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A HISTORY OF THE SOLAR RED SHIFT PROBLEM

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I. THE DEVELOPMENT OF THE SOLAR RED SHIFT PROBLEM (1896–1923)

WHEN Rowland[1] began his extensive mapping of the Fraunhofer spectrum in 1887, the Doppler principle[2] was thought to be the sole cause capable of producing displacements of spectral lines. He and his collaborator Jewell were therefore surprised to find, when comparing solar and electric arc wavelengths after applying the necessary corrections, that solar lines appeared displaced—generally towards the red—by several milli-Angstrom (mA) units relative to the corresponding arc lines.

Rowland, appreciating the inadequacy of his equipment for a task demanding such high precision, felt justified in attributing most of these small discrepancies to accidental errors, and to a possible systematic error due to unequal illumination of different portions of the grating. Moreover, the poor resolution afforded by the small solar image which he had been obliged to use caused Rowland to doubt whether the light projected on to the spectrograph slit had indeed been received exactly from the centre of the disk ; thus, the Doppler effect due to the solar rotation may not, in fact, have been eliminated. He was also aware that small differences in the wavelength measurements can be produced by the presence of turbulent conditions on the solar disk—a feature of primary interest and importance to modern astrophysical research.

Jewell, on the other hand, was not prepared to accept Rowland's view.[3] He carefully repeated all the measurements and discovered that the displacements between solar and electric arc wavelengths vary in amount from element to element, from line to line belonging to the same element, and even among observations of the same spectral line taken on different photographic plates. Thus it became apparent that

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[1] H. Rowland, 'Preliminary table of solar spectrum wavelengths', *Carnegie Institute of Washington*, 1895.

[2] C. Doppler, 'Über das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels', *Abh. böhm. Ges. Wiss.*, 1843, **2**, 465.

[3] L. E. Jewell, 'The co-incidence of solar and metallic lines', *Astrophys. J.*, 1896, **3**, 89.

accidental errors alone were unable to account for the observed discrepancies.

Jewell was, therefore, the first to establish the existence of systematic shifts of a physical character in solar wavelength determinations: he claimed that they could not be Doppler effects since they were not directly proportional to wavelength and appeared to increase with line intensity. The essential feature of Jewell's results was that, with few exceptions, all solar wavelengths appeared displaced towards the red end of the spectrum relative to the corresponding emission lines formed in the electric arc. Appropriately, these displacements were called 'red shifts', and it is with the controversial problem of their quantitative interpretation that the numerous researches quoted in this paper are concerned.

1. *The Pressure Effect and the Standard Light Source*

At the same time as Jewell made his discovery (1896), Humphreys and Mohler[4] found that shifts with characteristics similar to those observed on the Sun are produced in arc spectra when the pressure is increased beyond atmospheric; pressure, more than temperature, appeared to be the basic factor determining these shifts.

The essential features of this pressure effect which these two investigators established for pressures in the range from 1 to 14·5 atmospheres are: with increasing pressure the spectral lines in the arc broaden asymmetrically; their wavelengths are displaced towards the red; the increase in wavelength is proportional to the increase in pressure; and the amount of displacement varies from line to line.

A more significant contribution to our knowledge of the character of pressure shifts was soon forthcoming from the interferometric investigations of Fabry and Buisson.[5] These workers found from a study of neutral iron (FeI) lines that spectral lines should be classified into three groups, according to whether their Sun-arc (in air) displacements are large and to the red, small and to the red, or towards the violet. They discovered the same distinction when comparing lines in the electric arc (in air) with those in a vacuum arc. The behaviour of the individual FeI lines when the pressure was increased up to one atmosphere was found to be very complex, some lines broadening considerably and being shifted asymmetrically towards the red or violet, whereas all appeared

[4] W. J. Humphreys & J. F. Mohler, 'Effect of pressure on the wave-lengths of lines in the arc spectra of certain elements', *ibid.*, 114.

[5] C. Fabry & H. Buisson, 'Mesure des petites variations de longueur d'onde par la méthode interférentielle. Application à différents problèmes de spectroscopie solaire', *J. de Phys.*, 1910, **9**, 298.

to be finer and of nearly the same width (about 30 mA) when produced in the vacuum arc.

In an attempt to provide a quantitative estimate of the effect of pressure under different conditions of state, A. S. King began to study the effect of pressure on the lines of different elements, namely iron, titanium, calcium, etc., contained in the spectra produced in an electric furnace.[6, 7] His extensive researches[8] have been principally concerned with the shifts of iron lines, from which he deduced that the pressure effect does not depend on the temperature of the furnace, the density of the iron vapour in which the lines are produced, or the presence of vapours belonging to foreign gases.

Two positive results of King's investigations, however, are : for a given increase in pressure, the shifts of the arc (i.e. neutral) lines produced in the furnace and in the electric arc are identical, while the observed displacements of the enhanced (i.e. ionized) lines in furnace spectra are almost twice as large as those measured in the arc.

These and other discoveries left no doubt that the effect of pressure depends upon the nature of the light source employed. It gradually became known as the result of numerous researches by such eminent observers as Gale and Adams,[9, 10] Goos,[11] St. John and Ware,[12] Royds,[13, 14] St. John and Babcock,[15, 16] Gale and Whitney,[17] and others, that absolute wavelength measurements by different observers were not equally reliable, agreement being obtained only among lines which broaden symmetrically under pressure.

The major advance in the understanding of the problem which resulted

[6] A. S. King, ' The production of spectra by an electrical resistance furnace in hydrogen atmosphere ', *Astrophys. J.*, 1908, **27,** 353.

[7] A. S. King, ' An electric furnace for spectroscopic investigations, with results for the spectra of titanium and vanadium ', *ibid.*, 1908, **28,** 300.

[8] No fewer than 21 papers were published in the *Astrophysical Journal* from 1908 to 1929 by King and his collaborators.

[9] H. G. Gale & W. S. Adams, ' An investigation of the spectra of iron and titanium under moderate pressures ', *Astrophys. J.*, 1912, **35,** 10.

[10] H. G. Gale & W. S. Adams, ' On the pressure-shift of iron lines ', *ibid.*, 1913, **37,** 391.

[11] F. Goos, ' A further contribution towards the establishment of a normal system of wave-lengths in the arc spectrum of iron ', *ibid.*, 1913, **38,** 141.

[12] C. E. St. John & L. W. Ware, ' Standards of wavelengths and desirable data for them and for other lines ', *Phys. Rev.*, 1913, **1,** 67.

[13] T. Royds, ' An investigation of the displacement of unsymmetrical lines under different conditions of the electric arc ', *Bull. Kodaikánal Obs.*, 1914, No. 40.

[14] T. Royds, ' The cause of the so-called pole-effect in the electric arc ', *ibid.*, 1916, No. 54.

[15] C. E. St. John & H. D. Babcock, ' A study of the pole effect in the iron arc ', *Astrophys. J.*, 1915, **42,** 231.

[16] C. E. St. John & H. D. Babcock, ' The elimination of pole-effect from the source for secondary standards of wave-length ', *ibid.*, 1917, **46,** 138.

[17] H. G. Gale & W. T. Whitney, ' On the pole-effect in a calcium arc ', *ibid.*, 1916, **43,** 161.

from all these experiments carried out with furnace and arc spectra lay in the consequent realization that many of the anomalies found in earlier comparisons of Fraunhofer lines with the laboratory wavelengths were due not only to the pressure effect (whose features have been mentioned above) but also to a so-called 'pole-effect'. The latter gave rise to wavelength shifts that were found to be greatest for those lines which broaden asymmetrically under an increase in pressure[17, 18]; the magnitude of the effect varied from element to element, and depended upon the conditions for the functioning of the electric arc, namely the distance between the electrodes, the intensity of the exciting current and the material from which the electrode is made.

The physical explanation of the above results, known at that time, is that both the observed pressure and pole-effects are features of the Stark effect[19] which produces changes in atomic energy levels by splitting them into several components in the presence of an electric field. Under not too high a resolution the multiplicity of the transitions among the components of both atomic energy levels has the effect of broadening the spectral line asymmetrically, thus producing a shift in the 'centre of gravity' of the line profile. Consequently, in order to eliminate the pole-effect and to ensure uniformity in arc measurements among different observers, the International Astronomical Union (I.A.U.) adopted the following recommendation[20]:

> 'In order to obtain lines of constant wavelength, constant intensity distribution and adapted to high orders of interference, the adoption is recommended of the Pfund arc [21] operated between 110 and 250 volts, with 5 amperes or less, at a length of 12–15 millimetres used over a central zone at right angles to the axis of the arc, not to exceed 1–1·5 millimetres in width, and with an iron rod 6–7 millimetres as the upper pole and a bead of oxide of iron as the lower pole.
>
> 'As the secondary standards to the red of λ 6000 are all stable lines, and as the exposures with the above-mentioned arc may be rather long, it is recommended that the 6 mm., 6 ampere arc be retained for this region, and that a neon tube be used as an alternative or supplementary source.'

Many observers have since worked with standard vacuum arcs, or arcs in air, and applied pressure corrections to obtain the effective wavelengths *in vacuo*, believing that by doing so they have eliminated all effects of pressure. In view, however, of the anomalies found by King between pressure shifts of ionized lines excited in furnace and arc

[18] W. T. Whitney, 'The pole-effect in a calcium arc', *ibid.*, 1916, **44**, 65.

[19] J. Stark, *Die Atomionen chemischer Elemente und ihre Kanalstrahlenspektra*, Springer, Berlin, 1913.

[20] *Trans. Int. Astr. Un.*, 1922, **1**, 36.

[21] A. H. Pfund, 'Metallic arcs for spectroscopic investigations', *Astrophys. J.*, 1908, **27**, 296.

spectra, and the complexity of the Stark effect, it is evident that the adoption of one particular set of conditions cannot be expected to result in the elimination of systematic displacements for all laboratory wavelengths, although such effects can be minimized by selecting for measurement only such lines as are known to be insensitive to pressure changes (i.e. those which do not broaden appreciably under an increase in pressure). Consequently, one must always be wary of attaching significance to values of the Sun–arc displacements, especially to those which have been derived from a source that does not comply with the I.A.U. specifications. This realization is extremely important when one comes to assess the validity of the various interpretations put forward to account for the observed solar red shifts.

2. *The Solar Limb Effect*

The difficulties which we have been discussing do not apply to wavelength comparisons made between spectra from different regions of the Sun's disk, since in the case of such relative measurements all reference to terrestrial wavelength standards is avoided.

The first attempt at a quantitative comparison between wavelengths of the spectrum of the Sun's limb and those at its centre was made by Halm,[22] although it had been known many years beforehand that the two spectra present quite different appearances. After applying the necessary corrections for the Doppler effect of solar rotation at different heliographic latitudes obtained from his previous research, Halm[23] calculated the shifts of the two FeI lines at 6,302A relative to the two atmospheric oxygen lines in their immediate vicinity at selected disk positions on different solar radii.

As a result of comparing spectra of the centre of the disk with those referring to points at distances of $\frac{1}{2}R$, $\frac{3}{4}R$, R from it—R being the solar radius—he discovered that the wavelengths nearest the limb exceeded those at the centre by about 12 mA, while the intermediate measures indicated that the increase towards the limb was gradual. To this phenomenon, which was characteristic of the Fraunhofer lines only, Halm gave the name ' limb-effect '.

