XXXV. *Red Shifts in the Spectra of Celestial Bodies*

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Abstract

The red shift of the spectral lines of B-stars belonging to the Orion Nebula group, relative to the lines of the spectrum of the Nebula itself, is shown to be about ten times larger than the red shift which the theory of relativity predicts on the basis of the known values of their masses and radii. A similar discrepancy is found in the case of O-stars. It is suggested that the red shift may be due to a loss of energy in the radiation field of the star. If $\Delta\nu$ is the change of frequency of the line and ν its original frequency, the following formula is proposed.

$$\Delta\nu/\nu = -A \,.\, T^4 \,.\, l \tag{A}$$

when A is a constant, T the temperature of the radiation field and l the length of path traversed through the radiation field.

It is shown that formula (A) represents not only the observations on O- and B-stars, but also on A-stars, the Sun, supergiant M-stars, Wolf–Rayet stars and on the so-called cosmological red shift.

In addition to the red shift given by formula (A) the data from the Sun and from white dwarfs seem to suggest that there exists an additional gravitational red shift which is, however, only a fraction (about 1/5) of the red shift predicted by the theory of relativity.

§ 1. Introduction

The fact that the lines in the spectra of certain classes of stars reveal a systematic displacement towards the red end of the spectrum—a so-called 'red shift'—became evident as soon as the number of apparent measured radial velocities was large enough to make statistical investigations of the observational material possible. The effect is particularly pronounced for stars of high surface temperature, that is, stars of spectral type B or O; in all stellar statistical discussions it has been called the K-effect.

The study of this red shift has developed into an extremely complicated problem, and we know now that the red shift is of a very complex nature. The fact that the B-stars embedded in the Orion Nebula show a pronounced red shift relative to the lines in the spectrum of the nebula itself (Freundlich 1919, Struve and Titus 1944, Struve 1945), that the O-stars in numerous stellar clusters reveal a red shift relative to the

* A brief account of the main points of the present paper has been published (Freundlich 1954).

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B-stars belonging to the same cluster (Trumpler 1935), and other facts, including solar observations, leave no doubt that a physical effect exists producing displacements (red shifts) of the spectral lines. The discovery, on the other hand, that the K-effect depends on the galactic longitude and passes twice through a maximum and minimum along the periphery of the galactic plane (Freundlich and v. d. Pahlen 1923), makes it clear that another effect, probably of dynamical character (v. d. Pahlen and Freundlich 1928) is in operation too and partly responsible for the observed red shifts.

The present paper is concerned only with the red shifts of purely physical character, that is, with those red shifts which cannot be interpreted as Doppler effects. We mention the other red shifts, the K-effect, in order to make understandable why this complex problem has so far resisted all attempts to find a satisfactory explanation.

A solution of the problem of the physical red shifts appeared near at hand when the general theory of relativity predicted a systematic red shift of all spectral lines originating at a value of the gravitational potential which is lower than its value on the earth's surface. This shift should be $\Delta\lambda/\lambda = \Delta\phi/c^2$ where $\Delta\phi$ is the difference in gravitational potential, λ the wave length of the line, $\Delta\lambda$ the change of wavelength and c the velocity of light. Since the stars showing most clearly a systematic red shift were the stars of greatest masses, it appeared natural to interpret the observed red shift as a gravitational red shift. We shall see, however, that this interpretation is untenable. In the case of the Sun, where measurements of the displacement of lines in the spectrum are at least a hundred times more accurate than corresponding observations in stellar spectra and where, moreover, a detailed analysis along the disc is possible, all attempts to prove the existence of a general constant red shift as predicted by the theory of relativity have ended without any conclusive and convincing results. A small red shift seems indicated, but its value changes along the disc. Neither the reduced absolute value nor the increase of the red shift towards the limb can be brought in agreement with the theory of relativity unless special *ad hoc* assumptions are made.

