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THE NORTHERN LIMIT OF THE ZODIACAL LIGHT.

This investigation was undertaken at the suggestion of Director Campbell in order to determine, if possible, the nature of a faint light which for years has been noticed in the summer along our northern horizon by several observers.

Three hypotheses as to the origin of this light seem to require examination: that it is an aurora; that it is twilight; and that it is the Zodiacal Light.

The observations were begun in July, 1907, but at that time consisted merely in noting whether the light was visible or not. They have been continued during the present summer upon a somewhat more extended scale, but have been made only at intervals when time could be spared from another investigation. In consequence the results are by no means so definite as one might wish. Then, too, the air has been much less clear than usual this summer owing to many forest fires, sometimes less than fifty miles distant.

The general appearance of the phenomenon when observed near midnight with a clear sky and no moon is that of a flat arch of light with its maximum intensity near the north point of the horizon. At that time of night in the early part of July, 1908, the greatest altitude above the northern horizon was 18° . It extended westward about 40° and eastward to the Milky Way and was symmetrical with respect to the meridian. At the extremities it was only a degree or two

above the horizon, depending upon the clearness of the air at such a low altitude. When, however, the observations were made before midnight the maximum was always to the west of the north point and after midnight always to the east.

When this much had been established it seemed advisable to note, as accurately as possible, the extent to the east and west of the north point, the altitude and azimuth of the maximum brightness and the greatest altitude to which it could be traced. This greatest altitude was always directly over the maximum. A simple instrument was designed and constructed for observing the horizontal and vertical angles referred to and set up on the roof of the observatory. To simplify matters the zero for azimuth was taken as the north point and azimuth recorded as east or west.

The method of observation was to locate the various parts of the luminous area with reference to the stars; then, pointing to these places, to read the circles to the nearest degree and note the sidereal time. Owing to the faintness of the light any one position might be in error by as much as 5° , but it is not likely that many are out so much as that. The instrument was set up on July 2, 1908, and used whenever possible.

The observations are given below. Four are omitted as they are marked "very doubtful."

1908	Mt. Ham. Sid.T.	Azimuth Eastern End	Azimuth Western End	Maximum Altitude	Azimuth	Greatest Altitude	Remarks
June 27	18 ^h 17 ^m						Maximum directly beneath <i>Polaris</i> . At dark, light was continuation of Zodiacal Light.
	19 47				15° E		
30	18 29						Maximum directly beneath <i>Polaris</i> .
July 2	18 00		41° W	10°	3 W	16°	Eastern end in Milky Way. Observation very difficult.
	18 45		39 W	10	4 E	18	Eastern end in Milky Way. Observation very difficult.
	19 45		30 W	9	13 E	16	Eastern end in Milky Way. Observation very difficult.
	20 45	81° E	18 W	7	33 E	11	Eastern part crosses Milky Way. Observation easy.
	21 15	81 E	8 W	7	35 E	10	Altitude of eastern end 11° . This is in Zodiacal Light. Smoky near horizon to-night.

