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EVIDENCE FOR THE GRAVITATIONAL DISPLACEMENT OF LINES IN THE SOLAR SPECTRUM PREDICTED BY EINSTEIN'S THEORY

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ABSTRACT

Material.—The observational data are the *wave-lengths of 1537 spectral lines at the center and of 133 at the edge of the sun*, and their wave-lengths in a vacuum source.

Precision of the measures.—The probable error of single solar lines is ±0.0008 A. For groups of 40 lines, as in Table VII, the probable deviation from the mean is ±0.0003 A, and for groups of 33 lines, as in Table IX, ±0.0004 A. These uncertainties are small in comparison with the displacements predicted by the theory of relativity, which average 0.0100 A.

Other causes of line-displacement.—The discussion is preceded by consideration of *conditions* in solar and stellar atmospheres *that produce displacements* of lines. In stellar atmospheres radial velocity of recession determined by high-level lines is greater, and by low-level lines less, than that of lines of medium level. The displacements to the red at the center of the sun are greater for high-level, and less for low-level, lines than for lines of medium level of the same spectral region, by amounts consistent with the position of the sun in the evolutionary sequence (Fig. 1). These extra-Einsteinian phenomena require that, if lines at any level give the predicted displacement, lines of higher level give more, and lines of lower level less, than the predicted amount.

At the center of the sun.—Each of the 586 iron lines shows a displacement to the red, for sun *minus* vacuum, whose average is ±0.0083 A. The mean displacement for lines of medium level (520 km) is ±0.009 A; the theoretical Einsteinian displacement is +0.0091 A (Table X). For lines of higher level of class *b* (840 km) it is 0.0027 A greater, and for low-level lines (350 km) it is 0.0026 A less, than the calculated displacement (Table VII).

The general results for iron are confirmed by 6 lines of silicon, 18 lines of manganese, 402 lines of titanium, and 515 lines of cyanogen.

At the edge of the sun.—Lines of iron to the number of 133 give at the limb a mean red displacement for high- and low-level lines which is 0.0015±0.0004 A greater than that calculated from the theory of general relativity. This small residual, if real, is a true limb-effect. By themselves the lines of very low level give the predicted displacement. The progression shown in the fifth column of Table VII disappears. From all *CN* lines in the 3883 band the mean displacement at the edge of the sun is +0.0072 A. From 184 lines better suited to measurement, it is +0.0076 A. The calculated displacement is +0.0081 A.

Interpretation.—Lines in widely different spectral regions but at the same low level give negative values for O−C that are proportional to wave-length and hence are attributable to upward currents near the photosphere (Table XI). This interpretation is confirmed by the increase in wave-length at the limb and by the vanishing of the negative residuals for very low-level lines which there, in the absence of line-of-sight velocities, give the predicted displacement (Table IX).

In the higher regions of the sun's atmosphere displacements to the red may be brought about, according to Milne and Merfield, through the greater number of atoms absorbing from the red edge of the line—many of the upward-moving atoms normally absorbing from the violet edge having escaped owing to the high velocities engendered by the successive absorption and emission. The effect should increase with height. This is confirmed by the lines of exceptionally high level (Table V).

Level the determinative condition.—According to atomic theory, lines of lowest excitation potential are due to electronic transitions of greatest probability and repre-

sent the highest level for the vapor of a given element. Such lines will be the strongest and of highest level. Lines of different elements of very different intensities, but at the same level, give equal red displacements; while for lines of the same solar intensity, but at widely different levels, the lines of higher level give the greater red displacements. This points to level of origin rather than line-intensity as the controlling factor in line-displacement (Table III).

Relative levels of origin.—Any one of five methods may be used in allocating the levels, since all agree as to the order of levels: (1) solar rotation; (2) the Evershed effect; (3) flash spectra; (4) excitation potential; (5) deviations from relativity predictions.

Conclusion.—The investigation confirms by its greater wealth of material and in greater detail the announcement made at the Symposium on Eclipses and Relativity in Los Angeles, 1923, that the causes of the differences at the center of the sun between solar and terrestrial wave-lengths are the slowing of the atomic clock in the sun according to Einstein's theory of general relativity and conditions equivalent to radial velocities of moderate cosmic magnitude and in probable directions, whose effects vanish at the edge of the sun.

SOLAR PHENOMENA CONCERNED IN THE PROBLEM OF RELATIVITY

Any interpretation of the observed differences between wave-lengths in the sun's atmosphere and the corresponding wave-lengths as measured in terrestrial laboratories must take into account conditions and phenomena known to occur in stellar atmospheres. In order to put the general reader in touch with the essential features of the problem, the necessary facts, together with certain general considerations, will be summarized and discussed under the following headings: (*a*) "Magnitude of the Relativity Displacement," (*b*) "Precision of Measurement of Lines in the Solar Spectrum," (*c*) "Pressure in the Solar Atmosphere," (*d*) "Levels Defined by Fraunhofer Lines," (*e*) "Radial Currents in Solar and Stellar Atmospheres or Their Equivalent." These points will be taken up in detail before proceeding to the observations and the related discussion.

a) MAGNITUDE OF THE RELATIVITY DISPLACEMENT

The theoretical value of the gravitational displacement is proportional to M/R (M=mass, R=radius). It also varies directly as the wave-length. For the solar spectral lines it is equal to the Fizeau-Doppler effect corresponding to a velocity of 0.635 km/sec. away from the observer. In angstrom units, the theoretical displacements to the red for the sun, in the spectral regions included in these observations, are:

Wave-lengths.....	3800	4250	4725	5675	6600 A
Displacements....	+0.008	+0.009	+0.010	+0.012	+0.014

For Sirius and Procyon it is of the same order as for the sun, while for Arcturus it is a small fraction of that value,[1] and, in any case, far too small for measurement on ordinary stellar spectrograms except for such a remarkable star as the companion of Sirius, for which Adams[2] found a gravitational shift of 21 km/sec., agreeing, within the errors of observation, with the amount predicted by Eddington.[3]

b) PRECISION OF MEASUREMENT OF LINES IN THE SOLAR SPECTRUM

To determine the agreement attainable by different observers, using different apparatus, the Mount Wilson Observatory arranged a few years ago with Mr. Evershed, then at Kodaikanal, India, for the independent measurement of the wave-lengths of the fourteen solar lines listed in Table I.

The measures show practical agreement in the mean, with an average difference of only ±0.0015 A; nevertheless, two lines, λ 4447 and λ 4494, illustrate the care necessary in such measures to reduce the effect of insidious errors to a minimum. The mean sun *minus* arc for the group is +0.005 A, while these lines give

	Mount Wilson Sun−Arc	Kodaikanal Sun−Arc
λ 4447	+0.007 A	+0.012 A
λ 4494	+0.003	0.000

For both lines the measures at the two observatories deviate from the mean in the same direction, above for 4447 and below for 4494. The lines are of intensity 6 in the solar spectrum, but λ 4447 has a line of 00 intensity 0.06 A to the red, and λ 4494 a line of 00 intensity 0.08 A to the violet. The separation is so small that the strong and weak lines are in contact or even partially overlap, so that the influence upon the measured wave-lengths depends upon the intensity of the spectrograms. Rowland's table gives 14,000 lines in the region under consideration. The spectra of elements known to be present in the sun's atmosphere include a far larger number of lines, many of which might reasonably be expected to

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[1] For data on stellar masses and diameters, see Table IV.

[2] *Mt. Wilson Communications*, No. 94; *Proceedings of the National Academy of Sciences*, 11, 382, 1925.

[3] *Monthly Notices, R.A.S.*, 84, 308, 1924.

occur. The measured position of any moderately strong line may be slightly affected by a nearly coincident, but not observable, weak line. The effect of random errors thus introduced may be eliminated by using a very large number of lines, as in the present investigation, which depends on more than 1500 apparently free-standing lines.

Further evidence of the dependence that may be placed upon the measures is given by comparing the wave-lengths as measured at Mount Wilson Observatory with the A.O.B.S. wave-lengths[1] for the 201 lines common to the two lists. The Mount Wilson wave-lengths are based upon the secondary standards adopted by the International Astronomical Union in Rome, 1922. The A.O.B.S. wave-lengths are based upon the new neon standards which, in the region compared, differ by 0.002 A from the Rome standards. When this is taken into consideration, the result of the comparison is:

TABLE I

ORDER OF AGREEMENT BETWEEN MEASURES

Mount Wilson	Kodaikanal	Mount Wilson *minus* Kodaikanal	Mount Wilson	Kodaikanal	Mount Wilson *minus* Kodaikanal
4337.057........	.055	+0.002 A	4454.390.......	.391	−0.001 A
4375.946........	.946	.000	4461.662.......	.662	.000
4388.416........	.413	+ .003	4466.564.......	.565	− .001
4427.319........	.318	+ .001	4469.385.......	.384	+ .001
4442.351........	.352	− .001	4484.229.......	.231	− .002
4443.203........	.201	+ .002	4489.750.......	.751	− .001
4447.730........	.735	−0.005	4494.575.......	.572	+0.003

Sum, positive residuals, Mt. Wilson−Kodaikanal..................+0.012
Sum, negative residuals, Mt. Wilson−Kodaikanal..................−0.011

$$\text{Mean systematic difference, Mt. W.} - \text{A.O.B.S.} = +0.0002 \text{ A} .$$

The mean deviation between independent measurements of even limited groups of solar lines shows an accuracy far greater than is required to establish displacements of the magnitude predicted by the theory of relativity. In this connection it may be recalled that, in the observations upon which the accepted existence and

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[1] *Publications of the Allegheny Observatory*, **6**, 105 (No. 7), 1926.

magnitude of the general magnetic field of the sun rest, the maximum differential displacement in latitude 45° is 0.001 A,[1] a tenth of the average relativity effect.

c) PRESSURE IN THE SOLAR ATMOSPHERE

Until quite recent years a pressure of 5–7 atmospheres was assumed to obtain in the region of the sun's atmosphere accessible to spectroscopic investigation. It is now the accepted conclusion among solar investigators that the maximum pressure in the reversing layer is so low that for spectroscopic purposes it may be taken as zero. The low pressure is shown by direct spectroscopic measures[2] and by deductions from the theory of ionization.[3] The gravitation of the earth produces a total pressure upon its surface equal to the weight of its atmosphere less the centrifugal effect of rotation, but in the sun and in all bodies of stellar character the pressure of radiation outward yields a counter force that tends to balance the effect of gravitation upon their enveloping atmospheres, and for the high-level portions it nearly equals the gravitational attraction. In this respect the sun is in no way peculiar, but behaves like any other star.[4]

d) LEVELS DEFINED BY FRAUNHOFER LINES

The concept that the Fraunhofer lines in the spectra of the sun and stars refer to definite levels is steadily gaining acceptance and application.[5] The observational evidence for this concept rests upon

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[1] Hale, Seares, van Maanen, and Ellerman, *Mt. Wilson Contr.*, No. 148; *Astrophysical Journal*, **47**, 206, 1918.

[2] Evershed, *Kodaikanal Bulletin*, No. 18, 1909, and No. 36, 1916; Perot, *Comptes rendus*, **172**, 578, 1921; Salet, *ibid.*, **174**, 151, 1922; St. John and Babcock, *Mt. Wilson Contr.*, No. 278; *Astrophysical Journal*, **60**, 32, 1924.

[3] Saha, *Philosophical Magazine*, **40**, 809, 1920; St. John, *Contributions of the Jefferson Physical Laboratory*, **15**, 1921; Russell, *Mt. Wilson Contr.*, No. 225; *Astrophysical Journal*, **55**, 119, 1922; Stewart, *Physical Review*, **22**, 324, 1923.

[4] Eddington, *Monthly Notices, R.A.S.*, **77**, 16, 596, 1917; **83**, 32, 98, 431, 1922; *Astrophysical Journal*, **48**, 215, 1918; Fowler and Milne, *Monthly Notices, R.A.S.*, **83**, 417, 1923; St. John and Adams, *Mt. Wilson Contr.*, No. 279; *Astrophysical Journal*, **60**, 43, 1924.

[5] Rufus, Aldrich, R. H. Curtiss, *Popular Astronomy*, **32**, 22, 218, 228, 471, 547, 1924; R. H. Curtiss, *Publications of the Astronomical Society of the Pacific*, **38**, 148, 1926; Joy, *Mt. Wilson Contr.*, No. 311; *Astrophysical Journal*, **63**, 281, 1926.

the concordant results from solar rotation, flow near spots, flash spectra (Table II), differences between the spectra of limb and center, progression in excitation potentials, and the observed decrease in the strength of the general magnetic field with the heights above the photosphere at which the lines used have their origin.[1]

TABLE II

CORRELATIONS IN LEVEL

A. Data from Various Sources*

Lines	Rotation Obs.—Norm.†	Observer	Flow Near Spots	Height
	km/sec.		km/sec.	km
H_3 and K_3 Ca^+	+0.20	St. John and Ware	1.80 in	12000
$H\alpha$ hydrogen	+ .11	Adams and Evershed	1.50 in	10000
4226 *Ca*	+ .06	Adams	0.06 in	2100
High-level *Fe*	+ .02	Evershed	.00	1200
Medium-level *Fe*	.00	Adams and Evershed	.40 out	400
4196 La^+	−0.03	Adams	0.75 out	Low

B. Simultaneous Observations at High and Low Level‡

Lines	Equatorial Velocity	Observer	Flow Near Spots	Height
	km/sec.		km/sec.	km
5172 and 5183 *Mg*	2.03	St. John and Ware	0.36 in	2250
5165 and 5225 *Fe*	1.95	St. John and Ware	0.60 out	350
H_3 and K_3 Ca^+	2.12	St. John and Ware	1.80 in	12000
Weak *CN* lines	1.87	St. John and Ware	0.63 out	Low

* Adams, *Mt. Wilson Contr.*, No. 33; *Astrophysical Journal*, **29**, 110, 1909; and *Mt. Wilson Contr.*, No. 43; *Astrophysical Journal*, **31**, 30, 1910; Mitchell, *Astrophysical Journal*, **38**, 407, 1913; St. John, *Mt. Wilson Contr.*, Nos. 69, 74, 88; *Astrophysical Journal*, **37**, 322, 1913; **38**, 341, 1913; **40**, 356, 1914; Fox, *Astrophysical Journal*, **57**, 234, 1923; Evershed, *Monthly Notices R. A. S.*, **85**, 607, 1925.

† Norm. = Linear velocity for lines of medium level.