Fabry and Buisson, applying their interferometer to the limb-centre shifts of 14 spectral lines around 4,400A, [24] confirmed that Halm's limb-effect was not peculiar to the one element (iron) or to the one wavelength

[22] J. Halm, ' Über eine bisher unbekannte Verschiebung der Fraunhoferschen Linien des Sonnenspektrums ', *Astr. Nachr.*, 1907, **173**, 273.

[23] J. Halm, ' Spectroscopic observations of the rotation of the Sun ', *Trans. Roy. Soc. Edin.*, 1904, **41**, 89.

[24] C. Fabry & H. Buisson, ' Comparaison des spectres du centre et du bord du Soleil ', *C.R. Acad. Sci., Paris*, 1909, **148**, 1741.

region on which his investigation was based ; but no definite conclusions could be drawn concerning the characteristics of this newly-discovered phenomenon until more observational material had been accumulated with much better resolution and improved equipment. These requirements were soon fulfilled, however, when the 60-foot tower telescope was installed at the Mount Wilson Observatory.

Walter Adams, using this instrument in conjunction with a high-dispersion grating spectrograph, observed the limb–centre shifts of 470 Fraunhofer lines belonging to various neutral and ionized elements in the spectral range between 3,741A and 6,573A.[25] The effect of solar rotation was eliminated by the procedure of averaging the observed wavelengths at the East and West limbs in 0° heliographic latitude, a suitable arrangement of small prisms enabling the two spectra to be photographed simultaneously on either side of the spectrum of the central portion of the 170 mm. diameter solar image. Due care was naturally taken to avoid other possible sources of systematic error.

Two fundamental features which Adams discovered from an analysis of his extensive data were :

(i) The limb–centre shifts are directly proportional to wavelength.
(ii) The mean relative displacement for a group of enhanced (ionized) lines is higher than that for an equal number of arc (neutral) lines belonging to the same element.

A linear wavelength dependence is in accordance with the interpretation of the relative wavelength differences as velocity shifts, and so Adams considered the possibility that the second characteristic might be a Doppler effect between the hotter and cooler parts of the photosphere observed in solar granulation. However, since the measures of the FeI lines—which constituted the bulk of his material and on which the weight of his conclusions had necessarily to be based—showed a tendency to favour a higher-power wavelength dependence, he felt that pressure might be the dominant cause producing the shifts.

On the other hand, the behaviour of the cyanogen (CN) lines in Adams's observations suggested that the Doppler effect was also contributing towards the observed displacements. Laboratory experiments by Humphreys[26] and by Rossi[27] had shown that lines in the CN bands around 3,883A and 4,216A were quite insensitive to changes of pressure, yet the limb–centre shifts of those lines were not zero, as expected.

[25] W. S. Adams, ' An investigation of the displacements of the spectrum lines at the Sun's limb ', *Astrophys. J.*, 1910, **31**, 30.

[26] W. J. Humphreys, ' Changes in the wave-frequencies of the lines of emission spectra of elements, their dependence upon the elements themselves and upon the physical conditions under which they are produced ', *ibid.*, 1897, **6**, 169.

[27] R. Rossi, ' The effect of pressure on the band spectra of the fluorides of the metals of the alkaline earths ', *Proc. Roy. Soc. A*, 1909, **82**, 518.

Since their relative wavelength shifts never exceeded 2 mA—equivalent to a line-of-sight velocity of about 0·15 km./sec.—Adams felt that this difference could be attributed to ascending radial currents at the Sun's centre producing a violet displacement relative to the wavelengths at its limb, where these currents (being at right-angles to the line of sight) would produce no effect.

Now, although Adams's programme yields useful information concerning the variations of the relative displacements with wavelength and element, it affords no knowledge of the functional form of the wavelength variation across the disk. The importance of such measures for determining the contribution of the effect of radial currents was fully appreciated by Evershed and Royds,[28] who investigated this problem by projecting a primary solar image 14 mm. in diameter (enlarged to 28 mm.) upon the slit of a high-resolution grating spectrograph—centering it precisely so that the wide spectrum obtained represented a diameter of the Sun. They then measured the relative displacements of solar wavelengths along a radius at 2 mm. intervals as far as 10 mm. from the centre, and thereafter at 1 mm. intervals, to 13 mm.; the final measures referred to a point 0·25 mm. inside the edge of the solar image. This research led to the discovery that the centre-limb variation of the relative shifts of certain weak enhanced (i.e. ionized) iron and titanium lines could be well represented in terms of the cosine of the angle of emergence (θ)[29] of the observed radiation. Three lines in the red of mean Rowland intensity 5 showed an appreciable departure from this simple geometrical relation, while two strong FeI lines of intensity 8 exhibited an even greater departure, in the sense that the increase to the limb is less pronounced for the strong lines than for the weak ones.

3. *The Early Interpretations of the Solar Red Shifts*

When Jewell first made his discovery he thought that the cause of the displacements might be found in the different temperature and density of matter prevailing in the Sun, compared with the conditions employed to excite spectral lines in the laboratory. But being unable to find evidence for any such changes among the laboratory spectra, he suggested that the high pressure then thought to exist in the solar

[28] J. Evershed & T. Royds, 'On the change of wave length of the iron lines in passing from the centre of the Sun's disc to the limb', *Bull. Kodaikánal Obs.*, 1916, No.49.

[29] This is the angle between the outward direction of the normal at a selected point on the surface of the Sun and the observer's line of sight, and is the parameter usually employed in specifying the location of the point with respect to any given solar radius. It varies continuously from zero at the disk centre to 90° at the extreme edge of the Sun (i.e. $0 \leqslant \theta \leqslant 90°$).

atmosphere might be responsible for producing anomalous shifts, a belief which seemed to be justified in view of the similarity in the characteristics of the pressure shifts measured in the electric arc. Together with Mohler and Humphreys, Jewell[30] made an analysis of solar and arc wavelength displacements, and concluded that his measurements supported the existence of pressures between two and seven atmospheres in the solar 'reversing layer' where the Fraunhofer lines are produced. Jewell ignored the possible contribution of Doppler effects towards the observed displacements since the latter were not directly proportional to wavelength and, in general, the amount of the shifts appeared to increase with the intensity of the lines. The figures were not very reliable since there was no guarantee that the errors suspected by Rowland had been eliminated.

An important result which had emerged from Fabry and Buisson's work was that pressure could not be regarded as the sole cause responsible for the production of the solar red shifts. It if were, the asymmetrical broadening found by increasing the pressure in the arc lines should also be observed in the absorption lines of the solar spectrum ; but in fact, it is not. Furthermore, the appearance of absorption lines corresponds more closely to that of the spectrum produced in the vacuum arc and, as Evershed[31] was first to remark, this similarity in appearance favours a pressure below that of our atmosphere.

Evershed maintained that these observed characteristics are much more convincing than the unjustified assumption that pressure is primarily responsible for the solar red shifts, as Jewell had supposed. Consequently, he contended that the Doppler effect of localized radial convection currents yields the major contribution towards the measured values, while pressure exerts no appreciable influence on solar wavelengths. The results of further researches by the Kodaikánal observers[32] were interpreted by them as indicating that the pressure in the outer layers of the Sun was approximately atmospheric, in accordance with Evershed's viewpoint.

A necessary consequence of Evershed's interpretation is that the *absolute* (Sun-arc) values of the shifts at the limb should be zero, or at least very small, so in order to test its validity Evershed and Royds[33] made limb-centre comparisons of FeI wavelengths and added the values to the corresponding centre-arc shifts previously obtained. The resulting

[30] L. E. Jewell, J. F. Mohler & W. J. Humphreys, 'Note on the pressure of the "reversing layer" of the solar atmosphere', *Astrophys. J.*, 1896, **3**, 138.

[31] J. Evershed, 'Pressure in the reversing layer', *Bull. Kodaikánal Obs.*, 1909, No. 18.

[32] J. Evershed, 'A new interpretation of the general displacement of the lines of the solar spectrum towards the red', *ibid.*, 1913, No. 36. T. Royds, 'A preliminary note on the displacement to the violet of some lines in the solar spectrum', *ibid.*, 1914, No. 38.

[33] J. Evershed & T. Royds, 'On the displacements of the spectrum lines at the Sun's limb', *ibid.*, 1914, No. 39.

limb-arc displacements, however, were very much larger than anticipated and were quite incompatible with the radial current hypothesis. Yet neither did they support the belief that pressure is the major factor responsible for their production, for they exhibited no variation with wavelength nor dependence on line intensity. St. John, realizing the inadequacy of Evershed's equipment, undertook a similar programme at Mount Wilson,[34] taking special precautions to avoid sources of systematic observational error, but the results of his extremely careful investigation merely served to confirm the conclusions of Evershed and Royds. Evershed was unable to suggest any rational explanation of the large values obtained, and the only conclusion he could draw was that the Earth had some kind of repelling action on all lines coming from the Sun. This rather absurd hypothesis found no support from observations of Venus.[35, 36, 37] Yet the only way in which the situation could be satisfactorily resolved was by the introduction of another cause, besides pressure and the Doppler effect, that was capable of producing shifts of the order required ; for shifts due to pressure and pole-effects in the arc spectra were unlikely to be large enough to bridge the gap between the observed and required results—certainly not in St. John's work.

There were, in fact, two causes known at that time which seemed capable of resolving this problem. One was the famous theoretical prediction discussed in the following section ; the other was the theory of anomalous dispersion, which had been introduced as early as 1900 by the Dutch physicist Julius,[38] and later modified and revised in an attempt to account for the increasing number of observational facts that were steadily being assimilated.[39-43]

Basically, it stated that among the radiations emitted by the

[34] C. E. St. John, ' The principle of generalized relativity and the displacement of Fraunhofer lines toward the red ', *Astrophys. J.*, 1917, **46**, 249.

[35] J. Evershed, ' The displacement of the solar lines reflected by Venus ', *Observatory*, 1919, **42**, 51.

[36] J. Evershed, ' Displacement of the lines in the solar spectrum and Einstein's prediction ', *ibid.*, 1920, **43**, 153.

[37] C. E. St. John & S. B. Nicholson, ' On systematic displacements of lines in spectra of Venus ', *Astrophys. J.*, 1921, **53**, 380.

[38] W. H. Julius, ' Solar phenomena considered in connection with anomalous dispersion of light ', *Verh. Akad. Wet. Amst.*, 1900, 575.

[39] W. H. Julius, ' Les théories solaires at la dispersion anomale ', *Rev. Gén. Sci.*, 1904, **15**, 480.

[40] W. H. Julius, ' Sur l'explication des spectrohéliogrammes et des déplacements des raies spectrales et sur la diffusion anomale de la lumière ', *Arch. Néerl. Sci.*, 1910, **15**, 417.

[41] W. H. Julius, ' Les raies de Fraunhofer et la dispersion anomale de la lumière ', *ibid.*, 1912, **1**, 231.

[42] W. H. Julius, ' Dispersion anomale et raies de Fraunhofer ', *ibid.*, 1917, **4**, 59, 150.