1908	Mt. Ham. Sid.T.	Azimuth Eastern End	Azimuth Western End	Maximum Altitude	Azimuth	Greatest Altitude	Remarks
July 3	19 ^h 10 ^m		26° W	12°	11° E	17°	Eastern end in Milky Way.
	19 50		19 W	13	15 E	17	Eastern end in Milky Way.
	20 55	86° E	5 W	12	28 E	16	
	21 20	86 E	6 E				Maximum in Milky Way. Gradual increase in altitude from western to eastern end, 9° to 16°. Smoky near horizon to-night.
July 4	19 00		26 W	7	4 E	16	Haze in north from 16° altitude up.
	21 00	88 E	7 E	9	38 E	12	Altitude increases from western to eastern end, 8° to 15°.
19	18 08						Light directly connected with Zodiacal Light. Upper boundary a straight line from λ <i>Urs. Maj.</i> to ϵ <i>Virg.</i> and extending to right and left of these limits a short distance. Sky near horizon very thick from smoke.
20	19 00						Maximum at σ <i>Urs. Maj.</i> Light very faint. Smoky in north.
22	18 00	14 E		8	35 W	14	Western end in Zodiacal Light. Upper boundary a straight line.
23	18 00	5 E		7	34 W	10	Western end in Zodiacal Light. Upper boundary a straight line.
	18 30	12 E		7	32 W	12	Western end in Zodiacal Light.
	19 15			7	14 W	12	Western end in Zodiacal Light, eastern end in Milky Way.
	20 30		20 W	8	8 E	11	Eastern end in Milky Way. Smoky near horizon to-night.
24	18 00	8 E		8	34 W	13	Western end in Zodiacal Light.
	19 10		60 W	7	23 W	11	San Francisco and Oakland lights may affect western position. Eastern end in Milky Way.
	19 40			6	9 W	10	Not safe to take position of western end because of San Francisco and Oakland lights.
	20 30		16 W	6	9 E	11	Observation difficult. Eastern end in Milky Way.
25	17 52						Eastern end in Milky Way, western end in Zodiacal Light. Maximum half way between κ and λ <i>Urs. Maj.</i> Greatest altitude at ν <i>Urs. Maj.</i>
	20 05		32 W	7	3 E	10	Eastern end in Milky Way. Position of western end may be affected by San Francisco and Oakland lights.
26	17 56						Maximum was on perpendicular line joining point midway between λ and θ <i>Urs. Maj.</i> with horizon and at an altitude of 7°. Greatest altitude at intersection of the two lines. Western end in Zodiacal Light and eastern end at north point of horizon.
29	19 20			8	13 W	12	Very smoky up to 5° altitude.
	20 30		32 W	6	2 E	10	Observation very difficult because of faintness of light.
	23 10						Light directly connected with Zodiacal Light. Upper boundary a straight line from altitude 5°, azimuth 1° E to altitude 24°, azimuth 80° E. Sky milky, observation difficult. Director Campbell and I observed bright aurora line λ 5571 with spectroscope in all parts of sky. Line no brighter near light than far from it.
31							Some clouds. Could see aurora line with spectroscope wherever sky was clear except at zenith. Line no brighter at maximum of light than at a distance from it.
Aug. 27	18 50						Maximum at ν <i>Urs. Maj.</i> Light extending up at small angle until it reached ecliptic in west. Greatest altitude at maximum 8°.
Aug. 28							At 15 ^h 50 ^m Pacific S.T. the northern boundary of Zodiacal Light cone was a straight line from apex at δ <i>Gem.</i> to λ <i>Urs. Maj.</i>
Sept. 3							At 15 ^h 30 ^m Pacific S.T. <i>Venus</i> near apex of Zodiacal Light cone. Northern boundary <i>Venus</i> to ψ <i>Urs. Maj.</i> , southern boundary <i>Venus</i> to β <i>Cancr.</i>

These observations were not reduced until all had been made. The observations were reduced by means of an 18-inch celestial globe on which the points observed were located and the arcs and angles measured to the nearest degree. The azimuth of the Sun was determined for the several times of observation and compared with the azimuth of the maximum of the light observed. If the observed maximum was east of the vertical circle passing through the Sun the number of degrees is put in column 3 of the following table; if the maximum was west it is put in column 4. Column 5 gives

the distance from the Sun to the point of greatest altitude observed; column 6, the angle which the line joining the Sun with the point of maximum altitude makes with the perpendicular to the ecliptic; and columns 7 and 8 the distance from the Sun of the nearest intersection with the ecliptic of the great circle passing through the point of greatest altitude and the eastern or western limit of the light. If the space is left blank the observation did not furnish data for the determination of the quantity desired.

1908	Mt. Ham. Sid. Time	Mt. Ham. App't. Time	E.	W.	Distance from Sun	Incl.	Intersection with ecliptic	
							E.	W.
June 27	18 ^h 17 ^m	11 ^h 50 ^m	1°					
	19 47	13 20		3°				
30	18 29	11 50	2					
July 2	18 00	11 13	6		44°	0°		53°
	18 45	11 58	4		46	0		62
	19 45	12 58		1	42	10 E		82
	20 45	13 58	3		34	34 E	46°	104
	21 15	14 28	0		30	36 E	40	105
July 3	19 10	12 19	6		45	0		65
	19 50	12 59		2	43	18 E		67
	20 55	14 04		6	38	30 E	50	87
	21 20	14 29					72	
July 4	19 00	12 05	2		44	0		53
	21 00	14 05	5		32	47 E	62	93
19	18 08	10 11						99
20	19 00	11 00	6					
22	18 00	9 52		2	48	15 W	85	82
23	18 00	9 48	0		34	14 W	70	
	18 30	10 18		6	39	20 W	74	
	19 15	11 03	1		42	5 E		
	20 30	12 18	3		43	25 E	68	
24	18 00	9 44	1		37	18 W	79	
	19 10	10 54		5	42	10 W		67
	19 40	11 24	1		41	7 E		
	20 30	12 14	5		43	13 E		93
25	17 52	9 32	2					
	20 05	11 45	6		43	12 E		75
26	17 56	9 32	0		34	10 W		85
29	19 20	10 44	7		43	10 E		
	20 30	11 54	4		43	14 E		72
	23 10	14 34					60	
Aug. 27	18 50	8 25	9		29			

The three hypotheses for the light as mentioned above will now be examined.

