal light and of the corona cannot be made with sufficient reliability. From among the three published measurements, only Blackwell's data can serve as a good bridge between the corona and the zodiacal light. However, recognizing the difficulties of getting rid of the influence of the atmosphere, the final reliable conclusions concerning the connection between the corona and the zodiacal light can hardly be obtained until observations are made beyond the limits of the earth's atmosphere with the aid of rockets and satellites, as indicated in [70].

Figure 4 shows on a semilogarithmic scale the polarization versus the distance from the center of the solar disc for the outer corona, in accordance with the data of Van de Hulst[67], Michard et al[68] and Blackwell[69], and for the zodiacal light in accordance with

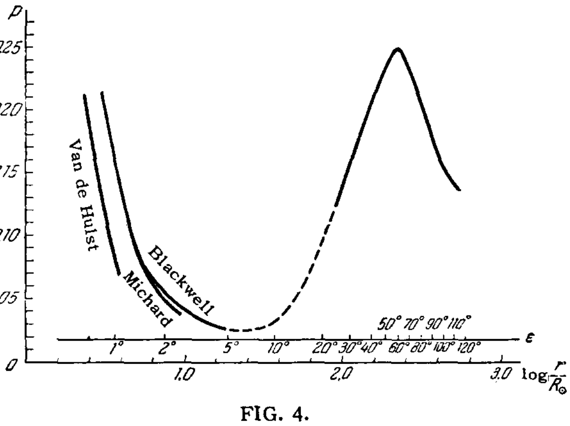

FIG. 4.

the average values of Table VI. The Van de Hulst and Blackwell curves do not coincide over the entire elongation interval in question. The Blackwell and Michard curves diverge at elongations close to 1.5°. The Blackwell curve for the outer corona can be joined with the curve for the zodiacal light (dashed section of Fig. 4). We obtain here a deep minimum at an elongation of approximately 6°. By examining the polarization versus elongation curve over the entire interval represented in Fig. 4, we can conclude that at elongations smaller than 6° the observed polarization is practically completely due to the K-corona, since the F-corona polarization should be quite low at such small elongations. Thus, the joining of the degree of polarization vs. elongation curves for the outer corona and for the zodiacal light can be regarded only as an illustration of the observed picture, but gives no ground for assuming the zodiacal light to be a continuation of the solar corona.

VIII. FLUCTUATIONS OF THE BRIGHTNESS OF THE ZODIACAL LIGHT

Many researchers who observed the zodiacal light visually have reported fluctuations in its brightness. Thus, for example, the experienced observer Jones[6] noted many times rapid pulsations of the brightness. In his diary of 30 January 1854 he wrote: "There is no doubt that pulsations of the zodiacal light exist" (cited in [71]). Schonberg and Pich[11] indicate that at Windhook the observers very rarely noted any pulsations, and that in all cases the pulsations were noted by only one observer, there being no cases when the same brightness pulsation was noted simultaneously by several observers.

During my own visual observations of the zodiacal light I also noted brightness pulsations on occasions. However, a perfectly similar situation can occur not only for zodiacal light, but for any point on the night sky. This phenomenon has therefore no direct bearing on the zodiacal light. It is possible that it is physiological in character, although it is perfectly natural to expect the glow of the night sky not to be quiescent and to be accompanied by small fluctuations of the same character as the fluctuations in the aurora brightness[72].

Hulburt[73] compared Jones' visual observations[6] over the two year period from 1853 through 1855 with the geomagnetic activity as measured in Greenwich. He separated there the so-called "abnormal periods" of zodiacal light, characterized by the presence of fluctuations of zodiacal light and an increase in its brightness. A total of 23 such periods were noted, 16 of which took place three days after a magnetic storm. The remaining seven cases of increased zodiacal-light brightness were not connected with magnetic storms. During the time from 1911 through 1929, Hulburt found five cases of abnormal bright zodiacal light, four of which were preceded by magnetic storms. It is quite obvious that since we are dealing here with zodiacal-light brightnesses not separated from other components, this picture can be due to fluctuations in the atmospheric component of the glow.