‡ St. John and Ware, *Annual Reports of the Mt. Wilson Observatory*, 1915, 1918.

At the high level of Ca^+ the eastward velocity in the equatorial region is 0.23 km/sec. greater than that shown by the very low-lying vapors of lanthanum. For that portion of the hydrogen atmosphere responsible for the $H\alpha$ line the period of the sun's rotation is 24 days, while for the lower reversing layer it is 25.35 days. The relative linear velocities represent a steady east wind of approxi-

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[1] Hale, Seares, van Maanen, and Ellerman, *Mt. Wilson Contr.*, No. 148; *Astrophysical Journal*, **47**, 206, 1918.

mately 400 km an hour in the upper atmosphere. In observations for solar rotation, we seem forced to the view that the specific behavior of Fraunhofer lines refers to restricted levels in the sun's atmosphere. The measures are relative and between lines of the same intensity and character. They are therefore free from the effects of any possible asymmetry.

Around spots, the vapors from below the photosphere, raised by the spot-forming vortex, flow outward along the solar surface—the Evershed effect—the outward velocity decreasing with the elevation and eventually becoming zero. The lowered temperature of the expanding gases produces the relatively dark umbra. Over the cooled region the radiation pressure which supports the chromospheric gases is reduced, and they fall[1] and form a secondary vortex in the chromosphere in which the flow is inward, the maximum velocity of inflow occurring at the highest elevation. In the observation of these velocities we have a method of sounding the solar atmosphere and of allocating the relative levels of the lines.[2]

The determination of the absolute heights reached by the gaseous layers responsible for the Fraunhofer lines has not attained high precision, but it is sufficient to assure one that the fifth column of Table II represents relative heights, although the actual heights may be only approximately known. The data in the second, fourth, and fifth columns, Table II, are most simply interpreted in terms of level, and, when so interpreted, show the same sequence of levels from high at the top to low at the bottom of the table.

From the like order in the arrangement of levels shown by solar rotation, by flow near spots, and by flash spectra, it may confidently be inferred that the heights to which the different constituents of the sun's atmosphere rise and the relative levels of origin of the Fraunhofer lines observed in these particular regions of the sun are representative of the general solar surface. This inference is reinforced by the similar relation between level and the strength of the general magnetic field for which the observations are made along the sun's meridian.

Still other observations show that certain lines originate in low-

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[1] S. R. Pike, *Monthly Notices, R.A.S.*, **87**, 56, 1926.

[2] St. John, *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 341, 1913.

lying layers and others in successive shells of the solar atmosphere. Thus ionized atoms, such as Ti^+, give long, lancelike lines in chromospheric spectra, in strong contrast with the shorter arrowheaded lines produced by normal atoms, though in the spectrum of the sun's disk the lines may be of the same intensity. This difference of behavior in the chromosphere is direct evidence that the atmosphere of ionized titanium is more extensive than that of the normal atom. Moreover, the sharpness of the Ti^+ lines in the spectrum of the disk and the known increase of ionization with decrease of pressure point to their high-level origin in the layers of maximum ionization. Plate I*b*, a reproduction of a small section of an eclipse spectrogram taken with Campbell's moving-plate camera in Spain, 1905, illustrates the characteristic behavior of *Ti* and Ti^+ lines of the same solar intensity for which the red displacements are respectively +0.009 and +0.012 A.

In comparisons of the spectra of the center and the limb of the sun, Adams[1] observed that lines of the heavy elements and the broad shading of the strongly winged lines are greatly weakened and in some cases are almost obliterated in the spectra of the limb. This he interpreted as evidence of the low level of their origin, the light from the low-lying layer being scattered in the longer path at the limb or, according to the present conception, cut off by its source's being below the optical depth.

Again in spectrograms of planetary nebulae made with a slitless spectrograph, the diameters of the monochromatic images show the distribution in level of the gaseous shells corresponding to the bright lines, greatly emphasized, however, in comparison with the levels of distribution in the sun. One needs only to imagine a shrinking to stellar proportions to have a mental picture of levels in the sun and other stars. Through the kindness of Dr. W. H. Wright, I am able to reproduce his spectrograms[2] of N.G.C. 7662, in Plate I*a*. Similar results for the sun were observed by Paddock[3] on spectrograms taken with an objective-prism telescope located just outside the edge of the shadow at the eclipse of January 24, 1925. The

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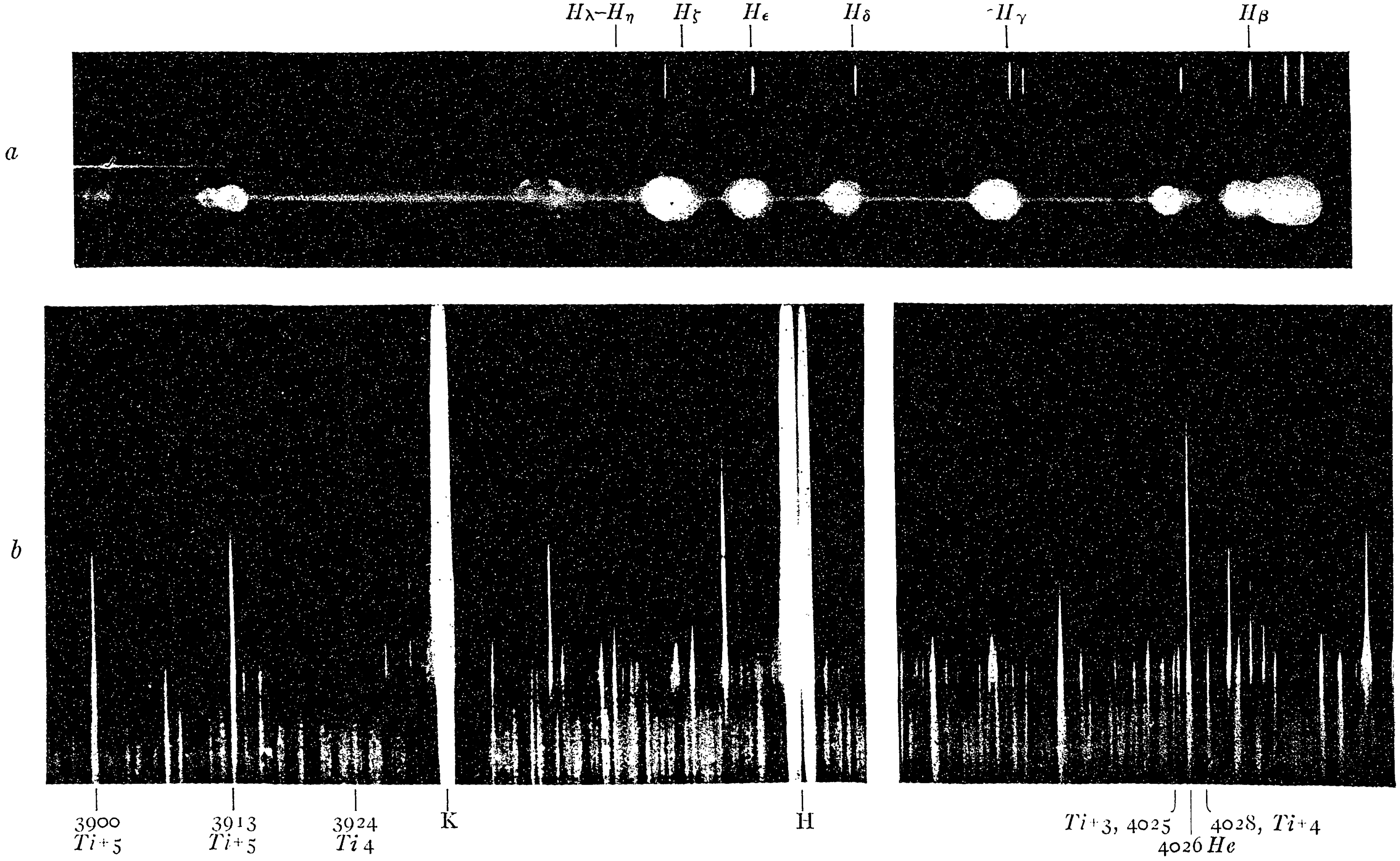
[1] *Mt. Wilson Contr.*, No. 43; *Astrophysical Journal*, **31**, 46, 1910.

[2] *Publications, Lick Observatory*, **13**, Plates XLV and XLVI, 1918.

[3] *Astrophysical Journal*, **66**, 1, 1927.

PLATE I



a. Nebular Spectrograms by W. H. Wright; N.G.C. 7662 with and without Slit
b. Moving-Plate Spectrogram by W. W. Campbell; Spanish Eclipse of 1905

hydrogen arcs show positive correlation between height and intensity. The only arcs of *Ba*, *Fe*, *Sc*, *Sr*, and *Ti* high enough to be observed were from their ionized atoms; and the only *Cr* arcs were from atoms in the lowest energy-state.

The heights to which the constituents of the solar atmosphere rise are mainly determined by their abundance, atomic weight, ionization potential, and selective radiation-pressure; but for the same element the levels registered by the different normal lines depend upon the excitation potential and the probability of the electron transitions concerned in their production. For an element in a given state of ionization, the lines of the multiplet of lowest excitation potential and, within the multiplet, the lines on the diagonal, due to transitions of greatest probability, represent the highest elevation above the photosphere. Since atoms in this state of excitation are the most numerous, form the most abundant constituent of the substances, and contribute most to their radiation or absorption, their lines will be strong and the level high.[1]

For each element the relation between level and line-intensity should hold for lines of the same class and spectral region, but lines of a given solar intensity corresponding to different elements, or classes, or spectral regions are not necessarily at the same level.[2]

That the level of origin and not the intensity of lines is the controlling factor and determinative of the characteristic differences in displacement for lines of different solar intensity may be illustrated by comparing the sun-*minus*-vacuum displacements for lines of the same intensity but of different levels, or for lines of different intensities but of the same level, as in Table III.

For the first two pairs—lines of equal intensity—the larger displacement goes with the greater height, while for the last pair—lines of very unequal intensities but at approximately the same level—the displacements are equal. For the middle pair—ionized and normal *Ti*—the difference in level follows directly from Saha's theory,[3] according to which high ionization characterizes the lower

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[1] Observational evidence on the relation of excitation potential appears in Tables VII and XIII.

[2] St. John, *Mt. Wilson Contr.*, No. 74; *Astrophysical Journal*, **38**, 343, 1913.

[3] *Philosophical Magazine*, **40**, 472 and 809, 1920.

pressure at high levels; and here again the lines of higher level show the greater displacement to the red, though the lines are of like solar intensity.

Although the classification of lines into groups for discussion is by line-intensity, it is, in accordance with the preceding discussion, fundamentally one based on level. Since the heights of individual lines are not yet exactly determined, and since, within the foregoing limitations, a close relation exists between level and intensity, relative levels, in a first approximation, may be inferred from the more accurately estimated intensities, or determined from the Evershed effect near spots, or from the differences in solar rotation.

TABLE III

RED DISPLACEMENT AND LEVEL IN THE SOLAR ATMOSPHERE

Element	No. of Lines	Mean λ	Mean Int.	Sun−Vac.	Height
					km
Ti+.........	2	3772	11.0	+0.013 A	6000
Fe...........	14	3870	11.0	.010	1100
Ti+.........	14	4250	4.7	.012	1300
Ti...........	12	4110	4.2	.009	520
Ti+.........	14	4250	4.7	.012	1300
Fe...........	12	3900	13.6	+0.012	1290

e) RADIAL CURRENTS OR THEIR EQUIVALENT

On high-dispersion spectrograms of Sirius, Procyon, and Arcturus, taken by Adams and Babcock in 1909–1910,[1] the radial velocities determined from high-level lines give positive residuals when compared with the results for lines of medium level, while lines of still lower level show negative residuals.[2] The results are shown in Table IV along with comparable data for the sun and seven other stars.

The residuals in the first line show that the line-of-sight velocity of Sirius away from the center of the solar system determined by the

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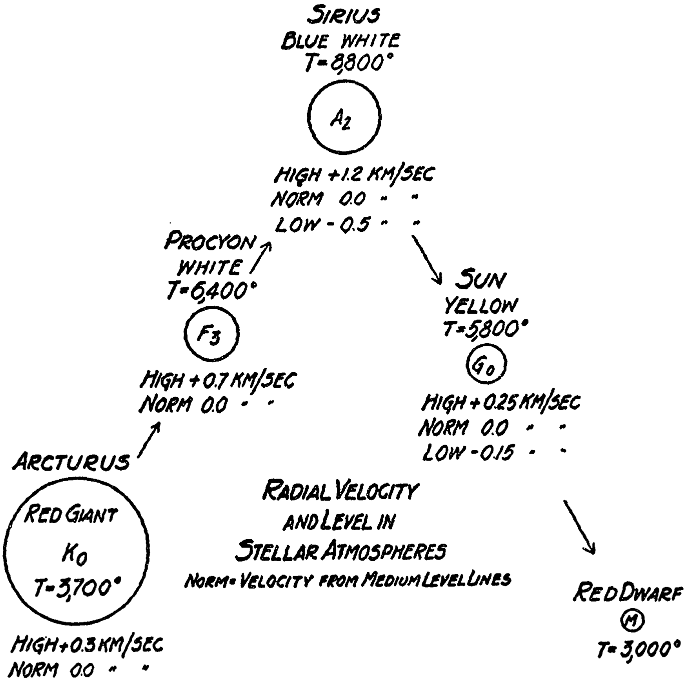
[1] *Mt. Wilson Contr.*, No. 50; *Astrophysical Journal*, **33**, 64, 1911.

[2] St. John and Adams, *Mt. Wilson Contr.*, No. 279; *Astrophysical Journal*, **60**, 43, 1924.

Hα line of high-level hydrogen is 2.6 km/sec. greater than that for lines of medium level, but that, when determined from low-level lines, it is 0.5 km/sec. smaller. Conversely, the residuals in the fourth line show that to an observer on Sirius, Procyon, Arcturus, or any other star, the motion of the sun, measured by the apparent Doppler displacement of the H_3 and K_3 lines of high-level Ca^+, would be



POSITION OF SUN IN EVOLUTIONARY SEQUENCE
FROM
RED GIANT TO RED DWARF

FIG. 1

0.45 km/sec. greater than that determined from lines of medium level; but, when measured by the displacement of the low-level lines of *La*, it would be 0.15 km/sec. smaller, and, for still lower lines, 0.25 km/sec. smaller.