[43] W. H. Julius, ' Le déplacement des raies de dispersion dans les spectres d'absorption ', *ibid.*, 1918, **5**, 116.

photosphere, those whose wavelengths are very near to those of the characteristic radiations of the vapours in the solar atmosphere must suffer abnormal refraction. It is, in effect, an application of Rayleigh's formula for scattering. Julius's theory met with violent opposition from several notable practical astrophysicists, in particular from St. John[44, 45] and Royds,[46] with the result that it was never allowed to dominate the problem in the same way as the pressure effect had done, although it certainly provided scope for discussion.

Nevertheless, there were those who believed that St. John's objections carried little weight owing to the practical impossibility of simulating the complex conditions prevailing in the solar atmosphere in experiments with a light-source in the laboratory. This view was held by Croze, who included a detailed account of anomalous dispersion and its probable implications in his lengthy memoir,[47] to which the reader is referred for a more comprehensive survey of the researches carried out before 1923, interpreted and presented from a contemporary (as opposed to a modern) point of view.

4. *The Einstein Effect and the Observed Displacements*

In 1911, Einstein[48] predicted that, as a consequence of the relation between mass and energy, the wavelength (λ) of every line in the solar spectrum should suffer a displacement ($\Delta\lambda$) to the red end of the spectrum relative to the corresponding lines produced in a terrestrial light-source, the amount of which is given by the formula

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\psi}{c^2} = 2{\cdot}12 \times 10^{-6},$$

where $\Delta\psi$ denotes the difference in gravitational potential between the Sun and Earth's surface, and c is the velocity of light. Since all spectral lines are produced in a relatively thin layer of atmosphere at the same distance from the Sun's centre, the quantity $\Delta\psi$ is effectively constant for all lines of all elements at any chosen position on the solar disk. This implies that the ratio $\frac{\Delta\lambda}{\lambda}$ possesses similar characteristics, which

[44] C. E. St. John, 'Anomalous dispersion in the Sun in the light of observations', *Astrophys. J.*, 1915, **41**, 28.

[45] C. E. St. John, 'Observational evidence that the relative positions of Fraunhofer lines are not systematically affected by anomalous dispersion', *ibid.*, 1916, **44**, 311.

[46] T. Royds, 'Anomalous dispersion in the Sun', *Bull. Kodaikánal Obs.*, 1915, No. 48.

[47] F. Croze, 'Les raies du spectre solaire et la théorie d'Einstein', *Ann. Phys., Paris*, 1923, **19**, 93.

[48] A. Einstein, 'Über den Einfluss der Schwerkraft auf die Austreitung der Lichtes', *Ann. Phys., Lpz.*, 1911, **35**, 905.

should be reflected in the observations of Sun-arc displacements if the theoretical considerations from which the relation is derived are valid.

The first person to recognize in the observations of the solar red shifts a possible verification of Einstein's prediction was Freundlich,[49] who noticed that the results of Fabry and Buisson for iron lines at the centre of the Sun's disk, and those of Evershed, corresponded very closely with the predicted values. He was also aware, however, that Evershed, Royds and St. John had clearly shown that the shifts of iron lines varied with intensity by an amount too large to be accounted for by differential pressure effects in the various layers of the solar atmosphere throughout which the spectral lines are formed. In addition, measurements by Royds (exempt from pole-effect) had yielded similar results for nickel and titanium,[50] and thus verified Jewell's original discovery that the shifts varied from element to element. They also showed that the Sun-arc shifts are not directly proportional to wavelength, and that their values at the centre of the disk were generally smaller than Einstein's prediction requires—facts which suggested that some other effect was producing anomalies in either solar or terrestrial wavelengths, or in both. Indeed, the observed increase in all these displacements in going from the centre to the limb was a feature of the solar lines only which was independent of the existence of the Einstein effect. Consequently, the observations at that time could not be regarded as constituting a decisive verification of this prediction.

The CN bands around 3,883A and 4,216A, however, were known to be insensitive to pressure, uninfluenced by pole-effect, and to exhibit only very slight displacements from centre to limb, which Adams had attributed to the Doppler effect. Hence, since these effects appeared to be so small in comparison with the predicted gravitational displacement —this varies between 8 and 9 mA over the narrow wavelength region in question—an accurate measurement of the shifts of these lines was thought to provide a means of testing whether the Einstein effect did in fact exist. Unfortunately, however, there are several reasons why the necessary precision cannot be attained in practice, the most significant of these being that the CN lines appear in a region of the solar spectrum which is overcrowded with Fraunhofer lines, and very few can be completely resolved.[51] Not only might there be blends and consequent asymmetries among the CN lines themselves, but also among CN lines

[49] E. F. Freundlich, 'Über die Verschiebung der Sonnenlinien nach den roten Ende auf Grund der Hypothesen von Einstein und Nordström', *Phys. Z.*, 1914, **15**, 369.

[50] T. Royds, 'The displacements of nickel and titanium lines in the Sun and arc', *Bull. Kodaikánal Obs.*, 1916, No. 53.

[51] C. E. St. John & L. W. Ware, 'The accuracy obtainable in the measured separation of close solar lines; systematic errors in the Rowland Table for such lines', *Astrophys. J.*, 1916, **44**, 15.

and metallic lines. The superposition of a metallic line on a CN line is likely to have the greater effect in shifting the true position of the latter.[52]

Evershed and Royds[33] were among the first to investigate this problem but, although they found good agreement with Einstein's prediction, they realized that the results were not at all reliable on account of the limitations of their equipment, and that certain anomalies would have to be accounted for on a quantitative basis before the Einstein effect could be invoked. K. Schwarzschild,[53] by measuring Sun-arc displacements at five different positions on the disk, from centre to limb, discovered that the observed values were always decidedly smaller than the gravitational red shift. His work was presented by Einstein at the Academy of Sciences in Berlin on 5 November 1914, and it produced a profound impression on all those interested in the development of the General Theory of Relativity. Nevertheless, there remained the possibility that the accidental errors due to displacements of the apparatus were not completely eliminated in Schwarzschild's measures, and since the diameter of the solar image was only 28 mm., small systematic errors were also liable to have been incurred through poor resolution.

St. John[34] made an extremely careful investigation of the shifts of the CN lines at the centre of the disk, using the 60 ft. tower telescope and a high-dispersion spectrograph—yielding a 170 mm. diameter image and a reciprocal dispersion of between 0·4 and 0·6 A/mm.—which are essential requirements for such work, the excellent 'seeing' conditions at Mount Wilson being an additional advantage in affording accurate results. He carefully selected a few (weak) CN lines which he believed to be least affected by the presence of blends, and employed four different procedures for obtaining the Sun-arc shifts from comparisons of rigorously simultaneous exposures at both the centre and limb of the Sun. Yet he was obliged to conclude that his results were radically opposed to Einstein's prediction.

Nevertheless, not all astrophysicists were satisfied with this result. Researches on the CN bands were again taken up by Grebe and Bachem,[54–57] who worked with equipment yielding a primary solar

[52] J. Evershed, 'The displacement of the cyanogen bands in the solar spectrum', *Observatory*, 1918, **41**, 371.

[53] K. Schwarzschild, 'Über die Verschiebungen der Bande bei 3,883A im Sonnenspektrum', *S.B. preuss. Akad. Wiss.*, 1914, 1201.

[54] L. Grebe & A. Bachem, 'Über den Einsteins effekt im Gravitationsverschiebung im Sonnenspektrum', *Z. Phys.*, 1920, **1**, 51.

[55] L. Grebe & A. Bachem, 'Die Einsteinsche Gravitationsverschiebung im Sonnenspektrum der Stickstoffbande $\lambda = 3883$ Å', *ibid.*, 1920, **2**, 415.

[56] L. Grebe, 'Über die Gravitationsverschiebung der Fraunhoferschen Linien', *Phys. Z.*, 1920, **21**, 662.

[57] L. Grebe, 'Sonnengravitation und Rotverschiebung', *Z. Phys.*, 1921, **5**, 105.

image only 12 mm. in diameter (enlarged to 50 mm.) and a dispersion of 1 A/mm., which was inferior to that used by St. John. But, by comparing microphotometric tracings of the intensity profiles of the solar and arc lines employed in their own investigations, they realized that such extreme care had to be exercised in the choice of lines adopted for such analysis that even St. John's results were liable to contain serious systematic errors which could invalidate his conclusion. In spite of this realization, further measurements by Evershed,[58] and a series of interferometric investigations by Pérot on CN, iron, and magnesium lines,[59–62] again made with inferior equipment, ultimately proved to be too unreliable to furnish a definite answer to the question of the existence of the Einstein effect.

The feature of Grebe and Bachem's work which distinguishes it from all previous researches is that the relativity effect was assumed to be implicit in the observed values of the absolute (Sun-arc) shifts, and the problem under consideration was not to decide whether this effect exists, but rather to explain why the measured displacements are smaller than the theoretical prediction demands. The discovery which exerted such an influence on these, and subsequent, investigations, was the knowledge that the analysis of photographs taken during the total solar eclipse at Sobral on 29 May 1919 by the Greenwich expedition had shown that the positions of stars in the star-field surrounding the Sun exhibited displacements which seemed to conform with another prediction based on the General Theory of Relativity.

After the result of this (light-deflection) experiment was announced,[63] it was generally taken for granted that the gravitational displacement of solar lines must also exist. But, as McCrea has since emphasized, these two predictions depend not only upon the basic theory itself but also upon different postulates concerning the properties of radiation.[64] Consequently one is not entitled to infer the existence of the gravitational red shift from the results of such eclipse experiments and, in any case, the latter favour a value for the light-deflection significantly higher than that deduced

[58] J. Evershed, 'On the displacements of the triplet bands near λ 3883 in the solar spectrum', *Bull. Kodaikánal Obs.*, 1920, No. 64.

[59] A. Pérot, 'Sur la variation avec la pression de la longueur d'onde des raies des bandes du cyanogène', *C.R. Acad. Sci., Paris*, 1920, **170**, 988.

[60] A. Pérot, 'Comparaison des longueurs d'onde d'une raie de bande du cyanogène dans la lumière du Soleil et dans celle d'une source terrestre', *ibid.*, 1920, **171**, 229.

[61] A. Pérot, 'Mesure de la pression de l'atmosphère solaire dans la couche du magnésium et vérification du principe de relativité', *ibid.*, 1921, **172**, 578.

[62] A. Pérot, 'Mesure de la pression dans l'atmosphère du Soleil', *ibid.*, 1922, **174**, 933.

[63] Joint Eclipse Meeting of the Royal Society and the Royal Astronomical Society (1919 November 6), *Observatory*, 1919, **42**, 389–391.

[64] W. H. McCrea, 'On the gravitational displacement of spectral lines', *Proc. Roy. Irish Acad.*, 1956, **57**, 173.

from Einstein's theoretical considerations.[65] Very recently, however, physical experiments of an entirely different character[66] appear to have provided an independent observational justification of the point of view adopted, although further work is still required before a decisive quantitative check on the Einstein effect can be obtained.

