THE ZODIACAL LIGHT AND THE GEGENSCHEIN AS PHENOMENA OF THE EARTH'S ATMOSPHERE.*

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Abstract

A quantitative atomospheric theory of the zodiacal light and the gegenschein is developed. Neutral particles sprayed out in all directions from the earth's atmosphere are ionized at 50,000 to 70,000 km levels by the ultra-violet light of the sun. Because of the wabble of the earth's magnetic field with the rotation of the earth ions near the equatorial plane stay for some time at these high levels to form a ring around the earth, ions at high latitudes fall quickly back to the earth to give aurorae. The gravitational magnetic drift of the ions forces the ion ring into a long oval stretching out away from the sun to 10^6 km. The pressure of the sunlight warps the oval into the plane of the ecliptic and makes the ions stream out like a comet's tail. The ions are fluorescent; they absorb the sun's ultra-violet light and emit a part of the absorbed energy as visible light. The oval ring is the zodiacal light; the comet tail ion stream is the gegenschein. The zodiacal cones in December are somewhat to the south of the cones in June; the evening cone is south and north of the morning cone in March and September, respectively. These theoretical inferences are in qualitative accord with observation. The theory suggests that the spectrum of the zodiacal light and the gegenschein be different from that of sunlight.

Quantitative estimates lead to a low ion density in the zodiacal ring, less than 10^3 ions$\cdot$cm^{-3} and to a *rate of escape of the terrestrial atmosphere* of 10^6 particles$\cdot$cm^{-2} $\cdot$sec^{-1} or 10^{-6} of the entire atmosphere in 10^6 years. These are perhaps under-estimates. The theory indicates that helium escapes more rapidly than the other gases because of its lightness and higher ionization potential. This may account for the small amount of helium in the atmosphere, which is regarded as being surprisingly low in the face of the estimated large rate of supply from the earth.

Variations in the zodiacal light, from the observations of Jones in 1853–1855 and of more recent observers, *are shown to occur usually during magnetic storms.* Similarly Barnard's observations of the variations in the gegenschein fall in with magnetic disturbances, although more data are needed to establish the connection clearly. The variations are in accord with the atmospheric theory.

Introduction

SHORTLY after sunset when the evening twilight has gone the zodiacal light appears as a faint cone of light in the west rising upward from the horizon, with a similar cone in the east before dawn.[1] At their apexes the cones narrow to a band which extends across the sky from one apex to the other. Thus the phenomenon is spoken of as a "band" of luminosity. The

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[1] For general descriptions of the zodiacal light and the gegenschein see Newcomb, Encyclopaedia Britannica, 13th ed., Vol. 28, page 998; Schmid, "Das Zodiakallicht," Hamburg, 1928; Bayldon, Pub. Ast. Soc. of the Pacific 12, 13 (1900); and references cited throughout the present paper.

band lies closely, but not exactly, along the plane of the ecliptic. It is usually less bright than the milky way and may be seen on any clear night when there is no disturbing illumination such as the moon, planets, the milky way, artificial lights, etc. At an angle of 30° from the sun, the closest angle to the sun at which the light can be seen when observed in the eastern or western sky, the band is about 40° wide.[2] The width of course is rather indefinite for the band is brightest near its center and fades into obscurity at the edges. Newcomb[3] and Barnard[4] in north latitudes around 45° during the midnight hours of the summer solstice observed a glow passing from the west to the east along the north horizon. They concluded that this was the zodiacal band, for it could not have been ordinary twilight because the sun was more than 18° below the horizon, and that therefore the band was about 70° wide along the sun's axis. With increasing angular distance from the sun the band decreases in width and in brightness. At 90° from the sun it is about 20° wide and at 150° about 10° wide. At 180°, the point directly opposite the sun, there is a faint knot of luminosity, sometimes appearing as a swelling in the zodiacal band, called the "gegenschein"[5]. Attempts to measure the parallax of the zodiacal band have always led to values close to zero, but, what is very curious, often negative. The parallax of the gegenschein, as determined by simultaneous observations in the northern and southern hemispheres, was found[6] to be zero within an error of 1° or 2°. Therefore the zodiacal light and the gegenschein have been considered to be far away, beyond the moon, or farther.

The zodiacal light is supposed to be sunlight scattered or reflected or emitted by particles in the plane of the ecliptic. Whether the particles come from the atmosphere or the earth or are planet dust widely scattered through the solar system is an unsettled question, although probably the planet dust theory is more generally held at the present time. Recently the physics of the outer fringe of the atmosphere[7] of the earth was developed, primarily for the purpose of the theory of aurorae and magnetic storms. At the time it was realized that the ideas might be brought to bear on the zodiacal light. Just how this was to be done was not clear until it was noticed (Hulburt, Amer. Phys. Soc. Bul. Dec. 30, 1929) that the fluctuations in the zodiacal light occurred at the same time as the magnetic disturbances. This indicated at once that the planet dust theory was open to objection and pointed the way to the development of the atmospheric theory. It is the purpose of this paper to give the evidence for the connection between the zodiacal light changes and magnetic storms and to describe a theory of zodiacal light based on the action of molecules and ions in the outer fringe of the terrestrial atmosphere. The theory offers an explanation of many features of the zodi-

[2] Hall, Monthly Weather Review **34,** 126 (1906).
[3] Newcomb, Astrophys. Jr. **22,** 209 (1905).
[4] Barnard, Astrophys. Jr. **23,** 168 (1905).
[5] Barnard, Popular Astronomy **7,** 169 (1899): **27,** 109 (1919).
[6] Scarle, Astrophys. Jr. **8,** 244 (1898).
[7] Maris and Hulburt, Phys. Rev. **33,** 412 (1929).

acal light and the gegenschein which the planet dust theory is inadequate to explain.

In company with almost all who have written about the zodiacal light we shall use extensively the classical observations[8] of Reverend George Jones USN, made for the most part in north latitudes 10° to 30° while on a voyage on the Pacific Ocean. From April, 2, 1853, to April 22, 1855, he observed the light every night, weather and other things permitting, and sketched on a chart of the heavens the zodiacal light as he saw it. The drawings, 341 in number, and their descriptions were published; they are by far the most complete and extensive series available. The observations are of gold, and whereas some writers, among them Jones himself, have wondered at apparent inconsistencies we have found that it is just these variances which fall in with the pattern of the theory, Jones wrote in his introduction, "I have put down all, exceptions and incongruities as well as others, not feeling authorized to omit any portion; for who can say, in a new science, that what seem to be exceptions are not a part of the general rule."

2. *Abnormalities in the zodiacal light and magnetic storms.* It was recognized long ago by Humboldt, Arago, Birt and others[8,9] that the zodiacal light is at times variable in intensity the entire body of the light alternately weakening for a few minutes and strengthening again. That the zodiacal light is often unusually intense during epochs of strong aurorae has been known for a long time. For example, in 1881 Groneman[9] referred to the fact as of common knowledge. Aurorae are known to occur in general during periods of magnetic disturbance, but no one has been interested in examining the exact relations with the zodiacal light. Turning to Jones' observations we find that occasionally he noticed and commented on fluctuations in the intensity of the zodiacal light; the entire body of the light grew brighter and dimmer in a period of two or three minutes. In a few cases he recorded an unusually wide spread of the zodiacal luminosity. One of his descriptions is as follows, "The changes were a swelling out, laterally and upwards, of the Zodiacal Light, with an increase of brightness in the Light itself; then, in a few minutes, a shrinking back of the boundaries, and a dimming of the Light; the latter to such a degree as to appear, at times, as if it was quite dying away; and so back and forth for about three quarters of an hour; . . . . ." We have plotted these abnormalities on a qualitative scale in dots as ordinates against the dates as abscissas; a portion of the plot is given in Fig. 1. The magnetic storms observed at The Greenwich Observatory[10] are plotted as short lines in the figure; 1, 2, and 3 mean a storm of moderate, strong and very strong intensity respectively. It is seen that the zodiacal light abnormalities occurred, usually during magnetic disturbances. To summarize the data: There were 27 magnetic storms, or groups of storms, in the period of Jones' observations, 17 of which were followed by cases of unusual zodiacal

[8] Jones, United States Japan Expedition, Vol. III, Washington, 1856. "Observations on the Zodiacal Light."