It will be shown in this paper that the observed red shifts of the solar and stellar lines are of a different nature from the red shifts predicted by the theory of relativity. The observations reveal a new effect which is probably of the greatest importance.

In the next section we shall first rediscuss the evidence from stellar spectra. After that we will draw some general conclusions which will lead to a new hypothesis about the red shift which we shall apply to the whole of the relevant observational material in the remaining sections.

§ 2. Discussion of the Red Shift in B- and O-Stars

The main difficulty in proving the existence of a physical red shift in stellar spectra lies in the separation of this effect from genuine Doppler effects. Strictly speaking, every observed line shift can be interpreted as a Doppler effect, and only independent evidence of a different character permits one to decide whether or not an observed line-shift is probably a Doppler effect.

The fact that the B-stars embedded in the Orion Nebula reveal a strong red shift was discovered early (Freundlich 1919). Using the latest observations and restricting the discussion to those 16 B-stars and 2 O-stars which constitute in a narrower sense the Orion Nebula group, the value of this red shift has been redetermined by Miss B. Middlehurst and Mr. T. B. Slebarski. Earlier, all stars had been discussed for which the right ascension α and declination δ were within the limits

$$5^{\mathrm{h}}\,13^{\mathrm{m}} < \alpha < 5^{\mathrm{h}}\,40^{\mathrm{m}}, \quad -9^\circ < \delta < 5^\circ,$$

as this group of B-stars had been defined by Kapteyn as the stars connected with Orion Nebula. Later investigations (Markowitz 1949) have, however, shown that in this wide range not all stars can be considered as organically connected with the nebula. The Orion Nebula group in the true sense is restricted to the area

$$5^{\mathrm{h}}\,30^{\mathrm{m}} < \alpha < 5^{\mathrm{h}}\,36^{\mathrm{m}}, \quad -6^\circ < \delta < -4^\circ.$$

In table 1 we have collected all data pertaining to 16 B-stars in this area belonging to the Orion Nebula.* Expressing the red shift in terms of a

Table 1

1	2	3	4	5	6	7
HD36959	29·2	11·7	B1k	12·0	6·5	1·18
HD36960	28·1	10·6	B1sk	15·5	9·9	1·00
HD37016	31·4	13·9	B2sk	10·8	4·4	1·44
HD37017	29·2	11·7	B2	10·1	3·9	1·65
HD37018	27·7	10·2	B2	13·4	12·4	0·69
HD37020	34·3	16·8	B2	8·0	3·9	1·31
HD37021	24·0	6·5	B2	6·1	2·4	1·65
HD37023	32·4	14·9	B0	9·2	3·4	1·74
HD37040	30·5	13·0	B3	8·7	5·8	0·98
HD37042	28·5	11·0	B1sk	9·3	4·2	1·41
HD37058	26·8	9·3	B3sk	6·6	3·6	1·18
HD37129	25·5	8·0	B3k	7·3	4·2	1·09
HD37209	29·4	11·9	B1s	10·4	7·9	0·83
HD37303	29·8	12·3	B3n	10·1	7·4	0·86
HD37334	28·3	10·8	B3	6·7	3·7	1·16
HD37356	29·1	11·6	B3sk	8·6	5·7	0·95

Column 1 gives the catalogue number of the star, Col. 2 the observed red shift v_{B} in km/sec, Col. 3 the residual red shift ($v_{\mathrm{B}}-v_{\mathrm{N}}$; $v_{\mathrm{N}}=17{\cdot}5$ km/sec=red shift of the nebula itself) in km/sec, Col. 4 the spectral type of the star, Col. 5 its mass in solar masses as unit, Col. 6 its radius in solar radii as unit, Col. 7 the expected relativistic red shift in km/sec.

* A separate paper discussing the astronomical data in more detail is in preparation.