Much greater interest attaches to the study of systematic fluctuations of the brightness of the zodiacal light removed from the influence of other glow components. Oscillations of this kind, which have a seasonal character and reach 20%, were observed by Elvey and Roach[14] by photoelectric means. According to these observations the evening zodiacal light has a maximum brightness in April—May and a minimum in January—February. The morning zodiacal light has an opposite seasonal dependence. The dependence obtained by the authors agrees with that obtained by Elvey[74] by reduction of the visual observations made by Japanese investigators.

Furuhata[26] found by his photoelectric observations of 1945—1949 fluctuations of the brightness of the zodiacal light with a period of several days, and also an appreciable annual variation, with the brightness of the zodiacal light changing by a factor of several times.

An analysis of the photometric observations of the zodiacal light in the visual region of the spectrum in the period from 1946 through 1950 has enabled us[16] to observe the existence of seasonal fluctuations in the brightness of the zodiacal light. It turned out that the brightness of the cone of the morning zodiacal light increased in the period from September through November, while the brightness of the evening zodiacal light decreased from January through the middle of March. Thus, although the results of Elvey and Roach[14] and of Divari[16] do establish the existence of seasonal brightness fluctuations, they give two different variations. A possible explanation of this discrepancy, given in [16], consists in the fact that the curve of Elvey and Roach was due to the disturbances induced in the zodiacal light by the so-called excess glow, which is responsible for the broadening of the isophots of the zodiacal light near the horizon. On the other hand, Regener[17], analyzing the isophot maps over the periods from 14 September through 31 January 1954 (9 maps), from 1 February through 4 February 1954 (11 maps), and from 21 February through 26 May 1954 (14 maps), saw no systematic changes of seasonal character in the brightness. Regener does not present any numerical material in his paper to confirm his conclusion, but indicates that there were considerable random fluctuations. The mean squares of the individual fluctuations of the brightness amounted to 11, 12, and 14% for each of the observation periods indicated above, respectively, i.e., the brightness fluctuations did take place and reached a noticeable magnitude.

Barbier[30] compared the ratio of the intensities of the zodiacal light for two days in 1953 as observed by him and as observed by Roach et al.[29] According to Roach et al it turned out that for the point in the ecliptic with elongation 40°, in green light,

$$\frac{I\,(14\ \text{April}\ )}{I\,(14\ \text{Jai}\ \ \ \ )}=0.66,$$

and according to Barbier[30], for the point in the ecliptic with elongation 39°, in blue light,

$$\frac{I\,(14\ \ \text{April}\ )}{I\,(14\,\text{January})}=1.25.$$

The author believes that this comparison shows that the brightness variation of the zodiacal light from night to night, at least for a small interval, are nonexistent. It must be noted with respect to this conclusion that no deduction can be drawn with respect to the existence of variations of the brightness by using only results of two nights of observations, since considerable random transparency errors may arise in this case, especially in blue light.

Thus, the conclusions drawn by some authors that the brightness of the zodiacal light is constant in time are not convincing.

There are also indications that the brightness of the zodiacal light changes from year to year. Thus, Dufay[75] has found reasons for stating that in the 20th century the brightest zodiacal light was observed in 1900, 1911, and 1923. According to his photometric observations, the brightness of the zodiacal light in 1923 was 15% higher than the brightness of the zodiacal light in 1925. Dufay reached the conclusion that the zodiacal light may be brighter two years before the minimum of solar activity. He indicates that the results of regular photoelectric observations carried out on the duMidi Peak starting with 1941 confirm this conclusion.

Blackwell and Ingham[76], observed the zodiacal light after the solar flare of 7 July 1958, and the grandiose magnetic storm which followed it on 8—9 July, and noted an intensification in the brightness of the zodiacal light.

They established a correlation between the brightness of the zodiacal light in all the employed spectral intervals and the solar activity, in agreement with the result of Hulburt[73].

Of great interest is the investigation of the connection between the zodiacal light and the moon. According to an analysis by Divari[77] the brightness of the zodiacal light depends on the phase of the moon. The zodiacal light is brightest near the new moon, when it is on the average 30% brighter than when the moon is 10 days old. This result, if verified further, can be of great importance to the theory of zodiacal light.