5. *The Relativity-Radial Current Interpretation*

A radical change in our knowledge of the physical conditions prevailing in the outer layers of the Sun that profoundly affected the subsequent development of the solar red shift problem was heralded in 1920 by Saha's Ionization Theory [67–69] which, in a very convincing way, accounted for most of the features of the solar spectrum which had hitherto baffled astrophysicists, and was therefore not long in becoming generally accepted. Saha realized that the differing appearance presented by the Fraunhofer lines depended basically upon ' the varying response of the elements with regard to the stimulus existing in the sun ', and not so much upon the abundances of these elements, as had previously been supposed. He believed, however, that the abundance was a major factor determining the marginal appearance of a line, i.e., that when the number of atoms taking part in the production of a Fraunhofer line becomes appreciable, the line would show itself in the solar spectrum. The difficulty of making a numerical assessment of the word ' appreciable ' led Fowler and Milne[70] to work with the maximum intensities of the lines rather than concern themselves with the uncertain conditions governing the marginal appearances. By finding that ionized magnesium (MgII) lines and neutral hydrogen (HI) lines both attained their maximum intensities at approximately the same temperature (about 10,000° K), Fowler and Milne were able to determine the second important parameter — besides temperature — in Saha's formula . This was the electron pressure, which they estimated at 10^{-4} atmosphere. Thus the reason for the similarity between solar and vacuum arc spectra was made apparent, and it was immediately realized that neither pressure nor anomalous dispersion in the solar

[65] A. H. Mikhailov, ' The deflection of light by the Sun's gravitational field ' (George Darwin Lecture for 1959), *Observatory*, 1959, **79**, 80.

[66] T. E. Cranshaw *et al.*, ' Measurement of the gravitational red shift using the Mössbauer effect in Fe^{57}', *Phys. Rev. Lett.*, 1960, **4**, 163.

[67] M. N. Saha, ' Ionization in the solar chromosphere ', *Phil. Mag.*, 1920, **40**, 472.

[68] M. N. Saha, ' Elements in the Sun (Paper B) ', *ibid.*, 809.

[69] M. N. Saha, ' On the problems of temperature radiation of gases (Paper C) ', *ibid.*, 1921, **41**, 267.

[70] R. H. Fowler & E. A. Milne, ' The intensities of absorption lines in stellar spectra, and the temperatures and pressures in the reversing layers of stars ', *Mon. Not. R. Astr. Soc.*, 1923, **83**, 403.

atmosphere could possibly have exerted any appreciable influence on the values of the observed red shifts.

Since the Doppler effect of radial currents could not be contributing towards the absolute shifts observed close to the Sun's limb — generally found to be at least as large as the Einstein effect — astronomers felt that there remained no alternative but to admit the validity of the theoretical prediction and to explain the observed Sun-arc displacements as resulting, in general, from the superposition of these two effects. The small excess (or over-relativistic) values observed in many of the limb-arc shifts could always be attributed to some unknown physical effect,[71] or assumed to reflect the presence of systematic observational errors. This relativity-radial current hypothesis, as it came to be called, has since been chosen as the conventional framework into which most subsequent attempts to interpret the solar red shift phenomenon have been forced.

II. A Discussion of Later Investigations (1923–63)

6. *St. John's Relativity-Radial Current Hypothesis*

St. John thought he could provide a satisfactory solution to the problem of the origin of the solar red shifts on the basis of the relativity-radial current interpretation, by retaining his earlier belief that level is the determinative condition in their production. He believed the dependence upon depth to be well established by concordant results from spectroscopic observations of solar rotation, sun-spots, flash spectra, differences between spectra from near the limb and at the centre of the Sun's disk, and the progression of the limb-centre wavelength differences with level of excitation. Accordingly, after subtracting the Einstein effect from each of his observed values, he attributed the positive and negative residuals thus obtained to variations in the effect of radial currents at different levels in the 'reversing layer', and not to pressure, as he had originally supposed.[72]

The observational data on which St. John's discussion[73] is based comprise measures of the absolute wavelengths of 1,537 spectral lines at the centre, 133 lines at the limb of the Sun, and their wavelengths in a vacuum arc source. (Actually, an arc in air with pressure corrections, and a vacuum arc, were both employed at different stages). All the values of the shifts on which St. John's conclusions were based are the

[71] St. John, for instance, used the term 'limb-effect' to mean this excess (absolute) shift, instead of employing it in Halm's original sense: namely, to denote the observed (relative) wavelength variation from centre to limb.

[72] C. E. St. John, 'Radial motion in Sun-spots. II. The distribution of the elements in the solar atmosphere', *Astrophys. J.*, 1913, **38**, 367.

[73] C. E. St. John, 'Evidence for the gravitational displacement of lines in the solar spectrum predicted by Einstein's theory', *ibid.*, 1928, **67**, 195.

means of closely agreeing grating measurements by St. John and interferometric observations by Babcock collected over a number of years, initially obtained at Mount Wilson with the 60 ft tower telescope and 30 ft focus spectrograph, and later with the 150 ft telescope in conjunction with the 75 ft spectrograph. Thus the results are heterogeneous, and might for this reason be expected to show inconsistencies among the individual values ; yet the internal agreement was so good that many of the terrestrial wavelengths have been adopted as secondary standards. On the other hand, a comparison of the FeI solar wavelengths used in his discussion by St. John with the solar standards adopted by the I.A.U. reveals the presence of marked discrepancies, the origin of which lies in the fact that the former were not independent determinations, but combinations of preliminary data obtained by Babcock with some from other sources.[74] This naturally raises doubts as to the reliability of the figures tabulated in St. John's paper.

In assessing the reliability of his conclusions, one must consider the validity of the procedure of grouping spectral lines. Basing results on groups of measurements has the advantage that both systematic and accidental errors are reduced ; the former by an uncertain amount, the latter by an amount depending on the number of individual measures comprising the group. In addition, this procedure will also minimize the effect of blends, whether they be known or unknown, whereas the position of any particular line might be seriously affected by a neighbouring line and so rendered unsuitable for discussion[75]. In principle, therefore, it is desirable to group measurements of the solar red shifts ; in practice, the selection of lines which will constitute each group presents some difficulty, for the production of every spectral line is governed by many factors.

St. John classified the lines according to line intensity, his criteria for selection being similarity in excitation potential and pressure classification (which refers to their behaviour under variations of pressure in the terrestrial light-source). He considered intensity rather than depth when discussing his measurements, for the simple reason that an estimate could always be made of the intensity of every spectral line which appears

[74] *Trans. Int. Astr. Un.*, 1934, **4**, 64. For the purpose of his investigation, St. John changed the scale of Babcock's measurements from that of 1928 to that of 1922.

[75] In a private communication to Professor E. Finlay-Freundlich, dated 29 November 1955, Dr E. H. Schröter remarked that as a result of a critical survey of the whole of St. John's material, he found that not more than 80 lines appear to be entirely free from blends, as judged by a comparison with the Utrecht Atlas (M. Minnaert, G. F. W. Mulders & J. Houtgast, *Photometric Atlas of the Solar Spectrum*, **1946**), while an examination of the rest of the data provided a convincing demonstration of the fact that lines with a violet blend exhibit a smaller red shift than those with a red blend. These facts were verified independently by the writer.

on a photographic plate, while there existed only a few lines whose levels of origin were considered to be well known. Moreover, many of the estimates of level had been made on irregular features and disturbed regions of the solar disk and could not be taken as representative of the solar atmosphere in its steady state. However, because of the complexity of spectral line formation, the manner in which intensity is related to depth inside the solar atmosphere differs from line to line, and (as St. John himself was aware) it does not follow that lines of equal intensity originate at similar levels.

The results of St. John's groupings of the observed centre-arc displacements of 497 FeI lines belonging to pressure classes *a* and *b* — lines measurable in the arc with very high accuracy — indicated that at least two factors are operative in determining the size of the shifts, namely line intensity and wavelength, in the sense that an increase in either of these quantities corresponds to an increase in the observed displacement. Since St. John was regarding the more predominant feature — the dependence of the red shifts on line intensity — as being the result of the correlation between intensity and depth, the fact that weak (and presumably low-lying) lines exhibited small shifts at the centre of the disk could be accounted for by assuming the existence of strong radial convection currents whose velocity decreases with increasing height inside the solar atmosphere. However, he could offer no satisfactory explanation for red shifts greater than the gravitational value which were observed in strong (high-level) lines such as the H and K lines of CaII.

Although the wavelength dependence is a feature which St. John considered only roughly in his groupings of the centre-arc measures, it is important to study its form in more detail with a view to deciding whether the observed shifts do indeed have the character of Doppler effects and exhibit a direct proportionality to wavelength. An analysis by the writer has, in fact, shown that such a dependence does provide a satisfactory interpretation of the data under discussion, bearing in mind that part of the scatter among the observed values may be produced by factors other than wavelength and line strength (e.g. level of excitation). The wavelength dependence of the limb-arc measures cannot be determined from St. John's data, since these refer to lines contained in the ultra-violet and green regions of the spectrum only. St. John's grouping of the limb-arc shifts indicates no clear relationship with line intensity, in accordance with his interpretation, for at the limb the effect of Doppler currents should vanish, leaving the Einstein effect which depends only upon wavelength and gravitational potential. However, the mean values of many limb-arc shifts were appreciably in excess of this limiting value — a discrepancy which St. John was unable to explain. In view of this difficulty, and the problem of accounting for the positive residual in the observed centre-arc shifts of very intense lines, one cannot accept St. John's opinion that his analysis of this extensive observational material provided a satisfactory verification of the relativity-radial current hypothesis.

7. *The Allegheny Observatory-Bureau of Standards Observations*

While St. John was busy accumulating the measurements of Sun-arc shifts on which he based his interpretation, an extensive set of interferometric observations covering the visible spectrum was being made at the Allegheny Observatory in collaboration with the spectroscopic section of the Bureau of Standards (i.e. A.O.-B.S. observations). The characteristic feature of the A.O.-B.S. investigation was the pronounced intensity dependence exhibited by the Sun-arc shifts, which differed from that in St. John's observations. Since this phenomenon appeared to be associated with an asymmetrical broadening of the lines towards the red, the A.O.-B.S. observers regarded its existence as an insuperable obstacle to the acceptance of the predicted relativity effect[76] and were consequently unwilling to accept St. John's explanation. The experimental arrangement employed by Burns, Meggers and Kiess for obtaining the A.O.-B.S. wavelengths was the following[77, 78, 79] :

An image of less than 4 mm. in diameter formed by a telescope of 40 cm. focal length was focussed upon one of the plates of a Fabry-Pérot interferometer, and the resulting system of interference fringes projected by a ring lens on to the slit of a powerful grating spectrograph which dispersed the light ; thus, by 'crossing' the two instruments, high resolution and dispersion were attained. The spectral lines so formed were photographed simultaneously alongside a neon comparison spectrum which yielded standard wavelengths whose values had been derived from a previous investigation carried out at the Bureau of Standards[80].

There were two reasons for working with such a small solar image. One of the primary aims of the A.O.-B.S. investigation was to provide accurate wavelengths in the solar spectrum since it was realized that various systematic errors were inherent in the values given by Rowland which 'no simple change can correct'. Hence the A.O.-B.S. solar wavelengths were to be compared with those measured by Rowland,

[76] K. Burns, 'A comparison of laboratory and solar wave lengths', *J. Opt. Soc. Amer.*, 1930, **20**, 216.