[9] Groneman, Archives Néerlandaises, Tome XVI.

[10] Maunder, Monthly Notices, Roy. Ast. Soc. **65**, 2 and 540 (1904–5).

light. There were 10 storms with no zodiacal light observations because of clouds, etc., and 10 instances when the zodiacal light might be regarded as abnormal with no accompanying magnetic storms.

A few more recent observations may be mentioned. Pachine[11] in Russia observed the zodiacal light to be remarkably brilliant and to exhibit fluctuations on January 28, 1911 at 6:30 P. M. The light appeared normal during the following days. The preceeding days were cloudy but the clouds were unusually illuminated and he concluded that the exceptional zodiacal brilliance began on the 25th. We do not know whether or not the illumination of the clouds might have been due to an aurora. A four-day magnetic storm of intensity 2 began at 4 hr, G. M. T., on January 24, 1911. Fluctuations in

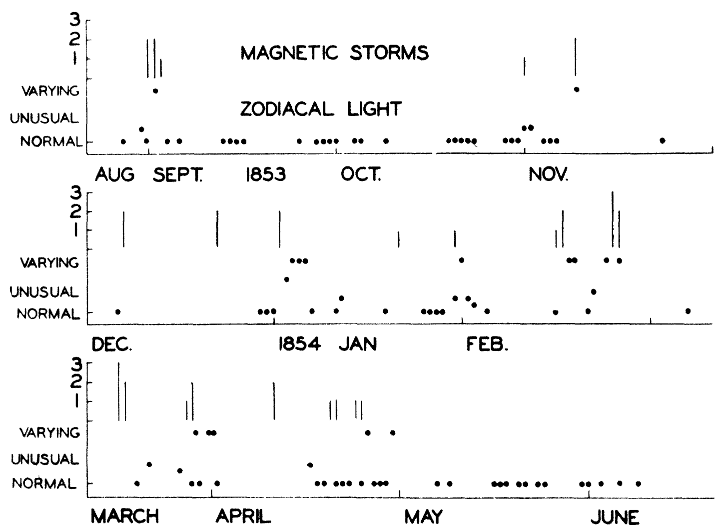

Fig. 1. The dots are the zodiacal light observations of Jones, the vertical lines are the magnetic storms.

the zodiacal light were observed by Hanahan[12] in South Carolina on February 4 and 13 and on March 5, 1913. The storms in this period were January 29 (1), February 13 (1), 24 (1), and March 13 (2). The fluctuations on February 13 fall in with a magnetic storm, the others do not. The zodiacal light was very brilliant on March 21, 1927, according to a photograph by Graff[13]. The period was one of magnetic activity, a seven-day magnetic storm lasting from March 13 to 20 of intensity 2 on March 16 and 1 on March 20. Fluctuations in the zodiacal light were seen simultaneously by two observers Kamei and Oraki[14] at widely separated points in Japan on November 3, 1929, at about 3 A. M. local time. A magnetic disturbance set in on November 2 at 23 hr,

[11] Pachine, Bul. Société Astronomique **27,** 68 (1913).
[12] See note by Glanville, Pop. Ast. **37,** 493 (1929).
[13] Graff, Grundriss der Astrophysik, page 481, Teubner, (1928.)
[14] See note by Glanville, Pop. Ast. **38,** 124 (1930).

G. M. T., rose to intensity 2 on November 3 and continued with decreasing violence through November 6.

Of course abnormalities in the zodiacal light may at times be due to local causes, such as variations in haze, etc., rather than to changes in the light itself, and in such cases there would be no connection between the zodiacal light behavior and magnetic disturbances. The foregoing facts, however, support the conclusion that the connection is genuine and this suggests that the zodiacal light is influenced by the same solar emission which gives rise to magnetic storms. All in all, the data indicated that the zodiacal manifestation occurred within less than two days after the storm began, sometimes it was observed a day or a few hours before the storm (see the theoretical discussion of section 13).

3. *The energy, polarization and spectrum of the zodiacal light.* The energy $\cdot$ $cm^{-2} \cdot sec^{-1}$ received at the earth from all the stars, from the total night sky (the non-polar aurora) and from the total zodiacal region was found[15] to be equal to that of 1440, 0.08 and 0.08 stars, respectively, of magnitude 1 on the Harvard visual scale. The energy of starlight at the earth is 3×10^{-3} erg. $cm^{-2} \cdot sec^{-1}$ and therefore that of the night sky and the zodiacal luminosity each amounts to $0.08 \times 3 \times 10^{-3} \div 1440 = 1.7 \times 10^{-7}$ erg $\cdot cm^{-2} \cdot$ Sec $\cdot^{-1}$. Assuming the zodiacal region to occupy 10^{-1} of the area of the sky, the energy emitted per $cm^{-2} \cdot sec^{-1}$ from the zodiacal region on the average is of the order of 10^{-6} erg $\cdot cm^{-2} \cdot sec^{-1}$. This means that the zodiacal region is ordinarily about 10 times as bright as the sky would be if there were no stars.

The zodiacal light was observed to be partially polarized,[16] about 15 per cent. Early observers[17] found that the spectrum of the zodiacal light was similar to that of sunlight, as well as could be judged from visual observations. More recently Fath [18] photographed the spectrum with a 12 hour exposure, from 3 to 4 A. M. for 12 days. The spectrum from λ5000 to 3900A was 2.2 mm long. Two absorption lines could be seen on the plate. Fath wrote, "A comparison of this plate with one of the sky spectrum taken with the same slit-width shows these lines to be *G* and the blend of *H* and *K* of the solar spectrum. These are the only two lines shown on the sky comparison plate within the limits of the spectrum obtained on the zodiacal light plate. There is no indication of bright lines on any of the spectrograms of the zodiacal light. Thus insofar as spectra of such low dispersion and resolving power can be trusted, we would seem to have good evidence to support the claim that the zodiacal light is reflected sunlight."

4. *The planet dust theory of the zodiacal light.* This theory assumed that there are dust particles in a flat lens shaped region with the sun at the center spreading out in the plane of the ecliptic well beyond the orbit of the earth. The particles were not molecules of a gas, for due to diffusion and light pressure molecules would not stay near the plane of the ecliptic. The particles

[15] Van Rhyn, Astrophys. Jr. **50,** 356 (1919).
[16] Wright, Amer. Jr. of Sci. and Arts **7,** 451 (1874).
[17] Smyth, Trans. Roy. Soc. Edinburgh **20,** 489 (1852).
[18] Fath, Lick Obs. Bul. **5,** 141 (1909).

were considered to be small solid bodies each moving in its independent orbit around the sun. It was suggested that they were small meteoroids of the solar system, possibly remnants of the spray and dust from the large splash which inaugurated our planet system.[19] The particles were assumed to reflect the sunlight, particles 1 mm in diameter and 5 miles apart of albedo 0.07, the albedo of the moon, being sufficient to account for the observed zodiacal luminosity.[20] Light reflected from minerals such as granite, clay, etc., was found to be partially polarized.[16]

Since the zodiacal light undergoes fluctuations in intensity it follows that all of the light can not be reflected sunlight. For the sunlight, at least in that portion of the spectrum accessible to us, does not fluctuate very much, the short period (a few hours or a day) variations[21] of the solar constant being usually less than 10 per cent, whereas the variations in the zodiacal light intensity, although not measured, would perhaps be of the order of hundreds of percent. Therefore the planet dust theory, if it be retained at all, requires some fundamental modification not heretofore contemplated.

