Kodaikanal Observatory.

BULLETIN No. XXXIX.

ON THE DISPLACEMENTS OF THE SPECTRUM LINES AT THE SUN'S LIMB.

An investigation of the displacements of the spectrum lines at the sun's limb was made by W. S. Adams in 1909, using the tower telescope and 30-foot spectrograph at Mount Wilson.* It was shown that, if we except the lines characteristic of the higher chromosphere which show little or no displacement, the great majority of the lines are displaced to the red relatively to the lines at the centre of the disk. This relative shift increases with the wave-length for all the elements investigated, and for iron the displacements increase rather more rapidly than in direct proportion to wave-length.

Dr. Adams adopts the explanation of this shift suggested by Halm, who believed it to be due mainly to pressure, the effective region of absorption at the limb being supposed to be at a lower level and therefore higher pressure than at the centre of the disk, owing to the relatively longer path of tangential rays in the lower levels of the reversing layer compared with the rays passing normally through the solar atmosphere, as at the centre of the disk.

As an alternative to this theory we might suppose the shifts to be due to motion in the line of sight. If the gases are ascending radially all over the sun with the required velocity, the relative shift to the red at the limb as compared with the centre of the disk would result. This however is ruled out because we find a descending, not an ascending movement, when the positions of the lines at the centre are directly compared with those from a terrestrial source. If the shifts are the result of movement then they can be explained only by a motion parallel to the solar surface, and directed away from the earth at all points of the solar circumference. This suggests that the earth itself controls the movement, exerting a repelling action on the solar gases.

Obviously the pressure theory presents a much more rational explanation of the phenomenon than the motion theory; yet there are difficulties in accepting the former which have not been in any way lessened, but on the contrary have been largely increased, by further research. An initial difficulty which appeals to us is the absence of any evidence of shading or indefinite edges on the red sides of the lines near the sun's limb. If the photospheric light coming from the limb passes through successive layers of diminishing pressure, one would expect the absorption to begin gradually at the red edge of a line, especially as the absorption would be weakest in the lowest and hottest layers where the pressure is greatest, and would increase as the rays entered the cooler regions of less pressure. The red sides of the displaced lines should therefore appear indefinitely bounded, yet no trace of any such effect is apparent. The lines of the limb spectrum are broader than those of the centre spectrum, but they are sharply bounded on both red and violet edges. Perhaps the strongest argument in favour of the pressure theory which Adams gave in his paper is based on the relative shifts of the iron lines which are most and least affected by pressure. He found that the lines most affected by pressure gave the largest limb — centre shifts, and he also argued that the large increase of shift with wave-length for the iron lines pointed to pressure as the main factor in the case.

We find it difficult to accept these results, because we consider that the relative shifts of different lines at the limb have no particular meaning when determined by reference to the lines at the centre of the disk, for these latter have shifts peculiar to themselves, and our measures show that the absolute shifts of the lines

* Astrophysical Journal XXXI, 30, 1910.

at the limb referred to a terrestrial standard show no relation to pressure shifts, and further, the absolute shifts do not increase with the wave-length.

We have discussed in Kodaikanal Observatory Bulletin Nos. XXXVI and XXXVIII the shifts of the lines at the centre of the disk compared with the arc in air, and consider that our results clearly show that pressure is not concerned in the general displacement of the solar lines towards the red. A small pressure effect is nevertheless traceable, but this indicates a pressure of less than one atmosphere in the region of iron absorption as observed at the centre of the disk.

This result seems to argue against any large pressure effect at the limb, such as would be deduced from the shifts limb — centre.

Determination of limb shifts.

In determining the absolute shifts of the lines at the limb we have simply combined our measures of the limb — centre shifts with the centre — arc shifts, the algebraical sum of the shifts representing the absolute or limb — arc shifts. A number of direct measures of the limb — arc shifts were also made by one of us, and these, so far as they go, confirm the indirect determinations.

The spectrograph employed has already been described in Kodaikanal Observatory Bulletin No. XXXVI. For the limb — centre shifts photographs are obtained by means of a reflecting device placed in front of the spectrograph slit. With this apparatus simultaneous exposures are made with light from the centre of the disk and from points one-thirtieth of the sun's radius inside the limb at the opposite ends of a diameter. The spectra form three contiguous strips on the plate each about 1·5 mm. in width. After the exposure on the sun, an exposure is made on the iron arc to impress the iron lines on the plate outside the solar spectra: these serve to determine accurately the inclination of the micrometer thread to the spectrum lines in measuring the displacements, but are not used to determine centre — arc or limb — arc shifts on these plates. In this way the total shift west limb — east limb due to the solar rotation may be accurately determined as well as the limb — centre shifts.

In table I we give a list of all the iron lines of which we have measures of both limb — centre shifts and centre — arc shifts. The algebraical sum of these given in column 6 represents the absolute shift of the lines near the limb when compared with the iron arc in air at 580 mm. pressure, the normal pressure at Kodaikanal.

TABLE I.—SHIFTS OF IRON LINES.