[77] K. Burns & W. F. Meggers, 'Standard solar wavelengths (4073–4754 Å)', *Publ. Allegheny Obs.*, 1927, **VI**, No. 7.

[78] K. Burns, 'Standard solar wavelengths (5805–7142 Å)', *ibid.*, 1927, **VI**, No. 8.

[79] K. Burns, 'Standard solar wavelengths (3592–4107 Å : 4761–5892 Å)', *ibid.*, 1927, **VI**, No. 9.

[80] K. Burns, W. F. Meggers & P. W. Merrill, 'Measurements of wave lengths in the spectrum of neon', *Bull. U.S. Bur. Stand.*, 1919, **6**, 765.

who had worked with a small solar image[81], and so it was desirable that the Allegheny observers should do likewise. The more compelling reason, however, was that in practice it would otherwise have been impossible at that time (1924–27) to obtain spectral line images of measurable intensity on many of the photographic plates unless the exposures were of several hours' duration, on account of the loss of much light in reflection and absorption by the interferometer, as well as at the slit and at the grating. Thus the A.O.-B.S. wavelength measures were based, both on principle and by necessity, upon the spectrum of integrated sunlight.

It was suggested by E. Lau[82] that the entire intensity dependence in the red shifts found from these observations could be accounted for through the use of the Fabry-Pérot interferometer, but Burns replied that he had estimated a mean wavelength shift due to the interferometer of only 0·3 mA under the actual conditions of observation. The belief that this is not the reason for the intensity dependence in the A.O.-B.S. investigation is supported by the lack of an intensity equation between the A.O.-B.S. and Rowland's wavelength measures — which Burns and Meggers felt was 'a most encouraging feature of the comparison' — since Rowland did not employ an interferometer. It follows, as a consequence of the general systematic increase in wavelength towards the limb (i.e. the limb-effect) exhibited by weak and moderately intense lines, that the procedure of projecting light from all regions of the disk indiscriminately upon the plate of the interferometer must cause an asymmetrical broadening towards the red and produce an intensity dependence. One has to be content with such a qualitative explanation, however, on account of the difficulty of separating this influence from the systematic errors associated with the interferometric technique employed by the A.O.-B.S. observers; namely the method of parabolic channels, as it later came to be called.[83] Another source of asymmetry is the presence of blends, which would be most likely to give rise to serious discrepancies in wavelength measurements of lines contained in the violet region of the spectrum, where the spectral line density is high. An analysis by the writer has also revealed that the observed wavelength dependence of the A.O.-B.S. red shifts is non-linear and consequently incompatible with the relativity-radial current interpretation — a fact which was not quoted by Burns and his collaborators in support of their viewpoint.

A comparison of the A.O.-B.S. solar wavelengths with the correspon-

[81] *Trans. Int. Astr. Un.*, 1938, **6**, 63. It is explicitly stated that Rowland's spectrograms are of 'more or less integrated sunlight', but the writer has been unable to find any reference to the actual size of the solar image used by Rowland.

[82] E. Lau, 'Über die Intensitätsverteilung von Absorptionslinien', *Phys. Z.*, 1926, **27**, 870.

[83] M. G. Adam, 'Interferometric measurements of wave-lengths', *Mon. Not. R. Astr. Soc.*, 1952, **112**, 564.

ding values obtained independently by eminent observers such as St. John and Evershed strongly suggests that the former should be employed neither as standards nor as a basis for examining the line strength or wavelength variation of the absolute (Sun-arc) shifts, on account of the fact that they contain anomalies which affect these dependencies. In principle, this would imply that little significance ought to be attached to the values of the correlation co-efficients derived by Adam[84] from an analysis of the A.O.-B.S. observations and her own interferometric measurements. As she herself has stated, a quantitative agreement between the A.O.-B.S. and the Oxford results is not to be expected on account of the differences known to exist between integrated-disk wavelengths and centre-of-disk values. A corollary to the foregoing discussion is that the A.O.-B.S. measures should not be used to test St. John's hypothesis, nor do they constitute any valid evidence against it.

8. *The Problem of the Limb Excess*

A serious difficulty against accepting the relativity-radial current interpretation was soon to come from further measurements of the limb-arc shifts which yielded values considerably in excess of the relativity effect at the Sun's limb where the Doppler effects of radial gaseous streaming must be negligibly small. From observations of the H and K lines of CaII in 200 prominence spectra obtained at Ewhurst, Evershed[85, 86] found that the relativistic red shift was exceeded. The exact amount of this discrepancy was uncertain, on account of the conditions in the arc and the fact that the effects of solar rotation may have been wrongly assessed because of the assumption that the red shifts not due to rotation are Doppler effects occurring at random.[87] Although the latter difficulty is inherent in all measurements of this nature and cannot be avoided, Evershed felt that more reliable values for the red shifts would be obtained if he were to compare the solar H and K lines directly with a carbon arc in which these lines are prominent, rather than measure their wavelengths indirectly against the 1922 I.A.U. iron standards, which he rightly suspected were still in need of correction. (It so happens, however, that the correction required in this spectral region is only –1 mA). Thus, when obtaining the shifts of the H and K lines in the reversing

[84] M. G. Adam, 'Interferometric measurements of wave-lengths. II', *ibid.*, 1955, **115**, 405.

[85] J. Evershed, 'The solar rotation and the Einstein displacement derived from measures of the H and K lines in prominences', *ibid.*, 1927, **88**, 126.

[86] J. Evershed, 'The solar rotation derived from the H and K lines in prominences (Second paper)', *ibid.*, 1929, **89**, 250.

[87] J. Evershed, 'On some measures of the solar rotation at different levels in the chromosphere', *ibid.*, 1925, **85**, 608.

layer[88], Evershed used a Pfund arc in air, operating at 5 amperes and 100 volts (which very nearly satisfies the I.A.U. specifications) with carbon between two mild steel pole-pieces. As a result of direct measurements, after addition of a small pressure correction of 1·7 mA, he found a mean centre-arc displacement of +20·7 mA for these two lines ; however, spectra obtained with light derived from a region 5″ to 10″ within the limb yielded a mean limb-arc shift of only +15·1 mA, thus indicating a *decrease* in wavelength from centre to limb.

The latter value had also been found by Evershed from previous observations of 380 prominence spectra at various points just *outside* the limb of the Sun, where light does not traverse any portion of the chromosphere and the lines are not broadened as they are in limb spectra. The analysis and comparison of all data collected during the entire period from August 1926 to December 1934 indicated that this figure was probably too large by 1·5 mA ;[89] consequently, Evershed based his final conclusion on the entire prominence data and stated : 'The shift of H and K may be said to exceed the relativity shift by not less than ·005 and not more than ·0065 A.' Precise interferometric measurements by C. V. Jackson of the H and K vacuum arc wavelengths,[90] when subtracted from the solar wavelengths given in the Revised Rowland Table (corrected to the 1928 standards), yielded Sun-arc shifts of 19 mA and 23 mA for the H and K lines respectively ; and when substituted for the arc wavelengths of St. John[91] on which Evershed had originally based his earlier measures of the wavelengths of these lines in solar prominences,[92] they gave a mean value of +14 mA. As Jackson[93] remarked, these figures were in complete agreement with Evershed's results and confirmed the

[88] J. Evershed, 'The shift towards red of the calcium, aluminium and iron lines in the solar spectrum', *ibid.*, 1931, **91**, 260.

[89] J. Evershed, 'The solar rotation and shift towards the red derived from the H and K lines in prominences (Third paper)', *ibid.*, 1935, **95**, 503. When considering the reality of such a small difference it is important to record that from the analysis of all 782 spectra Evershed discovered a latitude effect in his values which he believed might be related to sun-spot disturbances : between the solar equator and latitude 30°, the general red shift of the H and K lines in the prominences was approximately 14·6 mA, whereas at latitude 40° (outside the zone of sun-spot disturbances) it dropped to 10·5 mA. In addition, there is always the possibility that these statistical results may have been affected by small selection errors.

[90] C. V. Jackson, 'Interferometric measurements in the arc spectrum of iron', *Proc. Roy. Soc. A*, 1931, **130**, 395.

[91] C. E. St. John, 'The absolute wave-lengths of the H and K lines of calcium in some terrestrial sources', *Astrophys. J.*, 1910, **31**, 143.

[92] J. Evershed, 'The normal wave-lengths of the calcium lines H and K, and the relativity shift of these lines in the prominences and chromosphere', *Mon. Not. R. Astr. Soc.*, 1929, **90**, 186.

[93] C. V. Jackson, 'The wave-lengths of the H and K lines of calcium in the arc *in vacuo* and their red shifts in the solar spectrum', *ibid.*, 1932, **93**, 98.

reality of the decrease in shift between centre and limb as well as the excess of about 5 mA over the relativity shift at the edge of the disk.

Not only the H and K lines exhibited an excess shift, however. Evershed had also made measurements of the limb-arc and centre-arc shifts of two strong AlI lines in the H and K region of the spectrum, which yielded mean values slightly in excess of the Einstein shift, but no indication of a centre-limb wavelength variation. Similar results also applied to the NaI-D lines : earlier measures of these lines had failed to provide evidence of such a variation[94] and, from a re-determination of the Sun-arc shift of the DI line only, Evershed found a value of +13·4 mA,[95] which is less than 1 mA in excess of the relativity shift in this part of the spectrum. In view of the previous result, no distinction was made between light from centre and limb.

But the largest excess was found for the Hα line, which, despite its breadth, is still measurable with a high degree of consistency. A comparison between Curtis's value of the vacuum arc wavelength of this line[96] and the solar wavelength given in the Revised Rowland Table yields a centre-arc shift of +23 mA ; the limb-centre difference measured by Adams was +2 mA, hence the limb-arc shift amounts to +25 mA, an excess of 11 mA over the Einstein effect ! Along with the measures of the H and K lines and the AlI lines in the reversing layer, Evershed published the results of a large number of measurements on 22 FeI lines in the same spectral region[88], derived from spectra collected at Kodaikánal (from 1912–22) and at Ewhurst (from 1929–30). By grouping these wavelengths according to intensity, he found limb-arc shifts of +15·5 mA and +13·8 mA for the strong and weak lines respectively. Later measurements on seven strong and eight weak lines in the H and K region[89] (photographed both at the poles and at low latitudes) yielded a mean limb displacement of +14·6 mA, confirming the former set of results. Thus the FeI lines exhibit a similar excess to the H and K lines at the edge of the Sun, the essential difference between the two sets of results being that the FeI wavelengths *increase* towards the limb, whereas the CaII wavelengths *decrease*.

The significant features of these researches by Evershed were the intensity dependence of the centre-arc shifts which gave rise to over-relativistic values for the stronger lines measured (i.e. those of Rowland intensity 7 and over), and the large limb-arc shifts which were found in all cases to exceed the Einstein value. Evershed held the opinion that

[94] J. Evershed, 'The Einstein effect in the solar spectrum', *Observatory*, 1923, **46**, 299.

[95] J. Evershed, 'The red shift of the D lines of sodium in the Sun', *Mon. Not. R. Astr. Soc.*, 1937, **98**, 196.