5. *The atmospheric theory of the zodiacal light.* As described in the following pages the atmospheric theory assumes that fast flying atoms or molecules are sprayed out in all directions from the sunlit hemisphere of the earth which, after a number of hours, are ionized by the ultra-violet light of the sun. Under the action of solar radiation pressure and the earth's magnetic and gravitational fields ions at levels beyond 30,000 km form a sort of oblong ring around the earth approximately in the plane of the ecliptic. The ions absorb sunlight in the far ultra-violet region of the spectrum and re-emit a portion of the absorbed energy as visible light. This is the zodiacal light. This view encounters two difficulties at the outset, namely, the light might be expected to be unpolarized and the spectrum should be different from that of sunlight. The first difficulty may be got round for the present by suggesting that the fluorescence radiation might be polarized to some extent and by expressing the wish that the polarization observations be repeated. The difficulty with the spectrum is more serious, so serious in fact that if future observations show that the zodiacal spectrum is that of sunlight the atmospheric theory in the form given here will fall to the ground. We may remark that the solar corona and certain comet tails exhibited a spectrum more of less continuous which, in part at least, was not that of sunlight.[22]

6. *The ion spray to distances of 70,000 km.* In the earlier paper, reference 7, paragraph 3, it was shown that beyond 450 km above sea-level there were about 10^{-16} molecules and atoms in a $1 cm^2$ column of the atmosphere. These dance up and down, being knocked upward by thermal impacts from below and falling back under gravity, with practically no collisions except at the 450 km level where they experience 10^{14} collisions per sec. The thermal ve-

[19] Jeans, "Astronomy and Cosmogony," page 400, (1928).

[20] Russell, Dugan and Stewart, "Astronomy," Vol. 1, page 359 (1926).

[21] Annals of the Astrophys. Obs. of the Smithsonian Institution, IV, pages 17 and 207 (1922).

[22] Reference 20, pages 439 and 507; Slipher, Lowell Obs. Bul. 52; etc.

locities are hardly greater than 2 km sec^{-1} and the levels reached by the particles are on the average not above 2000 km. It was assumed that 2×10^6 of the collisions were of the second kind, *i. e.* collisions with excited atoms or molecules, which gave the particles velocities as great as 10 km·sec^{-1} (See reference 7 for a more detailed discussion.) In the present case the assumption is extended to include 2×10^7 collisions which result in velocities as high as 12 or 13 km·sec^{-1}. Thus 10^7 $cm^{-2}\cdot sec^{-1}$ fast moving atoms or molecules move out from the earth. They are ionized by the ultra-violet light of the sun in a time t given by the relation $t=a/I_0$ $(1-e^{-\beta})$, (reference 7, equation (1)) where a is the ionization potential of the atom or molecule, I_0 is the energy of the sun in the ionizing wave-lengths and β is the atomic absorption coefficient. β is defined in the usual way by

$$I = I_0e^{-\beta yx}, \tag{1}$$

where I is the intensity of the light after passing through x cms of atoms or molecules of density y. It is assumed that the sun is quiet, i.e. no aurorae or

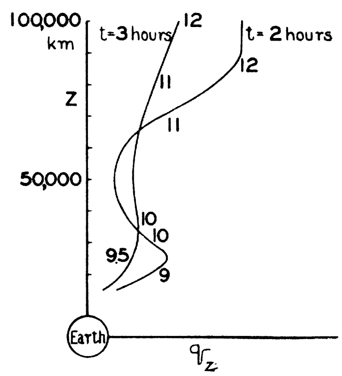

Fig. 2. The rate of supply q_z of ions as a function of the distance from the earth.

magnetic storms, and that its spectrum is that of a black body at 6000° K. The energy in the region from 725 to 750A of the solar spectrum falling $cm^{-2}\cdot sec^{-1}$ on the earth is 10^{-4} erg. With this value for I_0, with $\beta=3\times10^{-11}$ and with $a=3.1\times10^{-11}$ ergs, corresponding to 20 volts, t is 3 hours.

Assuming always 3 hours for the time of ionization, the heights z where the neutral atoms were ionized were calculated for various values of v the velocity of projection from the 300 km level of the earth's atmosphere. For example, an atom with $v=9.7$ km·sec^{-1} reaches $z=31,800$ km in 2.6 hours and falls back to 31,400 km in 0.4 hours where it is ionized; with $v=10$, 10.3 and 11 km·sec^{-1} the atoms are ionized at $z=39,800$, 48,000 and 70,000 km respectively. The v, z curves were plotted for $t=3$ hours and $t=2$ hours. Assuming that the velocities are equally distributed among the high flying atoms, in which case the number of atoms with a specified energy is proportional to the square root of the energy, the rate of production q_z of ions cm^{-3} was determined from the slopes of the v,z curves. The q_z,z curves are given in Fig. 2 for $t=2$ and 3 hours, q_z being in arbitrary units; the numbers written along each curve are the values of v of the atom which became ionized at the ordinate z. It is seen that q_z is greater at heights above 50,000 km than at lower heights. Since v can not go on increasing indefinitely q_z must grow less somewhere and we may assume that q_z reaches a maximum between 50,000 and 80,000 km and falls to low values at greater distances. The foregoing calculations can only be regarded as illustrative, but they serve to show that hypotheses, perhaps not unreasonable ones, of the sort which have been made lead to a rate of ion production which does not fall off rapidly with increasing z and which may even increase with z for a time.

In order to determine the distribution of the high flying ions around the earth it is assumed that the number of fast moving atoms or molecules emitted from each cm^2 of the surface of the high atmosphere in a direction ϕ is proportional to $\cos \phi \cos i$, where ϕ is the angle with the normal to the surface

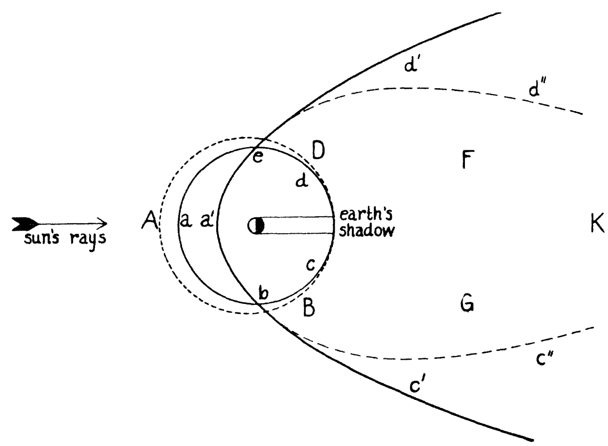

Fig 3. Cross section of the zodiacal ion ring in the plane of the earth's equator.

and i is the angle of incidence of the sunlight on the surface. Let q_θ be the total number of fast moving particles emitted from the day hemisphere in a direction at an angle θ with the sun's rays. The relation between q_θ and θ is thus the same as that which expresses the distribution of light reflected from a perfectly diffusing hemisphere or the variation of the intensity of moonlight with the phase of the moon. The relation is

$$q_\theta = q_0(1 + \cos \theta)/2, \quad (2)$$

where q_0 is the value of q_θ for $\theta=0$. The q_θ, θ curve is a cardioid. In Fig. 3, *abcde* is a circle around the earth in the plane of the equator with a radius of 50,000 km. From this circle as a base q_θ, calculated from (2), is measured outward and forms the curve *ABD*. This curve represents the rate of supply of high flying atoms and molecules, and hence of ions, at the high levels in the plane of the equator. Rotating the curve about *AK* as an axis forms a figure which represents the rate of supply of the high flying ions around the earth. Although (2) is an approximation, it is exact enough for our purposes. It assumes that the radius of the earth is small compared to 50,000 km, thereby neglecting the earth's shadow and giving values of q_θ greater than zero in the shadow, except for $\theta = 180°$. No ions can be formed in the shadow but ions can get there because some fast flying atoms shoot over the poles of the earth, become ionized and follow along a magnetic line into the shadow.