Doppler effect, that is in km/sec, we find for the mean red shift of the B-stars with respect to the nebula itself the equation*

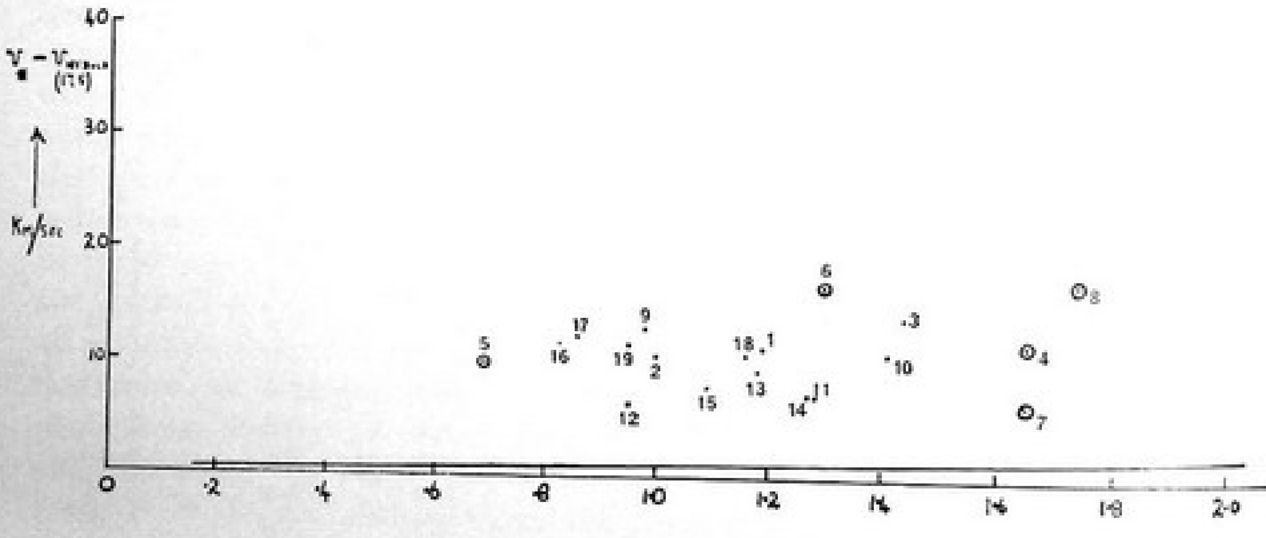
$$\overline{v_B}-\overline{v_{Neb}}=+11{\cdot}4\pm0{\cdot}2 \text{ km/sec},$$

which is larger than the predicted gravitational red shift by a factor of the order ten. The mean gravitational red shift is $+1{\cdot}2$ km/sec, while the individual values range from 0·7 to 1·7 km/sec. The uncertainties in the masses and radii cannot bridge the gap between the observational and the theoretically predicted red shift. In our earlier investigation (Freundlich 1919), using stars in the larger area, the existence of this effect was equally unambiguous; the resulting value was $+6$ km/sec. The investigation by Struve and Titus (1944), which was confined to the two O-stars and three B-stars in the Trapezium of the Orion Nebula, gives a red shift of the O-stars which is even as large as $+15$ km/sec. It will be shown below that this increase is probably real.

Figure 1 gives the distribution of the observed red shifts as ordinates

Fig. 1

Radial velocity—relativity red shift (calculated).



Calculated red shift—
km/sec.

⊙=Double star

Radial velocities of nineteen B-stars relative to the Orion Nebula, as a function of the relativistic red shift calculated from their masses and radii. If the red shift were purely the gravitational red shift all points should lie on the straight line at the bottom of this figure.

plotted against the expected value of the gravitational red shift. The values scatter only moderately around the mean. We could establish no correlation between the observed red shift and the gravitational red shift, the correlation coefficient being 0·17.

* In deriving this equation we excluded five variable B-stars. If these had been included the result would have been $+11{\cdot}3\pm0{\cdot}3$ km/sec. (All errors are probable errors.)

