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AN INVESTIGATION OF THE DISPLACEMENT OF UNSYMMETRICAL LINES UNDER DIFFERENT CONDITIONS OF THE ELECTRIC ARC.

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Whilst investigating the suitability of iron lines as standards of wavelength, St. John and Miss Ware found that in one of their photographs the wavelengths of lines of their group *d* were longer, and of group *e* shorter, than in other photographs [1], and Goos has concluded that the wavelengths of certain iron lines vary with current, arc length and region of the arc [2], also Fabry and Buisson detected shifts of opposite signs for the two kinds of unsymmetrical lines when the current in the arc was increased [3]. I have been led to similar results in the course of a comparison of the spectrum of the centre of the sun's disc with that of the electric arc [4]. In these experiments I found that when a short arc had been employed the solar displacements were for certain lines systematically different from those when a long arc had been used for comparison with the sun. This suggested a direct comparison of the centre of a short arc with the centre of a long arc, and it was found that the iron lines of group *d* and certain of group *c* (*i.e.*, lines unsymmetrically widened towards the red) were displaced in the short arc to the red, and the lines of group *e* (unsymmetrical towards the violet) to the violet, whilst symmetrical lines were practically undisplaced.

The existence of this displacement affecting almost exclusively those lines which are most shifted by pressure, seriously limits our means of estimating the pressure shifts in the sun. Also there is evidence that the wavelengths of the lines which are liable to undergo displacements are not normal even at the centre of a very long arc, for many of the solar displacements given in Table IX of Kodaikanal Observatory Bulletin No. XXXVIII are so large as not to be explained as due either to pressure or to motion in the line of sight It is therefore of pressing importance to investigate the cause of the displacements which occur in different conditions of the electric arc, and to find a light source giving normal wavelengths for all classes of lines.

Experimental details—The spectrograph employed for this investigation has been described elsewhere [5]. The third order spectrum was generally used except for regions less refrangible than λ 5800 for which the second order was used. The dispersion in the third order varies from 0·9 A per mm. at λ 3950 to 0·6 A per mm. at λ 5680.

The electric arc was supplied by a battery of 110 volts, the poles were vertical and an image, enlarged 3¼ times, was formed on the vertical slit of the spectrograph by means of a condensing lens. The comparison of the spectra from two different parts of the arc was made by means of an occulting screen sliding in front of the slit. The comparison spectrum was in every case the central portion of a long arc and was impressed on the photographic plate above and below a spectrum in the middle to be compared with it. Half of the exposure of the comparison spectrum was given immediately before exposing the middle spectrum, and the second half immediately afterwards. This guarded against the possibility of shifts due to temperature

(1) St John and Miss Ware, Astrophysical Journal, XXXIX, 5, 1913
(2) Goos, Astrophysical Journal, XXXVII, 48, 1913 and XXXVIII, 141, 1913.
(3) Fabry and Buisson, Astrophysical Journal, XXXI, 97, 1910
(4) Royds, Kodaikanal Observatory Bulletin No. XXXVIII
(5) Evershed, Kodaikanal Observatory Bulletin No. XXXVI.

changes or to mechanical disturbances passing unnoticed. A graduated scale on the occulting screen enabled the length of the arc to be controlled.

The atmosphere surrounding the arc was air at ordinary pressure (580 mm. at the level of the Observatory) or at reduced pressure. For the iron and copper arc metallic poles were used; in the cases of other elements salts were introduced on one or both poles of a carbon arc.

Investigation of Iron Lines.—It was found previously that the displacements of the iron lines in the short arc were associated with the unsymmetrical character of the lines, lines widened more towards the red were found to be displaced to the red, and those widened more towards the violet to the violet, whilst symmetrical lines were undisplaced. For the present purpose therefore spectrum lines may be classified as symmetrical (marked s in the tables), those widened unsymmetrically towards the red (marked ur) and those widened unsymmetrically towards the violet (marked uv). The study of the iron lines has been confined to two regions of the spectrum, namely, λλ 5365—5455 and λλ 5555—5638; these regions include 7 symmetrical lines and 16 strong unsymmetrical lines, 8 being widened more towards the red and 8 towards the violet.

The measured displacements of these iron lines under different conditions are given in Table I.

TABLE I.—DISPLACEMENTS OF IRON LINES IN A/1000.