7. *The ion ring around the earth.* It is assumed that the earth is electrically neutral at all points. Therefore any electric fields which exist are generated by the ions themselves and the motions of the ions at distances beyond several radii of the earth are approximately independent of the rotation of the earth on its axis[23], i.e. are the same whether the earth rotates or not. The centrifugal force due to the motion of the earth in its orbit around the sun is small and is neglected. When the neutral particles are ionized the ions and electrons thus formed are guided by the earth's magnetic field. They fall

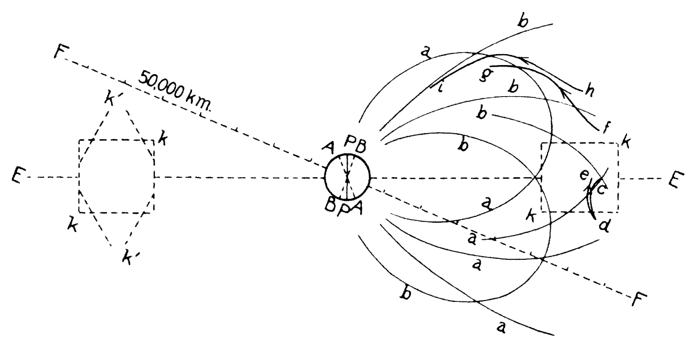

Fig. 4. A section in the plane through the center of the earth normal to the sun's rays; *kk* or *k'k'* is the zodiacal ion ring.

toward the earth along the magnetic lines of force under gravity and they drift across the magnetic field because of gravity, the positive ions going east and the negative electrons west. Dealing first with their fall we take into account the wabble of the magnetic field with the rotation of the earth. The magnetic axis makes an angle of about 20° with the geographic axis; the fact that the magnetic pole does not pass exactly through the center of the earth is of no consequence in the present discussion. In Fig. 4 *PP* is the geographic axis, *AA* is the magnetic axis with its magnetic lines given by curves *a* and *BB* is the magnetic axis 12 hours later with its magnetic lines *b*. The figure is in the plane through the center of the earth normal to the sun's rays. *EE* marks the plane of the earth's equator, and *FF* and *EE* mark the plane of the ecliptic at equinox and solstice, respectively; the angle between *EE* and *FF* is 23°. At equinox *PP* is in the plane of the drawing of Fig. 4, at solstice *PP* is tilted 23° out from the plane of the drawing.

An ion at *c*, Fig. 4, with an initial zero velocity component along the magnetic field *H*, falls under gravity along a number of slightly different curved

[23] Page, Phys. Rev. 33, 823 (1929).

paths depending on the time of day at which it starts to fall. One of the curved paths is given by *cde*, Fig. 4; the ion reaches *e* after about a day, and takes roughly a week to fall 20,000 km. Although the general path is *cde*, the actual path may be a spiral with a radius ρ which depends upon v, the velocity component across H, according to

$$\rho = mv/He. \tag{3}$$

m and e are the mass and charge of the ion, respectively; electromagnetic units are used throughout the paper. At 50,000 km with $v = 10$ km$\cdot$sec^{-1} ρ is 50 km for a nitrogen atomic ion, and is less for lighter ions as helium. Therefore ρ is small compared to the distances under consideration and in general the ions move along their paths in relatively tight spirals. An ion at f, Fig. 4, falls along the path fg reaching g in 1 day; an ion at h falls along hi and reaches the earth in less than a day. Thus the speed with which ions leave any level is a minimum on the earth's equator *EE* and increases rapidly on either side of *EE*. Since the rate of supply of ions at any level in the plane of Fig. 4 is constant the ion density y at a given level is a maximum at *EE* and falls off on either side by perhaps an order of magnitude or more at 20° from *EE*. Further, ions formed at the, say, 30,000 km level will remain there a shorter time than those formed at the 60,000 km level because of the greater gravitational attraction of the earth at the lower levels. This combined with the rate of supply curves of Fig. 2 indicates that the ion density y in the levels below 50,000 km down to perhaps 20,000 km may be much less than from 50,000 to 70,000 km.

Therefore the ions congregate into a ring around the earth lying roughly in the plane of the equator on the daylight side of the earth; on the night side, as is shown in sections 9 and 10, the ring is warped off the equatorial plane approximately into the plane of the ecliptic and is stretched out into a long oval by light pressure and by magnetic gravitational actions. Illustrative equivalent cross-sections of the ring at $\theta = 90°$ are shown by kk, Fig. 4. These are sketched 20° wide and 20,000 km deep, the actual cross-section is perhaps more like $k'k'$, Fig. 4; at $\theta = 0°$ the width is about 70° (section 9).

The total number of ions y_1 in any cross-section of the ring 1 cm thick is equal to $q_0 t$, where t is the time the ions remain there. Since t is a constant with respect to θ we have from (2)

$$y_1 = y_0(1 + \cos\theta)/2, \tag{4}$$

where y_0 is the value of y_1 at $\theta = 0$. An outflow of 10^7 high flying atoms cm$^{-2}\cdot$sec^{-1} from the earth means a supply of 10^5 ions and electrons$\cdot$cm$^{-2}\cdot$sec^{-1} into the portion of the ring nearest the sun, i.e. $q_0 = 10^5$. If t is ten days or 10^6 sec. there are 10^{11} ions in an average 1 cm^2 column out through the ring. With an equivalent cross section 20,000 km wide and 20,000 km deep the average ion and electron density y is 50, and y_0 is 2×10^{20}. At $\theta = 90°$ $y = 25$ and $y_1 = 10^{20}$. With such low densities there are practically no collisions, for the free path of an ion is 10^{14} cm. The ion densities are so low that it seems doubtful that the presence of the ions and electrons could be detected by experiments with wireless waves. It also seems doubtful that the diamagnetism[24] of the ions has any great effect upon the earth's magnetic field in the zodiacal region, although the field may be distorted to some extent.

It is assumed that ions absorb the solar ultra-violet radiation from λ900 to 1000A, or an equivalent amount. The energy received at the earth in this spectrum region is 1 $\text{erg}\cdot\text{cm}^{-2}\text{sec}^{-1}$, as calculated for a quiet sun at 6000 K. Assuming the atomic absorption coefficient β for the radiation to be 10^{-12}, the energy absorbed by the 10^{11} ions is 10^{-1} $\text{erg}\cdot\text{sec}^{-1}$. If 10^{-5} of the absorbed energy is emitted as visible light the ion ring emits 10^{-6} $\text{erg}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$, which is the observed value of the zodiacal luminosity (section3).