To insure the reality of the observed effect, we also derived the differences $v_B - v_{Ca}$ (v_{Ca} being the shift of the interstellar Ca lines) for all B-stars in whose spectra the interstellar H and K lines were measurable. The result was

$$\overline{v_B - v_{Ca}} = +10 \cdot 1 \text{ km/sec} \quad \text{or} \quad +8 \cdot 5 \text{ km/sec},$$

the second value resulting, if one or two exceptionally large values are omitted. We have not corrected for the rotation effect of the galaxy; firstly because this correction would be small compared to the scattering of the individually observed values, and secondly because near star groups do not clearly reveal the rotation of the galaxy at all. (Pismis 1938.)

Summarizing the result of this renewed investigation of the B-stars belonging to the Orion Nebula group we have:

The B-stars in the Orion Nebula group show a systematic red shift relative to the lines in the nebula amounting to at least +10 km/sec. This value is, by a factor of the order ten, larger than the red shift predicted by the theory of relativity.

This result confirms previous findings and it also agrees with other results to be considered below.

Let us now consider in more detail the question whether or not these large red shifts can be interpreted as gravitational red shifts. We can do this by comparing the masses calculated on the assumption that the red shift is due to the gravitational effect with the masses obtained from other evidence, especially in the case where the star is a component of a binary system. In the latter case its mass can be estimated from the orbital elements, or at least a limit determined giving the order of magnitude of the mass. For only two of the stars embedded in the Orion Nebula is an estimate of the masses possible by this method, viz., for BM Ori (HD 37021), a B2-star, and HD 37041, an O-star. In both cases the lines of only one component of the binary are observable and thus only a lower limit for the mass of the whole system can be derived. In both cases these limits correspond to the normally expected values for the spectral types in question, viz., $m_1 + m_2 \geqslant 2 \cdot 8\, m_\odot$ for BM Ori, and $m_1 + m_2 \geqslant 12 \cdot 9\, m_\odot$ for HD 37041. Although the red shift of BM Ori is exceptionally small, viz., only about half the mean value of 11·4 km/sec,* the red shift yields a mass for the one component alone of at least $25\, m_\odot$.† The red shift of HD 37041 would indicate a mass of $284\, m_\odot$, while the mass of the whole system is, according to the orbital motion only of the order $13\, m_\odot$.

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* The star seems in addition to be heavily obscured, for its apparent brightness is by two magnitudes lower than that of the other stars in the group; its radius as derived from its luminosity will, in consequence, come out abnormally small.

† With the normal value for its radius the red shift would give a mass of $55\, m_\odot$.

It is possible to base the proof that these large red shifts may not be interpreted as gravitational effects on a much wider range of observations. Bottlinger (1931) has investigated a few hundred B-stars and he finds, for instance, that of 42 B-stars of which the radial velocities, after being carefully corrected for the motion of the Sun and for the galactic rotation, exceed 10 km/sec, 39 are positive and only 3 negative. He finds the systematic character of the red shift so pronounced that he interprets these red shifts as pure gravitational displacements. The resulting masses range from about 100 to 1200 $m_{\odot}$. Among these stars are six which are members of binary systems and two (μ_2 Sco and Boss 5070) of which the mass can be determined by other means. Table 2 gives the data

Table 2

1	2	3	4	5
o Per	B2k	>9·2	10	168
ϕ_1 Per	B0ssk	>5·6	14	180
ζ CMa	B3	>0·8	8	160
τ CMa	O9sk	>14·9	17	250
θ_2 Cru	B3	>0·4	8	126
v Cen	B2	>0·02	10	150
μ_2 Sco	B3nn	24·0	8	115
Boss 5070	B2k	71·0	10	98

Column 1 gives the name of the star, Col. 2 its spectral type, Col. 3 the total mass of the binary system (m_1+m_2), Col. 4 the normal value of mass for the spectral type of the star in which the red shift is found, Col. 5 the mass calculated from the observed red shift, assuming it to be a relativistic red shift. All masses are expressed in solar masses as unit.

of these eight stars and it is clear that the masses derived from the red shifts are all too large by a factor of the order 10 to 20.