On the assumption that the larger part of the material of a star is expendable in radiation, a single star might go through almost every known spectral type, starting as a massive red giant, passing through various stages to class A or B and along the main sequence perhaps as far as class M, using up its active substance on its way.[1] When the first four stars of Table IV are arranged according to this evolutionary sequence, the magnitude of the effect seems to be correlated with temperature, being largest at the highest temperature, and, in the case of the sun, corresponding to the sun's position in the sequence (Fig. 1).

In the differential displacements of Table IV, we are concerned with phenomena that are characteristic of both solar and stellar atmospheres and independent of relativity effects. The comparison has been made by forming differences in displacement in the same spectral region; this eliminates relativity, the small change in the theoretical displacement with levels arising from the change in the effective radius of the sun being quite insensible. Even for a difference in level of 10,000 km, it amounts, in the case of the sun, to only one-seventieth of the total effect.

TABLE IV

COMPARATIVE RADIAL VELOCITIES FOR HIGH- AND LOW-LEVEL LINES

Star	Atomic State	Sp.	Temp.	Diam	Mass	Ca^+	$H\alpha$	$H\gamma$	High	Med	Low	Very Low
Sirius.........	Neutral	A2	8800°	4	2.5	......	+2.6	+2.0	+1.2	0.0	−0.5	....
Procyon......	Neutral	F3	6400	1.6	1.7	......	.....	.....	0.7	.0	......	....
Arcturus......	Neutral	K0	3900	3	20.0	......	.....	.....	.3	.0	......	....
Sun..........	Neutral	G0	5800	1	1.0	+0.43	.....	.....	.25	.0	−0.15	−0.25 (Ce^+)
γ Cygni*.....	Enh.	....	......	....	......	......	.....	.....	......	.0	......	−1.45 (Ce^+)
5 Giants......	Enh.	....	......	....	......	......	.....	.....	.40	.0	......	....
γ Cygni*.....	Enh.	....	......	....	......	......	.....	.....	.65	.0	......	....
δ Cephei min...	Enh.	....	......	....	......	......	.....	.....	.9	.0	......	....
δ Cephei max..	Enh.	....	......	....	......	......	.....	.....	+2.4	0.0	......	....

* Adams and Joy, *Mt. Wilson Communications*, No. 99; *Proceedings of the National Academy of Sciences*, **13**, 393, 1927.

The progressive decrease of red shift at lower levels finds a natural explanation in convection currents or their equivalent. It may fairly be assumed that convection currents are more pronounced the higher the temperature of the star; and the residuals in Table II, interpreted as Fizeau-Doppler effects, are in harmony with such a view. That Arcturus and other giants having lower temperatures than the sun show greater convection currents is not opposed to this view, since giants are of extremely low density as compared with the dwarf sun, and somewhat more rapid convection is perhaps to be expected.

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[1] Russell, Dugan, and Stewart, *Astronomy*, 2, 919, 1927.

In the case of the sun the assumption of upward currents, increasing in magnitude on nearing the photosphere, appears especially well founded and apparently justified by the behavior of easily ionized cerium (Table IV, fourth line), which gives the relatively large displacement −0.25 km/sec. The element is heavy and may be expected to occur at a very low level, an expectation confirmed by the fact that it gives a small value for the solar rotation and has a high velocity of outflow from spots. The very large negative displacement, −1.45 km/sec., that it shows in γ Cygni is also significant.

TABLE V

BEHAVIOR OF EXCEPTIONALLY HIGH-LEVEL LINES

(Unit for $\Delta\lambda$ = 0.001 A)

LINE	WAVE-LENGTH		$\Delta\lambda$			EQUIV. VELOC.	EVERSHED EFFECT	HEIGHT
	Sun's Center	Vac.	Obs.	Cal.	O−C	km/sec.	km/sec.	km
Ca+ (K_3).	3933.684	0.667	+17	8.5	+8.5	+0.63 dn	1.90 in	12000
Ca+ (H_3).	3968.494	.476	18	8.5	9.5	.71 dn		
Hα.......	6562.816	.793	23	14	9	.41 dn	1.50 in	10000
Hβ.......	4861.344	.327	17	10	7	.43 dn		9000
Hγ	4340.477	.466	11	9	2	.14 dn	1.00 in	6000
Mg.......	5183.621	.605	15	11	4	.23 dn	0.36 in	2500
Mg	5172.700	.686	14	11	3	.17 dn		
Na (D_2)...	5889.977	.963	14	12	2	.10 dn	0.18 in	2300
Na (D_1)...	5895.944	.930	14	12	2	.10 dn		
Ca.......	4226.742	0.731	+11	9	+2	+0.14 dn	0.06 in	2100

Evidence supporting the assumption of radial currents is also found in the fact that the residual displacements attributed to this source correspond to radial velocities which, for lines of the same level, are independent of wave-length. The details for a comparison of this kind appear in Table XI.

While the displacement of low-level lines to the violet in comparison with lines of medium level in the same spectral region finds a satisfactory interpretation in rising convection currents, the displacement of high-level lines to the red in a similar comparison presents an interesting question. This has been discussed by St. John and Babcock,[1] by Milne,[2] and more recently by Merfield.[3] Milne

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[1] *Mt. Wilson Contr.*, No. 278; *Astrophysical Journal*, **60**, 32, 1924.

[2] *Monthly Notices, R.A.S.*, **86**, 597, 1926.

[3] Read at the Royal Society of Victoria, Melbourne, Australia, 1926.

suggests that an asymmetrical velocity-distribution among the velocities of agitation of the individual atoms would remove the difficulties he sees in the suggestion of St. John and Babcock that an asymmetry to the red may be due to a more effective absorption by a cooler downward-moving vapor. "Unfortunately," he says, "the investigation of the velocity-distribution amongst the high-level atoms given in this [his] paper shows it to be a symmetrical Maxwellian one." He suggests, however, that the clue to the explanation of the displacement to the red may be in the expulsion of outward-moving atoms under radiation pressure with a consequent excess of absorbing centers on the red edge of the lines, though the dynamical evidence is wanting. Merfield finds on his eclipse plates a widening of the H and K lines above 8000 km, and reasons along the lines of Milne's suggestion as follows:

The widening of the H and K lines above 8000 km is attributed to high ionic agitation. After emission, some of the atoms may possess large outward velocities, and the next absorption will be from the violet side of the line where the radiation is stronger than at the center of the line. Successive emissions and absorptions will endow these atoms with an increasing outward acceleration, and some may escape from the sun. The velocities of descent are hardly likely to exceed the velocities of thermal agitation. Atoms with such velocities will be retained in the sun, whereas the velocities of ascent may reach the velocity of escape. There are then more atoms absorbing from the red wing than from the violet. Hence the absorption line will appear displaced to the red, and this feature should become more prominent with increasing height. This conclusion is supported by the data in Table V.

Although the measures on such strong lines, intensity 20 and above, are not of the high precision attained for lines of intensity 2–4, they suffice to show that, as a rule, for this class of line, the higher the level, the greater the downward velocity deduced from the positive residuals.

It should be repeated that the displacements discussed in this section are differences at the center of the solar disk between lines of different levels, in the same spectral region, and hence independent of relativity. The progression in the differences is plausibly explained as the consequence of ascending and the equivalent of descending currents, but whatever the ultimate explanation of these characteristic differences for lines of high and low level, it follows as surely as night follows day that, if the lines of any level give the predicted gravitational displacement, lines of higher level will show an excess, and lines of lower level a deficit, the deficit increasing with lowness of level, and this, it will be seen, is precisely what the observations indicate.

OBSERVATIONS OF IRON LINES AT THE CENTER OF THE SUN

The major weight of the conclusions deduced from the present investigation rests upon 497 iron lines of groups *a* and *b*, lines measurable in the arc with very high accuracy.[1] The results for these lines are confirmed by the somewhat less reliable data for 89 relatively unstable iron lines of groups *c*5, *d*5—lines showing marked pole effect in the arc[2]—for 18 similar manganese lines,[3] and for 515 closely spaced lines in the 3883 band of cyanogen. The results for the stable iron lines are further consistently supported by the data for 6 lines of silicon, 10 exceptionally high-level lines of calcium, sodium, manganese, and hydrogen, and for 402 lines of titanium measured in the vacuum arc by Brown and by Crew,[4] a total of 1537 lines.

The comparisons between the sun and arc are between the wave-lengths of the lines in the sun and the wave-lengths for the source in vacuum. In the case of iron lines of groups *a* and *b* not measured in the vacuum arc, the wave-lengths in air were reduced to the source in vacuum by applying the means of the closely agreeing pressure coefficients per atmosphere found by Gale and Adams[5] and by Babcock (unpublished). For groups *c*5 and *d*5 the coefficients are

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[1] *Transactions of the International Astronomical Union* (Rome, 1922), Commission (12) des étalons de longeur d'onde.

[2] St. John and Babcock, *Mt. Wilson Contr.*, No. 106; *Astrophysical Journal*, **42**, 231, 1915.

[3] Monk, *Astrophysical Journal*, **57**, 222, 1923.

[4] *Ibid.*, **56**, 53, 1922, and **60**, 108, 1924.

[5] *Mt. Wilson Contr.*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

derived from Brown's[1] measures and Babcock's unpublished data. For manganese the laboratory data are from Monk's paper.[2]

The solar wave-lengths from λ 4000 to the red are the means of the closely agreeing grating measures of St. John and the interferometer measures of Babcock, corrected for the rotation and orbital motion of the earth. To the violet of λ 4000, they are grating measures only, based upon simultaneous exposures to the sun and arc, extending over a series of years, made with the 30-foot spectrograph and the 60-foot tower telescope in the earlier period, and with the 75-foot spectrograph and the 150-foot tower telescope in the later period. The interferometer measures were in greater part made with the Snow telescope. Plates II and III show the heads of the spectrographs and the arrangement of the accessory apparatus. Plates IV and V are reproductions of grating and interferometer spectrograms similar to those upon which the wave-length measures depend.

The results of the measures on iron lines are given in detail in Table VI under sections A, B, and C, which correspond to the following pressure classes: *b*—Lines symmetrical under pressure; energy-level medium; pressure displacement small to medium; an inclusive and complex class. *a*—Low-temperature lines, flame lines; sharp and symmetrical; energy-level low; pressure displacement small. *c*5, *d*5—High-temperature lines; asymmetrical toward the red; pole-effect large; energy-level high; pressure displacement large.

The solar and vacuum wave-lengths are given in the first and second columns, respectively. In the third column are the red displacements, sun *minus* vacuum, and in the fourth column, the differences between these displacements to the red and those calculated from general relativity. The excitation potentials of lines identified in multiplets are in the fifth column, the approximate heights[3] in the sixth, and the temperature class (King) in the seventh column.

The results are summarized in Table VII. This table includes in the eighth and ninth columns additional data bearing on the levels at which the lines originate.

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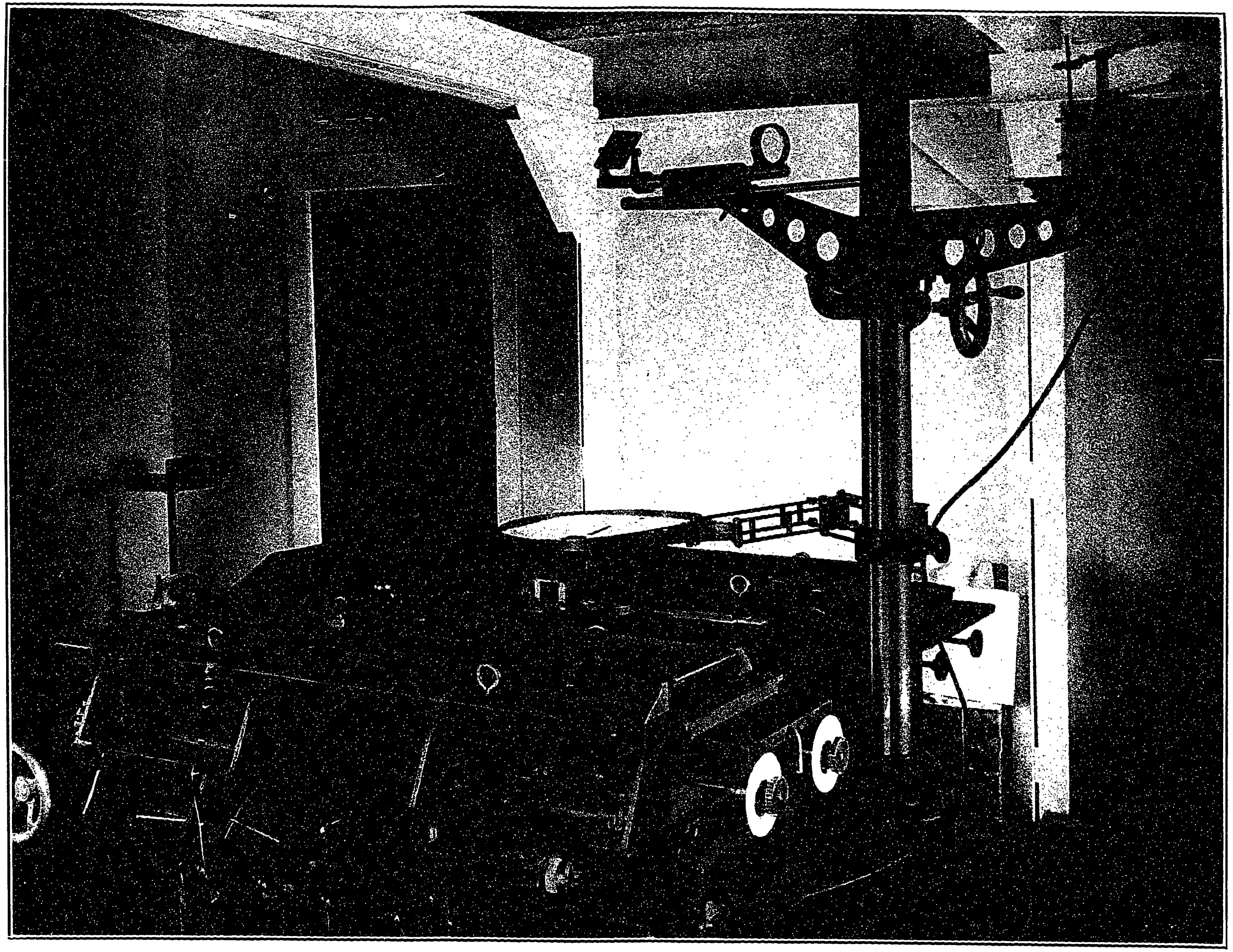
[1] *Astrophysical Journal*, **56**, 53, 1922.

