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THE CHANGE OF THE SOLAR VELOCITY WITH INCREASING DISTANCES OF THE STARS FROM THE GALACTIC PLANE

EMMA T. R. WILLIAMS

ABSTRACT

The analysis of the proper motions of 18,000 stars, made at the McCormick Observatory, together with several previous investigations of proper motions, of radial velocities, and of space motions, indicates that the solar velocity decreases with respect to stars of a given spectral class, at increasing distances from the galactic plane. The investigations in which no stars were excluded on account of high velocity or stream membership, such as the McCormick analysis, show the effect more clearly than those in which such stars were excluded.

In the study of the proper motions of faint stars, just completed at the McCormick Observatory,[1] the mean parallaxes of stars in various galactic zones were derived by two essentially independent methods: first, from secular parallaxes, and second, from τ-components. It was immediately obvious that there were pronounced systematic differences between the two sets of parallaxes, depending on galactic latitude. The probable source of the discrepancy seems to be that the solar velocity with respect to any given spectral class of stars, such as gK stars, has been assumed to be independent of galactic latitude. A decrease of the solar velocity with increasing distance in parsecs from the galactic plane is clearly indicated in many previously published investigations. This would explain the observed discrepancy satisfactorily, and suggests that with the present knowledge of solar motion the mean parallaxes of faint stars derived from τ-components are at least as reliable as those obtained from secular parallaxes.

First, we shall examine the McCormick methods and results. The secular parallaxes were reduced to mean parallaxes by means of the relation:

$$\bar{\pi}_v = \frac{4.74}{V_0} \times \text{secular parallax} ,$$

[1] Van de Kamp and Vyssotsky, *Pub. Leander McCormick Obs.*, **7**, in press; also *A.J.*, 1936.

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where $\overline{\pi}_v$ denotes the mean parallax obtained from v-components and V_0 denotes the solar velocity. The values adopted for V_0 varied with spectral class according to the best available material from bright stars.[2] When adopting V_0 for a mixed group, such as all twelfth-magnitude stars, for example, due allowance was made for the relative numbers of different spectral types and of giants and dwarfs. Except for the change in composition, however, the adopted value of V_0 was independent of latitude.

To obtain mean parallaxes from the observed τ-components, it was first necessary to correct the observed τ-components for the systematic effects of the accidental errors. Then the following relation was used:

$$\overline{\pi}_\tau = \frac{4.74}{\overline{V}_\tau} \times \overline{\tau}_{\text{corr.}}$$

Here $\overline{\pi}_\tau$ denotes the mean parallax obtained from the τ-components; $\overline{\tau}_{\text{corr.}}$ denotes the mean τ-component corrected as just explained; and $\overline{V}_\tau$ denotes the mean peculiar velocity of the stars, in kilometers per second and without regard to sign, *in the* τ *direction*. Since various regions of the sky were considered separately, it was necessary to allow for the changes in $\overline{V}_\tau$ in different parts of the sky due to the ellipsoidal distribution of peculiar velocities (thus making unnecessary any corrections of the type suggested by Fletcher[3]). Also, as with V_0, the adopted values of $\overline{V}_\tau$ varied with spectral class in accordance with the best available material from bright stars, and the same kind of allowance was made for the spectral and giant-dwarf composition of mixed groups.

Now, comparing the values of $\overline{\pi}_v$ with $\overline{\pi}_\tau$ derived by van de Kamp and Vyssotsky, we find in every case more than 10° from the galactic plane that the values of $\overline{\pi}_\tau$ are larger than the corresponding values of $\overline{\pi}_v$, whereas in the lowest galactic zone the situation is reversed, as is shown in Table I. The same effect is also conspicuous in the subdivisions by spectral classes; but the scatter is considerably larger, owing to the smaller number of stars in each group.

[2] Wilson and Raymond, *A.J.*, **40**, 121, 1930.

[3] *M.N.*, **92**, 780, 1932; **95**, 737, 1935.

