THE RED SHIFT OF THE IRON LINES AT THE EDGE OF THE SUN.

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In his paper on the gravitational displacement of the solar lines published in the *Astrophysical Journal*, 67, 1928, the late Dr. St. John states that "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 A. greater than that calculated from the theory of general relativity." This small residual he considered to be a true limb effect if real, but apparently of no great significance with regard to his main conclusion that "the causes of the differences at the centre 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 magnitude and in probable directions or equivalent conditions, whose effects vanish at the edge of the Sun."

My own measures of solar and arc lines in general sunlight and at the centre of the Sun's disc are in good agreement with those of St. John; and the conclusion I arrived at in 1923 was that "there is very little doubt that the Einstein effect is present in the solar spectrum." This was published in the *Observatory*, 66, 304, 1923, in which article I drew attention to the considerable excess of shift shown by certain high-level lines in the ultra-violet at the Sun's limb.

My very numerous measures of the strong and weak iron lines in the *H* and *K* region give a very much larger mean residual shift than is given by St. John, and they also show that the high- and low-level lines which at the centre of the Sun give very appreciable plus and minus residuals respectively give nearly equal shifts near the limb. There are two reasons why the shifts of the weak low-level lines are probably under-estimated. In the first place, my measures of the relative shift of these lines at numerous points across the

disc show that the increase of wave-length from the centre towards the limb becomes very rapid as the limb is approached, whereas the strong high-level lines show only a very small increase. As the measures are made always at a little distance within the limb, an appreciable correction to the limb is necessary for the weak lines. A further unknown correction due to scattered skylight, mainly from the centre of the Sun, is necessary, and this is especially the case for weak lines in the ultra-violet.

It may be for these reasons that St. John obtained very small residuals in the ultra-violet for the weaker lines. It is in any case quite certain that the group of *Fe* lines that I have measured in the *H* and *K* region give a true limb effect of at least +0·006 A., and this includes both high-level and low-level lines. It is also noteworthy that I have found the same excess over the Einstein effect in the calcium lines H_3 and K_3, not only as absorption lines in the chromosphere but also as emission lines high up in the prominences, where there can be no possible effect on the wave-length which might be thought to occur during the passage of the light through the gases of the Sun's atmosphere. This "limb effect," whatever its origin, is thus found well outside of the limb.

The discrepancy in our results has led me recently to make new measures of limb and arc in the red region, where atmospheric scattering is less than in the more refrangible part of the spectrum. In the year 1921 I measured the limb – arc shifts of five *Fe* lines, not subject to pole effect, in 17 grating spectra obtained at Kodaikanal. These gave such large values of the shift that I had doubts of its reality, but now I have obtained some excellent spectra at Ewhurst, and these give similar results. The difficulty in this region is the necessity for very long exposures in order to get good images of the arc lines. The iron arc requires about 30 times the exposure needed on the Sun's limb, although at the other end of the visible spectrum it is the Sun that requires the longer exposure. This difficulty almost precludes the use of the liquid prism: I have therefore employed a solid 60° prism of 2½-inch aperture backed by a 30° prism, and to get sufficient dispersion the light is made to traverse the two prisms six times to and fro, the resolving power being equivalent to nine 60° prisms of that aperture. With this equipment the exposure on the Sun's edge in winter is 15 seconds, and on the *Fe* arc about 8 minutes, the linear dispersion being 1·3 mm. = 1 A. This is ample for the purpose, and the spectra are well suited to the extremely accurate method of measuring by superposing positive images reversed on the negatives. I give in Table I the results of these measures.

TABLE I

λ	17 Grating Spectra $\Delta\lambda$	8 Prism Spectra $\Delta\lambda$	Weighted Mean $\Delta\lambda$
6136·631	+·026	+·027	+·026
6137·709	+·024	+·027	+·025
6191·577	+·025	+·030	+·027
6230·742	+·022	+·029	+·024
6252·572	+·022	+·027	+·024

These are the shifts observed at points on the Sun about ·98 of a radius from the centre, and are therefore under-estimates. The correction, however, is not likely to exceed ·001 A. The shifts have been corrected for the pressure in the arc assuming the Sun to be at zero pressure. This gives a true limb effect of at least +0·012 A.