A similar contradiction between masses derived from observed red shifts and values derived from other astronomical evidence appears in Trumpler's investigation (1935). In a number of star clusters Trumpler discovered a systematic red shift of the O-stars relative to the B-stars in the same cluster. Interpreting these red shifts as gravitational displacements, he is also led to values for the masses of O-stars which reach a few hundred solar masses, which are quite improbably large. O. Struve (1950) stresses this point, that Trumpler's mass values are fictitious and in contradiction to all other evidence. We shall use Trumpler's data below to fix the mean value of the systematic red shift for the O-stars.

There is a complete similarity of the results obtained by Bottlinger from a statistical discussion of a wide material of B-stars over the whole sphere, by Trumpler from star clusters which, as a whole are partly approaching us, partly receding from us, and finally the results obtained here from the B- and O-stars which form the Orion Nebula group. This similarity makes it obvious that these systematic red shifts cannot be Doppler effects. It is quite improbable that they are produced by a systematic motion of the stars in the Orion Nebula group relative to the nebula itself, or by a systematic motion of the O-stars relative to the B-stars in the same cluster, etc., always indicating a systematic recession inside a group of stars.

We see thus that the large red shifts reveal a physical effect which cannot be interpreted either as a gravitational displacement or as a true recession effect.

To conclude this section, let us consider the data pertaining to O-stars. The material consists of data about six star clusters (Trumpler 1935), Struve and Titus' observations (1944), about the O- and B-stars in the Trapezium of Orion, and the data about the Orion Nebula group. These data are summarized in table 3. From this table we see that while values for $v_O - v_B$ scatter over a wide range, we get a well defined value for the mean red shift for O-stars, viz., $\overline{v_O} = +17{\cdot}6 \pm 0{\cdot}5$ km/sec. In this determination of $\overline{v_O}$ we have excluded the two values where the B-stars were very early B-stars (B0 and B1·5). If they had been included we would have found $\overline{v_O} = +18{\cdot}9 \pm 0{\cdot}7$ km/sec. Our value is larger than

Table 3

1	2	3	4	5	6
NGC 2244		6	B2	+13·4	+23·4
NGC 2244	O6			+ 6·4	+16·4
NGC 2244	O9			+ 7·0	+17·0
NGC 2264	O7	11	B7·5	+13·8	+15·6
NGC 2353		5	B8·5	+15·3	+16·6
NGC 2362	O8·5	7	B3	+ 8·7	+14·9
NGC 6871	O9w	3	B1·5	+ 7·8	+20·8
NGC 6871	B0			+13·6	+26·6
NGC 7380	O9	4	B0	+ 3·2	+25·4
NGC 7380	O9	11	B7	+13·8	+16·2
Trapezium	O8	3	B1·7	+ 5·8	+17·8
Trapezium	O8	18	B2	+ 7·4	+17·4

Column 1 gives the catalogue number of the star cluster, Col. 2 the mean spectral type of the O-stars concerned, Col. 4 the mean spectral type of the comparison B-stars, Col. 3 the number of comparison stars, Col. 5 the difference in red shift between the O- and B-stars in km/sec, Col. 6 the red shift of the O-stars in km/sec after correcting for the red shift of the comparison stars. The last two rows pertain to the O-stars of the Trapezium in the Orion-Nebula. The first three comparison B-stars are also Trapezium stars, and in the last column 18 Orion Nebula B-stars are used as comparison stars.

the value of 13·8 km/sec derived by Trumpler, the reason being that Trumpler adds as correction for the B-stars simply the relativistic correction, not realizing that the B-stars reveal systematic red shifts exceeding the relativistic effect by a factor of the order 10. Struve and Titus obtained for the red shift of the two O-stars embedded in the Trapezium with respect to the nebula itself, the value +15·0 km/sec. This value also indicates a further increase of the red shift for the O-stars of higher temperature than the B-stars.