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Now, since

$$\frac{\bar{\pi}_\tau}{\bar{\pi}_v}=\frac{\text{Adopted } V_0}{\text{Adopted } \bar{V}_\tau}\times\frac{\bar{\tau}_{\text{corr.}}}{\text{Secular parallax}},$$

we may look for the cause of this systematic difference in any one of the four factors involved. Thus, one might doubt the assumption that the values of V_0 and $\bar{V}_\tau$ of a given spectral subclass, say gK, are the same for stars of tenth apparent magnitude as for stars of fifth apparent magnitude. But even if it were incorrect, we should still expect the ratio $V_0/\bar{V}_\tau$ to remain practically unchanged on account of the Strömberg relation between relative solar velocity and mean

TABLE I

$\bar{\pi}_T/\bar{\pi}_v$

Gal. Lat.	Apparent Magnitudes				
	12.5—	11.5–12.4	10.5–11.4	9.5–10.4	7.5–9.4
±41° to ±90°	1.84	1.29	1.61	1.37	1.52
21 40	2.00	1.75	1.13	1.54	1.43
11 20	1.57	1.09	1.17	1.28	1.04
0 10	0.84	0.89	0.90	0.82	0.86

peculiar velocities. Hence the systematic differences may not be accounted for in this manner. Neither do van de Kamp and Vyssotsky feel that systematic errors in the secular parallaxes or in the values of $\bar{\tau}_{\text{corr.}}$ could account for it. Therefore, we are led to examine the two possibilities: (*a*) that for a given type of star, V_0 varies with latitude; and (*b*) that there is a systematic variation with latitude in the lengths of the axes of the velocity ellipsoid, so that $\bar{V}_\tau$ varies in a manner that differs from the variation already allowed for.

Now, there is practically no evidence that the lengths of the axes of the velocity ellipsoid vary with latitude, but several investigators have found evidence of the variation of V_0 with latitude. Thus, from an investigation of proper motions and radial velocities of more than 2,000 stars brighter than sixth magnitude by Gyllenberg and Malmquist,[4] we find the data in Table II, where ξ, η, and ζ are the components of the solar motion.

[4] *Medd. Lund Astr. Obs.*, Ser. I, No. 108, 1925.

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TABLE II*

VALUES OF V_0 FOUND FROM RADIAL VELOCITIES

GAL. LAT.	A0–A5		F0–F8		gG0–gG5		K0–K5	
	No.	V_0	No.	V_0	No.	V_0	No.	V_0
0° to ±30°	328	21.4	182	17.5	126	19.1	372	27.1
±30 ±90	260	13.1	132	21.2	109	11.5	292	21.7

VALUES FOUND FROM RADIAL VELOCITIES AND PROPER MOTIONS OF B–M STARS, EXCEPTING dG0–dG5

Gal. Lat.	No.	ξ	η	ζ	V_0 p.e.
+30 to +90	525	14.3	8.0	7.9	18.2±1.1
0 +30	594	17.3	9.5	8.0	21.3 1.0
0 −30	683	18.2	8.7	9.0	22.1 0.9
−30 −90	399	13.4	7.2	6.0	16.3 1.2

* No stars were excluded because of membership in streams, and few because of high velocities.

Again, from a discussion by Robb[5] of 577 B8–A5 stars with known parallaxes, proper motions, and radial velocities, we find the information in Table III. Here,

$$U = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

has been adopted as a measure of the peculiar velocities of the stars, σ_1, σ_2, and σ_3 being standard deviations which measure the dispersion of the peculiar velocities along the three axes of the velocity ellipsoid.

TABLE III*

Gal. Lat.	No.	V_0 p.e.	U p.e.
0° to ±30°	324	15.6±.6	11.3±.3
±30 ±90	253	12.9 .6	11.8 .4

* No stars were excluded because of membership in streams; three stars with velocities of more than 100 km/sec were excluded.

Similarly, from an analysis by Jones[6] of the proper motions of the Boss stars, by the two-stream hypothesis, we find the results in

[5] *M.N.*, **94**, 406, 1934.

[6] *Ibid.*, **91**, 563, 1931.