λ (Rowland).	Intensity.	Limb — centre. Kodaikanal.	Limb — centre. Mt. Wilson.	☉ — arc.	Sum.	Remarks.	Number of measures. Limb — centre.	Number of measures. ☉ — arc.
		A/1000.	A/1000	A/1000.	A/1000			
3895·803	7	— 3	...	+ 14	+ 11		2	4
3899·850	7	— 4	...	+ 19	+ 15		4	4
3903·090	10	— 2	...	+ 17	+ 15		4	4
3906·628	10	+ 4	...	+ 11	+ 15		5	4
3920·410	10	— 1	+ 6	+ 15	+ 17	3 plates give zero shift and one plate — 6 (limb — centre).	4	4
3923·054	12	+ 7	...	+ 14	+ 21		4	4
3925·790	5	+ 7	...	+ 5	+ 12		3	1
3928·075	8	+ 2	...	+ 18	+ 20		2	4
3930·450	8	+ 2	...	+ 14	+ 16		5	4
3931·269	1	+ 8	...	+ 8	+ 16		3	1
3935·965	2	+ 4	...	+ 13	+ 17		3	1
3937·479	3	+ 3	...	0	+ 3		3	1
3948·925	4	+ 8	...	+ 6	+ 14		3	1
3950·102	5	+ 6	+ 6	+ 5	+ 11		4	1
3956·819	6	+ 6	+ 7	+ 4	+ 11		5	4
3966·212	3	+ 4	...	+ 4	+ 8		3	1
3969·413	10	+ 4	...	+ 14	+ 18		5	4
3977·891	6	+ 7	+ 6	+ 6	+ 13		6	3
3986·321	3	+ 6	...	+ 5	+ 11		2	1
3998·205	4	+ 7	...	0	+ 7		2	1
4005·408	7	+ 8	+ 8	+ 8	+ 16		1	3
4009·864	3	+ 9	...	— 5	+ 4		1	1
4022·018	5	+ 14	+ 9	0	+ 12		1	1
4045·975	30	+ 8	...	+ 6	+ 14		1	2

TABLE I.—SHIFTS OF IRON LINES—*cont.*

λ (Rowland).	Intensity.	Limb − centre. Kodaikanal.	Limb − centre. Mt. Wilson.	⊙ — arc.	Sum.	Remarks.	Number of measures. Limb — centre.	Number of measures. ⊙ — arc.
		A/1000.	A/1000.	A/1000.	A/1000.			
4062·599	5	+ 8	...	+ 4	+ 12		1	2
4063·759	20	+ 8	+ 8	+ 6	+ 14		1	4
4071·908	15	+ 3	...	+ 8	+ 11		1	3
4076·792	4	+ 7	...	+ 3	+ 10		1	1
4118·708	5	+ 6	...	+ 3	+ 9		3	2
4127·767	4	+ 5	...	+ 5	+ 10		2	2
4134·840	5	+ 6	...	+ 2	+ 8		2	2
4140·089	6	− 1	..	(+ 12)	+ 11	Limb — arc direct measure.	2	...
4144·038	15	...	+ 8	+ 14	+ 22		..	3
4147·836	4	+ 7	...	(+ 2)	+ 9	Limb — arc direct measure.	3	...
4154·667	4	+ 6	...	+ 7	+ 13		3	2
4175·806	5	+ 6	...	+ 2	+ 8		3	4
4181·919	5	+ 7	...	+ 4	+ 11		1	6
4187·204	6	+ 2	...	+ 7	+ 9	Unsharp line in arc	2	3
4191·595	6	+ 3	...	+ 2	+ 5		3	6
4202·198	8	+ 3	+ 5	+ 11	+ 15		4	4
4220·509	3	+ 7	+ 8	(0)	+ 8	Limb — arc direct measure.	1	...
4227·606	4	+ 4	...	+ 5	+ 9		1	2
4233·772	6	+ 7	+ 8	— 1	+ 7		1	3
4236·112	8	− 7	...	+ 4	− 3		1	3
4250·287	8	− 3	...	+ 6	+ 3		3	2
4260·640	10	+ 7	+ 4	+ 7	+ 12		2	1
4271·325	6	+ 3	...	+ 5	+ 8		3	3
4271·934	15	− 6	+ 6	+ 9	+ 9		2	3
4282·565	5	+ 7	+ 7	+ 7	+ 14		2	4
4308·081	6	+ 10	...	+ 8	+ 18		4	4
4315·262	4	+ 9	+ 8	+ 9	+ 18		7	4
4325·939	8	+ 2	+ 3	+ 10	+ 13		6	6
4337·216	5	+ 8	+ 8	+ 5	+ 13		6	4
4352·908	4	+ 6	+ 6	+ 4	+ 10		7	3
4369·941	4	+ 12	...	+ 11	+ 23		2	1
4376·107	6	+ 4	+ 5	+ 11	+ 15		2	2
4383·720	15	+ 1	...	+ 9	+ 10		2	5
4404·927	10	− 1	...	+ 9	+ 8		3	4
4415·293	8	+ 3	...	+ 12	+ 15		4	2
4427·482	5	+ 10	...	+ 3	+ 13		3	4
4430·785	3	+ 8	+ 8	+ 1	+ 9		4	3
4442·510	6	+ 4	+ 6	+ 8	+ 13		3	3
4443·365	3	+ 11	+ 7	+ 4	+ 13		2	2
4447·892	6	+ 4	+ 5	+ 14	+ 18		1	1
4454·552	3	+ 7	+ 7	+ 6	+ 13		2	2
4461·818	4	+ 7	+ 7	+ 7	+ 14		3	3
4466·727	5	+ 8	...	+ 12	+ 20		2	4
4494·738	6	+ 6	+ 10	+ 7	+ 15		3	4
4508·455	4	...	+ 11	+ 4	+ 15	p Fe in short arc	...	1
4515·508	3	...	+ 11	+ 3	+ 14	p Fe in short arc	...	1
4522·802	3	...	+ 10	− 2	+ 8	p Fe in short arc	...	1
4528·798	8	+ 4	+ 5	+ 10	+ 14		4	3
4531·327	5	+ 8	+ 7	+ 5	+ 12		5	2
4548·024	3	+ 4	+ 8	+ 6	+ 12		4	2
4549·642	2	...	+ 8	0	+ 8	p Fe in short arc	...	1
4556·063	3	...	+ 11	+ 1	+ 12	p Fe in short arc	...	1
4584·018	4	...	+ 12	+ 4	+ 16	p Fe in short arc	...	1
4592·840	4	+ 6	...	+ 8	+ 14		4	2
4603·126	6	+ 4	...	+ 8	+ 12		3	2
4607·831	4	+ 7	...	+ 2	+ 9		2	1
4619·468	3	+ 4	...	+ 5	+ 9		2	1
4625·227	5	+ 7	...	− 1	+ 6		2	1
4637·685	5	+ 4	...	+ 1	+ 5		2	1
4638·193	4	+ 5	...	+ 1	+ 6		2	1
4647·617	4	+ 7	...	+ 9	+ 16		1	2
4654·672	4	+ 6	...	+ 3	+ 9		1	1
4654·800	5	+ 9	...	+ 1	+ 10		1	1
4667·626	4	+ 6	...	− 1	+ 5		2	1
4679·027	6	+ 6	...	+ 2	+ 8		2	1
4707·457	5	+ 4	...	+ 5	+ 9		1	1
4733·779	4	...	+ 10	+ 1	+ 11		...	1
4736·963	6	...	+ 8	+ 1	+ 9		...	1
4787·003	2	...	+ 8	+ 4	+ 12		...	1
4789·849	3	...	+ 7	+ 6	+ 13		...	1
4859·928	4	...	+ 9	+ 2	+ 11		...	3