[96] W. E. Curtis, 'Wave-lengths of hydrogen lines and determination of the series constant', *Proc. Roy. Soc. A*, 1914, **90**, 617 (Table V).

both of these observed effects were direct consequences of using a small solar image (about 60 mm. in diameter), on account of scattered light in the case of the centre-arc values, and a combination of this with the low telescopic resolution at the limb postion. He attributed the large scatter found among the individual plate values to the existence of localized radial currents and to irregularities in the rotation shift at the centre and limb positions respectively.

In order to test his belief, Evershed next measured the limb-arc shifts of five strong FeI lines in the red region of the spectrum[97], where any effect of atmospheric scattering would be much less, and obtained the surprising result that the mean observed shift was practically twice the Einstein effect. He checked this by adding the limb-centre differences of Adams (1910) to the centre-arc shifts of St. John (1928) for four of these lines, and these indirectly obtained values yielded a mean limb-arc shift of $+25$ mA, precisely the same as that found from his own direct measurements — and, incidentally, the same as that which he had deduced for the Hα line.

It has already been pointed out that the wavelength dependence of the limb-arc shift (or of the excess above the Einstein effect) cannot be accurately determined on the basis of St. John's data, since his limb-arc measures refer only to lines contained in the ultra-violet and green regions of the spectrum. In order to supplement these values in the violet, blue and red, Evershed had made direct observations of the limb-arc shifts on spectra obtained both at Kodaikánal and at Ewhurst and — after applying the appropriate pressure corrections — he compared these with the corresponding shifts of 105 FeI lines for which the centre-arc displacements had been measured by St. John. The limb-centre values were available from previous researches carried out at Mount Wilson and at Kodaikánal.[33, 98] This comparison confirmed that the close agreement found in the red between the directly and indirectly obtained shifts also applied to the blue and violet regions of the spectrum. Furthermore, in the green and ultra-violet, St. John's own direct measurements of the limb-arc shifts were found to be verified. In this way it was established for the whole of the visible range that a large excess shift is characteristic of measurements made by different observers. Since in one case the observations were made with the large solar images of the Mount Wilson solar towers, this feature could not be a consequence of employing a small solar image, as Evershed had originally believed. Furthermore, although the wavelength variation in the excess shift was found to be

[97] J. Evershed, ' The red shift of the iron lines at the edge of the Sun ', *Mon. Not. R. Astr. Soc.*, 1936, **96**, 152.

[98] A. Aayar, ' On the displacements at the Sun's limb of lines sensitive to pressure and density ', *Bull. Kodaikánal Obs.*, 1915, No. 44.

irregular, the general tendency was for the values to increase towards the red, which is completely opposed to the explanation that the limb excess is an effect of scattered light.

With regard to the centre-arc displacements, Evershed (1936) stated: 'My own measures of solar and arc lines in general sunlight and at the centre of the Sun's disc are in good agreement with those of St. John', from which we may infer that the same intensity dependence characterizes both sets of observations; consequently, the results obtained by Evershed and his collaborators could not have been appreciably influenced by anomalies of the type found in the A.O.–B.S. data. Indeed, Evershed (1931) stated that, in contradiction to Burns and Meggers's results, his limb spectra showed perfect symmetry, and no indication of the broadening on the red edge. Since this condition is necessary for the acceptance of St. John's interpretation, Evershed's opinion was that 'there can be little doubt that the Einstein effect accounts for most of the shift in the solar spectrum.'[99] The problem of the limb excess, however, remained unsolved.

9. *The Limb-Effect and St. John's Hypothesis*

A weakness in St. John's investigation was the omission of intermediate measures across the disk which, on account of the variation of optical depth with disk position, are capable of providing a quantitative check on the depth-dependence of the Doppler currents derived from the centre-arc displacements on the basis of the relativity-radial current hypothesis. The pioneer observations by Halm, and by Schwarzschild (CN bands), are neither extensive nor accurate enough for this purpose, while in the early limb-effect investigation by Evershed and Royds the poor resolution afforded by the small solar image employed (14 mm. diameter, enlarged by a factor of two) limits the significance which can be placed on these results — particularly in view of the possibility that anomalies similar to those found in the A.O. – B.S. observations may influence the measurements.

A feature of the limb effect which first came to light in the reduction of the Kodaikánal observations was that the relative shifts exhibited no appreciable dependence upon the solar latitude at which they were observed. This discovery was later confirmed by Freundlich, von Brunn and Brück,[100] employing superior equipment at Potsdam, comparable in resolution and dispersion with that used by St. John. These observations are restricted to nine FeI lines with wavelengths between 4347 A

[99] J. Evershed, 'The problem of the red shift in the solar spectrum', *Observatory*, 1937, **60**, 271.

[100] E. F. Freundlich, A. von Brunn, & H. Brück, 'Über den Verlauf der Wellenlängen der Fraunhoferschen Linien längs der Sonnenoberfläche', *Z. Astrophys.*, 1930, **1**, 43.

and 4490 A (mean wavelength 4426 A) belonging to the same multiplet (^5D–$^7F°$), which were selected on the criteria of symmetry and sharpness of appearance in both solar and vacuum arc spectra. (An examination of the microphotometric tracings of these lines in the Utrecht Atlas shows that to some extent all nine lines are affected by blends which had not been apparent on visual inspection ; however, it is thought to be unlikely that the mean shifts resulting from this investigation are seriously affected by this cause.) The limb-centre wavelength displacements were measured at six positions along twelve different radii symmetrically disposed over the area of the Sun's disk. After carefully applying corrections for the effect of solar rotation, Freundlich and his collaborators found such excellent agreement among the values of the relative shifts of all nine lines at every disk position that they based their final results upon the mean values. The fact that the shifts of the different lines were found to be equal implied that the cause (or causes) responsible for their production is effective to the same extent in lines belonging to the same multiplet[101], while the fact that the variation of the shift across the disk was identical for all radii suggested that it should be sufficient in all investigations of the limb effect to confine the observations to one radius only.

The mean limb increase found from the Potsdam investigation bore no similarity to a cosine curve ; in fact, a secant law provided a better representation of the observations. The Potsdam observers therefore concluded that ' it is as impossible to explain the effect by radial streaming as by simple Compton scattering. ' The same belief was also held by Hunter, who discussed the existing observations of the limb effect and limb-centre differences and came to the conclusion that ' no hypothesis yet put forward will account for all the facts.'[102] This view, however, was abandoned that same year (1934) when McCrea and Mitra[103] pointed out that, since we see down to deeper atmospheric layers (i.e. regions of greater density) when viewing the Sun's disk at its centre than towards the limb, the postulated radial velocity should not be supposed constant, but should decrease towards the centre. This important consideration leads to a modification of the simple cosine law in keeping with the observed limb effect. McCrea and Mitra demonstrated that a quite good representation of the Potsdam measures can be obtained by assuming that the density gradient in the solar atmosphere is adiabatic : the

[101] The generality of this conclusion must be held in question, in view of Luise Herzberg's discovery that systematic variations can occur among the relative shifts of lines belonging to the same multiplet (*Canad. J. Phys.*, 1957, **35**, 766), a peculiarity which has also been detected independently by the writer (*Mon. Not. R. Astr. Soc.*, 1963, **125**, 1).

[102] A. Hunter, ' The solar limb effect ', *Mon. Not. R. Astr. Soc.*, 1934, **94**, 594.

[103] W. H. McCrea & K. K. Mitra, ' The solar limb effect ', *Observatory*, 1934, **57**, 379.

agreement was less satisfactory in the case of Evershed and Royds's limb-effect observations, but these carried much less weight. Thus it appears that St. John's hypothesis is quite compatible with the observed form of the limb increase, although these relative observations are in themselves insufficient to provide a complete test of this interpretation. Centre-arc values of the shifts must also be available in order to confirm that the radial velocities deduced from the limb-effect observations do in fact correspond to those derived from the absolute measures.

This dual requirement was fulfilled by a set of interferometric observations by Miss Adam[104] of the centre-arc shifts and limb-arc shifts at six different disk positions along the polar diameter, for fourteen Fraunhofer lines in the spectral region around 6100 A which were specially selected for discussion on the criterion of apparent freedom from blends and asymmetries, as judged by reference to the Utrecht Atlas. The wavelengths of these lines were based on neighbouring telluric lines, although neon comparison spectra were obtained at intervals during a sequence of solar exposures, and yielded a valuable confirmation of the stability of the apparatus. Since Adam found no evidence of systematic differences of behaviour across the disk with line strength, element, or centre-arc value, she decided that there was ' no justification for more than a statistical treatment of the present material ', and accordingly based her discussion upon the mean values obtained by averaging the shifts of all fourteen lines at each disk position. Further observations of centre-arc shifts, employing the method of circular channels first introduced by Treanor[105] in 1949 and subsequently developed at Oxford, have shown this procedure to be invalid because the variations of the absolute displacements from line to line are systematic (not random) in character. The overwhelming advantages of this interferometric method over the older method of parabolic channels are that it affords a direct comparison of the cadmium standard with any region of the spectrum, and permits a simultaneous exposure for the Sun and standard light source through the same optical train. It also provides a higher internal accuracy among the measures, as the circular channels give much clearer impressions on the photographic plates. Its application to interferometric measurements of solar wavelengths,[106] and the higher accuracy obtained from the

[104] M. G. Adam, ' Interferometric measurements of solar wave-lengths and an investigation of the Einstein gravitational displacement ', *Mon. Not. R. Astr. Soc.*, 1948, **108,** 446.

[105] P. J. Treanor, ' High-resolution interferometry of the solar spectrum ', *ibid.*, 1949, **109,** 389.

[106] M. G. Adam, ' Interferometric measurements of wave-lengths. I. Development of the method of circular channels and its application at 5080 Å and 6020 Å ', *ibid.*, 1952, **112,** 149. ' III. A note on observational technique in the method of circular channels ', *ibid.*, 1955, **115,** 422.

increase in resolution, have resulted in the discovery that appreciable discrepancies were incurred in Adam's absolute wavelengths due principally to scale errors in the secondary standards. These instrumental errors should have had no effect on the relative shifts however, since they affect the measured displacements of a particular spectral line at different disk positions in precisely the same way .

The mean limb-effect curves derived from the Oxford and Potsdam observations were found to be in excellent agreement, thereby suggesting that there is no significant change in the form of the relation with time[107], or with wavelength region throughout the visible spectrum ; furthermore, as Adam pointed out, neither did element nor line intensity seem to exert an appreciable influence on the limb-effect of individual lines included in her data. Adam used her observational material to test the relativity-radial current hypothesis, and obtained 'results which are inconsistent with our knowledge of the solar spectrum and of the physical conditions prevailing in the solar atmosphere.' This conclusion was based upon the negative result obtained from a consideration of the possibility that systematic radial velocities of about 1 km./sec. might be introduced by the solar granulation, since the rising (hotter) gases radiate more energy than the descending (cooler) gases, thereby producing a small asymmetry in the line profile with its associated shift. There are, however, two major reasons why this result now needs revision :

(a) The mean velocity ($\bar{v}$) used to determine the absolute values of the granular streaming was obtained from the observations after allowing for the relativistic red shift (in accordance with the conventional hypothesis) and correcting for the Lindholm effect.[108] However, the values of the Lindholm shift calculated by Adam from the damping constants determined by ten Bruggencate and Houtgast[109] are incorrect, since Adam made no allowance for the fact that the wavelength region to which her own observations refer (around 6100 A) differs from that for which the values of the damping constant had been obtained (5100 A). When this is taken into account, one finds that the correction to the mean centre-arc displacement is only 2·0 mA, as compared with the corresponding value of 4·1 mA adopted by Adam: the absolute corrections become decreasingly smaller as the limb is approached. A special study of the Lindholm effect in relation to the red shift problem has recently been made by Jorand[110], who computed a mean value of only 0·15 mA for six of the lines included

[107] This belief is contradicted by a comparison of additional observational data (E. G. Forbes, 'Some observational features of the solar limb effect', *ibid.*, 1962, **125**, 1).