8. *Radiation pressure.* The numerical assumptions of section 7 lead at once to a value for the radiation pressure on the zodiacal ions. The force of the radiation on y ions of mass m is myp, where p is the acceleration. If the energy flux of the radiation is I_0 the energy absorbed by the y ions is $I_0\beta y$ and the energy density of the absorbed radiation is $I_0\beta y/c$, where c is the velocity of light. Then $myp = I_0\beta y/c$, or

$$p = I_0\beta/mc. \tag{5}$$

With $I_0 = 1$ $\text{erg}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$, $\beta = 10^{-12}$ and $m = 2.3\times10^{-23}$ grams, as for a nitrogen atomic ion, p is 1.5 $\text{cm}\cdot\text{sec}^{-2}$. For helium and hydrogen atomic ions p is 5.2 and 20.8 $\text{cm}\cdot\text{sec}^{-2}$, respectively. The solar gravitational acceleration g_s is 0.6 $\text{cm}\cdot\text{sec}^{-2}$ at the earth. Therefore p is greater than g_s by perhaps an order of magnitude. This in keeping with the observed streaming away in the direction of the sun's rays of the particles in comets' tails. The motion indicated that in some cases the radiation repulsion was 12 times the solar gravitational attraction.[25]

In this paper we do not encounter any ionic velocities so great that the absorption coefficients and radiation pressure are influenced by Doppler effects, as Milne[26] found in dealing with stellar atmospheres. We may state without giving the calculations that light pressure and scattering effects calculated from the Rayleigh scattering formula are entirely negligible compared to the absorption and fluorescence processes which we have assumed.

Atomic absorption coefficients of order 10^{-11} or 10^{-12} as assumed in sections 6 and 7 may be too high, although one can not be very sure about it. Various theories[27] indicate values of β of order 10^{-15} to 10^{-17} near the heads of the principal series of hydrogenic atoms. Observations[28] on the lines and continuous spectrum near the heads of the principal series of the alkali metals give β of the order of 10^{-19}. In the ozone molecular band[29] β is 10^{-17} at about 2500A, and in the oxygen molecular band β is greater than 10^{-17} at 1500A,

[24] Gunn, Phys. Rev. **33,** 614 (1929), equation (12).

[25] Chambers, "The Story of the Comets," page 37, 1910.

[26] Milne, Monthly Notices, Roy. Ast. Soc. **86,** 459 (1925–26).

[27] Kramers, Phil. Mag. **46,** 836 (1923); Eddington, "The Internal Constitution of the Stars," equation 166.8; Pannekoek, K. Akad. Ansterdam, Proc. **29,** 1165 (1926); etc.

[28] Mohler, Phys. Rev. Sup. **1,** 216 (1929), and references therein.

[29] Fabry, Proc. Phys. Soc. London **39,** 1 (1926).

as judged from Lyman's[30] spectrograms of the oxygen band. One can not be very certain that these values of β give a correct idea of the order of magnitude of β in the far ultra-violet for the atmospheric atoms, which are probably helium, nitrogen and oxygen. However, in the present case we are not restricted to a definite as sumption about β; we require that the product βI_0 have certain specifiedvalues. If β should be less than 10^{-12} we can increase the assumed value of I_0, which is of course permissable within limits.

9. *The ion ring on the side of the earth near the sun is compressed toward the earth and on the side away from the sun is stretched out to a great distance.* It has been shown[7] that long free path ions, no matter what their velocities are, under the combined action of gravity and the earth's magnetic field move at right angles to these two vectors with a velocity w given approximately by

$$w = mg \sin \phi / He, \tag{6}$$

the positive ions going eastward and the negative ions and electrons westward. ϕ is the angle between g and H; w is a maximum at the equator and decreases rapidly at high latitudes. The drift of the ions and electrons constitutes an electric current flowing eastward around the earth if the circuit is complete. If the circuit is not complete electric fields are built up which react on the motion of the ions. At the surface of the earth $w = 4.6 \text{ cm} \cdot \text{sec}^{-1}$ for a singly charged nitrogen atomic ion at the equator, and is 1/26,000 of this or practically zero, for the electron. The eastward current i, due to the drift velocity w, is $i = y_1 ew$ where y_1 is the total number of ions in a cross-section of the ring 1 cm thick in a plane passing through the earth's axis. Since g and H are proportional to z^{-2} and z^{-3}, respectively, z being the distance to the center of the earth, $w = 4.6z/z_0$, where $z_0 = 6400$ km is the radius of the earth, and $i = 4.6ezy_1/z_0$. With $e = 1.59 \times 10^{-20}$

$$i = 1.14 \times 10^{-28} zy_1. \tag{7}$$

We note in passing that this current causes a negligibly small magnetic field at the earth. With $y_1 = 2 \times 10^{20}$ and $z = 50{,}000$ km, i from (7) is 10^3 amperes. The current causes a magnetic field at the earth less than 10^{-5} gauss, which is probably inappreciable.

In order that the zodiacal ion ring be in a steady state the drift current i must be a constant through all cross-sections of the ring. Therefore from (7) zy_1 should be a constant. The values of y_1 are given by (4) and hence

$$z = A/(1 + \cos \theta), \tag{8}$$

where A is a constant. The z, θ curve from (8) is the curve for the steady state and is shown by $c'ba'ed'$, Fig. 3. The branches bc' and ed' meet at infinity. This is wrong; actually they join at a finite distance. The error arises from the fact that (8) is derived through (4) from (2) which gives no ions at $\theta = 180°$. As explained in section 6 there are ions at all values of θ, and hence z in (8) is always finite. Therefore, the branches of the steady state

[30] Lyman, Astrophys. Jr. **27**, 87 (1908).

curve will be something like bc'' and ed''. The curve is quite different from the circular ring *abcde* in which the ions are produced. Therefore the ions immediately and continually flow from the circle to distribute themselves in the curve $c''ba'ed''$ although because of radiation pressure they probably never attain this distribution. The process is similar to that worked out[31] for the ions in the lower atmospheric levels from 100 to 200 km and is as follows:

Suppose that the ring were circular as *abcde*, Fig. 3, and that y_1 were given by (4). i would not be constant around the ring. Due to the drift w positive ions accumulate on the side b of the ring leaving a negative accumulation on side e. This gives rise to an electric field E' from the b to the e side of the ring. E' is in such a direction that, combined with H, it causes the charged particles of both signs to move at right angles to E' and H with a velocity $v' = E'\sin\phi/H$, where ϕ is the angle between E' and H. The movement together with the wabble of the earth's magnetic field (section 7) causes ions in or near the equatorial plane to move away from the sun roughly parallel to the equatorial plane. Thus ions and electrons formed in the region *bae*, Fig. 3, flow toward $ba'e$. If the ring has an angular width of 20° at $\theta = 90°$ then at a', i.e. at $\theta = 0$, because of its greater proximity to the earth and its greater supply and less loss of ions than $\theta = 90°$, the ring may have an angular width of as much as 70°, in agreement with the observations of Barnard[3] and Newcomb.[4] Likewise ions and electrons formed at *bcde*, Fig. 3, stream toward $c''GFd''$ maintaining their concentration in the equatorial plane, the motion being modified by radiation pressure after they get beyond 100,000 km (section 10). The flow or streaming of the ions away from the sun is a maximum at the equator and falls off rapidly at the higher latitudes. Therefore the details of the ion movements brought out here do not disturb the aurora theory[7] but offer helpful additions to the theory which will be considered in a future paper.