λ (Rowland)	Centre of arc 2 mms long – Centre of arc 7 mms long	Negative Pole – Centre (arc 7 mms long).	Positive Pole – Centre (arc 7 mms long	Negative Pole (arc 2 mms long) – Centre (arc 7 mms. long)	Positive Pole (arc 2 mms long) – Centre (arc 7 mms. long)	Centre of arc (7 mms. long) at 9½ amps – Centre of arc (7 mms long) at 4½ amps.	Centre of arc (2 mms. long) at 8½ amps. – Centre of arc (2 mms. long) at 3½ amps.
No. of Photographs .	1	7	1	2	2	1	1
5371 734 (s)	+ 1	+ 1	0	+ 2	0	– 1	+ 2
5397·314 (s)	– 1	+ 1	– 1	+ 2	0	0	+ 3
5405·989 (s)	0	+ 1	+ 1	+ 1	0	– 1	+ 2
5429 911 (s)	– 1	+ 1	0	+ 1	0	– 1	0
5434 740 (s)	+ 1	0	0	+ 3	– 1	– 1	+ 2
5447 130 (s)	– 1	0	0	+ 2	0	– 2	– 4
5455·834 (s)	– 2	0	– 1	+ 1	0	– 1	– 2
Mean (s)	– 0004 A	+ 0006 A	– 0001 A	+ 0017 A	– 0001 A	– 0010 A	+ 0004 A
5393 375 (ur)	+ 4	+ 12	– 1	+ 12	+ 2	+ 3	+ 8
5569 848 (ur)	+ 7	+ 10	+ 5			+ 3	
5573·075 (ur)	+ 8	+ 10	+ 5			+ 2	
5576 320 (ur)	+ 10	+ 16	+ 6			+ 5	
5586 991 (ur)	+ 6	+ 11	+ 3			+ 3	
5603·186 (ur)	+ 6	+ 12		...		+ 2	
5615 877 (ur)	+ 9	+ 10	+ 5			+ 2	
5624·769 (ur)	+ 5	+ 11	+ 3			+ 1	
Mean (ur)	+ 0069 A	+ 0115 A	+ 0043 A	+ 012 A	+ 002 A	+ 0026 A	+ ·008 A
5365 069 (uv)	– 10						...
5367·669 (uv)	– 12	– 12	– 7	– 11	– 5		– 13
5370·166 (uv)	– 8	– 11	– 3	– 6	– 4	– 3	– 9
5383 578 (uv)	– 9	– 13	– 8	– 9	– 4	– 5	– 7
5404 357 (uv)	– 8	– 12	– 5	– 10	– 6	– 4	– 9
5411·124 (uv)	– 10	– 12	– 7	– 9	– 5	– 5	– 12
5415·416 (uv)	– 12	– 12	– 6	– 7	– 6	– 8	– 14
5424 290 (uv)	– 12	– 13	– 6	– 7	– 5	– 10	– 11
Mean (uv)	– 0101 A	– 0121 A	– 0060 A	– ·0084 A	– 0050 A	– ·0058 A	– ·0107 A

It is seen from the table that only unsymmetrical lines undergo any notable displacement and these always in the direction of greater widening. How far this result is due to errors of estimating the correct position of the maximum intensity in an unsymmetrical line is discussed below. The largest displacements occur in the region near the negative pole of the iron arc, at the positive pole the displacement is about half that at the negative pole. A considerable displacement is also produced by shortening the arc (as was shown for other lines in Bulletin No. XXXVIII) or by increasing the current through the arc.

Fig. 1 of the accompanying plate is a three times enlargement of a portion of a photograph comparing the spectrum of the region near the negative pole with the centre of the arc and shows the different behaviour of the three lines λ 5383 (uv), λ 5393 (ur), and λ 5397 (s).

Investigation of the Calcium Triplet near λ 4580.—Since the sun and arc comparisons detailed in Kodaikanal Observatory Bulletin No. XXXVIII showed that the solar displacements of certain lines of some elements were much more abnormal than those of the iron lines, it was to be expected that these lines would also give larger displacements under varying arc conditions. The calcium triplet at λ 4580 was selected as being most convenient for investigation. In Table II are given the displacements measured using an arc between carbon poles on one of which a little calcium chloride had been placed. The displacement at the negative pole is greater than one-tenth of an Angstrom unit for each line of the triplet when the salt has been placed on the negative pole, and is not appreciably greater when the salt has been placed on both poles; one photograph illustrating the displacement is shown enlarged 3 times in fig. 2 of the accompanying plate The average displacement at the negative pole of the line λ 4607·510 (due to strontium impurity) on the same photographs is + 0 0004 A.

TABLE II.—DISPLACEMENTS OF THE CALCIUM TRIPLET NEAR λ 4580 IN THE CARBON ARC IN AIR.

λ (Rowland.)	Negative Pole — Centre (Arc 12 mms. long).		Positive Pole—Centre (Arc 12 mms long).	
	Salt placed on – pole.	Salt placed on + pole.	Salt placed on – pole.	Salt placed on + pole
Number of photographs.	3	4	1	1
4578 732 (ur) 4581·575 (ur) 4586·047 (ur)	+ 101 + 113 + 125	+ 51 + 62 + 69	+ 59 + 63 + 68	+ 50 + 56 + 58
Mean ...	+ ·113 A	+ ·061 A	+ ·063 A	+ ·055 A

When the salt is placed on the positive pole only, the displacement at the negative pole is reduced by nearly one-half and becomes about equal to the displacement at the positive pole. For the positive pole the displacement is approximately the same on whichever pole the salt has been placed. The result that the displacement at the negative pole is greater when the calcium salt has been placed on that pole is of great importance in tracing the cause of the displacements In order to keep the calcium content of the arc more constant than it is possible to obtain by placing a salt on the poles, the "flame" arc was also employed to produce these lines, the measures being given in Table III. The displacement is of the same order as that when the carbon arc is supplied with calcium salt, and when the flame arc carbon is the positive pole and an ordinary arc carbon the negative, the displacement at the negative pole is less than half that when both poles are flame arc carbons.

TABLE III.—DISPLACEMENTS OF THE CALCIUM TRIPLET NEAR λ 4580 IN THE "FLAME" ARC IN AIR.

