The Einstein Effect in the Solar Spectrum.

In a series of letters and articles in *The Observatory*, I have recorded the results of the work done at Kodaikanal in trying to discover the cause or causes of the displacements of the lines in the solar spectrum. I propose now to give an account of the latest results that have been reached, and their bearing on the Einstein gravitational theory of the line shifts, according to which every line in the Sun's spectrum should be shifted slightly towards red when compared with the corresponding line produced under terrestrial conditions.

It is, of course, well known that this gravitational effect should be the same in the spectra of all the elements, and for all positions on the Sun. The amount should be proportional to wave-length, increasing towards the red end of the spectrum, as in the case of a displacement due to motion in the line of sight; it should, in fact, be the equivalent of a motion of recession of 0·634 km./sec., or an actual displacement of 0·008 A. at λ 3790, 0·010 A. at λ 4730, and 0·014 A. in the neighbourhood of the Hα line in the red.

These quantities are easily measurable in the solar spectrum. Even when the linear dispersion in a photograph is no greater than one angstrom to the millimetre, the probable error from a set of six readings can be reduced with practice to a few units in the fourth decimal, or, say, one-twentieth of the Einstein shift, when the positive-on-negative method of measuring is employed. This means that we are able to fix the position of a line with a probable error not greater than a wave-length of green light, or $\pm$0·0005 mm., and this notwithstanding the fact that the finer solar lines have a width about a hundred times greater than this. The metallic lines in the electric arc are usually both narrower and more sharply bounded than the solar lines, and so can be measured with a still greater precision.

Owing to the finite width of the solar lines and their close crowding in the ultra-violet, there is a possibility of systematic error in the measures, due to the superposition of two or more lines, which would vitiate to a greater or lesser degree the determination of the centre of the line, assuming it to be single. All that can be done to avoid this source of error is to select lines which appear to be isolated and symmetrical, and which correspond closely in relative intensity with the lines in the comparison spectrum. But with the greatest care in the selection this source of error cannot be entirely eliminated; its effect can, of course, be reduced by averaging the results of many lines.

At Kodaikanal we have studied the lines of iron, titanium, calcium, nickel, sodium, and the compound cyanogen, in Sun and arc, and in all these we find a general shift of the solar lines towards red compared with the arc lines. The shift is therefore of the right sign, and it is also of the right order of magnitude required by the Relativity Theory.

An account of our researches and the results obtained up to the year 1920 is given in *The Observatory*, vol. xliii. p. 153, the general result being that our measures of the iron lines and also of the band lines of cyanogen are more or less favourable to the Relativity Theory, but that the measures of Venus spectra are unfavourable, indicating smaller wave-lengths in the light reflected by the planet than in direct sun-light.

In this article stress was laid on the absence of pressure effects in the Sun—that is to say, the total pressure of all the gases overlying the photosphere according to our researches does not anywhere exceed one atmosphere, and is probably much less than an atmosphere. This now receives further confirmation in considering the intensities of the absorption-lines from the point of view of Saha's theory of ionization in solar or stellar atmospheres. A discussion by R. H. Fowler and E. A. Milne suggests that very low pressures are highly probable in the Sun's reversing layer: "the discussion points in the direction of pressures lower than 10^{-4} atmosphere, rather than of high pressures"*.

It seems safe to assume, therefore, that the infinitesimal shifts of lines in the solar spectrum due to pressure may be entirely neglected, the solar pressure being assumed to be zero. Consequently, we may use any of the apparently single metallic lines for measuring the shifts, and these will give results of no less weight than those obtained with the cyanogen lines, which are unaffected by pressure. But in using the arc in air for comparison, a small correction should be applied for the pressure shift of the lines in the arc, amounting in most cases to a small fraction of the Einstein effect.

Recent measures of the iron lines in the ultra-violet region, using a prism spectrograph, confirm the earlier ones made with the Anderson grating in giving a mean shift at the Sun's limb considerably in excess of the Einstein displacement. This is especially the case with the strong lines representing high levels in the Sun, the mean shift for 10 lines in the region 3886–3930 being about 0·015 A., without allowing for the pressure shift of the arc comparison lines, which would increase it by about one unit in the third place. The predicted gravitational effect is 0·0085 A. At the centre of the Sun's disc the shift is smaller, but still in excess of prediction, being about 0·011, without allowing for the pressure in the arc. But recent measures of old plates taken in the year 1914, and of plates taken in 1921, 1922, and 1923, seem to show that the wave-lengths of these high-level lines are not constant; and this is especially evident in the limb spectra, where the lines can be measured with greater precision than at the centre of the disc.

The excess of shift at the limb for the high-level lines and its apparent variation suggests a motion effect varying possibly with the sun-spot period, and superposed on the gravitational effect. But this involves a tangential movement of recession at all points on the limb—in other words, an Earth effect.

If we consider only the weaker iron lines representing low levels in the reversing layer, the results are in much better agreement with prediction, and the wave-lengths appear to be quite constant throughout the sun-spot period. I have been able to detect no certain indication of change in plates taken in 1913, 1914, 1922, and 1923. Furthermore, comparing the shifts of the ultra-violet lines with those of lines in the red region, I have found

* R. H. Fowler and E. A. Milne, "The Intensities of Absorption Lines in Stellar Spectra." *Monthly Notices of the Royal Astronomical Society*, lxxxiii. p. 419.

that the relation of the shift to wave-length holds approximately—that is to say, in both regions the shift of these low-level lines corresponds to a motion of recession of about 0·75 km./sec. at the Sun's limb. At the centre of the disc the shift is the equivalent of 0·46 km./sec.; and this difference might readily be explained by a radial outward movement of the iron vapour of about 300 metres per second.