To work out E' and v' exactly throughout the region *BGFD*, Fig. 3, is intricate. Approximate calculations show that the ions and electrons stream away from *BcdD* about as rapidly as they are produced and that v' becomes less as z increases; beyond $z = 100{,}000$ km v' is negligible compared with the effects of radiation pressure. An average v' of order 1 km sec^{-1} from $z = 50{,}000$ km to 100,000 km is indicated.

10. *Radiation pressure causes the zodiacal ions and electrons to stream away in or near to the plane of the ecliptic.* The accelerations due to the pressure of solar radiation at the earth were estimated in section 9 to be 1.5, 5.2 and 20.8 cm·sec^{-2}, respectively, for a nitrogen, helium and hydrogen atomic ion; these are also the values of the earth's gravitational accelerations at about 210,000, 96,000 and 45,000 km, respectively. The solar gravitational attraction is just cancelled, or nearly so, by the centrifugal force due to the velocity of the earth in its orbit around the sun and may be neglected. Thus ions and electrons which are formed in the region *bcde*, Fig. 3, and which move out in

[31] Hulburt, Phys. Rev. **34**, 1167 (1929).

the equatorial plane with velocity v' find themselves subjected to a radiation pressure parallel to the ecliptic plane which beyond, say, $z=100{,}000$ km is equal to or greater than the earth's gravitational attraction.

In order to find out what happens to these particles we must examine the motion of a neutral ion cloud of finite size in a magnetic field H acted on by a constant force F, F being normal to H. Take H along the X-axis and F along the Y-axis. Then the ions drift along the Z-axis with a velocity F/He, the positive and negative ions going in opposite directions. As a result of the drift a separation of charge occurs which causes an electric field E along Z in such a direction that, combined with H, it causes the ions of both signs to move in the direction of F with a velocity v. The energy acquired from F goes into the kinetic energy η of the ions and the energy ξ of the electric field. At all times $v=E/H$. $\eta=mv^2y/2$ and $\xi=E^2/8\pi c^2$. Therefore $\xi/\eta=2H^2/8\pi c^2my=2.85H^2/y$. With H two or three orders of magnitude less than y, as in the present problem, ξ/η is less than 10^{-4}. Thus the energy taken by the field E is small compared to that of the moving ions. Therefore the ion cloud moves across the magnetic field under the action of the force approximately as it would if there were no magnetic field. This of course can not keep up indefinitely. For, as they recede from the earth the ions reach a region where the magnetic field is so small that the simple formulas used in the foregoing sentences become invalid. Actually the ion progresses along a cycloidal path and $v=E/H$ is approximately the average velocity of progression. The approximation breaks down when the radii ρ, equation 3, of the loops of the cycloid become comparable with the size of the ion cloud. This occurs at about $z=500{,}000$ km for a radiation pressure acceleration $p=5\ \mathrm{cm\cdot sec^{-2}}$ and an ion cloud 50,000 km across. At this distance the ions commence to progress away from the sun more slowly than they would if their acceleration were constantly 5 cm sec^{-2}, their motion being in large cycloidal loops. At greater distances, beyond 10^6 km, the earth's magnetic field becomes inappreciable, the ion paths straighten out and the ions move away under light pressure.

We now make use of what has been said about the motion of the zodiacal ions and electrons and give some numerical calculations. Ions formed on the day side of the earth for the most part do not drift to the night side. For an ion at a or a', Fig. 3, hardly stays there more than 10^6 sec (section 7) before falling back to the earth; its drift velocity w is of the order $10^2\ \mathrm{cm\cdot sec^{-1}}$, and in 10^6 sec it drifts eastward only 1000 km, which does not take it very far around the ion ring. Therefore the ions on the night side of the earth practically all come from those formed in the region *bcde*, Fig. 3. Consider ions and electrons at b, Fig. 3, at winter solstice; these are at the intersection of the planes of the equator and the ecliptic. Due to the combined effects of a light pressure acceleration $p=5\ \mathrm{cm\cdot sec^{-2}}$ in the ecliptic plane and an average velocity $v=1\ \mathrm{cm\cdot sec^{-1}}$ in the equatorial plane out to $z=100{,}000$ km, and zero beyond this (v' being due to E' which arises from the gravitational magnetic drift w, section 9) the ions move in 3×10^4 sec or 8.3 hr away from the sun to a position about 49,500 km from and 12,000 km south of the ecliptic. After this v' becomes negligible and the accelerations which act on the ions are p and g, g being the acceleration of the earth's gravitational attraction. In the next 4×10^4 sec or 11.2 hr the ions move away from the sun to z about 400,000 km, at this distance having a velocity around 3 or 4 km·sec^{-1}. The component of the vector $p+g$ toward the line AK, Fig. 3, is about 0.5 cm·sec^{-2}, and thus the ions progress about 4000 km toward AK. The ions then continue to progress away from the sun with a lessened acceleration until z is perhaps 10^6 km, at the same time they bear in slightly closer to AK. After this the effect of the earth's magnetic field becomes inappreciable and the ions stream away with the full light pressure acceleration p. The earth's shadow has practically no effect on the motion, the ions in the shadow moving along with those in full sunlight. This is because the ions in the shadow are few compared with those in the sunlight, since the cross-section of the shadow is small compared with that of the ion cloud, and because the ions in the

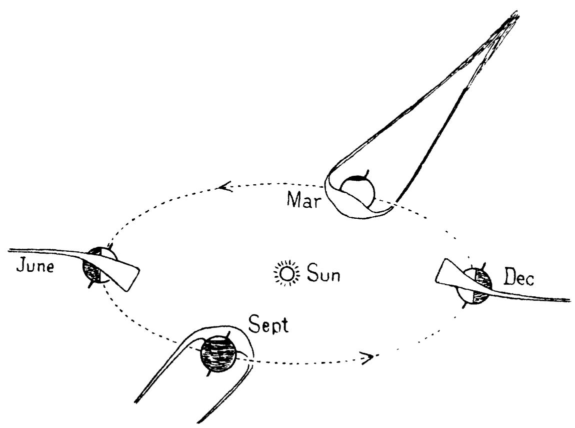

Fig. 5. The zodiacal ion ring at various seasons of the year.

sunlight move by setting up the electric field E, which acts equally on the sunlit and the dark ions.

11. *Comparison of the atmospheric theory of the zodiacal light with observation.* The results of the theory of the zodiacal ions worked out in sections 5 to 10 are represented in Fig. 5. The figure is not drawn to scale. On the daylight side of the earth the zodiacal ion ring is wide and follows the plane of the earth's equator. On the night side the ring is narrow, is warped off the equatorial plane roughly on to the ecliptic plane and trails off to a great distance. Referring to the portions of the zodiacal band at roughly $\theta=90°$ to 130° from the sun it is seen from Fig. 5 that both the morning and evening zodiacal cones should appear somewhat to the south of the ecliptic near winter solstice and to the north of the ecliptic near summer solstice. Around spring equinox the evening cone should be to the south and the morning cone to the north of the ecliptic, with a reversed position of the cones at autumn equinox. Fig. 6 gives a plot obtained from Jones' observations.[8] The ordinates are the positions in degrees to the north or south of the ecliptic of

the center of the zodiacal cone for $\theta = 90°$ to $130°$ at solstice and $70°$ to $130°$ at equinox, approximately; the dots and crosses refer to the evening and morning cones, respectively. The course of the dots and crosses is in accord with the theoretical deductions. The dots and crosses are together at the solstices, those at winter solstice being below those at summer solstice; the crosses are above the dots at spring equinox and below the dots at winter equinox. The observations of Cassini[8] made in 1685 to 1687 are plotted in Fig. 6, the circles being the evening observations and the triangles the morning observations. They agree well with those of Jones, as Jones himself remarked. The magnetic storms, shown by the vertical lines in Fig. 6, are discussed in section 13.