λ (Rowland)	Negative Pole—Centre (Arc 15 mms. long)			Positive Pole—Centre (Arc 15 mms long)		Centre of arc (6 mms. long) at 9 amps. —Centre of arc (6 mms long) at 3 amps.
	Both poles flame arc carbons.	+ pole, flame arc carbon – pole, ordinary carbon.	+ pole, ordinary carbon – pole, flame arc carbon.	Both poles flame arc carbons.	+ pole, flame arc carbon – pole, ordinary carbon.	
Number of photographs.	4	2	2	3	2	2
4578 732 (ur) 4581·575 (ur) 4586 047 (	+ 128 ... + 137	+ 49 + 47 + 57	+ 77 + 60 + 86	+ 59 + 47 + 56	+ 57 + 49 + 62	+ 34 + 28 + 37
Mean .	+ 132 A	+ ·051 A	+ ·074 A	+ ·054 A	+ 056 A	+ 033 A

Displacements of the Calcium Triplet near λ 4580 *in the Arc in Vacuo.*—The displacements of these lines in the "flame" arc in vacuo are very much smaller than in the arc in air, but they undoubtedly exist and probably under all the conditions in which they occur in the arc in air. The displacement near the negative pole disappears at less than a millimetre from the pole so that if the arc burns into a cavity in the electrode the shift is not seen at all The displacements observed in the arc at about 3 cms. pressure are given in Table IV. The shift at the negative pole is about one-ninth of that in the arc in air, and there is a shift due to increase of the current strength The largest displacement occurred when the region near the negative pole at 8 amperes was compared with the centre of the arc at 3¼ amperes, even then the mean displacement of the triplet amounted only to 0·024 A. These lines are probably very sensitive to pressure but since this did not vary more than a millimetre during an experiment the displacements are not due to pressure

TABLE IV.—DISPLACEMENTS OF THE CALCIUM TRIPLET NEAR λ 4580 IN THE "FLAME" ARC IN VACUO.

λ (Rowland.)	Negative Pole – Centre of Arc.	Centre of arc at 8 amps – Centre of arc at 3¼ amps	Negative Pole of arc at 7½ amps – Centre of arc at 3¼ amps
Number of photographs.	2	1	1
4578·732 (ur)	+ 10	+ 8	+ 23
4581·575 (ur)	+ 9	+ 5	+ 5
4586·047 (ur)	+ 10	+ 6	+ 23
Mean ..	+ ·010 A	+ ·006 A	+ ·024 A

Displacements and Phenomena near the Negative Pole of the Arc—The light from the neighbourhood of the negative pole is much more intense than that from the centre of the arc. When a calcium, or other, salt has been introduced into a carbon arc there can be seen near the negative pole a well-defined region of intensely luminous vapour extending more or less towards the centre of the arc according to the quantity of salt introduced, at the positive pole there is a similar intense region less luminous and extensive. Even with the enlarged image of the arc projected on the aluminium occulting screen in front of the slit, the intense region near the negative pole was very trying to the unprotected eye. It is in this intensely luminous region near the poles that the displacement occurs, in the parts of the arc outside it, though still distant from the centre, the displacement is very small compared with that in the parts within its limits. A series of photographs of the calcium triplet near λ 4580 in the flame arc was taken comparing the spectrum of different distances from the negative pole with the spectrum of the centre of the arc. The length of the image of the arc was kept constant at 2 inches and the mean displacement of the two lines λ 4578 and λ 4586 were as follows:—

Distance from image of negative pole	Displacement compared with centre of arc.
1 mm (inside intense region)	+ 0·132 A
3 ,, (,, ,,)	+ 0·107 A
9 ,, (just on limit of intense region)	+ 0·022 A
16 ,, (outside intense region)	+ 0·008 A
25 ,, (centre of arc)	(0·000 A)

The results for the iron lines and the calcium triplet near λ 4580 show that to investigate the relative behaviour of spectrum lines it is sufficient to confine the experiments to a comparison of the spectrum near the negative pole with that of the centre of the arc. It would take a long time to investigate the behaviour of all lines of every element, even of only unsymmetrical lines, but such a course is hardly necessary in order to show the characteristic features of the different types of lines and the displacement at the negative pole. Various types of unsymmetrical widening are met with even in the comparatively small number of lines which have been photographed. Some of the broad lines have large displacements, others small, depending on the amount of dissymmetry, some lines have one edge fairly sharp, others have both edges diffuse; lines which are comparatively narrow may be very unsymmetrical and undergo large displacement.

The majority of the unsymmetrical lines investigated are widened towards the red, but some were also chosen which are widened towards the violet.

Table V contains the results for all the lines which have been photographed. The second column quotes the character of the lines as given in Kayser's tables [1], chiefly from the data of Kayser and Runge, Exner and Haschek or Eder and Valenta. The direction of unsymmetrical widening can be seen in the spectrum of the region near the negative pole even of many lines whose character is not given by these authorities, but the most sensitive test is the direction of displacement.

TABLE V.—DISPLACEMENTS AT THE NEGATIVE POLE OF A LONG ARC COMPARED WITH THE CENTRE OF THE ARC.