The aurora hypothesis does not seem tenable for three reasons:

1st.—The light in question is seen only in the summer, during a period of about two months on either side of the summer solstice.

2d.—The spectroscopic evidence as given by the observations of July 29 and 31. The bright aurora line at λ 5571 could be seen in practically all parts of the sky and was no brighter when the spectroscope was pointed to the maximum of the luminous area than when pointed many degrees away and entirely outside this area. At this time there was no aurora visible as such. That the aurora line, λ 5571, can be seen when there is no visible aurora¹ may have been noted by

¹ It seems advisable to call attention to what appears to be a mis-statement in Scheiner's *Spectralanalyse der Gestirne*. On page 343 it is stated "Auch Wright hat häufig die grüne Nordlichtlinie im Spectrum des Zodiakallichtes wahrgenommen, aber nur dann, wenn dieselbe auch an ausserhalb des Zodiakallichtes gelegenen Stellen auftrat, was zuweilen geschah, ohne dass ein Nordlicht direct zu sehen gewesen wäre." In Wright's report of his work on the spectrum of the Zodiacal Light in *The American Journal of Science*, Series 3, 8, 45, 1874, occurs the statement, "On the other hand, the bright line was never seen when there was no aurora."

Vogel² although he does not definitely state it. Campbell³ seems to have been the first to call direct attention to this.

3d.—Columns 3 and 4 of the table show the maximum intensity to move with the Sun.

If the light were twilight it seems reasonable to suppose that the mean of the observations would show the maximum intensity to be on or very near the vertical circle passing through the Sun. Taking all the differences of azimuth from columns 3 and 4, the mean of the 29 observations shows the maximum to be 1:7 farther east along the northern horizon than this vertical circle. Such a large difference does not appear accidental. Moreover the observation of July 2, 18^h 45^m, shows that the light could be seen 46° north of the Sun, the Sun being at that time 30° below the horizon and thus 12° lower than the usually assigned limit for twilight. Observations⁴ made during the summers of 1907 and 1908 to determine the zenith distance

² "Die helle Linie erschien übrigens an den [three] genannten Tagen an allen Theilen des Himmels, der mit einem matten, lichten Schleier überzogen war, mehr oder weniger intensiv." *Astron. Nach.*, 27, 327, 1872.

³ *Astrophysical Journal*, 2, 162, 1895.

⁴ Not included in the observations published above.

of the Sun at the end of twilight or the beginning of dawn all agree in making the zenith distance of the Sun 108° . The twilight hypothesis, therefore, does not explain the phenomenon satisfactorily.

Of the three hypotheses that of the Zodiacal Light remains.

The observations of July 19, 22, 23, 26, 29, August 27 and 28 show a direct connection between this light and the ordinary cone of the Zodiacal Light, a practically straight line forming the northern boundary of both the cone and the light under observation. This connection was also seen from the summit of Mt. Whitney, altitude 14,500 feet, on August 24. (See note at end of paper.) During the summer months the Zodiacal Light can be readily seen at Mt. Hamilton both in the west in the evening and in the east in the morning. The connection was seen with both the western and eastern cones.

The 1.7 displacement of the maximum of the light to the east of the vertical circle passing through the Sun appears significant. If we assume the axis of greatest intensity of the Zodiacal Light to be in or near the ecliptic, then at midnight at the time of the summer solstice the axis will be perpendicular to the vertical circle passing through the Sun. Before midnight the western angle between the axis and the vertical circle will be less than 90° and after midnight the eastern angle will be less. In general, before the summer solstice the western angle will average less throughout the night than the eastern and vice versa. Now taking two points at the same altitude and symmetrically situated with respect to the vertical circle, the one to the west would average nearer the axis throughout the night for observations before the solstice and therefore be the brighter. In the same way, after the solstice, the eastern one would be the brighter. We might expect, therefore, that before the solstice the maximum observed intensity would be shifted toward the west and after the solstice toward the east, the shift varying with the distance of the Sun from the solstice. Now we find an observed displacement of 1.7 toward the east and all the observations upon which this observed displacement depends were made after the solstice. An examination of the values in columns 3 and 4 of the table will also show a tendency for the displacement to increase with the time. The observations thus agree with the hypothesis.