We may here consider also the limb effect of the hydrogen line $H\alpha$, which, notwithstanding its width of about 1 A. in the Sun, can be measured more accurately than the other hydrogen lines. The difference of wave-length of this line at the centre of the Sun compared with the vacuum tube is +0·023 A.,* and to this should be added the limb-centre shift of +0·002 A. measured by Adams.† The limb – vacuum wave-length is therefore

	+0·025 A.
Subtract Einstein effect	+0·014 „
Limb Effect	+0·011 A.

Thus the limb effect is the same order of size in this case also.

In measuring the shifts at the Sun's edge St. John made rather a curious selection of lines. For those of solar intensity 8–25 only the ultra-violet region between λλ 3787 and 3906 was used, and for lower intensities the same ultra-violet region, but in addition lines between λλ 5000 and 5567. He left out of account the entire range of the blue and violet and the red. Although he did not measure the limb shifts in these regions he gives long lists at the centre of the Sun, including almost the whole length of the visible spectrum. These are comparisons of the normal solar spectrum and the vacuum arc, and it so happens that for over a hundred of these lines we can deduce the limb shifts by adding the limb – centre shifts previously determined at Mt. Wilson and at Kodaikanal.‡ In Table II, which follows, I give the results for 105 *Fe* lines between λλ 3748 and 6495 that correspond in the various tables. These are all of St. John's classes A and B, but had I included his classes C and D, which are less trustworthy owing to pole effect, 30 lines would have been added to the list; and although these lines give a less uniform and slightly smaller limb shifts, the mean excess given by them over relativity is +0·003 A. No appreciable difference would therefore have been made in the general result.

In all this list only 18 lines occur in St. John's direct measures of limb shift. Four of these are in the ultra-violet, and 14 are in the green. The agreement with this list is very good in both regions, and only 4 lines in the green show a marked deficiency in the direct measures.

The figures in the last column of the table are also in good agreement with my values of the limb shift in the two spectral regions that I have specially studied. In the red region also the mean values from the 25 spectra

* This is the difference between Curtis's value of the wave-length of $H\alpha$ (*Proceedings of the Royal Society*, A, 90, 1914) and the solar wave-length in the Revision of Roland.

† *Astrophysical Journal*, 31, 45, 1910. This is the observed shift between centre and limb. Adams applied corrections to his observed values which are not justified by present knowledge of the very low pressure in the chromosphere.

‡ *Astrophysical Journal*, 31, 37–45, and *Kodaikanal Bulletin*, 39, 72–4, 1911.