λ (Rowland)	Character.*	Displacement in A/1000. Negative Pole – Centre. Unreversed.	Negative Pole – Centre. Reversed.	⊙ – Centre of arc.†
Aluminium.				
3944·160 (s)	...	+ 4	...	+ 3
3961·674 (s)	...	+ 4	...	+ 2
Barium.				
4239·91 (ur)	ur	+111	.	...
4242 83 (ur)	ur	+ 57	.	.
4264 45 (uv)	u	− 52	...	...
4283 27 (ur)	ur	.	+ 10	...
4291·32 (ur)	...	+ 11	.	...
4323 15 (uv)	uv	−157	...	
4325 38 (ur)	...	+ 51	...	
4333·04 (uv)	u	− 24	.	..
4350·49 (ur)	ur	+166	+ 3	.
4359·80 (ur)	...	+ 48	...	...
4467·36 (ur)		+ 50	..	..
4489·50 (uv)	uv	− 45	...	..
4498 82 (uv)	uv	− 42	...	
4506 11	..	..	0	...
4523 48 (ur)	..	...	− 11	...
4525·19 (ur)	ur	+ 44	..	...
4554 211 (s)	...	...	0	− 5
4574 08 (ur)	..		+ 8	
4579 84 (ur)		...	+ 10	
4673 69 (uv)	uv	−118	...	.
4691 74 (ur)	..	..	+ 4	...
4700 64 (ur)	ur	+216	..	...
4726 68 (ur)	...		+ 14	...
6063 33 (ur)	...	+ 37	+ 21	..
6111 01 (ur)	...	+ 39	+ 14	.
6141 98 (ur	..	+ 62	.	..
Calcium				
3933 825 (s)	..	...	+ 2	.
3957 177 (ur)	ur	+ 14	..	...
3968 625 (s)	..	...	− 2	...
3973 864 (ur)	ur	+ 17	...	...
4092·821 (ur)	ur	+ 107	.	...
4283 16	.		0	+ 6
4289 525 (uv)	..	− 9	+ 1	+ 10
4299 149 (uv)	..	− 11	− 2	+ 6
4302 692	.	...	0	+ 10
4307 907 (uv)	..	− 11	− 2	.
4318·817 (uv)	uv	− 12	− 2	...
4425 608	u	...	+ 3	+ 2
Calcium (*cont.*)				
4435 129	u	..	+ 2	+ 3
4435 851		.	+ 2	+ 2
4454 953	u	.	− 1	...
4456·794	..	...	0	+ 7
4527·101 (ur)	ur	+173	..	− 44
4578 732 (ur)		+101	..	− 25
4581·575 (ur)	..	+113		− 24
4586·047 (ur)	ur	+125	.	− 30
5857 674 (ur)	u	+ 111		..
6102 937 (ur)		+170	+ 21	− 27
6122 434 (ur)	...	+190	+ 14	− 24
6162·390 (ur)	.	+233	+ 15	− 28
6169·249 (ur)	.	+ 40	...	.
6169 778 (ur)	...	+ 42	.	..
Copper				
4531 04 (ur)	...	+ 34		...
4587 19 (ur)	u	+ 24	...	..
Iron §				
4045 975 (s)	...	0	...	+ 9
4063 759 (s)	...	− 2	...	+ 7
4071 908 (s)	..	− 2	...	+ 10
4325 939 (s)	..	+ 2	..	+ 12
4383·720 (s)	...	+ 1	...	+ 8
4404·927 (s)	..	+ 2	...	+ 7
Magnesium.				
4352·083 (ur)	ur	+ 75	...	..
5167·497 (ur)		+ 14	..	− 10
5172 856 (ur)	...	+ 13	.	− 7
5183·791 (ur)	..	+ 12		− 9
Sodium				
5682·869 (ur)	ur	+ 321 ?	− 19	− 127
5688·436 (ur)	ur	+ 392 ?	− 19	− 144
6154·438 (ur)	ur	+ 523		− 81
6160 956 (ur)	ur	+ 513	...	− 79
Strontium				
4607·510 (s)	.	+ 1	.	+ 1

* From the Tables in Kayser's Handbuch der Spectroscopie, Vols. V and VI

† From Kodaikanal Observatory Bulletin No XXXVIII.

§ See also Table I, column 3

It is seen from the table that, as found from iron lines, whilst symmetrical lines undergo very small, if any displacement unsymmetrical lines are displaced in the direction of their greater widening. Not a single exception to this has yet been met with; of lines which were previously known, or are now found, to be

[1] Kayser, Handbuch der Spectroscopie Vols. V and VI.

unsymmetrical, all are displaced (provided they are unreversed) either to the red or to the violet according to the direction of unsymmetrical widening. The fact of the displacement being dependent on the unsymmetrical character of the line makes it essential to remove any possibility of doubt that the displacements are not due to errors of estimating the true maximum of intensity of an unsymmetrical line since the tendency of the error is probably also in the direction of greater widening. This point is discussed below.

When an unsymmetrical line is reversed at the negative pole the displacement of the reversal is much smaller than that of the unreversed line; in the case of the sodium pair λλ 5682, 5688 (both ur) the reversal is displaced to the violet. The significance of these facts will be discussed later.

The dependence of the shifts on the unsymmetrical widening of lines seems to outweigh that on any other characteristics. For instance, the shift to the violet of the first subordinate series of barium is not characteristic of all first subordinate series but happens with barium since its series is unsymmetrically widened towards the violet. Similarly the shift tends to increase as we pass down a series only because the unsymmetrical widening becomes greater.

Reality of the Displacement of Unsymmetrical Lines.—The practice of dividing the exposure of the comparison spectrum into two halves, one before and the other after the middle strip of the photograph was exposed on the part of the arc to be investigated, has removed the possibility of fictitious shifts being undetected. A further safeguard has been the presence of symmetrical lines on nearly every photograph; the fact that these lines suffer no displacement at once shows that the shifts of other lines are not spurious

The dependence of the displacements on the unsymmetrical character of the lines makes it necessary to consider very carefully the error which enters into the estimation of the portion of maximum intensity of an unsymmetrical line, for the direction of the error is probably in the same direction as the displacements found. The error of measurement of the position of maxium intensity of a broad unsymmetrical line cannot be small, but it is perfectly clear from the photographs reproduced in the accompanying plate that a real displacement exists whose magnitude cannot be considerably affected by any possible error of measurement. In figure 2 especially is this obvious, where the lines of the region near the negative pole stand quite clear of those of the centre of the arc, and similar cases are frequently met with. In order to obviate as much as possible the false displacement due to errors of measurement, I have in the case of some of the iron unsymmetrical lines underexposed the widened lines until they appeared of the same width as those in the comparison spectrum. Under these conditions it may be assumed that the degree of unsymmetrical widening would be the same in the two spectra and the errors of estimating the position of the maximum intensity would be the same in both cases. Nevertheless, the measured displacement is still of quite the same order as in fully exposed photographs