When speaking of the variations of the brightness of the zodiacal light, it must be borne in mind that the procedure used by various authors to separate the brightness of the zodiacal light against the total night-sky radiation is far from perfect. As already indicated above, this procedure is usually based on various assumptions regarding the distribution of the night-sky brightness, the influence of the troposphere, etc. It is therefore necessary to approach with caution any conclusion concerning fluctuations of the brightness of the zodiacal light. It is possible that the fluctuations noted by some observers are due not to the zodiacal light but to other components of the night-sky glow, not taken into account accurately during the reduction of the observation data.

Nonetheless, the results reported above give no grounds for assuming that the brightness of the zodiacal light is constant. The observed fluctuations in the brightness apparently have no seasonal character, and are due to temporal variations whose nature has not yet been established.

IX. ELECTRONIC COMPONENT OF THE ZODIACAL LIGHT

Whipple and Gossner[57] called attention to the fact that the observations of the zodiacal light can be used to determine the electron density in interplanetary space. They found an upper limit for the electron density at a distance of 1 a.u., equal to 1,000 cm^{-3}.

Behr and Siedentopf[22], assuming that the entire observed polarization of the zodiacal light is due to scattering by free electrons, have found that the electron density at a distance of 1 a.u. from the sun is 600 cm^{-3}. The authors started there from the unproved assumption that the light scattered by dust particles is not polarized.

However, as shown by Fesenkov[78], who used observations made in Egypt in the fall of 1957, the polarization of the light scattered by the dust particles cannot be neglected. A similar conclusion is indicated by measurements of the polarization in the Arend-Rolland comets, where according to Blackwell[79] the degree of polarization of light reflected by the dust particles reached 25%. If we assume that the observed polarization in the Arend-Rolland comet is due only to electron scattering, then, as shown by Blackwell and Willstrop[80] it is necessary to assume very high electron densities, exceeding by 10^5 times the density obtained from investigations of the molecular spectrum.

Direct calculations of the degree of polarization, carried out by Giese[81], confirmed the conclusion that the light scattered from a mixture of solid dust particles should be partially polarized. The degree of polarization calculated by Giese does not agree with the results of measurements by Elsasser[31], leading Giese to assume that the polarization of the zodiacal light cannot be explained without involving the electron component. Using the same data, Giese and Siedentopf[82] reached the conclusion that in order to explain the zodiacal light it is necessary to assume that the electron density near the earth's orbit should be 300 cm^{-3}, which is half the density obtained by Behr and Siedentopf[22]. However, one cannot agree with such conclusions, since the values of the degree of polarization calculated by Giese for some mixtures of par-

Table VII

Elongation	30°	40°	50°	60°	70°	80°	90°
Giese[81]	14.8	16.6	18.6	20.1	20.6	20.3	19.6
Divari and Asaad[24]	15	17	20	22	21	18	13

ticles are in splendid agreement with the results of measurements of the degree of polarization made by other observers. For example, the degree of polarization calculated by Giese for a mixture of 75% iron particles and 25% H_2O, under the assumption that the spatial distribution of the particles obeys the 1/r law (r —distance from the sun) and the particle radius a has an a^{-2} distribution, is in good agreement with the degree of polarization measured by Divari and Asaad, as can be seen in Table VII.

Thus, the deductions of Behr and Siedentopf[22], Giese[81], and Giese and Siedentopf[82], that in order to explain the polarization of the zodiacal light it is necessary to presuppose the existence of an electron component, cannot be regarded as well founded.

Using spectrographic observations made in the Bolivian Andes (Chacaltaya), Blackwell and Ingham[51] found that the electron density near the earth's orbit cannot exceed 116 electrons/cm^3, under the assumption that the kinetic temperature of the electrons does not exceed 2×10^4 deg. However, Schmid and Elsasser[52] believe that Blackwell and Ingham have arbitrarily assumed, without suitable justification, a $1/r^2$ distribution for the electron density, in place of the slower decrease in electron density, for example the usually assumed 1/r dependence. Assuming a 1/r variation of the density, and modifying somewhat the average results of Blackwell and Ingham[51] (see above), Schmid and Elsasser[52] found that the electron density near the earth's orbit does not exceed 400 cm^{-3}.

Assuming that the electrons of interplanetary space should come from the solar corpuscular stream and should have velocities 500—2,000 km/sec, Johnson[83] believes that Doppler broadening of Fraunhofer lines of the zodiacal light should be observed if the electrons play an appreciable role in the formation of the zodiacal light. The absence of such a broadening is interpreted by Johnson as proof that the electron component does not have a noticeable value in the zodiacal light. We must point out here the already-mentioned result by Blackwell and Ingham[51], that there is no smearing of the Fraunhofer lines in the zodiacal-light spectrum.