TABLE I.—SHIFTS OF IRON LINES—*cont.*

λ (Rowland).	Intensity.	Limb − centre. Kodaikanal.	Limb − centre. Mt. Wilson.	⊙ − arc.	Sum.	Remarks.	Number of measures. Limb − centre.	Number of measures. ⊙ − arc.
		A/1000.	A/1000.	A/1000.	A/1000.			
4871·512	5	+ 8	+ 9	+ 4	+ 13		1	3
4872·332	4	+ 6	...	+ 3	+ 9		1	3
4890·948	6	+ 5	...	+ 8	+ 13		1	3
4891·683	8	− 1	...	+ 10	+ 9		1	3
4903·502	5	+ 17	...	0	+ 17		1	3
4919·174	6	...	+ 9	0	+ 9		...	2
4924·107	5	...	+ 9	+ 5	+ 14	p Fe in short arc	...	1
5018·629	4	...	+ 8	+ 16	+ 24	p Fe in short arc	...	2
5083·518	4	...	+ 9	+ 7	+ 16		...	2
5107·619	4	0	...	+ 4	+ 4		2	2
5107·823	4	+ 12	...	+ 4	+ 16		2	2
5139·427	4	+ 3	...	− 3	0	⊙ − short arc = − 11	2	4
5139·644	4	...	+ 7	0	+ 7		...	5
5162·449	5	+ 6	...	− 33	?	Faint and diffuse line in arc.	1	1
5167·678	5	+ 17	...	+ 16	+ 33	b_4.	1	4
5169·069	3	− 1	...	+ 11	+ 10		1	1
5169·220	4	+ 8	...	+ 18	+ 26	p Fe in short arc	1	1
5171·778	6	− 2	...	+ 15	+ 13		1	4
5191·629	4	+ 6	...	− 1	+ 5	⊙ − short arc = − 14	1	4
5192·523	5	0	...	+ 2	+ 2	⊙ − short arc = − 11	2	4
5195·113	4	+ 4	+ 8	+ 6	+ 12	⊙ − short arc = − 1	1	4
5216·437	3	+ 3	...	+ 6	+ 9	⊙ − short arc = + 1	2	3
5227·362	5	+ 3	...	+ 3	+ 6		1	3
5233·122	7	0	...	+ 7	+ 7		1	3
5266·738	6	+ 5	...	− 4	+ 1		1	2
5269·723	8	− 1	...	+ 9	+ 8		1	2
5281·971	5	+ 1	...	− 3	− 2	⊙ − short arc = − 9	1	2
5283·802	6	+ 4	...	− 1	+ 3	⊙ − short arc = − 7	1	2
5302·480	5	+ 3	...	− 3	0		2	2
5316·790	4	+ 9	+ 12	− 1	+ 10	p Fe in short arc	2	1
5324·373	7	+ 2	...	+ 9	+ 11		2	2
5328·236	8	+ 3	...	+ 15	+ 18		2	2
5328·721	4	+ 7	...	+ 8	+ 15		2	2
5340·121	6	+ 5	...	− 6	− 1		2	2
5405·989	6	...	+ 9	+ 9	+ 18		...	3
5424·290	6	...	+ 7	+ 30	+ 37	Faint and diffuse in arc	...	1
5429·911	6	...	+ 9	+ 6	+ 15		...	4
5434·740	5	...	+ 10	+ 8	+ 18		...	4
5447·130	6	...	+ 10	+ 5	+ 15		...	4
5455·834	4	...	+ 8	+ 19	+ 27		...	4
5569·848	6	+ 9	+ 11	+ 5	+ 15		4	1
5573·075	6	+ 5	...	+ 7	+ 12		4	1
5586·991	7	+ 5	+ 10	+ 4	+ 12		4	2
5615·877	6	+ 1	+ 9	+ 9	+ 14		4	...