Although the march of the crosses and dots of Fig. 6 is in qualitative agreement with the present theory, there is a quantitative discrepancy. At equinox the morning and evening cones are separated in latitude by

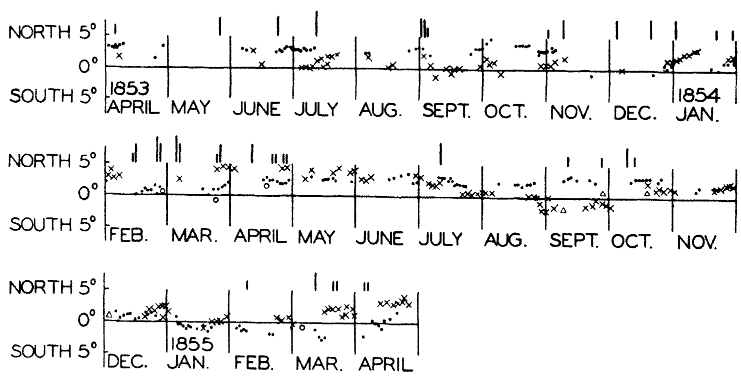

Fig. 6. Positions in degrees to the north or south of the ecliptic of the evening and morning zodiacal cones, shown by dots and crosses, respectively, from the observations of Jones. The observations of Cassini are shown by circles, evening, and triangles, morning.

about 5°, whereas if the cones lie partly along the earth's equatorial plane the separation should perhaps be greater than 5°, but not more than 46°. Whether the discrepancy is serious or whether it will disappear upon further attention to theory or observation can not be said at the present time. On the other hand the north and south shift of the cones of about 5° from winter to summer solstice agrees with the theory. If one plots from Jones' drawings the positions of the apexes of the zodiacal cones to the north or south of the ecliptic the points show the same general trend as those of Fig. 6, but much less pronounced and with many irregularities due no doubt to observational errors. The average deviation of the apexes from the ecliptic is less than 2°. This would be expected on the present view for the apexes of the cones are light from zodiacal ions which are probably more than 100,000 km away.

The dots and crosses of Fig. 6 are on the average about 2° to the north of the ecliptic, whereas one would expect the average over a year to be on the ecliptic. In explanation we follow a suggestion of others[9] and make use of the fact that the atmospheric transmission due to haze, etc., decreases toward the horizon. Thus if the ecliptic and the zodiacal cones had a slant, say, to the south of the vertical with the horizon, an observer would place the zodiacal cones too far to the north. Any traces of twilight would accentuate the error, although Jones avoided errors from twilight by making most of his observations after the sun was 18° below the horizon. The correction due to the slant of the cones shifts the points of Fig. 6 generally southward and therefore is qualitatively in the right direction to bring their average close to the ecliptic, without however disturbing the equinox and solstice relations brought out in the last paragraph. In more detail, from April to December, 1854, the zodiacal cones slanted in general to the south; the points of Fig. 6 in this period should therefore all be shifted a degree or so southward. In January, 1855, the ecliptic was nearly vertical and the points need no correction. In February the correction is northward on both dots and crosses, in March is zero for the crosses and slightly northward for the dots, and in the latter part of April is southward again for all the points. Thus we find a simple explanation of the curious fact[1,2,9] that in general observers in northern and southern latitudes have recorded the zodiacal cones to the north and the south of the ecliptic, respectively. From the foregoing analysis of Jones' observations it seems that it is not the latitude of the observer but the slant of the cones with the horizon that is important.

From Fig. 5 one can see how Jones and other observers sometimes got an apparent negative parallax of the zodiacal cones. At equinox the observer found himself south of the ecliptic in, say, the evening. He recorded the position of the evening cone against the stars. By the rotation of the earth on its axis he was carried to the north of the ecliptic in the morning and recorded the position of the morning cone. Upon comparing the two results he found to his surprise that the zodiacal cone had apparently moved with him from the south to the north of the ecliptic. Thus the parallax came out zero or negative, which is to be expected on the present view because the evening and morning cones are two different portions of a warped zodiacal band.

From the observations of Serpieri, Heis, Weber and others (see reference 9) as well as from those of Jones it seems to be an accepted fact that the zodiacal cones are longer at solstice than at equinox. The present theory does not provide an explanation of this. Qualitatively, at any rate, it does not point with any clearness to marked seasonal variations in the shape of the cones. The theoretical calculations of the motions of the zodiacal ions have been pretty rough and it is possible that many details, and perhaps important ones, have escaped us.

12. *Moon zodiacal light.* Here we have to deal with conclusions so incomprehensible on any theory that we think they are in error. Nor are we the first to think this, for Newcomb[1] commented on Bayldon's[1] observations as follows, "He (Bayldon) also describes the moon as adding to the zodiacal light in her first and last quarters, a result so difficult to explain that it needs confirmation." To give a typical experiment; the observer an hour or two after sunset could see as usual the western zodiacal cone but ordinarily he

could not see the zodiacal band extending across the sky down to the eastern horizon. The moon was about to rise in the east and he thought that he could see the zodiacal band near the eastern horizon. He concluded that this was due to an illumination of the zodiacal particles by the moonlight. However, the intensity of moonlight at the earth is 10^{-6} of that of sunlight and the conclusion would be that the brilliance of the zodiacal cone or band which is barely discernable when illuminated by sunlight is perceptibly increased by light 1,000,000 times weaker. The moon zodiacal light observations were made when the moon was less than 10°, and usually less than 5°, below the horizon. Therefore moon twilight would certainly have interfered with the observations and perhaps moon twilight was all that the observer saw. Jones recorded 13 moon zodiacal light observations and by chance 8 of these were during magnetic storms when the zodiacal light might have been unusually brilliant, because of the solar activity and not because of the moon.

On the present theory the moon, being about 380,000 km from the earth, moves through the zodiacal ions in the region K, Fig. 3. At 10,000 km from the center of the moon the acceleration of the moon's gravitation is 5 cm sec^{-2}, which is comparable with the light pressure acceleration. Therefore the moon might sweep a hole through the zodiacal ions probably less than 20,000 km in diameter. The magnetic moment of the moon may be estimated[32] to be considerably less than 10^{-2} of that of the earth and the effect of the moon's magnetic field on the ions is probably inappreciable beyond 1000 km from the moon compared to that of light pressure. The hole in the zodiacal ions caused by the moon would be difficult to observe, being wrongly oriented to the terrestrial observer, and being healed quickly by the ion flow would not be expected to give rise to zodiacal or gegenschein variations which could be detected.

13. *Zodiacal light variations and solar outbursts.* The effects of sunlight in producing the zodiacal ions and in stimulating them to emit light, which have been described for a quiet sun, are accentuated during solar outbursts. According to the ultra-violet light theory[7] of aurorae and magnetic storms the solar outburst is a flare of ultra-violet light. The ultra-violet flare would in general be expected to increase the number of the zodiacal ions and the intensity of their fluorescence. We make no attempt here to enter into a complete discussion of the complicated effects which the flare might produce, but a few simple cases are of interest. The zodiacal ion ring on the day side of the earth might be compressed toward the earth because I_0 is increased and t is decreased during the flare (section 6). Therefore the portion of the ring from $\theta = 0$ to 90° might be widened during a magnetic disturbance. Apparently this is what happened during the latter part of June 1853 according to Jones' observations. The position and shape of the ring on the night side of the earth would not be expected to be greatly changed by the flare. In keeping with this idea the magnetic storms are shown by vertical lines in Fig. 6, and it is seen that the course of the dots and crosses is on the whole undisturbed during the magnetic storms.