Thus, the observed facts indicate that there is no need for involving the electrons in the explanation of the zodiacal light.

X. LOCATION OF THE MATERIAL OF THE ZODIACAL LIGHT

The observation data analyzed above allow us to assume that the zodiacal light does not contain an electronic component. All the known peculiarities of the zodiacal light can be attributed to scattering of solar radiation by solid dust particles. However, it does not follow of necessity from the material in question that the dust particles responsible for the zodiacal light are concentrated in interplanetary space in the form of a cloud having an ellipsoidal or any other shape, with the sun as its center. Consequently, the planetary hypothesis of the zodiacal light is neither essential nor obvious from the point of view of the observed facts. The majority of the theoretical models of interplanetary clouds have been calculated under several assumptions with respect to the distribution of the dust density in interplanetary space, the albedo of the reflecting particles, their scattering indicatrices, their size distribution, etc. All the dependences were chosen to yield, without contradicting the other known facts, brightness and polarization variations (along the ecliptic) close to those actually observed. As a rule, this could always be done, since the parameters indicated above can be varied over a wide range, inasmuch as they are actually not known exactly. However, the extent to which any particular zodiacal-cloud model corresponds to reality always remained unclear. At present there are many known zodiacal-cloud models, differing appreciably from one another, but representing with sufficient accuracy the observed brightnesses and polarization along the ecliptic. Some of these models should by now be completely rejected, but at the time they could be regarded as acceptable in some sense. Thus, for example, the model of electron-dust cloud, obtained by Elsasser[84], cannot be accepted at present, since we can regard it as established by now that the role of the electrons in the zodiacal light is insignificant. Taking all the foregoing into account, we cannot take agreement between the calculated and observed brightnesses and degrees of polarization of the zodiacal light along the ecliptic as a basis for accepting any particular model.

James[55] reported that the H_β Fraunhofer line in the spectrum of the evening zodiacal light displays a blue shift, something interpreted by him as the result of the fact that the particles scattering the sunlight revolve about the sun in extraterrestrial orbits. Such an explanation, however, is not the only one possible. For example, the same effect can be obtained if the dust particles rotate around the earth along very elongated orbits with a major axis directed towards the sun, as illustrated in Fig. 5.

Thus, the observed facts do not exclude the possibility of the zodiacal light being due to a dust cloud surrounding the earth. If our result[77] concerning

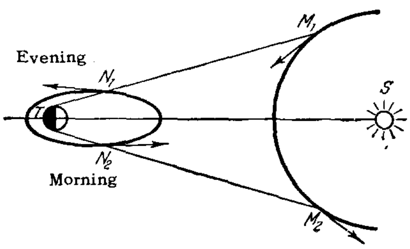

FIG. 5. Possible orbits of dust particles.

the connection between the brightness of the zodiacal light and the phase of the moon is confirmed, this will be direct proof that the cones of the zodiacal light are due to scattering of sunlight by a dust cloud near the earth. In this connection, we cannot simply reject the results of the observations by Schmid[12,85], who observed visually a diurnal displacement of the boundaries of the zodiacal-light cone relative to the stars. Attention must also be paid to the still uninvestigated phenomenon of so-called "lunar zodiacal light," observed by Jones[6] and Schmid[12]. The possibility of the zodiacal light being due to scattering of sunlight by particles of a dust cloud near the earth is more probable also in connection with the latest results of investigations of interplanetary space with the aid of space rockets and satellites (see, for example [86]), according to which the dust density near the earth is much higher than in interplanetary space.

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[1] J. D. Cassini, Mém. Acad. Sci. (Paris) **8**, 121 (1730).

[2] V. G. Fesenkov, Meteornaya materiya v mezhduplanetnom prostvanstve (Meteoric Matter in Interplanetary Space), AN SSSR, 1947.

[3] V. G. Fesenkov, Astron. zh. **35**(3), 323 (1958), Soviet Astronomy **2**, 299 (1959).

[4] W. John, Kosmos **50**(3), 140 (1954).

[5] D. E. Blackwell, Scient. Amer. **203**(1), 54 (1960).