[2] *Ibid.*, **57**, 222, 1923.

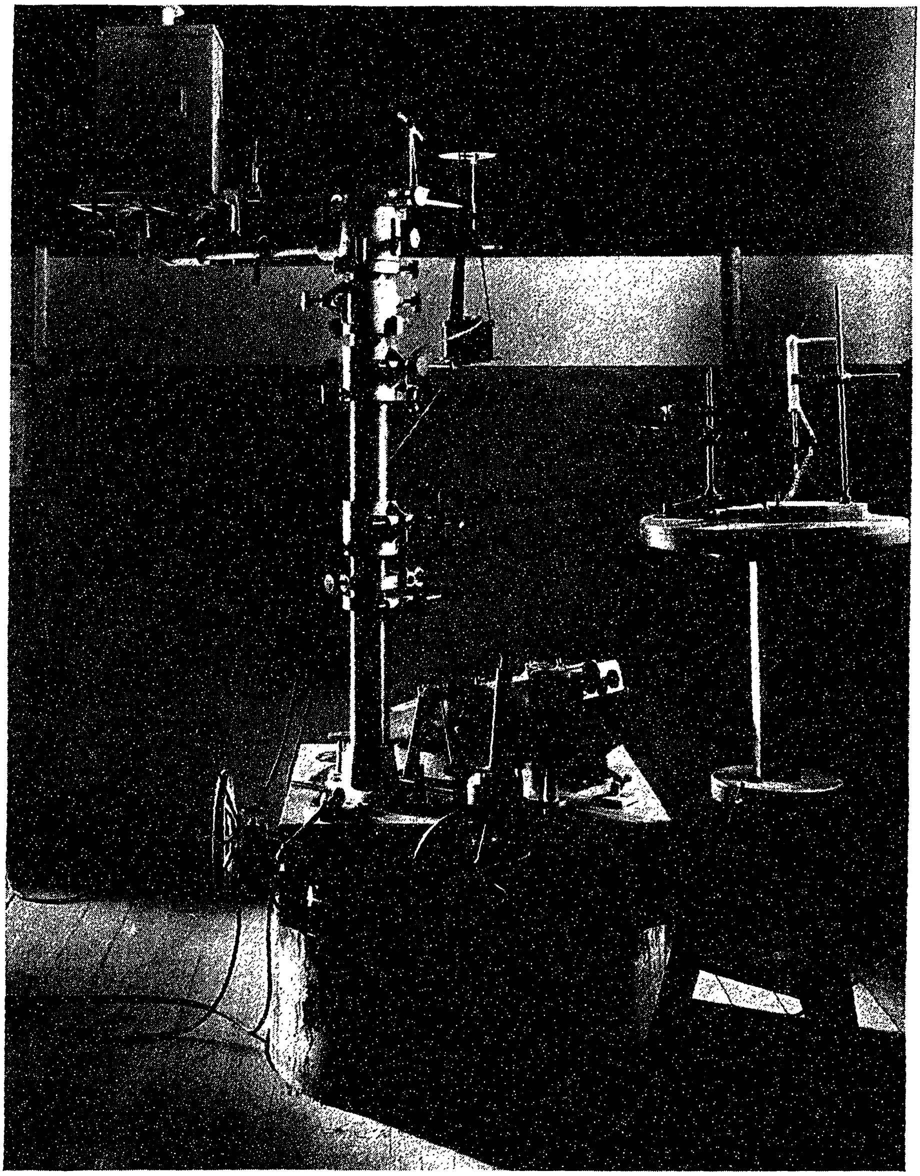
[3] Mitchell, *ibid.*, **38**, 407, 1913.

PLATE II



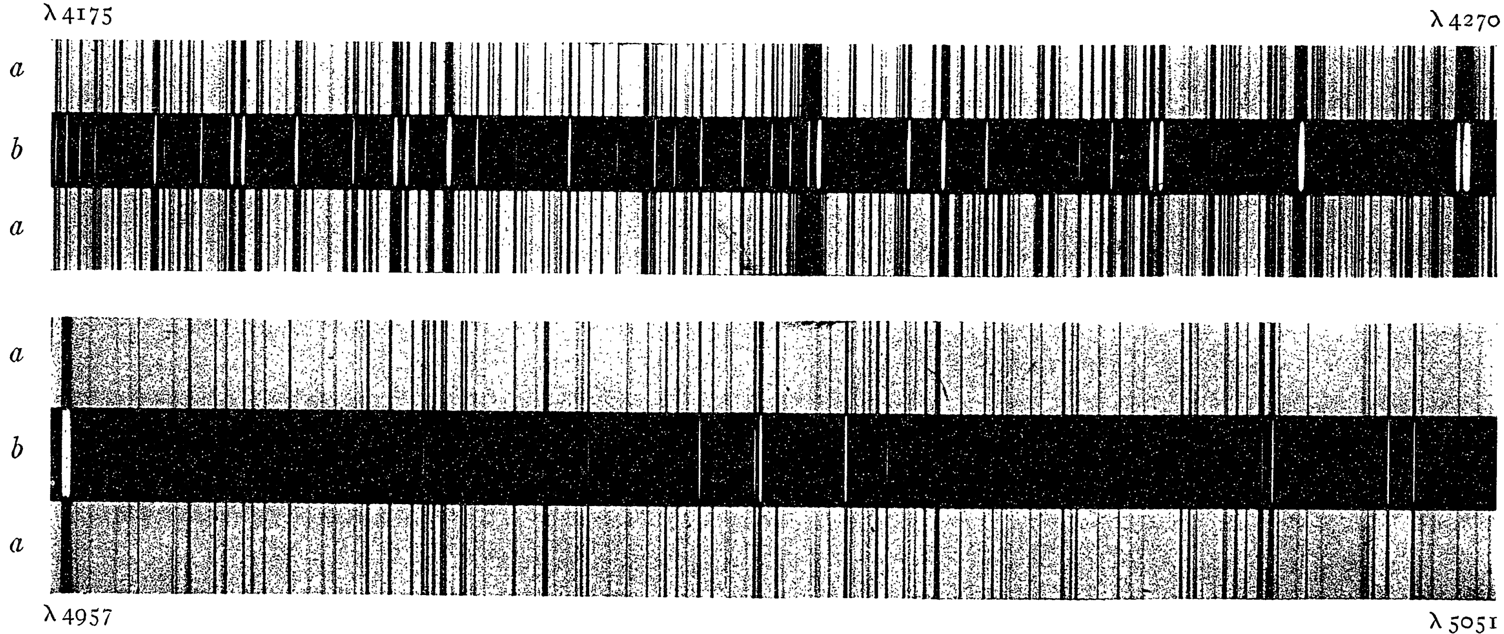
HEAD OF 75-FOOT SPECTROGRAPH OF 150-FOOT TOWER TELESCOPE, SHOWING MOUNTING FOR COMPARISON ARC

PLATE III



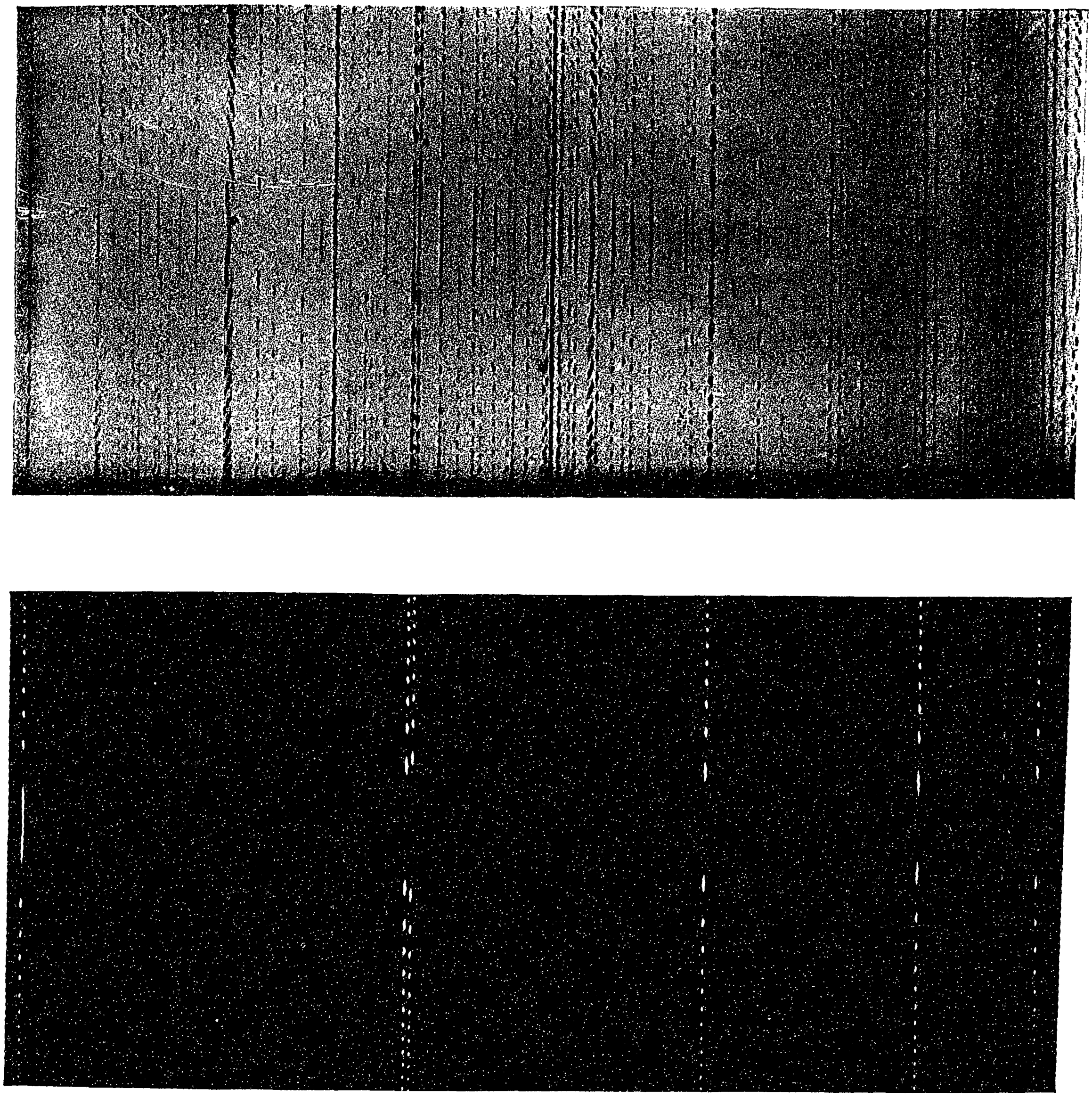
18-FOOT SPECTROGRAPH AND INTERFEROMETER OF THE SNOW HORIZONTAL TELESCOPE

PLATE IV



Simultaneous Exposures with 75-foot Spectrograph on Sun (*a*) and on Iron Arc (*b*). Enlargement Original Negative, 1.25

PLATE V



Interferometer Spectrograms of Sun (Above) and of Iron Arc (Below)

TABLE VI

WAVE-LENGTHS AT CENTER OF SUN
minus
WAVE-LENGTHS FROM SOURCE IN VACUUM
(Unit for Δλ=0.001 A)

Section A Iron Lines, Pressure Class *b*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 8–40; Mean 13.6						
3608.870....	859	+11	+ 3	1.007	500	I
3631.476....	463	13	5	0.954	600	I
3647.852....	843	9	1	.911	600	I
3709.257....	248	9	1	.911	400	II
3734.876....	866	10	2	.855	750	II
3749.497....	488	9	1	.911	....	II
3758.247....	234	13	5	.954	600	II
3763.805....	789	16	8	0.986	1000	II
3767.206....	193	13	5	1.007	1000	II
3787.893....	883	10	2	1.007	750	II
3795.014....	003	11	3	0.986	450	II
3815.853....	841	12	4	1.478	900	II
3820.438....	427	11	3	0.855	1200	II
3825.893....	882	11	3	0.911	1000	II
3827.834....	824	10	2	1.551	800	II
3834.235....	224	11	3	0.954	....	II
3840.449....	437	12	4	0.986	1200	II
3841.060....	049	11	3	1.601	1200	II
3849.979....	968	11	3	1.007	800	II
3878.029....	021	8	0	0.954	1200	II
3902.958....	947	11	3	1.551	900	II
3969.270....	259	11	3	1.478	....	II
4045.827....	814	13	5	1.478	1000	II
4063.607....	596	11	3	1.551	900	II
4071.751....	740	11	2	1.601	900	II
4132.069....	060	9	0	1.601	550	II
4143.880....	871	9	0	1.551	1000	I
4202.042....	031	11	2	1.478	600	I
4250.799....	790	9	0	1.551	700	II
4271.776....	764	12	3	1.478	800	II
4325.777....	764	13	4	1.601	900	II
4383.559....	548	11	2	1.478	1600	II
4404.763....	753	10	1	1.551	800	II
4415.137....	126	+11	+ 2	1.601	500	II
Means...	....	+11.0 ± 0.2	+2.7	1.245	840	....
Violet: Solar Intensity 6–7; Mean 6.2						
3585.720....	709	+11	+ 3	0.911	450	II
3621.468....	462	6	− 2	....	450	IV
3622.010....	005	+ 5	− 3	2.747	400	IV