[108] E. Lindholm, *Ark. Mat. Astr. Fys.*, 1941, **28B**, No. 3.

[109] P. ten Bruggencate & J. Houtgast, 'Bestimmung der Dämpfung zweier Fe-Multipletts für Mitte und Rand der Sonnenscheibe', *Z. Astrophys.*, 1941, **20**, 149.

[110] M. Jorand, 'Contributions à l'étude des effets influençant le décalage vers le rouge des raies d'absorption du spectre solaire', *Ann. Astrophys.*, 1962, **25**, 57.

in Adam's data. He attributes Adam's much higher value principally to the large values of the observed damping constant (γ) on which she based her calculations — these being a hundred times greater than the classical values — and to her inaccurate estimate of the effective level of formation of the Fraunhofer lines. Although Jorand emphasizes the preliminary nature of his results, it would appear that the Lindholm effect can have only a minor influence upon the form of the function representing the solar limb effect. For the time being, therefore, it seems justifiable to ignore it altogether as a cause which contributes significantly to the production of the solar red shifts.

(b) The value adopted by Adam for the intensity ratio between granula and intergranula (viz. $\frac{J_1}{J_2} = 1{\cdot}10$) was based upon the 5″ granulation observed by Plaskett[111]; most later estimates, however, by Keenan[112,113], Thiessen[114], Rösch[115,116] and others have agreed in yielding a much lower value of about 1″–1·5″ for the mean granule diameter. This estimate has been further confirmed by the high-definition solar photographs from 80,000 ft. obtained by Schwarzschild, Rogerson and Evans[117] from unmanned balloon flights, which indicated that the size of the elements range from 2″ down to 0·3″ and at the same time provided a verification of the fact that the granulation has a cellular, though highly irregular, character. The intensity ratio is very difficult to assess accurately, mainly on account of the influence of scattered light and atmospheric scintillation, but most observers have favoured a value greater than 1·10.

When due allowance is made for the above facts, one finds that granular velocities (v_1 and v_2 in Adam's notation) can be brought into good agreement with the values derived from curve-of-growth and line profile studies, which are of the order of 1·7 km./sec. However, although these observations by Adam may, after all, favour the relativity-radial current hypothesis and support the view that the steady state of the solar atmosphere is maintained by a microscopic circulation associated with the solar granulation, they suffer from the disadvantage that they were obtained with low telescopic resolution, on account of the necessity of

[111] H. H. Plaskett, 'Solar granulation', *Mon. Not. R. Astr. Soc.*, 1936, **96**, 414.

[112] P. C. Keenan, 'Dimensions of the solar granules', *Astrophys. J.*, 1938, **88**, 360.

[113] P. C. Keenan, 'Photometry of the solar granules', *ibid.*, 1939, **89**, 604.

[114] G. Thiessen, 'Zur Sonnengranulation', *Z. Astrophys.*, 1955, **35**, 237.

[115] J. Rösch, 'Données morphologiques nouvelles sur la granulation photosphèrique solaire', *C.R. Acad. Sci., Paris*, 1955, **240**, 1630.

[116] J. Rösch, 'Photographie à cadence rapide de la photosphère et des taches solaires', *ibid.*, 1956, **243**, 478.

[117] M. Schwarzschild, J. B. Rogerson & J. W. Evans, 'Solar photographs from 80,000 feet', *Astr. J.*, 1958, **63**, 313.

admitting light into the spectrograph from an area of 3 mm. diameter on the 180 mm. diameter Oxford solar image in order to limit the exposure time required to within reasonable limits. (The exposure times varied between 2 and 8 minutes for the plates measured). In consequence, the disk positions nearest to the edge of the disk are subject to very large uncertainties.

This deficiency has since been compensated by a careful determination by Adam[118] of the limb effect of three FeI lines close to 6300 A, made with the new Oxford 35-metre telescope and high-dispersion grating spectrograph, which yielded spectra of very well-specified disk positions with an exposure time of only 40 seconds and permitted the extension of accurate limb-effect measurements right up to the extreme limb of the Sun. The mean wavelength difference between this latter position and the centre of the disk corresponds to a velocity shift of 0·53 km./sec; when this is combined with a centre arc displacement of 0·31 km./sec — which Adam considers to be a likely value for the lines in question — there results an absolute shift of 0·84 km./sec, about 0·20 km./sec in excess of the relativity value. Similar results were also obtained by Higgs,[119] from the reduction of additional spectral plates collected with the same instrumentation. Thus the most recent and reliable observational data confirm and strengthen Evershed's discovery of a real limb excess which Adam believes to be 'quite inexplicable on the radial current theory'.

10. *Schröter's Two-Stream Model and its Application to the Solar Red Shifts*

A detailed investigation of the relativity-radial current hypothesis has been carried out in Potsdam by Schröter[120], who took into account the various stratifications in velocity and temperature, the dependence of the velocities on depth, and the physics of the line production, in his attempt to explain the observed shifts. Schröter considered the introduction of such additional factors to be very essential, and necessitated by the observed dependence of the Sun-arc shifts on the line width and by the deviation of the limb effect from a cosine law. With regard to these observed features he wrote: 'These two long-known facts are in contradiction to the demands of the theory of relativity, so that one must either negate the existence of the relativistic red shift, or one must try to explain the differences between observation and theory as due to the

[118] M. G. Adam, 'A new determination of the centre to limb change in solar wave-lengths', *Mon. Not. R. Astr. Soc.*, 1959, **119**, 460.

[119] L. A. Higgs, 'The solar red-shift', *ibid.*, 1960, **121**, 422.

[120] E. H. Schröter, 'Zur Deutung der Rotverschiebung und der Mitte-Rand-Variation der Fraunhoferlinien bei Berücksichtigung der Temperaturschwankungen der Sonnenatmosphäre', *Z. Astrophys.*, 1957, **41**, 141.

influence of additional solar physical effects. We shall adopt the latter point of view . . . ' On the basis of the above considerations, Schröter built up his Two-Stream Model of the solar atmosphere by determining the radial convective streaming which would result from temperature variations deduced from observations of the granulation. This procedure involved the adoption of values for the size and intensity ratio of the granules, and of the absolute measurements of the change in wavelength with position along a radius of the solar disk.

In order to reduce the arbitrariness resulting from the presence of the many variable factors in his theory, Schröter first tested whether his assumptions were compatible with certain independent observational data before applying them to the problem of the red shifts. He found that his Two-Stream Model yielded a satisfactory representation of the centre-limb variation of the average unresolved continuum (i.e. limb darkening), and provided an excellent representation of the centre-limb variation of the intensity in the wings of strong lines as well as accounting for that of the equivalent width of weak lines, which had previously raised difficulties in model description that could never be well explained. The success of his model in describing the centre-limb variation of various types of lines which no homogene model of the photosphere in local thermodynamical equilibrium is capable of doing, and which Böhm's original Three-Stream Model[121] had done but less convincingly, satisfied Schröter that it could be justifiably employed for the purpose of explaining the observations of the solar red shifts.

According to his model, and in agreement with certain observations, the granulum is brighter than the intergranulum (in the continuum) by a factor of about 1·45, from which it can be inferred that if the granulum contour is displaced towards the violet, and that of the intergranulum towards the red, the net result will generally be to produce a violet shift. The resulting contour will be asymmetrical, the form and amount of asymmetry (which determines the resultant shift) being a function of line intensity, the asymmetry being more effective as the relative contours become steeper. Hence strong lines may show a red or a violet shift, depending on whether the central intensity or the wings of a Fraunhofer line is chosen for measurement. This also implies that the asymmetry changes from the violet to the red region of the spectrum. The limb effect results from the condition that the stratification in the granula is not the same as that in the intergranula, thereby producing a difference between the limb darkening of the two continuum levels and in the centre-limb variation of the relative line contours. Schröter has demonstrated that this dependence, combined with the cosine law of projection

[121] K.-H. Böhm, 'Zur Deutung der Mitte-Rand-Variation der Fraunhofer-Linien', *ibid.*, 1954, **35**, 179.

and the constant relativistic shift, is capable of yielding a very good representation of Adam's 1948 observations ; also, the Potsdam measures can be quite well represented if, in accordance with his theoretical considerations, he assumes for the lines to which they refer a mean centre-arc shift of about 0·22 km./sec.

A consequence of Schröter's explanation is that every line with a different line strength will give a different limb-effect. Over-relativistic shifts at the disk centre can be interpreted on the above basis, but at the Sun's limb all values must converge to the predicted gravitational shift, since there the Doppler effects of radial currents should disappear. Thus his theory offers no explanation of the well-established excess shift at the limb. Additional evidence against Schröter's interpretation is contained in the values of the very accurate centre-arc shifts obtained at Oxford using the interferometric method of circular channels. From an examination of the relativity-radial current hypothesis on the basis of these observed data, Miss Adam[122] has found that the resultant outward streaming velocity at the centre of the disk amounts to 0·184 km./sec. and 0·107 km./sec for the lines contained in the Oxford (1948) and Potsdam (1930) investigations respectively, as compared with the corresponding value of 0·42 km./sec adopted by Schröter for both cases. When substituted in Schröter's theoretical expression for the limb effect, these revised velocities no longer agree with the observations (*loc. cit.*, Fig. 2). Moreover, Adam has drawn attention to the fact that, contrary to expectation, her observations yield no correlation between the shifts and excitation potential[123]. Thus it would appear that, so long as one insists on forcing the observations into the rigid framework of the relativity-radial current hypothesis, one can never account for the limb excess. In order to do so some other cause must be invoked or a new interpretation found.

One such possibility exists in the collisional displacements of solar wavelengths arising primarily from hydrogen-atom collisions, proposed by Spitzer[124]. Discussing the interpretation of the solar red shifts, Spitzer came to the tentative conclusion that ' the measured shifts are simply the sum of the relativity red-shift and a collisional violet shift ' ; but as a result of further researches carried out in Oxford during recent

[122] M. G. Adam, ' Interferometric measurements of wave-lengths. V. The radial current interpretation of solar red-shifts ', *Mon. Not. R. Astr. Soc.*, 1958, **118**, 106.

[123] Adam has also examined the wavelength dependency of the velocity shifts using the A.O.–B.S. wavelength measures and found that it bears no similarity to the required direct linear relation. However, since there are reasons for believing that these values are seriously affected by observational errors, whereas St. John's data satisfy that particular requirement, this should not be regarded as a significant objection against accepting the relativity–radial current hypothesis.