[6] G. Jones, United States Japan Expedition, vol. 3, Washington, 1856.

[7] E. Marchand, Compt. rend. **121**, 1134 (1895).

[8] G. P. Zakharov, Izv. Russkogo o-va lyubiteley mirovedeniya (News of the Russian Society of Amateur Cosmogonists) **3**, No. 10(2), 112 (1914); **6**, No. 3(27), 166 (1917); **4**, No. 2(14), 92 (1915).

[9] C. Hoffmeister, Veröff. d. Univer. Sternwarte zu Berlin-Babelsberg **10**, 1 (1932).

[10] C. Hoffmeister, Astron. Nachr. **271**(2), 49 (1940).

[11] E. Schönberg and R. Pich, Mitt. d. Univ. Sternwarte zu Breslau **5**, 1 (1939).

[12] F. Schmid, Astron. Nachr. **270**, 220 (1940).

[13] V. G. Fesenkov, La lumiere zodiacale (Doctoral Dissertation, Paris, 1914).

[14] C. T. Elvey and F. E. Roach, Astrophys. J. **85**, 213 (1937).

[15] W. Brunner, Publ. d. Eidgenössischen Sternwarte in Zürich **6**, 1 (1935).

[16] N. B. Divari, Astron. zh. **32**(1), 79 (1955).

[17] V. H. Regener, Astrophys. J. **122**(3) 520 (1955).

[18] D. E. Blackwell, Month. Not. **116**, (4), 365 (1956).

[19] D. E. Blackwell and M. F. Ingham, Month. Not. **122**(2), 113 (1961).

[20] M. N. Donitch, Bull. Astron. **17**, 95 (1953).

[21] M. N. Donitch, Bull. Astron. **20**, 15 (1955).

[22] A. Behr and H. Siedentopf, Zs. Astrophys. **32**(1), 19 (1953).

[23] A. W. Peterson, Astrophys. J. **133**(2), 668 (1961).

[24] N. B. Divari and A. S. Asaad, Astron. zh. **36** (5), 856 (1959), Soviet Astronomy **3**, 832 (1960).

[25] N. B. Divari and S. N. Krylova, Astron. zh. **40**(3), 514 (1963), Soviet Astronomy **7**, 391 (1963).

[26] M. Furuhata, Publ. Astron. Soc. Japan **2**, 156 (1951).

[27] D. Ya. Martynov, Astron. zh. **36**(4), 648 (1959), Soviet Astronomy **3**, 633 (1960).

[28] J. Stebbins and G. E. Kron, Astrophys. J. **126**, 266 (1957).

[29] Roach, Pettit, Tanberg-Hansen, and Davis, Astrophys. J. **119**(1), 253 (1954).

[30] D. Barbier, Mem. Soc. Sci., Liège, Quatr. Ser. **15**, 55 (1954).

[31] H. Elsässer, Sterne **34**(9/10), 166 (1958).

[32] M. F. Ingham, Month. Not. **122**(2), 157 (1961).

[33] R. Robley, Ann. Geophys. **18**(4), 341 (1962).

[34] Divari, Krylova, and Moroz, Geomagnetizm i aéronomiya **4**(5), 882 (1964).

[35] G. M. Nikol'skiĭ, ibid **1**, 3, 354 (1961).

[36] N. B. Divari, Astron. zh. **28**(3), 163 (1951).

[37] Bun-Ichi-Saito, Repts. Ionosph. and Space Res. Japan **14**(2), 180 (1960).

[38] Van Rhijn, Groningen Publ., No. 43, 1 (1929).

[39] V. G. Fesenkov, Astron. zh. **40**(1), 31 (1963), Soviet Astronomy **7**, 23 (1963).

[40] E. A. Fath, Lick Obs. Bull. **5**, 141 (1909).

[41] D. Ya. Eropkin and N. A. Kozyrev, Tsirk. GAO (Pulkovo) (Circular of the State Astonomical Observatory), No. 13, 21 (1935).

[42] C. Hoffmeister, Zs. Astrophys. **19**, 116 (1936).

[43] K. R. Ramanathan, Nature **129**, 280 (1932).

[44] M. G. Karimov, Astron. zh. **27**, 97 (1950).