In forming this table we have given Dr. Adams' values of the limb shifts in column 4 under the heading "Mount Wilson" and these values have been used in forming column 6 for the lines which we have not yet measured. For lines measured at both observatories the mean of the two determinations of limb — centre has been used. For most of the common lines the agreement between Mount Wilson and Kodaikanal is excellent, but there are two or three marked discrepancies such as the lines 3920·410 and 4271·934, which according to our measures are shifted towards the violet instead of towards the red as in Dr. Adams' determinations. The values in column 6 for these lines must be subject to considerable uncertainty.

As regards the relative accuracy of the different determinations, we give in the last two columns of table I the number of measures on which each value depends. In most cases several plates taken at different dates and in different solar latitudes have been used for each determination of limb — centre or sun — arc shift. There appear to be considerable systematic variations in the amount of the shifts given by different plates, for both limb — centre and centre — arc, so that values obtained from one plate only are subject to this variation from the mean in addition to the greater accidental error of measurement.

The sun — arc measures are the same as those given in Kodaikanal Observatory Bulletin No. XXXVI, with additions and improved values for many of the lines obtained from later measures.

Limb shifts in relation to the intensity of the lines.

The first point to be noted in these measures is the relation to intensity. If the lines are grouped according to their intensity in the sun the following mean results are obtained :—

TABLE II.—MEAN SHIFTS IN RELATION TO INTENSITY.

Intensity.	Number of lines.	Limb – centre.	Centre – arc.	Limb – arc.
8 and over	24	+ 0·0023 A	+ 0·0107 A	+ 0·0130 A
7 and 6	33	+ 0·0047	+ 0·0063	+ 0·0110
5	26	+ 0·0074	+ 0·0037	+ 0·0111
4	34	+ 0·0073	+ 0·0051	+ 0·0124
3 and under	20	+ 0·0066	+ 0·0038	+ 0·0104

In this table all the lines of table I are used in forming the means excepting two. These are the lines at λ 5162·449 and λ 5424·290, which give very anomalous shifts due to peculiar conditions in the arc. Many other lines also are probably affected by the arc conditions, especially those which widen unsymmetrically under pressure, but as it is not at present possible to classify all the lines of table I it has seemed best to take general means, excluding only those above-mentioned lines which give enormous centre — arc shifts which are almost certainly not connected with solar conditions.

Although individual lines for each intensity give very different shifts for both limb — centre and centre — arc, the relation to intensity is well marked in the means. The limb shifts increase as the intensity diminishes from the strongest lines to intensity 5, whilst the centre shifts decrease over the same range. Below intensity 5 the shifts are nearly constant. If the arc lines may be considered to be in their normal positions, then the relation to intensity of the limb — centre shifts is only an apparent one and is really due to the varying shifts of the lines at the centre of the disk, for the added shifts given in the last column " limb — arc " show practically no relation to intensity.

Relation between limb shifts and pressure shifts.

If we group the total shifts, limb — arc at 580 mm. pressure according to the amount of the pressure shifts, the following results are obtained :—

TABLE III.—MEAN SHIFTS IN RELATION TO PRESSURE SHIFTS.

Region.	Number of lines.	Mean pressure shift per atmosphere.	Mean shift limb — arc.
A.—Lines most affected by pressure.			
4187–4528	13	+ 0·0097 A.	+ 0·0092 A.
4859–5615	14	+ 0·0134	+ 0·0096
B.—Lines least affected by pressure.			
3895–4466	40	+ 0·0022	+ 0·0140
4531–5455	19	+ 0·0029	+ 0·0140

It is here seen that the mean limb shifts do not increase as do the pressure shifts in passing from the more refrangible to the less refrangible groups of lines, and that the lines most affected by pressure are least shifted at the limb.