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 6–7; Mean 6.2—*Continued*						
3640.395....	390	+ 5	− 3	2.716	400	IV
3651.475....	468	7	0	....	400	IV
3676.323....	312	11	+ 3	....	....	IV
3684.124....	111	13	+ 5	....	....	IV
3687.467....	458	9	+ 1	0.885	400	I
3689.470....	465	5	− 3	....	400	IV
3716.452....	447	5	− 3	....	400	IV
3724.387....	378	9	+ 1	....	400	III
3732.408....	397	11	+ 3	....	350	III
3743.370....	363	7	− 1	0.986	600	II A
3753.622....	613	9	+ 1	2.167	500	III
3765.553....	541	12	+ 4	....	800	IV
3798.523....	513	10	+ 2	0.911	....	II
3799.560....	549	11	+ 3	0.954	750	II
3805.351....	344	7	− 1	....	750	IV
3807.546....	539	7	− 1	2.213	500	III
3865.535....	526	9	+ 1	1.007	900	II
3872.512....	504	8	0	0.986	700	II
3887.061....	051	10	+ 1	0.911	600	I
3956.688....	679	9	+ 1	2.681	500	III
3977.752....	743	9	+ 1	2.188	700	III
4005.256....	247	9	0	1.551	800	II
4067.990....	984	6	− 2	....	450	III
4137.007....	002	5	− 4	....	500	IV
4307.914....	906	8	− 1	1.551	....	II
4442.351....	342	9	0	2.188	350	III
4447.730....	720	10	+ 1	2.213	450	III
4494.575....	568	7	− 3	2.188	400	III
4602.951....	944	7	− 3	1.478	350	I
4678.857....	852	+ 5	− 5	....	400	V
Means...	....	+ 8.2	0.0	1.617	520	....
Violet: Solar Intensity 5						
3587.761....	751	+10	+ 2	2.839	350	IV
3603.211....	204	7	− 1	2.681	300	IV
3623.193....	187	6	− 2	2.394	400	IV
3625.148....	146	2	− 6	2.820	500	IV
3649.512....	508	4	− 4	....	400	IV
3650.286....	279	7	− 1	2.422	400	IV
3659.525....	518	7	− 1	2.443	....	IV
3695.057....	053	4	− 4	....	400	IV
3707.053....	049	4	− 4	2.985	400	IV
3760.057....	051	6	− 2	....	500	III
3786.684....	677	7	− 1	1.007	450	III
3790.100....	093	7	− 1	0.986	750	II
3797.524....	516	8	0	....	....	III
3846.811....	803	+ 8	0	....	....	IV

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 5—*Continued*						
3876.053....	043	+10	+2	1.007	500	III
3888.526....	516	10	+2	1.601	500	II
3907.942....	936	6	−2	....	500	IV
3909.839....	830	9	+1	....	500	III
3916.739....	735	4	−5	....	....	IV
3918.653....	644	9	+1	....	....	IV
3925.653....	646	7	−1	....	500	IV
3940.892....	881	11	+3	0.954	600	II
3949.963....	956	7	−1	2.167	500	III
3951.174....	168	6	−2	....	500	IV
3971.334....	325	9	+1	2.681	400	III
4021.872....	870	2	−6	....	....	III
4062.451....	445	6	−2	....	600	III
4066.986....	981	5	−4	....	500	III
4098.185....	183	2	−7	....	500	IV
4107.496....	492	4	−5	....	450	III
4118.557....	549	8	−1	....	....	IV
4123.755....	748	7	−2	....	500	....
4134.687....	682	5	−4	....	500	IV
4175.645....	640	5	−3	....	500	III
4181.766....	758	8	−1	....	....	III
4199.107....	098	9	0	....	....	III
4282.413....	405	8	−1	2.167	700	III
4337.057....	049	8	−1	1.551	600	II
4367.592....	580	12	+3	....	500	IV
4466.564....	553	11	+2	....	500	II
4531.160....	152	8	−2	1.478	400	II
4691.429....	414	+15	+5	....	400	....
Means...	....	+7.1	−1.3	2.011	490	....
Violet: Solar Intensity 4						
3586.119....	112	+7	−1	....	400	IV
3589.113....	106	7	−1	0.855	350	III
3608.156....	148	8	0	2.839	....	IV
3630.356....	351	5	−3	2.839	500	IV
3632.985....	978	7	−1	....	400	IV
3637.874....	861	13	+5	2.927	350	IV
3643.628....	624	4	−4	2.927	500	IV
3645.828....	821	7	−1	....	400	IV
3647.429....	426	3	−5	1.551	400	IV
3669.527....	522	5	−3	....	....	IV
3677.319....	308	11	+3	....	400	IV
3678.870....	862	8	0	....	....	IV
3687.661....	655	6	−2	....	400	III
3698.610....	608	+2	−6	....	....	IV

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
		Violet: Solar Intensity 4—*Continued*				
3702.038....	033	+5	−3	....	350	IV
3704.470....	463	7	−1	....	....	IV
3711.230....	225	5	−3	....	....	IV
3718.413....	407	6	−2	....	400	IV
3735.336....	326	10	+2	2.927	....	IV
3756.943....	939	4	−4	....	600	IV
3760.538....	532	6	−2	....	....	III
3774.834....	825	9	+1	2.213	....	IV
3794.349....	340	9	+1	....	500	III
3821.188....	180	8	0	....	500	IV
3833.319....	311	8	0	2.548	500	IV
3843.266....	258	8	0	....	....	IV
3850.828....	819	9	+1	0.986	....	II
3852.581....	574	7	−1	2.167	....	IV
3873.769....	762	7	−1	....	....	IV
3885.521....	511	10	+2	....	500	III
3891.936....	928	8	0	....	600	V
3893.404....	394	10	+2	....	600	IV
3906.756....	748	8	0	....	....	V
3909.670....	664	6	−2	3.269	500	V
3910.851....	846	5	−3	....	500	IV
3913.639....	634	5	−3	2.269	....	III
3918.326....	319	7	−1	....	....	....
3918.426....	418	8	0	....	....	IV
3925.950....	944	6	−2	....	600	IV
3947.540....	533	7	−1	2.819	....	IV
3948.787....	778	9	+1	....	....	IV
3952.617....	605	12	+4	....	600	IV
3956.465....	459	6	−2	....	....	IV
3981.777....	774	3	−5	2.716	....	III
3983.973....	961	12	+4	2.716	....	III
3994.121....	117	4	−4	....	....	IV
3997.403....	394	9	+1	2.716	600	III
3998.060....	056	4	−4	2.681	500	III
4017.161....	155	6	−3	....	400	III
4070.779....	772	7	−2	....	....	III
4076.639....	636	3	−6	....	400	IV
4078.368....	362	6	−3	....	....	IV
4085.015....	011	4	−5	....	500	IV
4085.319....	312	7	−2	2.747	....	IV
4100.749....	744	5	−4	0.855	....	II A
4114.453....	449	4	−5	....	450	IV
4120.215....	211	4	−5	....	400	IV
4126.193....	188	5	−4	....	400	IV
4127.615....	612	3	−6	....	550	IV
4132.910....	904	6	−3	1.601	500	III
4154.507....	503	4	−5	....	500	III
4170.914....	905	9	0	....	....	IV
4184.902....	895	+7	−2	....	500	III

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 4—*Continued*						
4245.266....	260	+ 6	− 3	....	500	III
4352.745....	737	8	− 1	2.213	500	III
4369.781....	773	8	− 1	....	500	III
4592.661....	655	6	− 4	1.551	350	I
4630.130....	125	5	− 5	2.269	300	....
4632.927....	915	12	+ 2	1.601	400	III
4638.019....	015	4	− 6	....	350	IV
4643.472....	466	6	− 4	....	....	....
4745.809....	803	6	− 4	....	350	V
4772.824....	815	9	− 1	1.551	350	III
5079.232....	225	7	− 4	2.188	500	IV
5328.544....	532	12	+ 1	1.551	500	II
5701.559....	549	+10	− 2	2.548	500	III
Means...	....	+ 6.8	− 1.7	2.204	460	....
Violet: Solar Intensity 3						
3587.432....	423	+ 9	+ 1	....	350	IV
3599.632....	625	7	− 1	....	350	IV
3617.322....	316	6	− 2	....	400	IV
3632.561....	557	4	− 4	....	400	IV
3638.305....	298	7	− 1	2.747	350	IV
3655.473....	464	9	+ 1	....	400	IV
3687.103....	099	4	− 4	....	....	IV
3711.413....	408	5	− 3	....	....	IV
3715.917....	913	4	− 4	....	400	IV
3725.500....	496	4	− 4	....	400	....
3727.100....	096	4	− 4	2.927	400	IV
3730.394....	386	8	0	....	350	IV
3730.952....	945	7	− 1	....	350	IV
3731.383....	374	9	+ 1	....	350	IV
3738.314....	307	7	− 1	....	500	IV
3742.625....	621	4	− 4	2.927	300	IV
3756.074....	069	5	− 3	....	300	IV A
3768.036....	030	6	− 2	2.213	....	IV
3773.701....	691	10	+ 2	....	500	IV
3776.463....	456	7	− 1	....	500	IV
3777.458....	448	10	+ 2	....	500	IV
3778.705....	697	8	0	2.188	....	....
3781.193....	187	6	− 2	....	....	IV
3785.954....	948	6	− 2	....	....	IV
3789.186....	178	8	0	....	....	IV
3792.160....	156	4	− 4	....	....	IV
3801.685....	680	5	− 3	....	450	IV
3804.016....	012	4	− 4	....	600	....
3808.736....	731	+ 5	− 3	2.548	....	IV

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
		Violet: Solar Intensity 3—*Continued*				
3810.762....	758	+4	−4	....	....	IV
3816.347....	340	7	−1	2.188	400	IV
3836.339....	332	7	−1	....	....	IV
3839.265....	258	7	−1	....	500	IV
3859.225....	214	11	+3	....	....	III
3861.346....	341	5	−3	....	....	IV
3867.226....	219	7	−1	....	....	IV
3890.851....	844	7	−1	....	800	IV
3897.902....	896	6	−2	....	....	IV
3937.339....	330	9	+1	....	....	IV
3942.450....	443	7	−1	....	....	IV
3943.350....	342	8	0	2.188	....	IV
3944.900....	892	8	0	....	....	IV
3945.129....	119	10	+2	....	....	IV
3955.965....	958	7	−1	....	....	IV
3961.151....	147	4	−4	2.846	....	....
3964.528....	520	8	0	....	....	V
3966.075....	066	9	+1	1.601	....	III
3985.398....	393	5	−3	....	400	IV
3986.182....	176	6	−2	....	500	IV
3989.867....	859	8	0	2.269	....	V
3995.992....	987	5	−3	....	....	IV
4001.672....	666	6	−2	2.167	500	III
4003.773....	766	7	−1	....	....	V
4006.635....	631	4	−4	....	500	IV
4007.281....	277	4	−4	2.747	600	IV
4009.719....	715	4	−4	2.213	....	III
4044.619....	614	5	−4	....	500	IV
4067.282....	274	8	−1	....	....	III
4074.797....	792	5	−4	....	500	IV
4079.848....	846	2	−7	....	500	IV
4095.983....	975	8	−1	....	500	IV
4121.812....	807	5	−4	....	300	IV
4122.525....	520	5	−4	....	500	IV
4125.888....	884	4	−5	....	300	....
4156.812....	803	9	0	....	500	III
4182.389....	384	5	−4	....	450	IV
4207.135....	130	5	−4	....	400	IV
4208.612....	606	6	−3	....	350	V
4213.655....	650	5	−4	....	500	IV
4220.349....	344	5	−4	....	450	IV
4266.971....	968	3	−6	....	400	IV
4285.453....	446	7	−2	....	....	IV
4408.427....	418	9	0	....	450	III?
4422.578....	570	8	−1	....	....	III
4430.624....	617	7	−2	....	450	III
4443.203....	195	8	−1	....	....	III
4454.390....	383	7	−2	....	500	III
4517.537....	530	+7	−3	3.943	350	....

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 3—*Continued*						
4547.856	850	+ 6	− 4	....	400	V
4602.011	005	6	4	1.601	350	....
4619.299	293	6	4	....	350	IV
4683.570	564	6	4	....	300	....
4710.292	285	7	3	....	350	IV
4735.852	846	6	4	....	250	....
4741.538	531	7	3	....	300	V
4788.766	757	9	1	....	300	....
4789.660	653	7	3	....	400	V
4839.554	549	5	5	....	300	....
4924.779	773	6	4	2.269	350	V
5098.709	701	8	3	2.167	400	IV
5198.718	710	8	3	2.213	....	IV
5216.285	276	9	2	1.601	350	II
5250.656	648	8	3	2.188	400	IV
5307.371	363	+ 8	− 3	1.601	350	III?
Means	....	+ 6.5	− 2.2	2.334	420	....
Violet: Solar Intensity 2						
3637.001	994	+ 7	− 1	....	....	IV
3669.156	150	6	− 2	....	....	IV
3674.774	765	9	+ 1	....	....	IV
3703.830	824	6	− 2	....	....	IV
3722.030	026	4	− 4	....	....	....
3728.673	668	5	− 3	....	....	IV
3757.460	458	2	− 6	....	....	IV
3778.517	511	6	− 2	2.985	....	IV
3781.940	938	2	− 6	....	....	....
3782.455	450	5	− 3	....	....	IV
3790.761	756	5	− 3	2.167	....	IV A
3791.511	504	7	− 1	....	....	....
3793.487	481	6	− 2	3.025	....	....
3793.878	872	6	− 2	....	....	IV
3802.287	282	5	− 3	....	....	....
3811.896	892	4	− 4	....	....	IV
3813.642	638	4	− 4	....	....	IV
3825.410	404	6	− 2	....	....	....
3827.582	572	10	+ 2	....	....	IV
3830.766	758	8	0	2.597	....	IV
3837.143	133	10	+ 2	2.597	....	IV
3846.419	412	7	− 1	....	....	IV
3871.760	750	10	+ 2	....	....	IV
3935.828	815	13	+ 5	....	....	III
3967.433	423	10	+ 1	....	....	IV
3970.401	391	+10	+ 1	....	....	IV

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 2—*Continued*						
3976.870....	865	+ 5	− 3	....	....	....
3990.381....	379	2	− 6	....	....	V
3996.973....	968	5	− 3	....	500	V
4000.468....	464	4	− 4	....	....	V
4006.319....	314	5	− 3	....	500	IV
4173.325....	320	5	− 4	....	....	IV
4205.546....	543	3	− 6	....	....	....
4225.964....	956	8	− 1	....	....	IV
4226.433....	426	7	− 2	....	....	IV
4229.522....	516	6	− 3	....	....	....
4242.736....	730	6	− 3	....	....	....
4246.094....	090	4	− 5	....	400	V
4248.233....	228	5	− 4	....	....	IV
4258.621....	614	7	− 2	....	....	....
4265.268....	260	8	− 1	....	....	....
4268.758....	747	11	+ 2	....	....	IV
4302.197....	190	7	− 2	....	....	....
4309.040....	035	5	− 4	....	....	....
4321.800....	798	2	− 7	....	....	....
4343.707....	700	7	− 2	....	400	....
4346.563....	557	6	− 3	....	....	....
4348.949....	942	7	− 2	....	....	....
4351.556....	548	8	− 1	....	....	IV
4358.514....	505	9	0	....	....	IV
4367.914....	906	8	− 1	1.601	....	III A
4373.570....	563	7	− 2	2.548	400	....
4387.901....	895	6	− 3	....	....	IV
4447.139....	133	6	− 3	....	....	IV
4490.780....	773	7	− 3	3.926	....	....
4547.027....	022	5	− 5	1.551	....	....
4549.476....	470	6	− 4	....	....	....
4574.730....	724	6	− 4	2.269	350	....
4587.139....	132	7	− 3	....	350	....
4595.367....	363	4	− 6	....	350	....
4596.071....	063	8	− 2	....	350	....
4635.857....	848	9	− 1	....	300	....
4687.396....	389	7	− 3	....	300	....
4721.002....	997	5	− 5	....	300	....
4757.587....	580	7	− 3	....	300	....
4771.714....	702	12	+ 2	2.188	....	....
4786.816....	810	6	− 4	....	....	IV?
4800.655....	651	4	− 6	....	300	....
4802.888....	883	5	− 5	....	....	....
4838.523....	517	6	− 4	3.402	350	....
5131.478....	473	5	− 6	2.213	350	....
5242.501....	494	7	− 4	....	250	IV
5329.998....	993	+ 5	− 6	....	....	....
Means...	....	+ 6.3	− 2.6	2.429	350	....