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Table IV. This table by itself is, of course, no evidence in favor of the change of V_0 with latitude, for the unit $1/h$ is proportional to the peculiar velocities of the stars, so that the dependence on latitude might be ascribed to a variation in the peculiar velocities. Again, it might be due to the variation in spectral composition, since it is known that the ratio V_0/U is about 1.2 for A stars and about 0.8 for G, K, and M giants.[2] However, as will be seen from Tables III and VI, any appreciable variation in U seems to be unlikely. In this connection, Smart's recent investigation[7] of the variation of mean peculiar velocities with latitude indicates an increase of 7 ± 3 per cent in the peculiar velocities between 0° and 43° galactic latitude. Smart has grouped together stars of all spectral types from A to M. This treatment would be expected to show a slight increase with

TABLE IV*

Gal. Lat.	Speed of Solar Motion in Terms of Unit $1/h$
0° to ±10°	1.110
±10 ±30	1.152
±30 to ±60	0.792

* B stars, members of moving clusters, and faint components of multiple stars were excluded.

latitude, since the A stars are of higher galactic concentration and have considerably smaller peculiar motions than the others.

Finally, in a recent study based on radial velocities, with terms for the galactic rotation included in the solution, Nordström[8] finds the values for the relative solar motion given in Table V. Thus, Nordström's data show a much smaller effect. His exclusion of stars of large radial velocity, however, tends to obscure the effect, since relatively more large-velocity stars have been excluded in low latitudes than in high latitudes, while in the McCormick material the exclusions were essentially[9] limited to faint components of double stars.

It seems more probable that any variation of V_0 and U would depend more on the distance from the galactic plane than on the galactic latitude. Accordingly, the space motions of 627 giants pub-

[7] *Ibid.*, **96**, 165, 1936.

[8] *Medd. Lund Astr. Obs.*, Ser. II, No. 79, 1936.

[9] Three stars out of the 18,000 were excluded from the $\bar{\pi}_r$ because of very large proper motions.

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lished by Balanovsky[10] have been analyzed to determine their variation with $|Z|$, the distance in parsecs from the galactic plane. The A stars were omitted since there were relatively few of them and

TABLE V*

V_0 FROM STARS OF PARALLAX $\leq 0\overset{''}{.}015$

GAL. LAT.	A		F–G		K0–K2		M	
	No.	V_0	No.	V_0	No.	V_0	No.	V_0
	Stars Brighter Than Apparent Magnitude 6							
0° to ±30°	231	15.9	175	17.3	332	18.6	154	21.8
All latitudes	416	15.7	270	15.9	567	18.3	299	21.7
	All Apparent Magnitudes							
0° to ±30°	308	17.1	289	17.8	453	18.3	218	21.9
All latitudes	573	16.9	477	17.0	829	17.7	425	21.2

* Faint components of multiple systems, high-velocity stars and a number of members of the Ursa Major and Taurus streams were excluded.

TABLE VI*

A5–M STARS OF ABSOLUTE MAGNITUDE −1.0 TO +1.9

$\|Z\|$	No.	V_0	U
0–30 parsecs	256	20.6±0.9	20.1±0.6
31–60 parsecs	196	20.4 1.1	22.1 0.8
61–90 parsecs	104	18.0 1.4	20.6 1.1
Over 90 parsecs	71	15.7±1.5	19.2±1.2

* No stars were excluded.

since the values of V_0 and U for A stars are systematically smaller than for the late-type giants. The results are given in Table VI.

To summarize, then, the values of the solar velocity, V_0, and of the peculiar velocities, U, collected in Tables II, III, IV, V, and VI indicate that the variation of the ratio V_0/U with galactic latitude (or

[10] *Bull. Astr. Inst. Leningrad*, No. 11, 1925.

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more probably with the distance $|Z|$ from the galactic plane) is due to a progressive decrease of V_0 with increasing distance from the plane of the Milky Way, and not to any progressive change in U. The investigations with relatively few excluded stars show the change in V_0 most clearly.

Figure 1 shows approximately the variation in V_0 with $|Z|$, as indicated by various investigations, as well as the variation in V_0, which would be sufficient to reconcile the $\bar{\pi}_v$ and $\bar{\pi}_\tau$ values of the McCormick material.