If the limb — arc shifts are corrected for the defect of pressure at Kodaikanal from normal and the results for the two spectral regions are averaged, the limb — arc shifts for normal pressure become + 0·0065 A for the lines most affected by pressure, and + 0·0134 A for the lines least affected by pressure. If the wave-lengths of the arc lines are supposed to be unaffected by other conditions, this would mean a total pressure at the limb of 0·24 atmosphere only, but it is very questionable whether the arc under the conditions of our experiments does give " normal " wave-lengths for many of the lines. Dr. Royds has shown that lines which are unsymmetrical in the arc (*i.e.*, the majority of lines with large pressure shifts) are displaced in the short arc compared with the long arc.* This shift is not due to pressure differences or to motion, but appears to be a density effect, and there are reasons for believing that in the long arc (5 to 7mm.) the conditions, although approaching more nearly to solar conditions than in the short arc, are still far from being the same as in the reversing layer, where the gases appear to be of the last degree of tenuity. Many of the arc lines therefore which we have compared with the sun, and especially those which give abnormal pressure shifts, may be

* Kodaikanal Observatory Bulletin No. XXXVIII.

affected by this density shift which would in general tend to reduce the sun — arc shifts for the lines most affected by pressure.

It would seem probable therefore that this density shift may partly account for the low values obtained for the lines most affected by pressure. Even if we concede that the whole difference of shift between the lines most and least affected by pressure (which would amount to about 0·007 A when the arc is at normal pressure) is due to the density effect, the figures would imply an absolute pressure near the limb of one atmosphere only, and the difference of pressure between limb and centre of disk about one-fourth of an atmosphere.

It is probable that a better knowledge of the effect of pressure at the limb may be gained by a comparison of the shifts of only those lines which widen symmetrically in the arc under pressure. In our list there are only 45 lines which are known to be of this character, and the pressure shifts of these lines do not vary very widely: they may nevertheless be separated into two groups comprising the more and the less affected lines.

In table IV the shifts of the symmetrical lines are set out in detail with the mean values in Angstrom units at the foot of each column. The pressure shifts in column 2 are from the tables of Gale and Adams.*

TABLE IV.—MEAN SHIFTS OF SYMMETRICAL LINES IN RELATION TO PRESSURE SHIFTS.

λ	Pressure shift. 8 Atmospheres.	Limb shift.	Centre shift.	Total shift.
A.—Lines most affected by pressure.				
3903·090	+ 22	− 2	+ 17	+ 15
3969·413	22	+ 4	14	18
4045·975	23	8	6	14
4134·840	27	6	2	8
4144·038	29	8	14	22
4202·198	25	4	11	15
4271·934	22	0	9	9
4337·216	27	8	5	13
4369·941	23	12	11	23
4383·720	27	1	9	10
4454·552	23	7	6	13
4531·327	29	7	5	12
5227·362	31	3	3	6
5269·723	27	− 1	9	8
5328·236	29	+ 3	15	18
5328·721	26	7	8	15
5405·989	27	9	9	18
5429·911	29	9	6	15
5434·740	27	10	8	18
5447·130	31	10	5	15
5455·834	29	8	19	27
Means ...	+ ·0264	+ ·0058	+ ·0091	+ ·0149
B.—Lines least affected by pressure.				
3895·803	+ 11	− 3	+ 14	+ 11
3899·850	12	− 4	19	15
3906·628	11	+ 4	11	15
3920·410	10	2	15	17
3923·054	11	7	14	21
3928·075	12	2	18	20
3930·450	13	2	14	16
3956·819	14	7	4	11
3977·891	17	7	6	13
4005·408	19	8	8	16
4063·759	20	8	6	14
4071·908	21	3	8	11
4282·565	21	7	7	14
4308·081	21	10	8	18
4315·262	19	9	9	18
4325·939	20	3	10	13
4352·908	17	6	4	10
4376·107	18	4	11	15
4404·927	21	− 1	9	8
4415·293	18	+ 3	12	15
4427·482	17	10	3	13
4443·365	19	9	4	13
4461·818	15	7	7	14
4466·727	18	8	12	20
Means ...	+ ·0164	+ ·0049	+ ·0097	+ ·0146

* Astrophysical Journal XXXV, 8, 1912.

The mean total shift limb — arc is practically identical for the two sets of lines, although the mean pressure shifts are in the ratio 1 : 1·6. This would of course imply that the total pressure at the limb is about the same as that of the air at Kodaikanal, or three-fourths of an atmosphere. It must be said however that some of the values of the limb — centre shifts are very uncertain and need revision, especially those which give low values for the total shift. If we eliminate from the lists the five lines which yield total shifts less than 10, the mean shift for the most affected lines would be + 0·0165 A, and for the least affected lines + 0·0149 A, a difference which would imply a total pressure at the limb of 1·27 atmosphere above the pressure at Kodaikanal, or about one atmosphere above normal pressure.