[32] From equation (12), Gunn, Phys. Rev. **34**, 335 (1929).

A flickering of the intensity of the ultra-violet wave-lengths of the flare which cause the fluorescence of the zodiacal ions would cause pulsations in the entire body of the zodiacal light, as are observed. Various types of flares would be expected to occur (see the discussion of an earlier paper[33]), in particular, the ionizing wave-lengths might be feeble compared to the fluorescent wave-lengths. This might occur at any time or when the flare was warming up to storm intensity. In the first case there might be zodiacal light changes with no accompanying magnetic storm, and in the second case the zodiacal light variation would be followed by the magnetic storm. Instances of both these possibilities are found in the data of section 2. For example, the zodiacal light fluctuations of November 3, 1929, (section 2) were seen at about 3 A.M. and the magnetic storm began 4 hours later. Similarly, auroral displays and vagaries in the propagation of wireless waves are known[33] to occur before a magnetic storm at times. The Radio Division of this Laboratory has noticed on a few occasions that wireless communication was very unusual several days before a magnetic storm; the storm was actually predicted in advance, the feeling at the time being that the prediction was about as certain as a weather prediction.

14. *The gegenschein.* The ions which stream away from the region *bcde*, Fig. 3, form a sheet mainly in the ecliptic plane extending throughout the region *BGKFD*, which seen edge-on is the zodiacal band. The ion densities are somewhat greater near the boundaries bc'' and ed'' of the sheet than in the interior regions. As shown in section 10 the boundaries swing into some extent toward the line AK, and at about $z=0.5\times10^6$ km the ions progress more slowly away from the earth until $z=10^6$ km is reached, whereupon they stream away with the full light pressure acceleration like the particles of a comet's tail. Thus looking end-on at the ion stream the terrestrial observer sees it as a patch of greater luminosity on the zodiacal band. This is the gegenschein. If the cross-section of the stream were 100,000 km in width along the ecliptic and 40,000 km high and if the equivalent optical distance were 10^6 km, the patch would be 6° wide along the ecliptic and 3° high, as seen from the earth, and its parallax as determined by two observers 20,000 km apart would be 1°. These values agree with observation[5,6]; Barnard[5] stated that the brighter portion of the gegenschein is about 7° in diameter fading insensibly into the night, the luminosity sometimes being perceptible to a diameter of more than 30°. The present theory of the gegenschein is of course quite different from the meteorite theory of Gyldèn and of Moulton.[34]

That the gegenschein may be a comet tail appendage of the terrestrial atmosphere was mentioned long ago by Arrhenius, Evershed and others.[1] Barnard[5] suggested that the atmosphere surrounding the earth acts as a lens to give a concentration of light somewhere along the line AK, Fig. 3. This would make a spot of illumination if there were particles there to be illuminated. Exact calculations are difficult but approximate ones show that the con-

[33] Hulburt, Phys. Rev. **34**, 344 (1929).

[34] Moulton, "Celestial Mechanics," page 305 (1914).

centration of the light due to the lens, or refraction, effects probably occurs beyond $z = 0.5 \times 10^6$ km and that the concentration is not very great, perhaps about the same as the effects of diffraction. The apex of the cone of the earth's geometrical shadow is at $z = 1.37 \times 10^6$ km.

The present theory gives no clear indication of marked seasonal variations in the appearance of the gegenschein, but Barnard[5] found that the gegenschein "undergoes singular changes in form and that these changes are periodic with the seasons." To explain Barnard's observations we turn to the magnetic storms. In a time of solar quiescence the gegenschein would be a small spot elongated into the zodiacal band along the ecliptic. During a magnetic storm the spot would be larger for the number of gegenschein ions and their fluorescent light would be increased. From 73 observations extending over 15 years Barnard concluded that the gegenschein was large and round in February, March (especially in the latter part of the month), April, August, September, the first part of October, and November. It was small and elongated along the ecliptic in January, July and the latter part of October. The milky way interfered with observations in June and December, and there were few observations in May. These facts are pictured in Fig. 7.

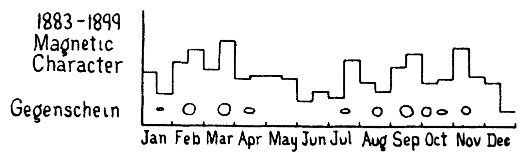

Fig. 7. Average magnetic character curve and Barnard's observations of the gegenschein for the years from October 1882 to February 1899.

Barnard made the 73 observations of the gegenschein from October 1883 to February 1899. We have added together all the magnetic storms for the first and last halves of each month throughout this period and have plotted the results in the broken curve of Fig. 7. In the addition storms of intensity 1, 2, 3 and 4 counted as 1, 2, 3 and 4, respectively. The curve is a magnetic character curve for the 15 years. It is seen that very roughly the gegenschein was large during epochs of magnetic storms and small during magnetic calm. The magnetic character curve has an ill defined maximum near equinox and a minimum near solstice, and thus has a sort of seasonal period. Fig. 7 can not be regarded as offering convincing evidence of a connection between magnetic storms and changes in the gegenschein. Further evidence would be desirable. It suggests, however, that the seasonal variations in the gegenschein were perhaps due to solar disturbances rather than to the tilt of the earth's axis.

15. *The rate of escape of the earth's atmosphere.* Zodiacal ions and electrons in the region *BDFG*, Fig. 3, which get beyond roughly 100,000 km move away under the solar radiation pressure. They do not come back to the earth. The zodiacal light and the gegenschein are the last fleeting evidences of particles which are leaving the earth never to return. If 1/10 of the high flying atoms

and molecules pass into space *via* the zodiacal band and the gegenschein, there is a loss of 10^6 particles $\cdot$ cm$^{-2}\cdot$ sec^{-1} from the atmosphere, or 10^{-6} of the entire atmosphere in 10^6 years. This is, if anything, an under-estimate, but a rate of escape of this amount, or even two or three orders of magnitude greater, seems small and open to no objection on general cosmogonical grounds.

We may go a step farther. Geophysicists[35] have found a difficulty in explaining the smallness of the amount of helium, 10^{13} atoms in a 1 cm^2 column, present in the earth's atmosphere. They estimate that the average acid rock sets free helium at the rate of 10^7 atoms of helium per year per gram of rock, and therefore that, say, 100 grams of acid rock per cm^2 would in 10,000 years produce the 10^{13} helium atoms. Thus in the long periods of geological time much more helium would be produced than is found to exist, especially so since no processes are recognized which would remove the helium by absorption back into the crust of the earth. The present theory points a way out of the difficulty in that it suggests that helium may escape from the atmosphere more rapidly than the other gases. For helium atoms, being lighter, will be sprayed away from the earth with greater velocities than the heavier nitrogen or oxygen molecules and atoms. More energy is required to ionize helium than the other gases and hence the helium particles reach much greater distances from the earth before being ionized and swept away by radiation pressure. Therefore, compared with oxygen or nitrogen ions, few of the fast flying helium ions return to the earth, and the rate of escape of the helium into space may be of the same order of magnitude as the rate of supply from the earth.

[35] Holmes, Geological Mag. **2,** 60 (1915), and references given in Jeffreys, "The Earth."