It might be argued that the displacements are apparent only, being due to the complete absorption of one side of the unsymmetrical line by the outer portion of the arc, leaving visible in the photograph really only a portion of the line apparently displaced[1], on this view the emission line from the inner portion of the arc, as well as the absorption line from the outer regions are supposed, if it were possible to isolate them, to be undisplaced. In the sodium pair λλ 5682, 5688, the absorption line can be seen under proper density conditions to be almost at the very edge of the emission line, and it is easy to conceive of a case a little more extreme in which the absorption line actually reaches to the edge leaving only one component of the emission line visible. The argument might conceivably hold for some cases but it cannot apply to the majority. It must be remembered that the displacement can be made, by choosing the proper portion of the arc, to have any value from zero up to the maximum observed at the negative pole, and the smaller displacements occur with the line so broad that any undisplaced absorption line must be visible. Indeed so far from having to suppose an absorption line not shifted, the actual absorption line observed in reversed lines is in many cases displaced, a fact which disposes of the hypothesis.

The possibility of anomalous dispersion in the arc must also be considered It is conceivable that at the negative pole, for example, there is a density gradient sufficient to cause wavelengths on each side of

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[1] Exner and Haschek believe this to be possible (Die Spektren der Elemente bei Normalem Druck, Vol. I., p., 28.)

the absorption line, for which the refractive index would be abnormal, to be refracted out from the direction of the condensing lens and missing from the spectrum. There are, however, several facts against the anomalous dispersion hypothesis. Firstly, it fails to account for the displacement of unreversed lines. Secondly, for some of the lines widened unsymmetrically towards the red, the displacement of the reversal is to the red (*e.g.*, the calcium lines λλ 6102, 6122, 6162) and for others to the violet (*e.g.*, the sodium lines λλ 5682, 5688); these cannot be reconciled by the hypothesis. Thirdly, the unsymmetrical lines undergo large sun—arc displacements whose signs are opposite to those of the displacements at the negative pole; the existence of an anomalous dispersion band in the apparent absorption line does not assist in any way in explaining these shifts

There is also the possibility of the displacement being due to the enhancement of a satellite on one side which blends with the principal line to produce apparently a single line displaced. A satellite is known to exist for example, on the red side of the calcium line λ 4586 shown in fig. 2, but to account for the greatly varying displacements which can be obtained in different portions of the arc, we must suppose that not only is the satellite enhanced until stronger than the principal line, but also is itself displaced. Besides, many lines known to be single are displaced.

The Cause of the Displacement of Unsymmetrical Lines under different conditions of the Electric Arc.—In Kodaikanal Observatory Bulletin No. XXXVIII, I have suggested that differences of density are the cause of the displacements between the short and the long arc, and presumably, between the sun and the long arc. There is now a considerable amount of evidence to elucidate the origin of the displacements under different arc conditions, and density is the only cause which can explain all the phenomena. Very significant are the following facts:—

(*a*) When the current strength is increased, thus increasing the amount of vapour in the arc, the lines are displaced in the same direction as at the negative pole. With an iron arc of 2 mms. length doubling the current strength produced a mean displacement of — 0·011 A for seven lines unsymmetrical towards the violet or nearly equal to that between the negative pole and centre of the long arc for the same lines (see Table I); with an iron arc 7 mms. long doubling the current strength did not, from the appearance and sound of the arc itself, produce nearly so great a difference in the rate of production of vapour and the displacement was smaller. Increasing the current in a "flame" arc 6 mms. long also produced a displacement of the calcium triplet near λ 4580 of + ·033 A.

(*b*) The displacement of the calcium triplet near λ 4580 at the negative pole is larger when the salt has been placed on that pole than when on the positive; with the flame arc the displacement at the negative pole is larger when both poles are flame arc carbons or when the negative pole only is a flame arc carbon, than when the positive pole only is a flame arc carbon.

(*c*) When an unsymmetrical line is reversed at the negative pole, as frequently is the case, the displacement of the reversal is much smaller than would be expected in an unreversed line of the same degree of unsymmetrical widening. There are many cases, such as the calcium triplet λλ 6102, 6122, 6162, which are reversed in one photograph (calcium salt placed on the poles) and unreversed in another (sodium salt with calcium impurity placed on the poles), the displacements of the emission lines of the triplet in the latter average + 0·198 A and of the absorption line in the former + 0·015 A.

(*d*) Take the example of the sodium pair λλ 5682, 5688. As mentioned previously, the reversal of these lines appears under certain conditions of vapour density, almost at the violet edge of the lines. The reversal is so far to the violet that the maximum of the emission lines appears quite undisturbed by the absorption, as has been observed by Duffield in the case of certain iron lines under pressure [1] and by others; on this assumption the emission line at the negative pole is displaced by + 0·36 A, an amount not inconsistent with the solar displacement. Whether the displacement is so great as this may be doubtful, but it is at any rate practically certain that the displacement of the emission line for lines so obviously unsymmetrical towards the red is to the red. It is, therefore, important to note that the reversal is displaced by — 0·019 A, that is to the violet, of the line at the centre of the arc or in the direction opposite to that of the emission line.

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[1] Duffield, Phil. Trans. Roy Soc. A. 208, 111, 1908.