If the total pressure at the limb were of the order of 6 atmospheres, as might be deduced from the mean total shift of symmetrical lines which is almost + 0·015 A, then there should be a difference of shift between the lines most and least affected by pressure of 0·0075 A, a quantity which could not fail to appear in the mean results.

In this discussion we have taken no account of differences of level of the effective regions of absorption for the different lines. The reason is that the limb — arc shifts, as we have shown in table II, are not appreciably affected by differences of intensity. If the intensities of the lines near the limb are related to level in the same way as St. John has found for sun spots on the disk, then in the region of iron absorption level appears to have little or no effect on the displacements. For the symmetrical lines these are remarkably constant, not only for lines of greatly differing intensity but also for lines in very different regions of the spectrum.

Another reason for believing that the limb shifts are not due to pressure alone is furnished by the displacements of those iron lines which with increased pressure are shifted to the violet (Mt. Wilson group *e*) in contrast to the majority which are shifted to the red. For these lines we have only measures of limb — centre, the total shifts being unknown, but if the displacements at the limb of the majority of lines to the red is due to increased pressure alone then the lines of group *e* ought to be shifted to the violet. We have at present only two photographs of limb and centre containing lines of group *e* but their evidence is quite decisive, for each line is displaced to the red. These two plates include the regions λλ 5365 to 5455 and λλ 5555 to 5638, and the average displacement limb — centre is given in the following table, together with the pressure shift per atmosphere according to Gale and Adams * :—

TABLE V.

	Pressure shift per atmosphere.	Mean shift Limb – centre.
Lines displaced *slightly to the red* by increased pressure ... ... (λλ 5371, 5397, 5405, 5429, 5434, 5447).	+ 0·004 A.	+ 0·008 A.
Lines displaced *greatly to the red* by increased pressure ... ... (λλ 5393, 5565, 5569, 5573, 5576, 5586, 5603, 5615, 5624, 5638).	+ 0·023 A.	+ 0·008 A.
Lines displaced *greatly to the violet* by increased pressure ... (λλ 5365, 5383, 5411, 5415, 5424, 5555, 5565, 5598).	— 0·018 A.	+ 0·005 A.

The lines shifted to the violet by pressure have, it is seen, smaller displacements to the red than the other lines. Assuming that this relative shift is due to pressure, the deduced pressure at the sun's limb is, according to whether we compare these lines with the first or the second group in the table, one-seventh or one-fourteenth of an atmosphere above that at the centre of the disc ; either of these amounts is comparatively insignificant. It should be mentioned, however, that the relative shift of these lines compared with the other lines is not *necessarily* due to pressure because we do not yet know the displacement at the centre of the sun, for in the arc the wave-lengths are not normal.† It may possibly be that the smaller displacement at the limb of the lines shifted to the violet by pressure will be compensated by a larger displacement at the centre as was shown above to be the case for lines of different intensities.

Limb shifts in relation to wave-length.

Our results do not confirm that large increase of shift with wave-length which Adams obtained with a much smaller number of lines. It is true that the relative shifts limb — centre tend to increase towards the red end of the spectrum, but this is counteracted by a decrease in the centre — arc shifts, so that the total

* Astrophysical Journal XXXVII, 391, 1913. † See Kodaikanal Observatory Bulletin No. XXXVIII.

shift limb — arc remains sensibly constant whether we take all the lines of table I or only the symmetrical lines. These results are shown in table VI, where the lines of table I are grouped in three different regions of the spectrum, and the shifts for each group averaged. As in table II the lines 5162·449 and 5424·290 have been omitted.

TABLE VI.—MEAN SHIFTS IN RELATION TO WAVE-LENGTH.

Number of lines.	Region.	Limb — centre.	Centre — arc.	Limb — arc.
		(A) All lines except two.		
49	3895–4282	+ 0·0046 A	+ 0·0069 A	+ 0·0115 A
45	4308–4789	+ 0·0069	+ 0·0052	+ 0·0121
43	4859–5615	+ 0·0060	+ 0·0055	+ 0·0115
		(B) Symmetrical lines only.		
23	3895–4325	+ 0·0044 A	+ 0·0106 A	+ 0·0150 A
22	4337–5455	+ 0·0063	+ 0·0082	+ 0·0145

The symmetrical lines have been grouped in two regions only, owing to the small number of lines available. Both table A and table B exhibit the same characteristic inverse relation between the limb shift and the centre shift which results in sensibly constant values of the total shift, or limb—arc shift. The symmetrical lines give higher values, probably from the absence of the anomalous shifts caused by peculiar conditions in the arc.

If the total shifts at the limb were due to pressure we should expect to find a marked increase in the mean values for the less refrangible lines. For the symmetrical lines the mean pressure shift of the 23 more refrangible lines is 0·0025 A per atmosphere, and of the 22 less refrangible lines it is 0·0030 A per atmosphere. But the less refrangible lines represent lower levels in the reversing layer than the more refrangible lines, so that the mean limb shifts should increase in a greater ratio than 25 : 30. As they do not increase at all but tend to be smaller for the less refrangible lines, we conclude that pressure is not concerned in the general shift of the lines towards the red.