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
Violet: Solar Intensity 1						
3709.539....	534	+5	−3	....	....	....
3751.826....	820	6	−2	....	....	....
3775.862....	857	5	−3	....	....	....
3782.615....	612	3	−5	....	....	....
3785.709....	706	3	−5	....	....	....
3789.579....	572	7	−1	....	....	....
3790.659....	656	3	−5	....	....	....
3795.540....	532	8	0	....	....	....
3808.288....	284	4	−4	....	....	....
3824.084....	077	7	−1	2.577	....	IV
3845.702....	694	8	0	....	....	....
3931.131....	124	7	−1	3.252	....	....
3932.639....	631	8	0	2.458	....	IV
3932.917....	917	0	−8	....	....	....
3967.977....	964	13	+5	....	....	IV
3973.658....	655	3	−6	....	....	V
4004.838....	833	5	−4	....	....	....
4290.386....	382	4	−5	....	....	....
4290.882....	870	12	+3	2.819	....	....
4338.273....	264	9	0	2.167	....	....
4432.577....	572	5	−4	....	....	....
4439.891....	884	7	−2	2.269	....	IV
4450.325....	321	4	−6	2.269	....	....
4456.335....	331	4	−6	....	....	....
4479.613....	609	4	−6	3.671	....	IV
4480.147....	142	5	−5	....	....	IV
4514.195....	189	6	−4	....	....	....
4523.408....	403	5	−5	....	....	....
4526.570....	563	7	−3	....	....	....
4552.556....	547	9	−1	....	....	....
4558.115....	108	7	−3	....	....	....
4566.526....	520	6	−4	....	....	....
4600.941....	937	4	−6	....	....	....
4661.541....	537	4	−6	....	....	....
4661.981....	975	6	−4	....	....	....
4680.308....	298	10	0	1.601	....	....
4689.503....	495	8	−2	....	....	....
4701.057....	050	7	−3	....	....	....
4734.107....	100	7	−3	....	....	....
4737.637....	633	4	−6	....	....	....
4740.347....	343	4	−6	....	....	....
4779.447....	439	+8	−2	....	....	....
Means...	....	+5.9	−3.1	2.565	....	....
Red: Solar Intensity 5–8; Mean 6						
6065.499....	488	+11	−2	2.597	400	III
6136.631....	619	+12	−1	2.433	400	III

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Red: Solar Intensity 5–8; Mean 6—*Continued*						
6137.709	698	+11	− 2	2.577	400	III
6157.739	727	12	1	....	....	V
6173.348	338	10	3	2.213	....	III
6191.577	564	13	0	2.422	300	II
6200.327	318	9	4	2.597	....	IV
6213.443	434	9	4	2.213	....	III
6215.157	147	10	3	....	....	....
6219.294	285	9	4	2.188	....	III
6230.742	730	12	1	2.548	....	III
6252.572	562	10	3	2.394	....	III
6265.148	140	8	5	2.167	....	III
6297.808	798	10	3	2.213	....	III
6318.036	024	12	1	2.443	....	III
6335.345	337	8	5	2.188	....	III
6358.695	681	14	0	0.855	....	I A
6393.620	607	13	1	2.422	....	III
6421.367	357	10	4	2.269	....	III
6430.863	854	9	5	2.167	....	III
6495.001	988	13	1	2.394	....	II
6592.934	923	11	2	2.716	....	III
6678.007	997	+10	− 4	2.681	....	III
Means...	....	+10.7	− 2.6	2.319	375	....
Red: Solar Intensity 2–4; Mean 3.2						
5956.709	698	+11	− 2	0.855	....	....
5975.356	349	7	− 6	4.529	....	V
6027.064	055	9	− 4	....	....	V
6127.918	907	11	− 2	....	....	....
6137.009	995	14	+ 1	2.188	....	....
6165.369	361	8	− 5	....	....	....
6240.659	651	8	− 5	2.213	....	....
6270.237	229	8	− 5	2.846	....	....
6280.628	619	9	− 4	0.855	....	I A
6315.323	309	14	+ 1	....	....	....
6322.701	690	11	− 2	2.577	....	III
6344.162	155	7	− 7	2.422	....	III
6355.043	034	9	− 5	2.833	....	III
6380.756	748	8	− 6	....	....	V
6475.640	633	7	− 7	2.548	....	IV
6518.384	377	7	− 7	2.819	....	....
6609.126	120	6	− 8	....	....	IV
6663.470	452	18	+ 4	....	....	IV
6750.173	160	+13	− 1	....	....	IV
Means...	....	+ 9.7	− 3.7	2.426	....	....

TABLE VI—*Continued*

Section B Iron Lines, Pressure Class *a*

Solar Intensity 8–40; Mean 13.7

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
3679.924....	914	+10	+ 2	0.000	500	I A
3705.578....	567	11	3	.051	750	I
3719.949....	937	12	4	.000	1500	I
3737.143....	132	11	3	.051	1500	I
3745.576....	562	14	6	.087	1500	I
3748.273....	263	10	2	.110	750	I A
3856.383....	372	11	3	.051	1200	I A
3859.924....	914	10	2	.000	1800	I
3886.296....	284	12	4	.051	1600	I
3899.721....	710	11	3	.087	1000	I
3906.492....	483	9	1	.110	750	I
3920.271....	260	11	3	.121	1000	I
3922.925....	913	12	4	.051	1200	I
3927.935....	922	13	4	.110	1000	I
3930.310....	298	+12	+ 4	0.087	1000	I
Means...	....	+11.3	+ 3.2	0.064	1140	....

Solar Intensity 4–7; Mean 5

Wave-Lengths		Δλ		E.P.	Level in Km	Temperature Class
Sun's Center	Vac.	Obs.	O−C			
3649.308....	304	+ 4	− 4	0.000	400	I A
3733.332....	319	13	+ 5	.110	....	I A
3745.912....	901	11	+ 3	.121	....	I A
3878.582....	573	9	+ 1	.087	....	II
3895.669....	659	10	+ 2	.110	1200	I
4172.764....	749	15	+ 6	.954	600	II A
4174.919....	914	5	− 4	.911	500	II A
4375.946....	932	14	+ 5	.000	500	I
4427.319....	312	7	− 2	.051	600	I
4461.662....	654	8	− 1	.087	500	I
4489.750....	742	8	− 1	0.121	400	I A
4733.599....	594	5	− 5	1.478	400	I
5012.077....	072	5	− 6	0.855	500	I
5083.347....	342	5	− 6	.954	400	I
5107.459....	452	7	− 4	0.986	500	I
5107.653....	645	8	− 3	1.551	500	II
5150.854....	843	11	0	0.986	400	I
5171.612....	599	13	+ 2	1.478	600	II
5194.951....	943	8	− 3	1.551	400	I
5332.910....	902	8	− 3	1.551	350	I
5371.503....	492	11	0	0.954	500	I
5397.143....	130	13	+ 2	.911	800	I
5405.787....	777	10	− 1	.986	600	I
5429.708....	699	9	− 3	0.954	600	I
5434.536....	524	12	+ 1	1.007	500	I
5446.926....	917	+ 9	− 2	0.986	500	I

TABLE VI—*Continued*

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERA-TURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Solar Intensity 4–7; Mean 5—*Continued*						
5455.626....	612	+14	+ 2	1.007	500	I
5497.528....	519	9	− 3	1.007	500	I
5501.479....	467	12	0	0.954	400	I
5506.793....	781	+12	0	0.986	400	I
Means...	....	+ 9.6	− 0.7	0.834	516	....
Solar Intensity 1–3; Mean 2.6						
4173.935....	927	+ 8	− 1	0.986	....	II A
4206.704....	698	6	3	.051	400	I A
4216.193....	187	6	3	.000	400	I
4258.326....	320	6	3	.087	400	I A
4291.475....	467	8	1	.051	....	I A
4348.949....	942	7	2	....	500	....
4389.256....	248	8	1	.051	400	II A
4435.158....	151	7	2	.087	....	II A
4939.695....	689	6	5	.855	350	I
4994.139....	133	6	5	0.911	500	I
5123.732....	725	7	4	1.007	400	I
5127.370....	363	7	4	0.911	300	I
5142.938....	932	6	5	0.954	400	I
5151.919....	914	+ 5	− 6	1.007	400	I
Means...	....	+ 6.6	− 3.2	0.533	404	....

TABLE VI—*Continued*

Section C Iron Lines, Pressure Class $c5$, $d5$

WAVE-LENGTHS		Δλ		E.P.	LEVEL IN KM	TEMPERATURE CLASS
Sun's Center	Vac.	Obs.	O−C			
Solar Intensity 6–10; Mean 6.9						
4187.049....	043	+ 6	− 3	2.439	600	III
4191.439....	435	4	− 5	2.548	550	III
4233.613....	607	6	− 3	2.471	400	III
4235.951....	942	9	0	2.415	650	III
4250.132....	124	8	− 1	2.458	700	III
4260.488....	479	9	0	2.389	500	III
4271.166....	158	8	− 1	2.439	800	III
4736.783....	777	6	− 4	3.197	400	II?
4890.765....	760	5	− 5	2.863	600	III
4891.504....	496	8	− 2	2.839	600	III
4919.000....	992	8	− 3	2.853	400	III
4920.516....	507	9	− 1	2.820	500	III
4957.612....	598	14	+ 3	2.796	500	III
5232.954....	942	12	+ 1	2.927	400	III
5266.565....	556	9	− 2	2.985	350	IV
5283.631....	621	10	− 1	3.227	350	IV
5324.193....	181	12	+ 1	3.197	400	IV
5339.939....	932	7	− 4	3.252	250	V
5569.633....	620	13	+ 1	3.402	500	IV
5586.773....	757	16	+ 4	3.354	750	IV
5615.664....	645	+19	+ 7	3.318	500	IV
Means...	....	+ 9.4	− 0.9	2.862	510	....
Solar Intensity 2–5; Mean 3.8						
3667.262....	261	+ 1	− 7	....	500	IV
3739.531....	523	8	0	....	....	IV
3855.853....	844	9	+ 1	....	....	....
3920.845....	835	10	+ 2	....	....	....
3948.111....	103	8	0	....	600	....
3963.117....	106	11	+ 3	....	....	V
4024.734....	732	2	− 7	....	....	V
4063.290....	284	6	− 3	3.354	....	....
4084.503....	497	6	− 3	3.318	400	IV
4136.530....	510	20	+11	....	500	....
4154.815....	810	5	− 4	....	500	IV
4157.790....	787	3	− 6	....	400	IV
4195.342....	335	7	− 2	....	....	IV
4196.216....	216	0	− 9	....	....	IV
4222.223....	216	7	− 2	2.439	500	III
4225.463....	457	6	− 3	....	....	IV
4227.442....	433	9	0	....	....	III
4238.031....	023	8	− 1	....	500	IV
4238.818....	814	4	− 5	....	....	IV
4247.434....	431	3	− 6	....	400	III
4299.252....	239	+13	+ 4	2.415	....	III

TABLE VI—*Continued*

Wave-Lengths		Δλ		E.P.	Level in Km	Tempera-ture Class
Sun's Center	Vac.	Obs.	O−C			
Solar Intensity 2–5; Mean 3.8—*Continued*						
4388.416....	408	+8	−1	....	400	IV
4401.300....	289	11	+2	3.587	....	....
4446.845....	836	9	0	3.671	350	....
4469.385....	380	5	−5	....	400	IV
4484.229....	225	4	−6	3.587	350	IV
4525.148....	143	5	0	....	....	IV
4531.634....	629	5	0	3.912	350	....
4598.127....	119	8	−2	3.269	300	....
4607.655....	653	2	−8	3.252	350	V
4613.215....	207	8	−2	3.278	....	V
4625.054....	051	3	−7	3.227	350	IV
4637.512....	507	5	−5	3.269	350	IV
4707.287....	278	9	0	3.227	....	IV
4859.749....	745	4	−6	2.863	350	III
4882.150....	147	3	−7	3.402	350	....
4938.822....	816	6	−4	2.863	350	IV
4946.397....	390	7	−4	3.354	350	IV
4950.113....	109	4	−7	3.402	350	....
4957.309....	300	9	−1	2.839	....	III
4966.097....	092	5	−5	3.318	350	V
4982.509....	504	5	−6	....	300	....
4983.861....	852	9	−2	....	300	V
4985.261....	257	4	−7	....	350	V
5001.872....	867	5	−6	....	400	V
5014.951....	945	6	−5	....	350	V
5022.243....	239	4	−7	....	350	V
5027.131....	131	0	−11	....	350	V
5068.773....	770	3	−8	....	500	V
5137.395....	383	12	+1	....	350	V
5139.263....	256	7	−4	....	350	IV
5139.475....	464	11	0	....	500	IV
5191.467....	455	12	+1	....	500	IV
5192.355....	345	10	−1	2.985	500	IV
5215.190....	180	10	−1	3.252	300	IV
5217.398....	390	8	−3	3.197	300	V
5229.862....	852	10	−1	3.269	400	V
5263.316....	309	7	−4	3.252	350	V
5281.800....	793	7	−4	3.025	350	IV
5302.309....	301	8	−3	3.269	350	V
5466.407....	399	8	−4	....	300	....
5473.912....	903	9	−3	4.136	450	....
5476.578....	566	12	0	4.086	....	IV
5576.101....	090	11	−1	3.415	500	IV
5624.559....	542	17	+5	3.402	400	IV
5638.274....	262	12	0	4.202	350	V
5753.135....	128	7	−5	....	400	V
5775.091....	082	+9	−3	4.202	....	....
Means...	....	+7.2	−2.8	3.322	390	....