[45] M. G. Karimov, Izv. Astrofiz. in-ta AN Kaz SSR (News, Astrophysics Institute, Academy of Sciences Kazakh SSR) **5**, 120 (1957).

[46] G. A. Tikhov, DAN SSSR **73**, 53 (1950).

[47] Z. V. Karyagina, op. cit. [45], **5**, 110 (1957).

[48] N. B. Divari and A. S. Asaad, Astron. zh. **36**(2), 327 (1959), Soviet Astronomy **3**, 320 (1959).

[49] J. Cabannes and J. Dufay, Compt. Rend. **201**, 696 (1935).

[50] J. M. Beckers, Proc. Konikl. Nederl. Akad. wet. **B62**(4), 248 (1959).

[51] D. E. Blackwell and M. F. Ingham, Month. Not. **122**(2), 129 (1961).

[52] Th. Schmidt and H. Elsässer, Zs. Astrophys. **56**(1), 31 (1962).

[53] N. B. Divari, DAN SSSR **122**(5), 795 (1958).

[54] P. V. Shcheglov, Priroda (Nature) **8**, 85 (1963).

[55] J. F. James, New Scientist **17**, 135 (1963).

[56] Z. V. Karyagina, Astron. zh. **37**(5), 882 (1960), Soviet Astronomy **4**, 828 (1961).

[57] F. Whipple and J. Gossner, Astrophys. J. **109**(3), 380 (1949).

[58] K. K. Chuvarev, Izv. Krymskoĭ astrofiz. observ. (News of the Crimean Astrophysical Observatory) **10**, 54 (1953).

[59] J. Dufay, Compt. rend. **181**, 399 (1925).

[60] V. G. Fesenkov, Astron. zh. **37**(5), 794 (1960), Soviet Astronomy **4**, 479 (1961).

[61] J. L. Weinberg, Nature **198**, 842 (1963).

[62] V. G. Fesenkov, op. cit. [45] **12**, 3 (1961).

[63] C. Allen, Month. Not. **106**, 137 (1946).

[64] H. C. Van de Hulst, Astrophys. J. **105**, 471 (1947).

[65] Rense, Jackson, and Todd, Geophys. Res. **58**, 368 (1953).

[66] F. E. Roach and G. von Biesbroeck, Sky and Tel. **13**(5), 144 (1954).

[67] H. C. Van de Hulst, Bull. Astron. Inst. Netherlands **11**, 410, 135 (1950).

[68] Michard, Dollfus, Pecker, Laffinuer, and d'Azambuja, Ann. d'astrophys. **17**, 320 (1954).

[69] D. E. Blackwell, Month. Not. **115**(6), 629 (1955).

[70] V. G. Fesenkov and N. B. Divari, Astron. zh. **33**(3), 391 (1956).

[71] W. E. Glanvill, Popular Astron. **38**, 541 (1930).

[72] N. B. Divari, Izv. AN Kas. SSR, ser. astron. (News, Academy of Sciences, Kazakh SSR, Astronomy Series) **4**, 3 (1961).

[73] E. O. Hulburt, Popular Astron. **38**, 215 (1930).

[74] C. T. Elvey, Astrophys. J. **86**, 84 (1937).

[75] J. Dufay, Publ. de l'Observ. de Lyon **5**, 8 (1947).

[76] D. E. Blackwell and M. F. Ingham, Month. Not. **122**(2), 143 (1961).

[77] N. B. Divari, Astron. zh. **40**(4), 717 (1963), Soviet Astronomy **7**, 547 (1964).

[78] V. G. Fesenkov, Meteoritika **17**, 107 (1959).

[79] D. E. Blackwell, Observatory **77**, 900, 187 (1957).

[80] D. E. Blackwell and R. V. Willstrop, Month. Not. **117**(6), 590 (1957).

[81] R. H. Giese, Zs. Astrophys. **51**(2), 119 (1961).

[82] R. H. Giese, H. Siedentopf, Zs. Astrophys. **54**(3), 200 (1962).

[83] H. M. Johnson, Observatory **78**, 904, 125 (1958).

[84] H. Elsässer, Zs. Astrophys. **33**, 274 (1954).

[85] F. Schmid, Beitr. Geophys. **9**(2), 13 (1908).

[86] W. A. Alexander, Trans. Amer. Geophys. Union **44**(2), 464 (1963).

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