The Cyanogen Bands.

The shifts of the cyanogen bands at the limb and at the centre of the disk give additional evidence which is strongly against the view that pressure is the cause of the limb shifts, for the bands or flutings are not appreciably affected by pressure, and therefore the shifts found between limb and centre and centre and arc can only be explained by motion in the line of sight.

In the paper already cited Dr. Adams refers to his measures of the cyanogen flutings at λ 3883 and λ 4216, for which he finds a small positive shift limb — centre. His mean result for several plates and for 14 bands near 3883 is + 0·002 A. A few measures of these bands have also been made at Kodaikanal with results which confirm Adams' measures, showing a relative shift to red at the limb which is notably smaller than that of the iron or titanium lines. The mean shift limb — centre of the best defined bands is + 0·002 A from 5 plates.

The values vary considerably from plate to plate, and Adams considered this shift to be due to ascending movements of the cyanogen at the centre of the disk, causing a violet shift at the centre or a relative shift to red at the limb.

Obviously the determination of the absolute shifts of the CN bands at the centre of the disk compared with the bands in the carbon arc is of crucial importance in testing Adams' hypothesis and in connection with limb shifts generally. Accordingly we have made very careful sets of measures of the bands near 3883 in eight comparison spectra of the carbon arc and the centre of the disk, using carbon terminals or one terminal carbon and the other iron.

In table VII the mean results are given for two sets of measures of 4 plates, each by different measurers, the initials N, N, R, and E at the head of columns 2 and 3 indicate the measurers Nagaraja Ayyar, Narayana Ayyar, Royds and Evershed respectively.

TABLE VII.—SHIFTS OF CN BANDS AT CENTRE OF DISK IN A/1000.

λ (Rowland).		N.N.R. (4 plates).	E. (4 plates).
3863·533	... ...	+ 10	...
3864·438	... ...	+ 10	+ 7
3876·448	... ...	− 6	+ 1
3876 {·556 ·622}	... ...	+ 6	+ 4
3877 ·481	... ...	− 2	+ 1
3877 {·587 ·646}	... ...	+ 6	+ 6
3879 {·331 ·394 ·458}	... ...	...	+ 5
3879 {·796 ·851}	... ...	...	+ 3
3880 {·465 ·532 ·596}	... ...	...	+ 7
3880 {·815 ·931}	... ...	+ 5	+ 4
3881 {·729 ·825}	... ...	+ 8	+ 7
3882 {·828 ·893}	... ...	+ 9	+ 7
Means	... ...	+ 0·0052 A	+ 0·0045 A

Each set of 4 plates was photographed independently at different dates and required different corrections, to be applied for the earth's movements relative to the sun. The lines or bands chosen for measurement were those most clearly defined in the sun and free from evidence of any interference by lines due to other substances. All of them are assigned by Rowland to C only. As the two sets of measures were made quite independently rather a different selection was made, but the agreement of the values for the common lines is as good as could be expected considering the breadth of many of the bands of which the component lines are only partially resolved in the photographs. There is a general agreement also in the differences of shift for the different lines or bands, showing that these differences are not due to errors of measurement, but are possibly due to the peculiar conditions in the arc, which as we have shown tend to produce small, or even negative, sun — arc shifts in the case of some of the iron lines. The two lines 3876·448 and 3877·481 which give negative shifts in the first set of measures and small positive shifts in the second set would seem to be affected in this way, and the difference in the measures may be due to a shorter arc having been used in the first set of photographs than in the second.

Both sets of measures agree in showing a general shift of the CN bands to the red at the centre of the disk amounting to + 0·005 A, a value which is almost certainly too small, as the general effect of the arc conditions is to reduce the sun — arc shifts. If the lines giving negative shifts are excluded the general mean becomes + 0·0064 A, equivalent to a motion of *descent* on the sun of 0·50 km/sec. This is the same order of velocity as we have found for iron in the reversing layer, being intermediate between the velocities obtained from the high level and low level iron lines. According to St. John the CN bands represent a rather low level in the solar atmosphere, or about a mid-level in the reversing layer, so that the velocity found above is in strict harmony with our results for iron.

As the cyanogen gas in the sun is descending at the centre of the disk and not ascending, the limb — centre shifts to the red cannot be explained as due to a violet shift at the centre. If the limb — centre and centre — arc shifts are added, the total or limb — arc shift amounts to about + 0·008 A, indicating a recession at the limb parallel to the solar surface of 0·62 km/sec. But this movement of recession at the limb suggests a similar movement for iron and other elements. For iron the total shift at the limb is as we have shown + 0·015 A for the symmetrical lines, and almost constant for different spectral regions. This would imply velocities varying from 1·1 km/sec. at λ 4000 to 0·9 km/sec. at λ 5000.

The velocity interpretation of the limb shifts of the iron lines seems forced upon us by the CN shifts, and involves very remarkable consequences, for we have to suppose the iron and other gaseous substances receding from the earth at opposite points on the sun's limb, at the centre, and by inference all over the disk and all round the circumference, the velocity increasing from the centre of the disk towards the limb where, unimpeded by the denser gases at the base of the reversing layer, it attains a velocity of about 1 km/sec.