(e) The displacements exist in those parts of the arc where the lines are widened and are greatest where the widening is greatest The cause of the displacement may be the same as that of the widening *i.e.*, either density, temperature, or some electrical effect such as ionisation, but the effect of increasing the quantity of material in the arc on the width of lines is so obvious that this is probably the chief cause.

The explanation of the reversal phenomena on the density hypothesis is obvious The vapour in the outer regions of the arc is of low density (and low temperature) and therefore produces a narrow absorption line superposed on the broad emission line due to the vapours of high density (and high temperature) in the inner regions. The displacements of the absorption line at the negative pole will therefore not be so great as that of the emission line, and may, when the density of the absorbing layer is smaller than that at the centre of arc (which gives the comparison spectrum), be displaced in the opposite direction.

The fact that the shift at the negative pole is greater than that at the positive, implying greater density of vapour there, may be explained as due to the metallic ions, which would carry a positive electric charge being carried over to the negative pole by the electrical field.

There may be other hypotheses brought forward to explain the displacement of unsymmetrical lines, the most important of which is pressure. The iron lines which undergo displacement under different conditions of the arc, are those which have large pressure shifts, and the directions of displacement are those which would result from an increased pressure in the arc due to a sudden production of vapour at the poles. The amount of pressure required to produce the observed displacements can be calculated, as is done in Table VI. It is altogether inconceivable that pressures of 8 atmospheres above atmospheric can be produced locally in the arc burning in free air at atmospheric pressure.

TABLE VI.—PRESSURE NECESSARY TO PRODUCE THE MEASURED DISPLACEMENTS.

Line and element.	Displacement at Negative Pole.	Pressure shift per atmosphere.	Pressure necessary to produce displacement.
6102, 6122, 6162 } Ca	+ 0·197 A	+ ·024 A	8·2 atmospheres above atmospheric.
5682, 5688 } Na	+ 0·36? A	+ ·055 A	6·5 atmospheres above atmospheric.
5682, 5688 } Na (absorption lines)	— 0·019 A	+ ·055 A	0·35 atmospheres below atmospheric.
4531 Cu	+ 034 A	+ ·009* A	3·8 atmospheres above atmospheric
		+ ·022 † A	1·5 atmospheres above atmospheric
Fe ur lines	+ ·011 A	+ ·022 A	0·5 atmospheres above atmospheric
Fe uv lines	— 012 A	— 017 A	0·7 atmospheres above atmospheric

* According to Humphreys. † According to Duffield.

The effect of pressure would be to displace all lines, whereas it has been found that symmetrical lines are not systematically displaced either one way or the other.

The fact of absorption lines at the negative pole having smaller displacement than the emission lines could also be explained as due to lower temperature of the outer regions of the arc, instead of to lower vapour density. The temperature hypothesis does not however explain the other phenomena, for example the displacement due to increase of current density or to shortening the arc.

Ionisation effects may be present in the arc, and in the explanation given above it is not impossible that for the phrase "density of vapour," "density of ions" should be substituted, for in the arc the two are indistinguishable since practically the whole of the vapour will be ionised. The former is more probably the cause of the displacement, and the point can perhaps be tested in furnace spectra.

There is no difficulty in accounting for a density effect on wavelength. Soon after the announcement of the pressure shift Schuster pointed out the importance of determining whether the shift was dependent on the total pressure or on the proximity of molecules of the same nature[1] Many observers have tried to detect the effect of the latter but generally with negative results. Exner and Haschek however did find an effect[2] but their conclusions have not gained universal acceptance.[3] The probable reason why negative results have been obtained is that most spectral lines are symmetrical and therefore show no displacement due to density. So far as my experiments go it appears that the displacement of symmetrical lines under pressure is due solely to the total pressure of the surrounding atmosphere, but there is as yet no direct evidence as to whether the displacement of unsymmetrical lines under pressure is due entirely to increased density or partly to the increased total pressure.

The intimate relation between the unsymmetrical character of spectrum lines and their density displacement is of great importance in the theory of the vibrations of elections within the atom and of the mutual influence of molecules due to their proximity. Whatever theory is put forward of the origin of spectrum lines and of their displacements must be able to explain not only the displacements of unsymmetrical lines due to pressure and density to the red or to the violet according as the widening is towards the red or the violet, but also the absence of a density effect on symmetrical lines for which a pressure effect exists.

Consequences of the density effect on other investigations of the displacement of spectrum lines and investigations of wavelength standards.—It is necessary to consider whether the existence of the displacement of unsymmetrical lines by different conditions in the electric arc do not affect the conclusions drawn from the displacements of spectrum lines in other researches in which an electric arc has been employed to produce the spectrum.

The pressure in the reversing layer of the sun can be estimated by comparing the relative sun—arc displacements of the lines most and least affected by pressure The lines most shifted by pressure, however, are comprised almost entirely of unsymmetrical lines, and since these lines undergo shifts within the arc itself, the sun — arc displacements can be varied at will according to the part of the arc selected for comparison with the sun. It was shown in Kodaikanal Observatory Bulletin No. XXXVIII[4] that even in the centre of very long arc, the conditions producing the shifts in different parts of the arc, whether they be density or not, still do not approach those in the sun. So long, therefore, as the electric arc is used for comparison with the sun, unsymmetrical lines must, for the present, be left out of account altogether in studying the pressure displacement in the sun. Considering only symmetrical lines the pressure in the reversing layer at the level of the iron lines is about three-quarters of an atmosphere[4] and the pressure at the limb is probably not much greater than this.[5]

Also, the arc is the source which has been chiefly employed for the investigation of pressure displacements, and similar considerations will apply. The arc does not always burn well under pressure, and it is a practical impossibility to keep the arc conditions identical with those for the comparison spectrum either as to length or as to the portion of the arc which falls on the spectrograph slit, although this latter in the case of astigmatic spectrographs may not be so important. It will not be surprising, therefore, if the supposed pressure displacement of the unsymmetrical lines does not turn out to be at least partly due to the displacements which occur in different parts of the arc at constant pressure. For instance knowing that the calcium triplet λλ 6102, 6122, 6162, is displaced by 0·198 A at the negative pole compared with the centre of the arc, we cannot ignore the possibility that the shift of these lines under pressure is partly due to this displacement unless it is shown that special precautions have been taken to exclude the polar regions of the arc from entering the spectrograph.