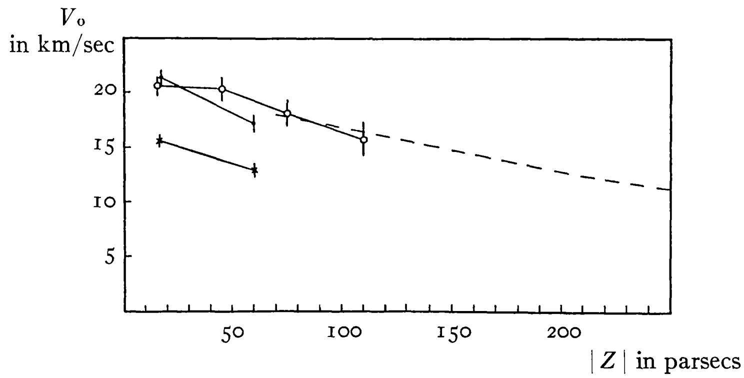

FIG. 1.—Relation between the solar velocity, V_0, and the perpendicular distance from the galactic plane, $|Z|$.

• B to M giants, Table II. × A stars, Table III. o A5 to M giants, Table VI. --- variation in V_0 sufficient to reconcile McCormick $\bar{\pi}_v$ with $\bar{\pi}_\tau$.

NOTE ON THE VARIATION OF THE POSITION OF THE APEX WITH LATITUDE

From the point of view of galactic rotation, the decrease of V_0 with $|Z|$ corresponds to a higher velocity of rotation for the stars at a distance from the galactic plane than for the stars of the same spectral subtype in the plane. If this is correct, we should expect that the apex derived from stars of high latitude would be at a smaller longitude than that derived from the low-latitude material of the same spectral subclass. Now, it is fairly clear from numerous studies that the longitude of the apex is probably somewhat smaller for stars of low galactic latitude than for stars of high galactic latitude, *when all spectral classes are combined together.* This results from the fact that the apex of the B and A stars is at a smaller longitude than

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the apices of the late-type giants. The data are too meager to tell much about the variation of its position with latitude in the separate spectral classes.

Mention should also be made of the possibility of a progressive variation in the position of the apex with Z, which was reported first by Mineur[11] and independently by Rosenhagen[12] from radial velocities. They found that the η-components of the sun's velocity range from about 13 km/sec relative to stars 150 parsecs south of the sun to 2 km/sec relative to stars 150 parsecs north of the sun. This results in a shift in the longitude of the apex from about 60° in the first case to about 5° in the second. It is found also in Nordström's investigation of radial velocities.[8] On the other hand, it is not found in Mohr's study of space velocities[13] nor in the work of Gyllenberg and Malmquist (see the values of η in the second part of Table II). Finally, there is practically no trace of it in the proper-motion work of van de Kamp and Vyssotsky;[1] for all stars in latitude zone +40° to +90°, which are about 500 parsecs north of the sun, they find 34°.3 for the longitude of the apex, which is to be compared with 36°.6 for the corresponding zone in the south.

I wish to thank Professor Vyssotsky for many helpful suggestions.

Leander McCormick Observatory
University of Virginia
June 8, 1936

[11] A series of articles by Mineur and collaborators: *M.N.*, **90**, 789, 1930; *B.A.*, (2) I Mem. et Var., **6**, 355, 1931; *C.R.*, **195**, 208, 1932.

[12] *A.N.*, **242**, 401, 1931.

[13] *M.N.*, **92**, 562, 1932.

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FRAUNHOFER'S SPECTRUM IN THE INTERVAL FROM 77,000 TO 110,000 A

ARTHUR ADEL AND V. M. SLIPHER

ABSTRACT

Recent observations of one hundred fine structure lines in the solar grating spectrum, lying in the interval from 77,000 to 110,000 A, are described in connection with previous measurements of the solar prismatic spectrum.

During the winter of 1934–1935 and the summer of 1935, the infra-red solar spectrum was examined with low[1] and with high resolving power. This report is an account of the analysis made with high resolving power, but is preceded by a brief review of the earlier work in order to reveal the relative significance of the Sun's prismatic curve and the fine structure of its spectrum.