Measures have also been made in an intermediate region near the Hγ line. Here similar results are obtained, the stronger lines giving the larger shifts. The mean of eleven lines of moderate intensity is 0·45 km./sec. at the centre, and 0·71 km./sec. at the limb—nearly in agreement with the weaker lines in the ultra-violet.

In *The Observatory*, vol. xliii. pp. 160–161, Dr. St. John refers to some measures of lines in the red region, and of iron lines in the blue, which give mean values Sun – arc considerably below the Einstein shift. But this refers to the centre of the Sun's disc, where my measures also yield values in these regions in defect of the predicted shift. It would be of interest to learn whether my results for the iron lines in the ultra-violet and at the Sun's limb have been confirmed at Mount Wilson. St. John's measures of the magnesium triplet in the green region would also appear to be unfavourable to the Einstein effect, b_1 yielding +0·001 A. and b_2 +0·003 A.; but he is comparing the arc in air with the Sun at zero pressure and making no allowance for the pressure in the arc. According to Perot the pressure shift of these lines is large, being +0·009 A. for b_1 and +0·007 A. for b_2 at 1 atmosphere. Adding these shifts, both lines would give +0·010 A., in close agreement with the predicted shift +0·011 A.

A very large number of measures of iron lines has been made in the Hγ region between the lines 4337 and 4494 at the limb, at the centre, and in general sun-light. Photographs of sun-light spectra were taken systematically during four years to detect possible variations; but there is little evidence of change in the mean values for all the lines for each year, although the year 1918 gives a mean shift 0·0014 A. less than the following three years, which give identical results. The evidence for change in individual lines would seem to be stronger: this is especially true in the case of the line 4376, which gave a mean value from fifty plates in 1919 0·002 A. below, and from thirty-four plates in 1920 the same amount above, its mean wave-length for the four years. If this is not a real change, it might possibly be explained by a change in relative intensity of some faint and indistinguishable companion-line. The other lines measured in this region appear to be more stable, although 4337 has shown some puzzling variations in individual plates.

During 1922 a study was made of the D-lines of sodium in Sun and arc. Here, again, the result appears favourable to the Einstein effect. Measuring the sharp emission-lines in the arc and the absorption-lines in the Sun, the mean of thirty-three plates gave the following results :—

	D1.	D2.
13 plates at centre of disc ..	+·0055 A.	+·0099 A.
20 plates at limbs	+·0053 A.	+·0063 A.
Mean of 33 plates	+·0054 A.	+·0078 A.

There is here shown to be no increase of shift between the centre and the limb, such as is shown very clearly by the low-level iron lines and the cyanogen bands. The difference between D1 and D2 is probably due to the pressure in the arc. The pressure shift for these lines is very large, and amounts roughly to 0·010 A. for D1 and 0·008 A. for D2 for three-fourths of an atmosphere, according to Humphreys' measures. Assuming a zero pressure in the Sun, and adding these figures, the true Sun-arc shift is approximately :—

D1.	D2.
+0·0154	+0·0158

The Einstein effect is +0·0124, the difference amounting to 0·003 A. only. This small excess over prediction may be explained by the fact that the D emission-lines in the arc appear to be always displaced by a few units in the third decimal towards violet with reference to the absorption-lines. The result is subject to some uncertainty, as the correction for pressure is approximate only, but it is evident that there is a reasonably close agreement between the observed and predicted shift.

I will now pass in brief review the evidence given by the light reflected from Venus. The spectrum of the planet at various positions in her orbit has been photographed and measured more than 160 times during four apparitions east and four west of the Sun. As has already been recorded, the spectra obtained near elongations, when the angle V–S–E was small and the image of the planet large, gave mean results in very close agreement with the control plates of direct sun-light, even in the case of each individual line measured. But when the planet was not very far from superior conjunction either east or west, with the angle at the Sun between 70° and 130°, there was usually a very considerable difference, the light reflected by the planet showing smaller wave-lengths. The best series of plates giving the most consistent results was obtained in July 1918 with the angle V–S–E about 90° and Venus a morning star. The mean result of seven plates gave practically no shift towards red for most of the lines, the control plates giving +0·007 A. for the same lines. This cannot have been due to any effect of atmospheric dispersion, owing to the low altitude of the planet, which might cause bias in guiding and so result in unequal illumination of the slit. It is almost certain, however, from later experience that these plates give unreliable results.

A new prism spectrograph was erected in 1921. This was built specially for the Venus work, and, using it in conjunction with a large reflector arranged as a skew Cassegrain, a narrower slit could be used with a much larger image of Venus, and the exposure time could be reduced to between 30 and 40 minutes only. A series of twelve spectra photographed in November and December 1921 gave shifts in close agreement with the control plates of direct sun-light. The angle V–S–E was large, varying from 137° to 149°—that is to say, the light came from a hemisphere of the Sun facing away from the Earth about 142°, and this gave lines displaced towards the red by practically the same amount as is found in ordinary sun-light.

Further confirmation was obtained in a final series of six plates obtained in 1922 April and June, with the planet an evening star. These results I therefore take to be final in proving that the shift to the red is found in light coming from any part of the Sun.

Reviewing the evidence as a whole, there seems to me to be very little doubt that the Einstein effect is present in the solar spectrum. The observed shifts over the entire face of the Sun, and in the unseen hemisphere, seem impossible to explain by motion, pressure, or anomalous dispersion. Assuming the gravitational effect to be the principal factor, there now remains to be explained the considerable excess of shift shown by the high-level lines in the ultra-violet, especially at the Sun's limb, and the large differences of shift in individual lines observed throughout the spectrum.

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