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[1] Schuster, Astrophysical Journal, III, 292, 1896

[2] Exner and Haschek, Die Spektren der Elemente bei Normalem Druck, Vol. I

[3] See Kayser Handbuch der Spectroscopie, Vol. II, 297, 308, 309, 310 and Eder and Valenta, Astrophysical Journal, XIX, 251, 1904.

[4] Royds, Kodaikanal Observatory Bulletin No XXXVIII.

[5] Evershed and Royds Kodaikanal Observatory Bulletin No. XXXIX.

Pressure displacements have also been investigated in the furnace.[1] The same pressure produces much larger shifts in the furnace spectrum than in the arc, and since this is true for symmetrical as well as for unsymmetrical lines, density effects, which do not displace symmetrical lines, fail to account for it. Nevertheless there is a difference between the behaviour of symmetrical and unsymmetrical lines. The following Table VII, compiled from the data of Gale and Adams[2] for the iron arc and of King[3] for the furnace, shows that the ratio of furnace displacement to arc displacement is considerably smaller for the iron lines unsymmetrically widened towards the red, than for symmetrical lines. This fact can be explained if the arc under pressure has been short or the exposure made on a region near the poles, for either of these would cause the shift of the unsymmetrical lines to be larger than the true pressure effect.

TABLE VII.—COMPARISON OF PRESSURE DISPLACEMENTS OF IRON LINES IN FURNACE AND ARC

Ratio $\frac{\text{furnace displacement at 9 atmospheres.}}{\text{arc displacement at 9 atmospheres}}$

Region		Symmetrical lines		Lines unsymmetrical towards the red
λλ 4063—4461	...	2·48 (26 lines)	... ...	1·49 (5 lines).
λλ 5227—5341	...	1 97 (7 lines)	.. ...	1·37 (2 lines).

Although these experiments were not directed to the determination of standards of wavelength they have an obvious bearing on the choice of light source for standard lines. It does not seem necessary to abandon the arc in air so long as symmetrical lines are chosen as standards, but with this source it cannot be expected that independent experimenters will get sufficiently concordant results for unsymmetrical lines on account of the great sensitiveness of these lines to density effects. The arc in vacuo is better for unsymmetrical lines but is not sufficiently convenient for ordinary usage.

What we shall consider as the light source giving "normal" wavelengths for unsymmetrical lines is entirely arbitrary but is of importance when we wish to interpret the displacements in heavenly bodies such as the sun. We have now at least three causes of displacement of spectrum lines:—(1) motion in the line of sight, (2) pressure, and (3) density It is desirable to eliminate the density shift since we have at present no means of estimating it quantitatively. Whether the arc under reduced pressure or the furnace will prove the more suitable source for comparison with the sun is a matter for investigation.

Test of unsymmetrical character—The presence of displacements at the negative pole is a simple and powerful means of testing the unsymmetrical character of spectrum lines if we can assume the generality of the rule that only unsymmetrical lines are displaced and these in the direction of their greater widening. In the arc at ordinary pressures the unsymmetrical widening in most cases is not so obvious that its direction is evident; the displacement at the negative pole is, however, generally sufficiently large that the direction of displacement can be at once seen by inspection, although in some cases it would be necessary to measure the displacement. Consider the case of the copper line λ 4578. In the arc at atmospheric pressure this line is so diffuse that it is quite impossible to say whether it is unsymmetrical or not, but supposing that it were important to learn its character for determining its series relationship or other reason, the fact that its displacement at the negative pole amounts to +0·024 A would show that it is unsymmetrical towards the red, but that the dissymmetry is not great in proportion to the width of the line since the copper line λ 4531 comparatively narrow undergoes a larger displacement. This conclusion as to the character of the λ 4578 line is in agreement with that found by Duffield[4] in the arc under pressure.

The method is not so sensitive for lines which reverse at the negative pole since the displacement of the reversal is generally small. As however the unsymmetrical character is in the case of reversed lines easier to detect owing to the reversal not being central, this limitation is not very serious.

[1] King, Astrophysical Journal XXXIV, 37, 1911, XXXV, 183, 1912
[2] Gale and Adams, Astrophysical Journal XXXV, 10, 1912
[3] King, Astrophysical Journal XXXIV, 37, 1911
[4] Duffield, Phil. Trans Roy. Soc. A. 209, 205, 1908.

SUMMARY.

1. When the spectrum of the region of the arc near the negative pole is compared with that of the centre, the unsymmetrical lines are seen to be displaced in the direction of their greater widening; *i.e.*, lines widened more towards the red are displaced to the red at the negative pole, and those widened more towards the violet are displaced to the violet. Symmetrical lines have very small displacements if they are really displaced at all. The displacement amounts to over one-tenth of an Angstrom unit for 18 lines examined, a number which could probably be easily multiplied by extending the investigation to other elements and regions of the spectrum. The largest displacement yet measured is 0·52 A for the sodium pair λλ 6154, 6160.