TABLE II

λ Revised Roland	Int.	Limb − ○ Mt. Wilson	Limb − ○ Kodaikanal	○ − Vacuum Arc St. John	Limb − Vacuum Arc A/1000
3748·273	10	+ 2	...	+ 10	+ 12
3834·235	10	4	...	11	15
3846·419	2	5	...	10	15
3871·760	2	8	...	10	18
3895·669	7	...	− 3	10	7
3902·958	10	...	− 2	11	9
3906·492	10	...	+ 4	9	13
3920·271	10	...	6	11	17
3922·925	12	...	7	12	19
3925·653	5	...	7	7	14
3927·935	8	...	2	13	15
3930·310	8	...	2	12	14
3931·131	1	...	8	7	15
3935·828	2	...	4	13	17
3937·339	3	...	3	9	12
3948·787	4	...	8	9	17
3949·963	5	6	6	7	13
3956·688	6	7	6	9	15
3966·075	3	...	4	9	13
3969·270	10	...	4	11	15
3977·752	6	6	7	9	16
3986·182	3	...	6	6	12
3998·060	4	...	7	4	11
4009·719	3	...	9	4	13
4021·872	5	9	14	2	14
4045·827	30	...	8	13	21
4062·451	5	...	8	6	14
4063·607	20	8	8	11	19
4071·751	15	...	3	11	14
4076·639	4	...	7	3	10
4118·557	5	...	6	8	14
4127·615	4	...	5	3	8
4134·687	5	...	6	5	11
4143·880	15	8	8	9	17
4154·507	4	...	6	4	10
4175·645	5	...	6	5	11
4181·766	5	...	7	8	15
4202·042	8	5	3	11	15
4220·349	3	8	7	5	12
4258·326	2	6	...	7	13
4271·776	15	6	...	12	18
4282·413	5	7	8	8	15
4291·475	2	7	...	8	15
4307·914	6	...	10	8	18
4325·777	8	3	− 2	13	14
4337·057	5	8	+ 8	8	16
4352·745	4	...	6	8	14
4369·781	4	...	12	8	20
4375·946	6	5	4	14	18
4383·559	15	...	1	11	12
4404·763	10	...	− 1	10	9
4415·137	8	...	+ 3	11	14

λ Revised Roland	Int.	Limb – ○ Mt. Wilson	Limb – ○ Kodaikanal	○ – Vacuum Arc St. John	Limb – Vacuum Arc Adams
4427·319	5	...	10	7	17
4430·624	3	8	8	7	15
4442·351	6	8	4	9	15
4447·730	6	5	4	10	15
4454·390	3	7	7	7	14
4461·662	4	7	7	8	15
4466·564	5	...	8	11	19
4489·750	4	7	...	8	15
4494·575	6	10	6	7	15
4522·640	3	10	...	8	18
4531·160	5	7	8	8	15
4547·856	3	8	4	6	12
4549·476	2	8	...	6	14
4592·661	4	...	6	6	12
4602·951	6	...	4	7	11
4619·299	3	...	4	6	10
4638·019	4	...	5	4	9
4678·857	6	...	6	5	11
4733·599	4	10	...	5	15
4741·538	3	8	...	7	15
4745·809	4	9	...	6	15
4786·816	2	8	...	6	14
4789·660	3	7	...	7	14
4924·779	3	8	...	6	14
4994·139	3	8	...	6	14
5083·347	4	9	...	5	14
5171·612	6	...	– 2	13	11
5194·951	4	8	+ 4	8	14
5198·718	3	7	...	8	15
5216·285	3	...	3	9	12
5328·544	4	...	7	12	19
5332·910	4	10	...	8	18
5405·787	6	9	...	10	19
5429·708	6	9	...	9	18
5434·536	5	10	...	12	22
5446·926	6	10	...	9	19
5455·626	4	8	...	14	22
5497·528	5	12	...	9	21
5501·479	5	10	...	12	22
5506·793	5	11	...	12	23
5956·709	4	10	...	11	21
6065·499	7	12	...	11	23
6136·631	8	13	...	13	26
6173·348	5	14	...	10	24
6191·577	9	14	...	13	27
6213·443	6	14	...	9	23
6230·742	8	11	...	12	23
6252·572	7	13	...	10	23
6265·148	5	13	...	8	21
6318·036	6	14	...	12	26
6380·756	4	8	...	8	16
6430·863	5	12	...	9	21
6495·001	8	13	...	13	26

given in Table I agree almost exactly with the same lines in Table II. These comparisons are given in detail in Table III, where my values in column 3, it must be understood, have been obtained with an open arc at ¾ atmosphere at Kodaikanal and 1 atmosphere at Ewhurst. A correction has therefore been applied to allow for the atmospheric pressure in the arc, assuming, of course, a zero pressure in the Sun. These corrections are derived from the pressure shift measures of Adams and Gale,* and Babcock.†