But a movement constant in direction relative to the earth and maintained at all seasons of the year means an earth effect—an actual repulsion of the solar gases by the earth, and not apparently by the other planets.

While fully appreciating the absurdity of this idea we feel that there may be some justification for it in the apparent influence of the earth on the distribution of sunspots on the visible disk and of the prominences on the east and west limbs. That the earth exerts some sort of influence on solar phenomena which is not shared by the other planets is a startling and perhaps incredible supposition, but the facts which have recently been disclosed in this connection have not yet been explained otherwise.

There appears in fact to be no alternative to this earth-effect hypothesis, at any rate with regard to the cyanogen shifts at the limb, unless we assume some cause for line shifts other than motion or pressure. According to the "Theory of Relativity" of Einstein, the sun's gravitational field should diminish the frequency of the light emitted, and the mean shift to the red found by us at the centre of the disk agrees very closely with the theoretical gravitational shift calculated by E. F. Freundlich.* But the large variations of shift from line to line at the centre of the disk which depend mainly on intensity, and the constancy of the limb shifts for different wave-lengths are facts which would apparently offer serious difficulties to this explanation. One of us has found † that the displacement at the centre of the sun's disk decreases rapidly with depth; it would presumably vanish at a depth a little lower than that of the faint iron lines whilst the gravitational force can only be slightly smaller than at higher levels and may, indeed, be larger.

Summary.—The main results of this investigation and the conclusions reached may be briefly recapitulated in the following paragraphs :—

(1) In studying the limb shifts it is considered essential to determine the total shifts limb — arc instead of the relative shifts between limb and centre of disk as has been done hitherto.

(2) The total shifts of 139 iron lines at the sun's limb have been determined by adding the limb — centre shifts to the centre — arc shifts, and also directly in some cases by measuring the limb — arc shifts.

(3) The limb — centre shifts and the centre — arc shifts are found to be related to the intensity of the solar lines in an opposite sense, the former decreasing as the intensity increases and the latter increasing at about the same rate. The total or limb — arc shifts are therefore approximately constant for all intensities.

(4) The relation between limb — arc shifts and pressure shifts is discussed for all the lines with known pressure shifts. Grouping the lines into those more or less affected by pressure and into different spectral regions, it is found that the more affected lines are much less shifted than the less affected. This result is believed to be partly due to certain peculiar conditions in the arc which tend to reduce the sun — arc shifts, and especially the shifts of those lines most affected by pressure.

(5) Taking symmetrical lines only, which are presumably free from the disturbing effects of the arc conditions, there is found to be no difference of shift between groups of lines whose average pressure shifts differ in the ratio 1·6 to 1. This implies a pressure in the effective region of absorption at the limb equal to that of the air at Kodaikanal or $\frac{3}{4}$ atmosphere, a result which may however be considerably modified by further research.

(6) The large shifts of the symmetrical lines at the limb, amounting to 0·015 A towards the red, cannot be due to pressure because, if so, the differential shifts of the lines more and less affected by pressure would be of an order of magnitude which could not fail to appear in the measures. Moreover the pressure hypothesis requires that certain iron lines should be displaced at the limb to the violet whereas they are actually shifted to the red of their positions at the centre of the disk.

* Physikalische Zeitschrift XV, 2, 1914.

† Kodaikanal Observatory Bulletin No. XXXVI.

(7) It is shown that although the relative shifts, limb — centre, of the iron lines tend to increase toward the longer wave-lengths, the total shifts, limb — arc, remain remarkably constant when means are taken in three spectral regions between λ 3895 and λ 5615. This constancy of shift is also shown strikingly by the symmetrical lines alone, and tells heavily against the pressure theory.

(8) The constancy of the limb — arc shifts for symmetrical lines of greatly differing intensity shows that level is not an important factor in determining the limb shifts, if it may be assumed that intensity is related to level for lines near the limb as it appears to be for lines in sunspots on the disk.

(9) The cyanogen bands are shown to be displaced towards the red at the limb relatively to the centre of the disk, and at the centre compared with the arc. As these bands are not shifted appreciably by pressure the shifts can only be explained by assuming a movement of recession from the earth—a descending motion on the disk and a movement parallel to the solar surface at the limb. The total shift is about 0·008 A, indicating a recession near the limb of 0·62 km. per sec.

(10) The shifts of the iron lines, amounting to a mean value of 0·015 A for the symmetrical lines, is interpreted similarly as due to a recession of the iron vapour at the limb of about 1 km. per sec. A movement of recession from the earth at the centre and over the entire disk also follows.

(11) The view that the solar gases are actually repelled by the earth receives some support from other lines of evidence, but an alternative hypothesis is considered, namely, that the sun's gravitational field affects the wave-length of the light emitted, in accordance with Einstein's Theory of Relativity.

KODAIKANAL,
1st *June* 1914.

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T. ROYDS.

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