The prismatic spectrum, shown in Plate XV, was secured on January 2, 1935—a particularly clear day—within an hour on each side of apparent solar noon, at Ann Arbor (lat. 42°17′). A potassium bromide prism served as the dispersing element and a vacuum thermocouple as the detecting element of the Wadsworth-Littrow self-recording spectrometer used in the experiment. The telluric spectrum was examined over the range from 50,000 to 210,000 A. Reference to Plate XV immediately discloses the excellent atmospheric window defined on the short-wave side by the extensive absorption by water vapor stretching from 50,000 to 77,000 A, and on the long-wave side by the comparatively narrow ozone band extending from 90,000 to 100,000 A. Beginning at 100,000 A, the energy of transmitted sunlight decreases in an approximately uniform manner until the atmospheric curtain at 135,000 A is abruptly begun. Several small, but relatively unimportant, absorption bands occur between.

For reasons given elsewhere,[1] there are but three atmospheric molecules possessing pure rotation and rotation-vibration spectra; these molecules are therefore responsible for the spectra discussed in

[1] Arthur Adel, V. M. Slipher, E. F. Barker, *Phys. Rev.*, **47**, 580, 1935.

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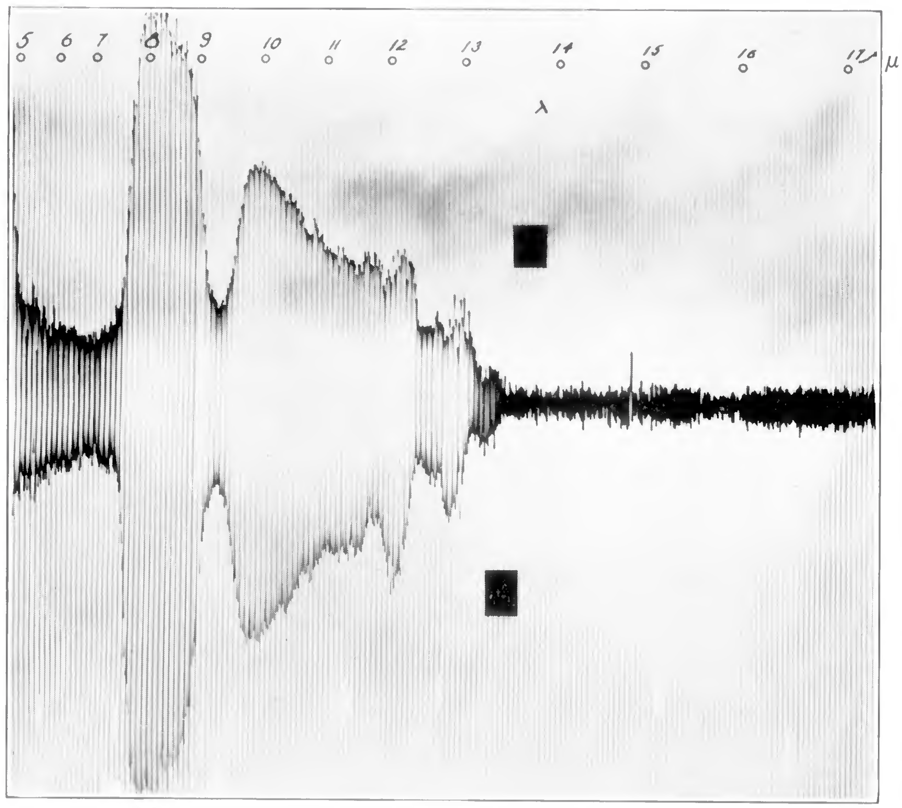
PLATE XV



FRAUNHOFER'S SPECTRUM

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this paper. They are water vapor, ozone, and carbon dioxide. Absorption bands of the first two have already been mentioned while the most intense absorption band in the infra-red spectrum of the carbon dioxide molecule is responsible for the atmospheric curtain which begins at 135,000 A. Its influence extends to approximately 170,000 A, and within this region it is aided by the comparatively weak ozone band whose center lies in the neighborhood of 150,000 A. Beyond 170,000 A the curtain is maintained by absorption due to transitions between rotational states of the water-vapor molecules.