OBSERVATIONS OF IRON LINES AT THE SUN'S EDGE

The advantage of observations at the limb is the elimination of Doppler shifts produced by radial currents in the sun's atmosphere. At the center of the image the full force of radial currents is effective, while at a distance from the center of 98.5–99 per cent of the radius, where the limb observations were made, the effect of ascending and descending currents is inappreciable. Such measures, on the other hand, are subject to some uncertainty because of a possible limb effect. The spectral lines for this region present a different appearance from those observed at the sun's center, which might lead to the expectation of some influence on the wave-lengths. As will be seen later, the mean differential effect between limb and center which can be attributed to this cause is very small for the lines measured.

TABLE VII

SUMMARY OF DATA FOR IRON LINES IN TABLE VI

(Unit for $\Delta\lambda$=0.001 A)

Class	No. of Lines	Mean λ	$\Delta\lambda$		Equiv. Veloc.	E.P.	Evershed Effect	Level in Km	Solar Intensity
			Mean Obs.	O−C					
					km/sec.		km/sec.		
b, Violet..	34	3943	+11.0	+2.7	+0.21 dn	1.245	0.03 out	840	13.6
	33	3917	8.2	0.0	.00	1.617	.45 out	520	6.2
	42	3974	7.1	−1.3	− .10 up	2.011	.57 out	490	5
	76	4026	6.8	−1.7	− .13 up	2.204	.63 out	460	4
	95	4106	6.5	−2.2	− .16 up	2.257	.69 out	420	3
	73	4219	6.3	−2.6	− .19 up	2.429	.75 out	350	2
	42	4269	5.9	−3.1	− .22 up	2.565	.84 out	Low	1
b, Red...	23	6295	10.7	−2.6	− .12 up	2.319	.62 out	375	6
	19	6311	9.7	−3.7	− .18 up	2.426	.76 out	325	3
a........	15	3830	11.3	+3.2	+ .25 dn	0.064	.05 in	1140	13.7
	31	4856	9.6	−0.7	− .04 up	0.834	.41 out	515	5
	14	4629	6.6	−3.2	− .21 up	0.533	.66 out	400	2.6
*c*5, *d*5....	21	4865	9.4	−0.9	− .06 up	2.862	.33 out	510	6.9
	68	4728	+ 7.2	−2.8	−0.18 up	3.322	0.58 out	390	3.8

The solar rotation does not enter as a disturbing factor because the tabulated displacements are the means for points in the same heliographic latitude at opposite limbs. The effect of solar rotation is therefore completely eliminated. The influence of random hori-

TABLE VIII

WAVE-LENGTHS AT EDGE OF SUN

minus

WAVE-LENGTHS OF SOURCE IN VACUUM

(Unit for $\Delta\lambda = 0.001$ A)

Iron Lines of Pressure Classes *a* and *b*

WAVE-LENGTHS		$\Delta\lambda$		CLASS
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 8–25; Mean 11.9				
3787.893.......	883	+10	+ 2	*b*
3795.014.......	004	10	2	*b*
3815.852.......	841	11	3	*b*
3820.438.......	429	9	1	*b*
3825.894.......	883	11	2	*b*
3827.833.......	824	9	1	*b*
3834.235.......	224	11	3	*b*
3840.448.......	437	11	3	*b*
3841.060.......	049	11	3	*b*
3849.979.......	969	10	2	*b*
3856.384.......	372	12	3	*a*
3859.923.......	914	9	0	*a*
3878.031.......	021	10	2	*b*
3886.296.......	284	12	4	*a*
3899.721.......	710	11	2	*a*
3902.956.......	947	9	1	*b*
3906.495.......	483	+12	+ 4	*a*
Means.....	....	+10.4	+ 2.2	....
Solar Intensity 5–7; Mean 5.8				
3790.105.......	095	+10	+ 2	*b*
3797.524.......	517	7	− 1	*b*
3798.524.......	513	11	+ 3	*b*
3799.560.......	549	11	+ 3	*b*
3805.355.......	345	10	+ 2	*b*
3807.549.......	540	9	+ 1	*b*
3824.455.......	444	11	+ 3	*a*
3846.811.......	804	7	− 1	*b*
3865.535.......	526	9	+ 1	*b*
3872.513.......	504	9	+ 1	*b*
3876.056.......	044	12	+ 4	*b*
3887.061.......	051	10	+ 2	*b*
3888.527.......	517	10	+ 2	*b*
3895.669.......	659	10	+ 2	*a*
5049.837.......	825	12	+ 1	*a*
5110.423.......	413	10	− 1	*a*
5171.610.......	599	11	0	*a*
5227.204.......	190	14	+ 3	*a*
5371.508.......	492	+16	+ 5	*a*

TABLE VIII—*Continued*

Wave-Lengths		Δλ		Class
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 5–7; Mean 5.8—*Continued*				
5397.148.......	130	+18	+ 7	*a*
5405.794.......	777	17	+ 6	*a*
5429.713.......	699	14	+ 4	*a*
5434.543.......	524	19	+ 9	*a*
5446.931.......	917	14	+ 3	*a*
5497.534.......	519	15	+ 3	*a*
5501.478.......	467	11	− 1	*a*
5506.796.......	781	+15	+ 3	*a*
Means.....	....	+11.8	+ 2.4	....
Solar Intensity 3–4; Mean 3.4				
3789.186.......	179	+ 7	− 1	*b*
3794.350.......	341	9	+ 1	*b*
3801.690.......	682	8	0	....
3804.021.......	014	7	− 1	....
3810.766.......	760	6	− 2	*b*
3816.351.......	341	10	+ 2	....
3821.190.......	181	9	+ 1	*b*
3833.323.......	312	11	+ 3	*b*
3836.340.......	333	7	− 1	....
3839.269.......	259	10	+ 2	*a*
3850.830.......	820	10	+ 2	*b*
3852.584.......	575	9	+ 1	....
3859.225.......	214	11	+ 3	*b*
3861.351.......	342	9	+ 1	*b*
3867.226.......	220	6	− 3	*b*
3873.773.......	764	9	+ 1	*b*
3885.522.......	512	10	+ 2	*b*
3890.854.......	845	9	+ 1	*b*
3891.937.......	929	8	0	*b*
3893.406.......	395	11	+ 3	*b*
3897.903.......	897	6	− 2	*b*
4994.146.......	133	13	+ 2	*a*
5041.085.......	074	11	0	*a*
5041.773.......	758	15	+ 4	*a*
5051.651.......	637	14	+ 3	*a*
5079.237.......	226	11	+ 1	*b*
5079.757.......	742	15	+ 4	*a*
5083.356.......	341	15	+ 4	*a*
5098.715.......	704	11	0	*b*
5107.470.......	452	18	+ 7	*a*
5107.659.......	645	14	+ 3	*a*
5123.742.......	723	19	+ 9	*a*
5141.756.......	748	8	− 2	*b*
5142.545.......	541	4	− 6	*b*
5142.943.......	933	+10	− 1	*a*

TABLE VIII—*Continued*

WAVE-LENGTHS		Δλ		CLASS
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 3–4; Mean 3.4—*Continued*				
5150.860.......	843	+17	+ 6	*a*
5151.926.......	913	13	+ 2	*a*
5198.731.......	712	19	+ 8	*a*
5216.294.......	277	17	+ 6	*a*
5250.666.......	649	17	+ 6	*a*
5254.968.......	953	15	+ 4	*a*
5307.375.......	364	11	0	*a*
5322.055.......	046	9	− 2	*b*
5332.920.......	900	20	+ 9	*a*
5365.417.......	402	15	+ 4	*a*
5379.585.......	575	10	0	*b*
5398.295.......	282	13	+ 3	*b*
5455.634.......	612	+22	+10	*a*
Means.....	....	+11.6	+ 2.0	....
Solar Intensity 0–2; Mean 1.5				
3789.580.......	571	+ 9	+ 1	*b*
3793.484.......	479	5	− 3	....
3793.882.......	873	9	+ 1	....
3795.541.......	532	9	+ 1	....
3797.954.......	949	5	− 3	*b*
3801.815.......	805	10	+ 2	....
3802.288.......	284	4	− 4	....
3808.293.......	288	5	− 3	....
3813.645.......	639	6	− 2	....
3824.082.......	075	7	− 1	....
3825.414.......	405	9	+ 1	....
3830.768.......	758	10	+ 2	....
3837.146.......	133	13	+ 5	....
3845.698.......	693	5	− 3	....
3846.423.......	413	10	+ 2	*b*
3871.761.......	751	10	+ 1	*b*
3893.932.......	925	7	− 1	*b*
3897.460.......	450	10	+ 2	*b*
5028.140.......	129	11	0	*b*
5029.630.......	621	9	− 2	*b*
5065.207.......	199	8	− 3	*b*
5131.485.......	475	10	− 1	*a*
5235.402.......	390	12	+ 1	*b*
5242.510.......	493	17	+ 7	*a*
5247.068.......	049	19	+ 9	*a*
5250.228.......	209	19	+ 8	*a*
5251.982.......	968	14	+ 3	*b*
5288.541.......	530	11	0	*b*
5298.794.......	786	8	− 3	*b*
5326.157.......	151	6	− 5	*b*
5330.008.......	993	+15	+ 3	*a*

TABLE VIII—*Continued*

Wave-Lengths		Δλ		Class
Sun's Edge	Vacuum	Obs.	O−C	
Solar Intensity 0–2; Mean 1.5—*Continued*				
5332.678.......	670	+8	−3	*b*
5403.835.......	820	15	+3	*b*
5436.602.......	591	11	0	*b*
5464.292.......	283	9	−2	*b*
5532.761.......	749	12	0	*b*
5535.431.......	416	15	+3	*b*
5546.518.......	509	9	−3	*b*
5553.591.......	583	8	−4	*b*
5562.717.......	709	8	−3	*b*
5567.406.......	398	+8	−3	*b*
Means.....	....	+9.9	0.0	....

zontal currents is reduced to a minimum by combining measures in different latitudes and on photographs made on many different days.

The wave-lengths of the separate lines at the edge and in vacuum are entered in the first and second columns, respectively, of Table VIII. The displacements, λ edge *minus* λ vacuum, are entered as Δλ in the third column, and the residuals, displacement observed *minus* displacement calculated from general relativity, in the fourth column. The results are summarized in Table IX.

TABLE IX

Summary of Observations at the Sun's Edge
Iron Lines—Classes *a*, *b*

(Unit for Δλ=0.001 A)

No. of Lines	Wave-Length	Δλ		Level in Km	Int.
		Observed	O−C		
17........	3849	+10.4	+2.2	840	11.9
27........	4567	11.8	+2.4	520	5.8
48........	4600	11.6	+2.0	440	3.4
41........	4671	+9.9	0.0	350	1.5

DISCUSSION

From the point of view of general relativity it is significant that the displacement at the center and edge of the sun for every line in Tables VI and VIII is toward longer wave-length. For convenience, the discussion of this material is based on the summaries in Tables VII and IX.

At the center, for the region λ 3917, the average displacement to the red of lines of medium level, class *b*, intensity 6, is that predicted by general relativity. For lines of higher level it is greater, and for lines of lower level it is less than the calculated magnitude, the discrepancy in the latter case increasing systematically with decrease of level for each pressure class, as shown in the fifth column of Table VII. The relative levels are given by the horizontal velocities of outflow of the gases of the reversing layer from the spot vortex in the eighth column, the lowest level corresponding to the highest outward velocity,[1] and by the heights and intensities in the ninth and tenth columns.

At the limb the average displacement for low-level lines, mean intensity 1.5, originating at 350 km, is in exact agreement with Einstein's theory. For the next three levels, extending to 850 km, the deviations are sensibly constant and, in the mean, equal +0.0022 A. For the four groups observed at the limb, including 133 lines, the mean deviation from the theoretical displacement predicted by relativity is +0.0015 A.

The progression with level shown by the displacements at the center (Table VII) is that brought to light in section *e*, page 10, as something independent of relativity and there attributed to the action of radial currents. Such currents, however, cannot explain the total displacements between the sun and the arc, which are always positive. To do so would require the very improbable assumption of radial currents descending at all levels. An even more conclusive reason is that the sun-*minus*-vacuum displacements at the limb (Table IX), where radial currents can have no effect on the position of the line, are not zero. Practically speaking, the progression which is so conspicuous at the center disappears at the limb, which greatly strengthens the hypothesis that radial currents exist; but at the limb

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[1] St. John, *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 342, 1913.

there remains a mean positive displacement which, on the whole, is greater even than that at the center of the disk. Hence at the limb, some cause other than radial currents is also operative in producing displacements.

The universal positive displacement of lines at all levels, both at center and limb, was formerly attributed to a higher pressure in the sun than in the vacuum or open arc, but the pressure is now known to be practically zero in the atmospheres of the sun and stars. The red displacements cannot now be ascribed to increase of pressure over that in the arc.

Differences in the character of spectral lines at the center and the limb, as already suggested, raise a question as to the existence of a true limb effect. Such an effect may well account for the small systematic difference of +0.0015 A shown by the measures at center and limb after allowing for the progression attributed to radial currents, but leaves the bulk of the relatively large red displacement unexplained. The only other known agency which can account for this is the gravitational displacement of relativity. Allowance for this leaves, for the sun's center, the progressive sequence of residuals $O-C$ in the fifth column of Table VII, positive at high levels and negative at low levels, which are attributed, respectively, to descending and ascending currents. Ascending convection currents are to be expected at low levels; at high levels Milne's and Merfield's suggestion of the equivalent of downward currents is confirmed by the behavior of lines of very high level (Table V). The hypothesis of vertical currents requires zero effect at some intermediate level. For the center of the sun, relativity fixes this level at that for lines of group *b* of mean solar intensity 6 (see Table X), which by pure chance was originally selected to represent the medium level.

At the limb, the corresponding residuals in the fifth column of Table IX are practically constant. Here there is no question of radial currents, and the small mean difference, in so far as real, is provisionally regarded as a true limb effect.