The figures in the last two columns of the table aid in the determination of the apparent shape of the light observed. As stated above the figures give the distance from the Sun (in degrees) of the intersection with the ecliptic of the great circle drawn from the point of greatest observed altitude through the point of greatest eastern or western elongation. The total range of

intersections is from 40° to 105° . When the results of the last four columns of the table are plotted, using the Sun as origin and the ecliptic as the axis of abscissas it is seen that the light observed is distributed fairly symmetrically with respect to the Sun. It passes 46° to the north and intersects the ecliptic about 70° on either side. This applies, of course, only to the part north of the ecliptic. Assuming symmetry with respect to the ecliptic also we have the lenticular appearance of the Zodiacal Light. The effect of atmospheric absorption would be to bring the intersections too close to the Sun. The apex of the Zodiacal Light cone can be seen at various distances from the Sun ranging from 40° to over 100° . This agreement between the observed position of the apex and the position of the intersections is as satisfactory as can be expected from the nature of the objects observed.

The observations of August 28 and September 3 together with the results of others made after the reduction of the observations given above lead to the following table of results. The first column gives the distance of the apex of the Zodiacal Light cone from the Sun; the second column the angle made by the north side of the cone with the ecliptic; the last column the latitude of the intersection of the prolongation of the northern boundary of the cone with the great circle passing through the Sun perpendicular to the ecliptic.

		Apex from Sun	Angle with Ecliptic	Latitude
August	28	47°	47°	38°
September	3	45	56	46
	24	76	45	44
	25	81	42	41
	26	80	41	41
	27	80	39	39
	28	79	38	38
	29	82	31	31^5
	30	81	39	39
October	1	82	39	39
	3	83	46	46
	4	84	55	55
	5	88	59	39
	6	88	45	45

The mean of the results in the last column shows that we should expect the Zodiacal Light to extend 42° north of the Sun if we neglect curvature of the boundary and the effect of atmospheric absorption. The former would decrease and the latter increase the distance. Observations above the northern horizon give 46° .

In the classic volume of observations of the Zodiacal Light by Jones⁵ I find that by extending the boundaries of the "diffuse" light they would in many cases

⁵ Given half weight in mean on account of conditions under which the observation was made.

⁶ *Observations of the Zodiacal Light*. Vol. 3 of the Report on the United States Japan Expedition, 1856.

exceed latitudes of 45° both north and south of the Sun. The writer has not at present the time necessary to investigate carefully this great wealth of material and therefore desires only to call attention to the agreement between the observations of Jones and his own.

From the evidence at hand it seems fair to conclude that the phenomenon observed is the Zodiacal Light, and probably the same phenomenon as seen by Herrick,⁷ Newcomb,⁸ and Barnard.⁹ For the sake of completeness the observations should extend over another summer, say from May 1 to August 10. It could then be determined whether the maximum is to the west of the vertical circle passing through the Sun before the solstice and to the east after the solstice. It seems best, however, to publish these preliminary results for the benefit of any who may be interested in the matter of making the necessary observations next summer. It would also be of great value to have observations made at stations in the southern hemisphere from the first of November to the end of January.

In this paper it has been assumed that the axis of the Zodiacal Light is in or very near the ecliptic, in accordance with many observations. Some recent work places the axis in the plane of the Sun's equator.

⁷ *Silliman's Jour. of Science*, 39, 331, 1840.

⁸ *Astrophysical Journal*, 22, 209, 1905.

⁹ *Ibid.*, 23, 168, 1906.

This would not materially change the conclusions reached. Mention has also been made of the apex of the Zodiacal Light cone. This is taken as the point of intersection of the two sides of the cone. No real apex is seen at Mt. Hamilton as the cone near the "apex" merges directly into the zodiacal band which can usually be traced across the entire sky.

In conclusion, I wish to acknowledge my indebtedness to Director Campbell for his coöperation and suggestions, and especially for the trouble taken to secure the Mt. Whitney observations under trying circumstances. It is also a pleasure to acknowledge some suggestions from Mr. W. H. Wright, Astronomer in the Lick Observatory.

E. A. FATH.

MT. HAMILTON, October, 1908.

NOTE.—Director Campbell spent the night of August 24, 1908, on the summit of Mt. Whitney, altitude 14,500 feet, latitude $+36^\circ 35'$. At the request of the writer he kindly undertook some observations of the Zodiacal Light; it being arranged that the writer should make simultaneous observations at Mt. Hamilton. The Mt. Whitney observations are as follows:

"At 8^h 15^m Pacific Standard Time the Zodiacal Light could be faintly seen in the west. It extended along the ecliptic and then around the northwest horizon almost to the north point. Under β *Urs. Maj.* its altitude was $\frac{1}{3}$ that of β . At midnight nothing could be seen along the north horizon. Air exceptionally clear."

The observations at Mt. Hamilton showed nothing further. The smoke from the forest fires doubtless obscured the faint light.

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