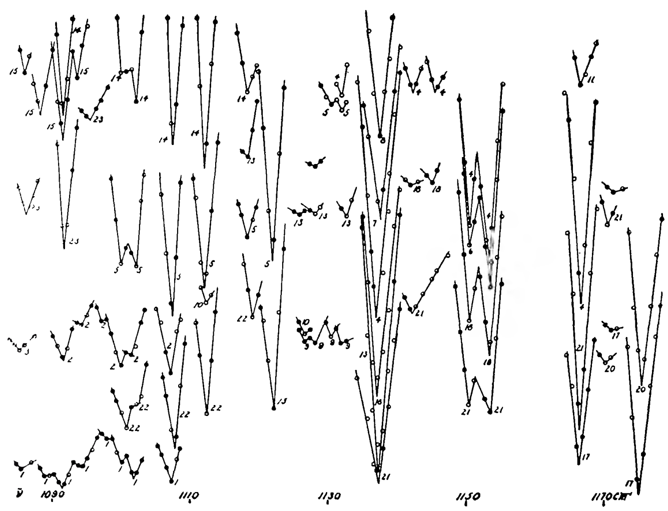

FIG. 1

The study of the solar spectrum made with the grating concentrates on the region from 77,000 to 110,000 A. This phase of the experiment was also carried out at the Physics Laboratory of the University of Michigan, approximately six months later, and consequently with a correspondingly shorter air path traversed by sunlight. The grating spectrometer, the thermocouple, and the amplifying system have been described in detail elsewhere.[2] A twelve-hundred-line grating, ruled by Barker, was used and the slit width equivalent was maintained at approximately 1.5 cm^{-1} throughout the spectral region in question. Numerous runs were made, and one hundred and one lines were recorded. Each of these lines was

[2] J. D. Hardy, *ibid.*, **38**, 2162, 1931.

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TABLE I

No. of Line	Average Position	No. of Times Observed	Comparative Strengths	No. of Line	Average Position	No. of Times Observed	Comparative Strengths
1.....	909.6 cm^{-1}	2	S*	52....	1072.8 cm^{-1}	3	W
2.....	914.4	2	W	53....	1075.2	6	S
3.....	920.4	2	W	54....	1078.3	3	M
4.....	922.3	2	W	55....	1082.0	4	W
5.....	925.4	2	W	56....	1086.0	5	M
6.....	929.3	2	W	57....	1088.4	3	M
7.....	934.8	2	W	58....	1091.9	5	S
8.....	941.5	2	S	59....	1094.3	3	W
9.....	943.4	2	S	60....	1095.8	2	W
10.....	945.3	2	W	61....	1097.7	3	W
11.....	949.0	3	S	62....	1100.3	5	S
12.....	954.3	2	M	63....	1102.3	5	S
13.....	956.0	3	M	64....	1107.6	5	S
14.....	960.2	2	M	65....	1112.4	4	S
15.....	962.8	2	W	66....	1118.5	4	S
16.....	967.8	3	M	67....	1122.2	3	SS
17.....	969.4	2	M	68....	1126.3	3	W
18.....	972.0	2	S	69....	1128.3	3	W
19.....	974.4	2	M	70....	1130.4	3	W
20.....	976.8	3	M	71....	1132.4	4	W
21.....	980.2	3	W	72....	1137.3	7	SS
22.....	984.3	3	W	73....	1142.0	3	W
23.....	988.4	3	W	74....	1145.1	2	W
24.....	990.8	3	W	75....	1150.3	4	S
25.....	993.3	2	W	76....	1153.3	4	S
26.....	995.7	3	M	77....	1166.3	4	S.
27.....	997.6	2	W	78....	1170.4	4	W
28.....	1001.4	3	M	79....	1175.3	2	S
29.....	1005.0	3	M	80....	1182.3	2	W
30.....	1006.8	2	M	81....	1183.7	2	W
31.....	1008.8	3	W	82....	1188.4	2	S
32.....	1111.1	3	M	83....	1192.6	2	W
33.....	1015.6	3	M	84....	1199.6	3	S
34.....	1018.5	3	M	85....	1206.6	2	W
35.....	1021.3	2	W	86....	1213.3	2	S
36.....	1022.8	3	W	87....	1219.8	2	S
37.....	1026.5	2	W	88....	1225.8	2	S
38.....	1029.5	3	M	89....	1230.4	2	W
39.....	1033.8	3	W	90....	1238.2	2	M
40.....	1037.6	2	W	91....	1240.8	4	M
41.....	1040.3	2	M	92....	1244.7	3	M
42.....	1041.6	2	W	93....	1249.5	2	W
43.....	1043.7	3	†	94....	1255.1	3	S
44.....	1051.9	3	W	95....	1261.9	2	W
45.....	1054.1	2	M	96....	1276.7	2	W
46.....	1056.2	3	M	97....	1281.5	2	W
47.....	1058.1	2	W	98....	1285.0	2	W
48.....	1060.8	4	W	99....	1288.9	2	W
49.....	1062.5	3	W	100....	1291.0	2	W
50.....	1067.0	5	S	101....	1297.8	2	W
51.....	1071.0	2	M				