One important test at least can immediately be applied to these conclusions with the aid of the present data. The red displacement of relativity is proportional to wave-length. Residuals found for lines of the same level, by allowing for a displacement varying in this manner, must correspond to radial motions which are independent of wave-length. Table XI gives such a comparison for two large groups of lines having the mean wave-lengths 4026 and 6295 A. Judged by the velocity of outflow from spots (third column, Table XI), the levels for the two groups are the same. The wave-lengths, total displacements, and residual displacements have the same ratio, as they should; and, finally, the upward velocities in the last column, which are equivalent to the negative residuals in the fifth column, are equal, in accordance with what was to have been expected.

TABLE X

LEVEL OF LINES GIVING THE EINSTEIN DISPLACEMENT

(Unit for Residuals = 0.001 A)

LINES	INT.	$\Delta\lambda$ Obs.	$\Delta\lambda$ O−C	EQUIV. VEL.	EVERSHED EFFECT	LEVEL	NO. OF LINES
				km/sec.	km	km	
Fe class *b*....	6.2	+8.2	0.0	0.00	0.48 out	525	32
Fe class *a*....	5	+9.6	− .7	− .04 up	.41 out	515	30
Ti..........	4.2	+9.1	+0.4	+0.03 dn	0.45 out	520	12
Means...	....	+9.0	−0.1	0.00	0.45 out	520	....

TABLE XI

DISPLACEMENTS OF LINES AT SAME LEVEL BUT IN DIFFERENT SPECTRAL REGIONS

NO. LINES	MEAN λ	VELOCITY OF OUTFLOW	$\Delta\lambda$ Sun−Vac.	$\Delta\lambda$ O−C	EQUIVALENT VELOCITY
		km/sec.			km/sec.
76...........	4026	0.63	0.0068 A	−0.0017 A	0.13 up
23...........	6295	0.62	0.0107	−0.0026	0.12 up
Ratio....	1.56	....	1.57	1.53	....

It should be noted that convection currents or other conditions producing similar effects are not arbitrarily introduced into the picture for the purpose of explaining the deviations of the observed displacements from the predictions of relativity. Instead, they are interpretations of the progression in the displacements, appearing in the stars as well as the sun, which is independent of relativity.

The particular interpretation adopted for the displacements which depend upon difference in level is not important in the present discussion, but their presence and effect should be taken into account in any consideration of line-displacement, as they were for the first time in my paper at the Los Angeles meeting of the American Association for the Advancement of Science,[1] September 23, 1923; again in *Monthly Notices of the Royal Astronomical Society*, December, 1923; and later in a paper before the National Academy of Sciences, April, 1924.[2] The displacements of low-level lines to the violet with respect to lines of medium level appear, however, to find an adequate explanation in currents rising from or through the photosphere; and of high-level lines to the red, in an excess of absorption on the red edge of the lines. The practical disappearance of these relative displacements at the limb strongly supports the interpretations adopted here.

In the main, the deviations from relativity to be expected in the case of lines observed at the sun's center will be negative, for 99 per cent of the 20,000 lines in Rowland's tables are lower in level than those of class *b*, intensity 6, which fulfil the prediction of Einstein. Only about 200 solar lines originate above the medium-level lines. These give positive residuals when observed and calculated displacements are compared.

The discussion of the measures at the sun's center up to this point has been based upon the 395 *Fe* lines of class *b*. Class *a* includes the *Fe* lines of lowest energy-level, the ultimate lines, and should represent the highest level reached by iron vapor in the sun's atmosphere. This is confirmed by the data in the seventh and eighth columns of Table VII. The highest-level lines of group *b* (840 km), mean intensity 13.6, show outflow, while the highest-level lines of group *a* (1140 km), mean intensity 13.7, show inflow around spots. The larger positive residual for group *a*, fifth column, and the greater downward velocity, sixth column, are a logical consequence of this difference in level, which itself is a consequence of the differences in excitation potentials. The two groups consist of lines

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[1] *Publications of the American Astronomical Society*, **5**, 84, 1923.

[2] *Mt. Wilson Communications*, No. 96; *Proceedings of the National Academy of Sciences*, **12**, 65, 1926.

in the same spectral region and of the same mean solar intensity. This would seem to eliminate any possible effects of an asymmetry varying with intensity or wave-length[1] and to leave difference in level as the effective condition.

The results for groups *c*5 and *d*5, because of pole-effect and asymmetry in the arc, would not have high weight if they stood alone; but their agreement with group *b* shows that pole-effect is practically eliminated. The close agreement between measures by Fabry and Buisson[2] and the present measures on the same eight lines of these groups adds further weight to them:

Fabry and Buisson, λ sun−λ arc in vacuum........+0.0075 A
Present measures, λ sun−λ arc in vacuum..........+0.0071

SUPPLEMENTARY EVIDENCE FROM OTHER ELEMENTS

A large number of measures have also been made at the sun's center for elements other than iron. These observations, which fully confirm the results and conclusions stated above, are here summarized for each of the elements in question.

Silicon.—The silicon lines are similar to the iron lines in behavior. This is illustrated in Table XII where the high-level lines are at the top and the low-level lines at the bottom.

Titanium.—The titanium spectrum has recently been measured in vacuum by Brown[3] and by Crew.[4] The lines of neutral titanium, Table XIII, show results consistent with the behavior of the iron lines and add the important fact that even very low-level lines, intensity 000–00, are displaced to the red by nearly 0.006 A. The march of excitation potential in the sixth column compared with level in the seventh column brings out clearly what was shadowed forth for iron in the seventh column of Table VII, namely, that lines of low energy-level are high-level lines in the sun. The titanium lines are identified in multiplets, and the excitation potential is known for each. Relatively few *Fe* lines are so identified. Nevertheless, the same relation between energy-level and height above the photosphere was evident for iron, but not so perfectly shown as for the titanium lines. Its emergence under the not very favorable condi-

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[1] Burns and Kiess, *Publications of the Allegheny Observatory*, **6**, 139 (No. 8), 1927.

[2] *Astrophysical Journal*, **31**, 113, 1910. [3] *Ibid.*, **56**, 53, 1922. [4] *Ibid.*, **60**, 108, 1924.

tions for iron indicates that the correlation represents a real relationship between the energy-level of the atom and the height at which atoms in a particular state of transition are present in detectable quantity. Excitation potentials are therefore properly included in section *d* with other criteria for determining the relative levels of Fraunhofer lines. They may be used, however, only for the lines of a given element taken in the large.

Manganese.—The arc spectrum of manganese has many unsymmetrical lines with large pole-effect, and, in general, the quality of the lines is not so high as for lines of the same pressure groups of iron. Monk[1] has made a short series of measures in vacuum. For these the sun-*minus*-vacuum displacements, as shown by the third section of Table XIV, yield results in agreement with those of iron at like level.

TABLE XII

NEUTRAL SILICON AND IRON AT SAME LEVEL

(Unit for $\Delta\lambda = 0.001$ A)

No.	Mean λ	Δλ		Equivalent Velocity	Level	Intensity
		Sun−Vac.	O−C			
				km/sec.	km	
1 *Si*........	3905	+11	2.7	+0.21 dn	800	12
34 *Fe*........	3943	11	2.7	+ .20 dn	840	13.6
5 *Si*........	5675	9.4	2.6	− .14 up	325	2
42 *Fe*........	6305	+10.2	3.2	−0.15 up	350	4.5

For *Fe* and *Mn* at the same level, as shown by the velocity of outflow from spots, the negative residuals give upward currents of the same velocity (top of third section, Table XIV). The longer the wave-length, the deeper we see into the sun's atmosphere. When *Mn* lines λ 5453 are compared with *Fe* lines λ 4269, the negative residuals for manganese show an upward current of higher velocity corresponding to its lower level (bottom of third section, Table XIV).

Cyanogen.—Lines in the 3883 band have been used by several investigators—Schwarzschild, St. John, Grebe and Bachem, and

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[1] *Astrophysical Journal*, 57, 222, 1923.

Evershed—in the study of the gravitational displacement of solar spectrum lines. The choice of lines for this purpose was made at a time when the pressure in the sun's atmosphere was thought to be of the order of 5–7 atmospheres. As band lines show no appreciable pressure shift, their use seemed to eliminate one variable. High pressure in the sun was then the accepted interpretation of the displacements to the red, now attributed to the sun's gravitational field.[1] The choice was unfortunate because of the high density of line-distribution, the overlapping of series, and the probability of undetected blends.

TABLE XIII

NEUTRAL TITANIUM

(Unit for Δλ=0.001 A)

No. of Lines	Mean λ	Δλ		Equiv. Veloc.	E.P.	Level	Solar Intensity
		Mean Obs.	O−C				
				km/sec.		km	
12.....	4110	+9.1	+0.4	+0.03 dn	0.324	520	4.2
32.....	4604	9.7	+ .1	.00	0.765	390	3
58.....	4496	9.2	−0.3	− .02 up	1.177	385	2
46.....	4537	8.1	−1.5	− .10 up	1.586	380	1
66.....	4770	7.0	−3.1	− .19 up	1.774	Low	0
188.....	4864	+5.9	−4.4	−0.27 up	1.934	Very low	000–00

My original investigation was confined to some 40 lines and gave negative results. In view of later work on the complete band, these lines might be called the "Forty Thieves." The present investigation includes the whole band, 515 lines, for which results are given in the left half of Table XV. It is assumed that random errors introduced by faulty measures, blends, and overlapping series are as likely to be positive as negative, and that their effect will be practically eliminated from the mean. As a check on the validity of this assumption, an excellent fourth-order spectrogram of the band was sent to R. T. Birge, of the University of California, for examination of the structure of the band, with special reference to the overlapping of series. As a result of his study of the plate, he selected a list of 184 lines which he considered especially suited to measurement. The results for these are given in the right half of Table XV.

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[1] Birge, *ibid.*, **59**, 45, 1924.

TABLE XIV

Manganese Lines; Mixed Classes

λ Sun's Center *minus* λ Arc in Vacuum
(Unit=0.001 A)

Wave-Lengths		Δλ		Class	E.P.	Level in Km	Solar Int.
Sun's Center	Vac.	Observed	O−C				
Solar Intensity 2–7; Mean 3.9							
4490.091	079	+12	+ 2	*c*	2.940	400	3
4502.226	220	6	− 4	*c*	2.907	300	2
4709.720	711	9	− 1	*b*	2.876	350	2
4739.115	106	9	− 1	*b*	2.928	350	3
4754.041	037	4	− 6	*d*	2.272	400	7
4761.530	518	12	+ 2	*b*	2.940	350	3
4762.377	367	10	0	*b*	2.876	400	5
4765.866	855	11	+ 1	*b*	2.928	300	3
4766.425	423	2	− 8	*b*	2.907	350	4
4783.426	426	0	−10	*d*	2.288	500	6
4823.516	512	+ 4	− 6	*d*	2.309	750	5
Means	....	+ 7.2	− 2.8	....	2.743	405	3.9
Solar Intensity 00–1; Mean 0							
5394.678	672	+ 6	− 5	*a*	0.000	....	1 1
5399.476	480	− 4	−15	*d*	3.836	....	1
5420.360	353	+ 7	− 4	....	2.133	....	0 0
5432.550	544	+ 6	− 6	*a*	0.000	....	1
5470.640	640	0	−12	*b*	2.154	....	0 0
5516.785	772	+13	+ 1	*b*	2.169	....	0 0
5537.764	753	+11	− 1	....	2.177	....	00 00
Means	....	+ 5.6	− 6.0	....	1.781	....	0

Comparison with Iron

Element	No. of Lines	Mean λ	Δλ		Equiv. Veloc.	Evershed Effect	Level in Km	Solar Int.
			Obs. Mean	O−C				
					km/sec.	km/sec.		
Fe	68	4728	+7.2	−2.8	−0.18 up	0.58 out	390	3.8
Mn	11	4714	7.2	2.8	.18 up	.60 out	405	3.9
Fe	42	4269	5.9	3.1	.22 up	0.84 out	Low	1
Mn	7	5453	+5.6	−6.0	−0.33 up	....	Lower	0

The 43 lines in my original paper are included among the 515 lines. Their remeasurement agrees well with the original measures, which failed to show displacements to the red in agreement with the Einstein theory of gravitation. Their influence, however, is counteracted in the final mean, based upon the far greater number of lines. The results for the center of the sun are reduced to the limb by adding 0.0026 A, the mean of the limb-*minus*-center displacement for *CN* lines found by Adams and of more recent measures by St. John. Since wave-lengths at the edge of the sun are free from the effect of radial currents, their displacement at the edge of the sun in reference to arc wave-lengths furnishes an appropriate measure of the red shift of Fraunhofer lines. For the *CN* lines the displacement at the limb is of the sign and approximate magnitude required by the theory of relativity.

TABLE XV

RED DISPLACEMENT OF THE CYANOGEN LINES IN THE 3883-BAND

(Unit for $\Delta\lambda = 0.001$ A)

Region	No. of Lines	$\Delta\lambda$	Region	No. of Lines	$\Delta\lambda$
λ 3729–λ 3782....	103	+3.8	λ 3793–λ 3819...	49	+4.4
3782– 3810....	103	4.2	3819– 3850...	46	4.3
3810– 3843....	103	5.1	3850– 3866...	45	5.5
3843– 3865....	103	4.6	3866– 3881...	44	+5.7
3865– 3883....	103	+4.9			
Mean for 515 lines (center)		+4.6	Mean for 184 lines (center)		+5.0
Mean for 515 lines (limb)..		7.2	Mean for 184 lines (limb)..		7.6
Relativity shift..........		+8.1	Relativity shift..........		+8.1

CONCLUSION

Lines originating at a level of 520 km above the sun's photosphere show displacements at the center of the sun in agreement with those given by general relativity (Table X).

Below this level, in the region where 99 per cent of solar lines originate, upward currents exist in the sun's atmosphere, which increase in strength with nearness to the photosphere. The iron lines of lowest level give a velocity of approximately 0.22 km/sec. upward; the effect vanishes at the edge of the sun so that for these lines the difference, λ at edge of sun *minus* λ for arc in vacuum, is the predicted Einstein displacement. When the high-, medium-, and low-level lines of iron are considered, the mean residual, λ at edge of sun *minus* λ for arc in vacuum, differs from Einstein's prediction by +0.0015 A. This difference, if real, is a true limb effect.

This investigation confirms by its greater wealth of material and in greater detail the conclusion announced in the Symposium on Eclipses and Relativity at Los Angeles, September 17, 1923, that the causes of the differences at the center of the sun between solar and terrestrial wave-lengths are the slowing up of the atomic clock in the sun according to Einstein's theory of general relativity, and radial velocities of moderate cosmic magnitude and in probable directions, or equivalent conditions whose effects vanish at the edge of the sun.

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