2. There is a displacement in the region near the positive pole of about half the magnitude of that at the negative pole.

3. A displacement of the same sense as that at the poles is produced at the centre of the arc by increasing the current, or by shortening the arc.

4. The displacement at the negative pole is reduced if only the positive pole is supplied with the material producing the spectrum

5. Displacements occur in the arc in vacuo also, but to a much smaller extent than in the arc in air. The arc in vacuo is therefore the better source for the determination of standards of wavelength and for comparison with the sun's spectrum.

6. When a line reverses in the region near the negative pole the displacement of the reversal is much smaller than that of the unreversed line, but is generally in the same direction; in the case of very unsymmetrical lines such as the sodium pair λλ 5682, 5688, the displacement of the absorption line is in the opposite direction relative to the line at the centre of the arc.

7. The cause of the displacement is shown to be increase of vapour density of the material producing the spectrum. The pressure required to produce the displacements observed is too large to be entertained as existing in the arc in air and other possible hypotheses have also to be rejected.

8. The vapour density in the sun's reversing layer is lower than that at the centre of the arc under the conditions of my experiments.

9 The intimate relation between the unsymmetrical widening and the displacements due to increased density or to pressure, as well as the absence of any density effect on symmetrical lines for which a pressure effect exists, are believed to be of importance in the theory of these shifts and of the vibrations of the electrons in the atom.

10. The possibility of displacement at the negative pole seems to be a simple and effective means of testing the unsymmetrical character of spectrum lines, since no exceptions have been found (in unreversed lines) to the generality of the rule that unsymmetrical lines are displaced in the direction of their greater widening.

11. The bearing of the density effect on some other investigations of displacements in which the arc has been used is discussed.

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KODAIKANAL OBSERVATORY,
August 6th, 1914.

T. ROYDS,
Assistant Director

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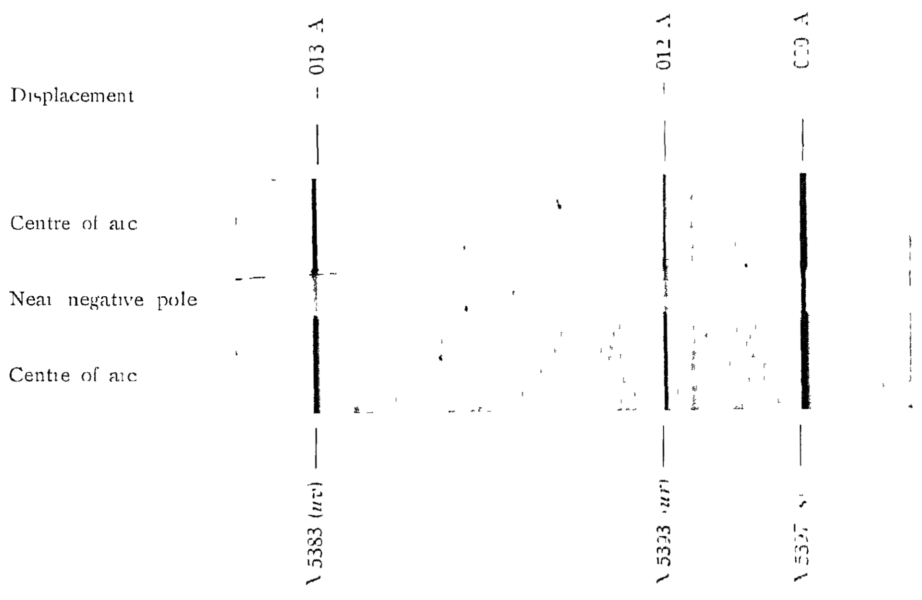

Fig. 1. IRON LINES.

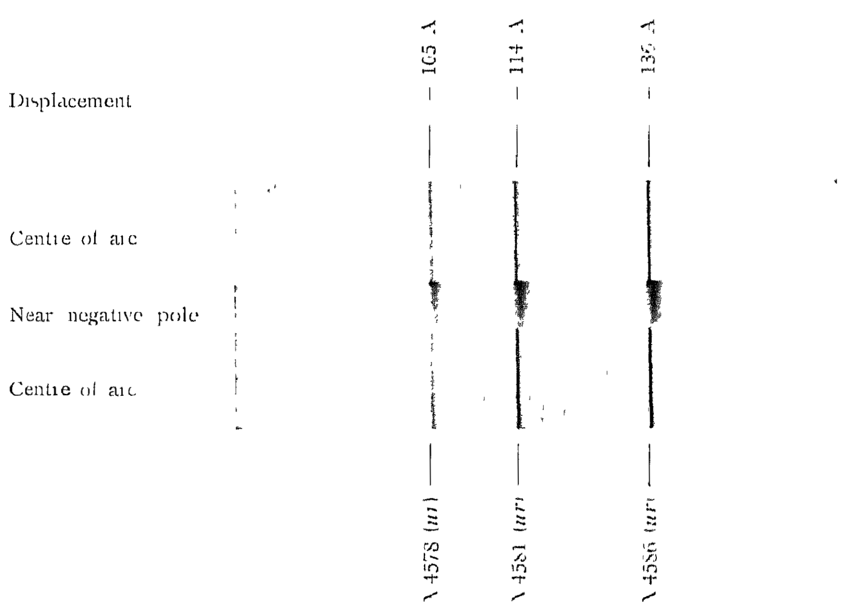

Fig. 2—CALCIUM TRIPLET near λ 4580.