TABLE III

Group 1

Wave-length	Limb – Vacuum Arc from Table II A/1000	Limb – Vacuum Arc Evershed A/1000	No. of Spectra Measured
3895·669	7	14	32
3902·958	9	13	38
3906·492	13	16	43
3920·271	17	15	78
3922·925	19	15	78
3925·653	14	13	21
3927·935	15	15	76
3930·310	14	16	72
3935·828	17	17	28
3949·963	13	14	44
3956·688	15	14	56
3966·075	13	13	49
3969·270	15	16	59
3977·752	16	13	39
Means 3932	+0·0141 A.	+0·0146 A.	
Subtract Einstein effect	−0·0083 „	−0·0083 „	
Limb effect	+0·0058 A.	+0·0063 A.	

Group 2

Wave-length	Limb – Vacuum Arc from Table II A/1000	Limb – Vacuum Arc Evershed A/1000	No. of Spectra Measured
4375·946	18	15	35
4383·559	12	11	19
4404·763	9	12	20
4415·137	14	10	20
4427·319	17	12	29
4442·351	15	17	28
4447·730	15	20	28
4454·390	14	13	25
4461·662	15	13	28
4466·564	19	18	28
4489·750	15	12	18
Means 4433	+0·0148 A.	+0·0139 A.	
Subtract Einstein effect	−0·0094 „	−0·0094 „	
Limb effect	+0·0054 A.	+0·0045 A.	

* *Astrophysical Journal*, 35, 10, 1912. † *Ibid.*, 67, 240, 1928.

Group 3

	Wave-length	Limb – Vacuum Arc from Table II A/1000	Limb – Vacuum Arc Evershed A/1000	No. of Spectra Measured
	6136·631	26	26	25
	6137·709	...	25	25
	6191·577	27	27	25
	6230·742	23	24	25
	6252·572	23	24	25
Means omitting 6137	6203	+0·0248 A.	+0·0252 A.	
Subtract Einstein effect		−0·0131 „	−0·0131 „	
	Limb effect	+0·0117 A.	+0·0121 A.	

While these comparisons show a general agreement between the combined measures in Table II and direct measures of the limb shift, considerable errors may occur where but few plates have been measured of solar lines. There are always local currents, either parallel to or radial to the Sun's surface which upset our measures, and only mean values from at least 20 spectra can give reliable results. It is possible that future work may indicate considerable corrections for some of the lines. The irregular way in which limb shift and limb effect vary with wave-length seems to suggest this. In a general way from the violet to the red the shift increases as a Doppler or Einstein effect increases, but in the blue between λλ 4500 and 4900 the values are much too small. This is shown in Table IV, where I give the mean shift and mean limb effect for each consecutive set of ten lines, excepting the last set containing 15 lines. The first column gives the corresponding mean wave-length. It will be noted that in the red the limb effect is nearly equal to the Einstein effect; in other words, the shift at the limb is probably equal to the Einstein effect × 2.

TABLE IV

Mean Wave-length	Mean Limb Shift A/10,000	Mean Limb Effect A/10,000
3877	139	57
3941	147	64
4028	143	58
4172	136	48
4330	160	68
4444	148	54
4578	127	30
4917	140	36
5375	185	71
6121	230	106

It is to be hoped that arc and Sun limb spectra may be obtained at future solar eclipses, either total or annular, in order to get values of the limb effect freer from the effects of scattered light than is possible under ordinary conditions. Apart from the fact that the values given in these tables are

probably under-estimated, it is certain that the limb effect is very far from being a negligible quantity. Unfortunately it seems to land us on the horns of a dilemma, for we must either suppose that the excess over relativity is a Doppler effect, in which case we have to imagine the solar gases to be receding at all times from the Earth, or that the general theory of relativity requires a factor of 2 to be introduced in the slowing down of the atomic clocks. I believe that no astronomer will care to impale himself on either of these horns, but in that case he has to find an explanation of the limb effect which applies equally to the absorption lines of the reversing layer and to the emission lines in the prominences beyond the limb.

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