[124] L. Spitzer, ' On the interpretation of measured solar wave-lengths,' *Mon. Not. R. Astr. Soc.*, 1950, **110**, 216.

years,[125,126] it is impossible to ignore the contribution of organized Doppler motions at the photospheric level, as Spitzer originally believed. Since the laboratory emission lines as well as the solar absorption lines are liable to suffer collisional shifts, the limb excess can also be accounted for on the basis of Spitzer's interpretation as a consequence of a violet shift in the arc wavelengths of moderately intense and strong lines. However, in view of the theoretical and observational difficulties connected with the testing of this interpretation, its validity still cannot be properly assessed.

11. *Freundlich's Hypothesis*

An alternative proposal of a quite different character has been put forward by Freundlich.[127] From a study of radial velocity measurements of certain B- and O-type stars, Freundlich formed the opinion that the wavelength shifts observed in stellar spectra are proportional to the effective temperatures ; and as a result of comparing these stellar observations with the *solar* red shifts, he inferred that the effect may vary in accordance with a fourth-power temperature dependence. St. John (1928) had also remarked on this correlation, and had interpreted it on the basis of the relativity-radial current hypothesis as signifying the existence of a systematic variation in the strength of radial gaseous motions in stars of different spectral types. He had also considered that low density was the factor primarily responsible for the shifts observed in lines contained in the spectra of cool Giant stars.

Freundlich, on the other hand, realizing the difficulties confronting the conventional hypothesis, sought for another explanation and made the bold (though tentative) suggestion that these features may instead constitute evidence for a photon-photon interaction in the intense radiation field surrounding a star. Accordingly, he took T to be the temperature of the radiation field in which a photon of frequency ν travelling through an effective geometrical depth l suffers a loss in frequency ($-\Delta\nu$) due to numerous interactions with the other photons 'en route'. He proposed the formula :

$$-\frac{\nu\Delta}{\nu} = \mathrm{A}\mathrm{T}^4 l$$

to describe this phenomenon, A being a constant of proportionality whose physical nature was obscure. In the case of the Giant stars, the

[125] A. B. Hart, 'Motions in the Sun at the photospheric level. IV. The equatorial rotation and possible velocity fields in the photosphere', *ibid.*, 1954, **114**, 17.

[126] H. H. Plaskett, 'Motions in the Sun at the photospheric level. VIII. Solar rotation and photospheric circulation', *ibid.*, 1959, **119**, 197.

[127] E. Finlay-Freundlich, 'Red shifts in the spectra of celestial bodies', *Phil. Mag.*, 1954, **45**, 303.

much larger value of l was assumed to compensate for the lower temperature in producing appreciable wavelength shifts.

The validity of Freundlich's formula was immediately questioned by McCrea[128], the Burbidges[129], Helfer[130], and shortly afterwards by Schröter,[131] all of whom criticized the weakness of the observational evidence on which it was based. Yet despite some of these objections, ter Haar[132] defended it on principle, emphasizing that there are definite wavelength shifts of physical origin in stellar spectra which cannot be satisfactorily accounted for by existing astrophysical theory. ter Haar was not prepared to accept Freundlich's interpretation, however, since he found that the cross-section of the postulated photon-photon interaction — like other feasible processes which he also considered — was much too small to be the mechanism responsible for the production of the shifts[133]. This view is also held by Melvin[134], who has shown that if such an interaction were responsible, the contribution of the radiation field well outside the Sun's atmosphere would be about a thousand times greater than that originating from within — a fact which is directly opposed to the observed steep increase of the centre-limb wavelength variation (i.e. the limb-effect) of weak and moderately-intense Fraunhofer lines close to the edge of the solar disk. Another, but no less significant reason why Freundlich's hypothesis was not accepted is that, in its application to the solar red shift phenomenon, it seemed to preclude the existence of the gravitational red shift (Einstein effect).

The above criticisms have now been rendered obsolete by a series of researches by the writer in collaboration with Professor Freundlich[135] which have resulted in the realization that the proposed formula is simply an alternative empirical formulation of the relativity-radial current interpretation in which the Einstein effect is contained implicitly.[136] Moreover, it is restricted to weak and moderately intense lines for which the limb-effect curve is wholly determined by the continuum contrast ratio between the granulum and intergranulum, and not by the physical properties of Fraunhofer line formation. In practice, the observational

[128] W. H. McCrea, 'Astrophysical considerations regarding Freundlich's red-shift', *ibid.*, 1954, **45**, 1010.

[129] G. Burbidge & M. Burbidge, 'On the observational data relating to Freundlich's proposed red-shift law', *ibid.*, 1954, **45**, 1019.

[130] H. L. Helfer, 'Finley–Freundlich red-shift hypothesis', *Phys. Rev.*, 1954, **96**, 224.

[131] E. H. Schröter, *Die Sterne*, 1956, **32**, 140.

[132] D. ter Haar, 'Some more remarks on Freundlich's red shift', *Phil. Mag.*, 1954, **45**, 1023.

[133] D. ter Haar, 'On Freundlich's red shift', *ibid.*, 1954, **45**, 320.

[134] M. A. Melvin, 'Freundlich red-shift formula', *Phys. Rev.*, 1955, **98**, 884.

[135] E. Finlay-Freundlich & E. G. Forbes, 'On the red shift of the solar lines', I. *Ann. Astrophys.*, 1956, **19**, 183. II. *Ibid.*, 1956, **19**, 215. III. *Ibid.*, 1959, **22**, 727.

[136] E. G. Forbes, 'On the red shift of the solar lines'. IV. *Ibid.*, 1962, **25**, 337.

difficulties involved in making a reliable assessment of this parameter and in attempting to provide a quantitative estimate of its dependence on wavelength and disk position, set a limit to the significance that can be placed upon schematized inhomogene model atmospheres such as Schröter's Two-Stream Model[120] and Voigt's Three-Stream Model[137,138] on which our understanding of the properties of both the absolute and relative values of the solar red shifts has been based.

12. *Conclusion*

The period 1896–1923 was one of great improvement in the experimental techniques and equipment employed in attempts to explain the causes responsible for the production of the solar red shifts. Its importance lies in the consequent elimination of sources of observational error which invalidated many of the earlier measurements. Although these attempts met with little success, many reasons for the difficulties in attaining the necessary accuracy had become apparent. Yet we have seen that despite the extensive researches subsequently carried out by St. John, Evershed, Adam and others, one very significant observational feature, namely the excess, or over-relativistic, red shift at the edge of the Sun's disk, appears to be irreconcilable with the relativity-radial current interpretation.

This same systematic effect is also reflected as a discrepancy between the value of the velocity shift required to provide an accurate representation of the solar limb effect data for moderately intense Fraunhofer lines —on the basis of Schröter's theoretical considerations—and that predicted from a statistical study of the interferometric measurements of centre-arc shifts obtained with the high-resolution Oxford equipment. The accuracy with which Schröter's Two-Stream Model does represent the relative observations tends to rule out the possibility that the errors liable to be incurred through a wrong choice of atmospheric model are sufficient to account for this discrepancy, which amounts to 0·24 km./sec or more. On the other hand, the high quality of the Oxford observations is opposed to the alternative explanation that a large part of the disagreement arises from the procedure of interpolating the centre-arc shifts from Adam's statistical relation, although direct measurements of the absolute (centre-arc) shifts for the lines comprising the limb-effect data are strictly necessary to confirm this view.

The only possible way of resolving this difficulty *without* invoking some undiscovered additional physical cause would be to postulate the existence of high-speed random gaseous motions parallel to the solar

[137] H.-H. Voigt, '"Drei-Strom-Modell" der Sonnenphotosphäre und Asymmetrie der Linien des Infraroten Sauerstoff-Tripletts', *Z. Astrophys.*, 1956, **40**, 157.

[138] H.-H. Voigt, '"Drei-Strom-Modell" der Sonnenphotosphäre. II. Die infraroten Nickellinien λ 7789 und λ 7798 Å', *ibid.*, 1959, **47**, 144.

photosphere and to take account of the hitherto-ignored contribution of the relativistic (or second-order) term in the Doppler formula. Recent work carried out at the Mount Wilson Observatory[139] has, in fact, yielded evidence of *horizontally moving* gaseous currents distributed uniformly across the surface of the Sun, diverging from centres at which upward-flowing gases reach the photosphere ; and the *transverse* Doppler effect of such randomly-directed motions with speeds of between 350 and 550 km./sec are equivalent, in magnitude and direction, to the observed systematic line-of-sight velocity of between $+0{\cdot}2$ and $+0{\cdot}5$ km./sec. The same range contains the values of the over-relativistic red shift at the edge of the solar disk estimated by Adam[118] from data collected at Oxford, and those derived by Higgs[140] from a study of the asymmetries in centre-of-disk and limb intensity profiles of three FeI lines close to 6300 A.

In the case of Evershed's extensive observations on prominence spectra, referred to earlier, a value of about 500 km./sec suffices to explain (on the basis of this interpretation) the mean excess shift of between $+5$ and $+6{\cdot}5$ mA in the H and K lines ; mean speeds of this order being in excellent agreement with directly observed motions in ascending prominences, which are found to vary between 50 and 700 km./sec.[141] The characteristic 'moustaches', or fine structure in flare emission, and the associated red asymmetry observed in the core of the Hα line in flare spectra[142], is another solar phenomenon that may be due to the respective effects of the first- and second-order terms in the Doppler formula. Finally, it is interesting to note that systematic intensity variations in the wings of the first four Balmer lines (Hα — Hδ) on both the red and violet sides, at distances of the order of 10 A from the line centres, discovered by David[143] from an analysis of photo-electric observations at Göttingen and ascribed by him to errors in the adopted values of the theoretical absorption coefficient and to the presence of unresolved metallic lines (in the neighbourhood of the Hγ and Hδ lines), might alternatively be interpreted on the basis of the present considerations as constituting evidence for the first-order effects of such high-velocity random motions in the lower chromosphere.

In principle, therefore, the proposed relativity *Doppler* current hypo-

[139] R. B. Leighton, I.A.U. Symposium No. 12 : 'Aerodynamic Phenomena in Stellar Atmospheres', Suppl. to Vol. XXII of *Nuovo Cimento*, 1961, pp. 321–5.

[140] L. A. Higgs, 'Asymmetry of solar line profiles', *Mon. Not. R. Astr. Soc.*, 1962, **124**, 51.

[141] K. O. Kiepenhauer, I.A.U. Symposium No. 12 : Suppl. to Vol. XXII of *Nuovo Cimento*, 1961, p. 420 (Table II).

[142] A. B. Severny, *ibid.*, p. 409.

[143] K.-H. David, 'Die Mitte-Rand-Variation der Balmerlinien Hα–Hδ auf der Sonnenscheibe', *Z. Astrophys.*, 1961, **53**, 37.

thesis seems capable of providing a satisfactory quantitative description of existing solar red shift data, thereby settling the controversial problem of the origin of this phenomenon ; nevertheless, it also introduces certain other difficulties in the interpretation of the Fraunhofer line profiles which would have to be carefully investigated before its validity can be properly assessed. Whether the continued improvement of astronomical equipment and techniques and the further refinement of inhomogene model atmospheres will indicate the need for introducing minor modifications to compensate for such effects as optical 'roughening' and collisional wavelength displacements, as suggested by Jorand[110], is a question which future research will also decide.