* S = strong; W = weak; M = intermediate; SS = very strong.
† Ozone band center.

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measured two or more times. Table I lists their positions and relative strengths, as well as the number of times each was measured.

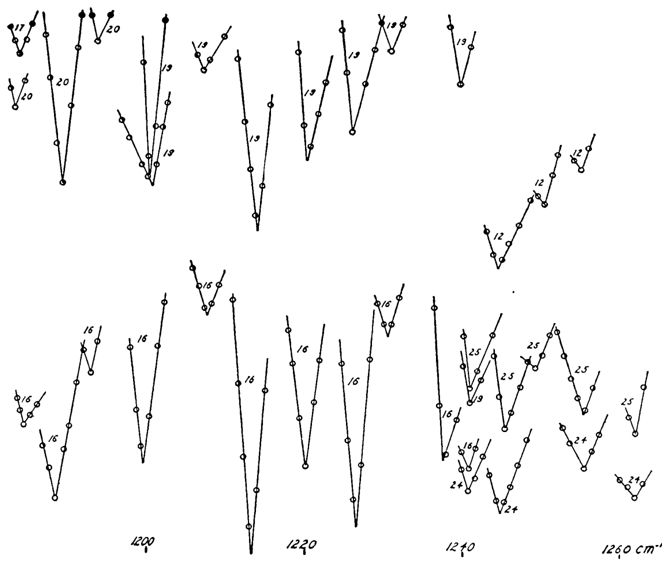

FIG. 2

TABLE II

No. Associated with Line in Fig. 2	Time of Observation (Day and Hour)	No. Associated with Line in Fig. 2	Time of Observation (Day and Hour)
1	July 17 3:15– 4:00	14	July 29 8:30– 8:55
2	18 10:40–11:15	15	29 10:10–10:30
3	18 11:20–11:50	16	29 11:40–12:20
4	20 1:10– 1:45	17	29 1:00– 1:25
5	20 1:50– 2:30	18	29 1:30– 2:00
6	26 10:10–10:20	19	29 3:10– 3:35
7	26 10:25–10:45	20	29 3:40– 4:10
8	26 10:45–11:00	21	29 4:15– 4:45
9	26 3:30– 3:40	22	30 8:00– 8:25
10	26 3:45– 3:55	23	30 8:30– 8:55
11	26 4:00– 4:15	24	Aug. 11 10:20–10:55
12	26 4:20– 5:00	25	12 10:20–10:40
13	29 8:00– 8:30		

The fine structure in the region of ozone absorption between 90,000 and 100,000 A has already been published and applied to a discussion of the form of the ozone molecule.[3] The majority of the

[3] Arthur Adel, V. M. Slipher, Omer Fouts, *ibid.*, **49**, 288, 1936.

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remainder of the one hundred and one lines are shown in Figures 1 and 2, and belong to the atmospheric window lying between the strong water vapor and the ozone bands. They are most probably due to absorption by the water-vapor molecule. The numbers associated with the lines refer to the times of observation as recorded in Table II.

The authors wish to express their appreciation of grants-in-aid by the American Academy of Arts and Sciences and by the Faculty Research Council of the University of Michigan. We are indebted to Mr. Omer Fouts for his valuable aid with the spectroheliometer.

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Ann Arbor, Mich.
Lowell Observatory
Flagstaff, Ariz.
July 1936

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