Summarizing the results of this section, we see that *the observations show clearly the existence of a red shift which increases rapidly with the surface temperature of the star. For a B2-star of effective temperature* 20 000°K *the new effect amounts to* $\Delta\lambda/\lambda = 3{\cdot}3 \times 10^{-5}$ *corresponding to a Doppler effect of* +10 *km/sec.* The red shift is larger than the value predicted by the theory of relativity according to our present knowledge of stellar masses and radii by a factor of the order 10. For O-stars the red shift rises to about +18 km/sec. Since O-stars are rare and the physical conditions at their surface not yet sufficiently understood (their spectra show, e.g., emission lines), their surface temperatures are not yet safely known, but they must be considerably higher than the surface temperature of the B-stars and must exceed 25 000°K. We will therefore base the value of the red shift on the above mentioned value of +10 km/sec for a B2-star of 20 000°K.

§ 3. General Remarks on the Nature of the New Effect

The most essential feature of the new red shift is that it becomes predominant for stars of the highest surface temperatures, when it exceeds widely the relativistic red shift. For the Sun, on the other hand, for which the most detailed and most accurate data concerning line displacements exist, the observed average red shifts fall short of the relativistic prediction. This means that the situation is just the opposite from that for the B- and O-stars. In addition, the red shift reveals along the solar disc a pronounced systematic behaviour by increasing steeply towards the limb in all directions from the Sun's centre. For this limb effect no explanation has been offered up to now.

It seems to me that it is possible to understand all these phenomena if we give up the efforts to explain them as purely gravitational effects. Instead, I propose to introduce as an additional hypothesis that light passing through deep layers of intense radiation fields, loses energy—perhaps due to photon–photon interaction—and that the energy loss is proportional both to the density of the radiation field and to the length of path of the light through the radiation field. Using for the density of the radiation field Stefan–Boltzmann's law, we have thus

$$\Delta\nu/\nu = -A \,.\, T^4 \,.\, l, \qquad (1)$$

where A is a constant and l the length of path. We shall assume that light emerging from the surface of a star loses energy chiefly inside the stellar atmosphere, where an intense inward flux of radiation exists. We choose, therefore, tentatively, l equal to the depth down to which we see into the Sun's or the star's atmosphere. For the Sun, the value of l is of the order of magnitude 10^7 cm (Unsöld 1938). The same value of l will be chosen as a first approximation for other stars too, except for super giants, for which the depth of the atmosphere seems to exceed that of a dwarf star by a factor of the order 10^3. It must be stressed that, of course, all these assumptions are of a preliminary nature, until the theory of this new effect is better established.

With $l=10^7$ cm and $\Delta\nu/\nu=-3{\cdot}3\times10^{-5}$ for a B-star of 20 000°K effective temperature, we get for the constant A,

$$A=2\times10^{-29} \text{ degrees}^{-4} \text{ cm}^{-1}. \qquad (2)$$

We have actually used formula (1) to apply the corrections in table 3—and thus to derive from the values of v_O-v_B the mean systematic red shift for O-stars. In this way, we found for this red shift the value +17·6 km/sec, mentioned above.

In the following sections it will be shown that formula (1) gives a satisfactory description of the observed red shift along the solar disc, explains the red shift observed in other stellar spectra and may even permit an interpretation of the cosmological red shift other than that of an expanding universe.

§ 4. The Red Shift of the Solar Lines

(i) *Summary of the Present Situation*

According to the general theory of relativity the solar lines should be displaced relative to corresponding terrestial lines by the amount

$$\Delta\lambda/\lambda=2{\cdot}12\times10^{-6}.$$

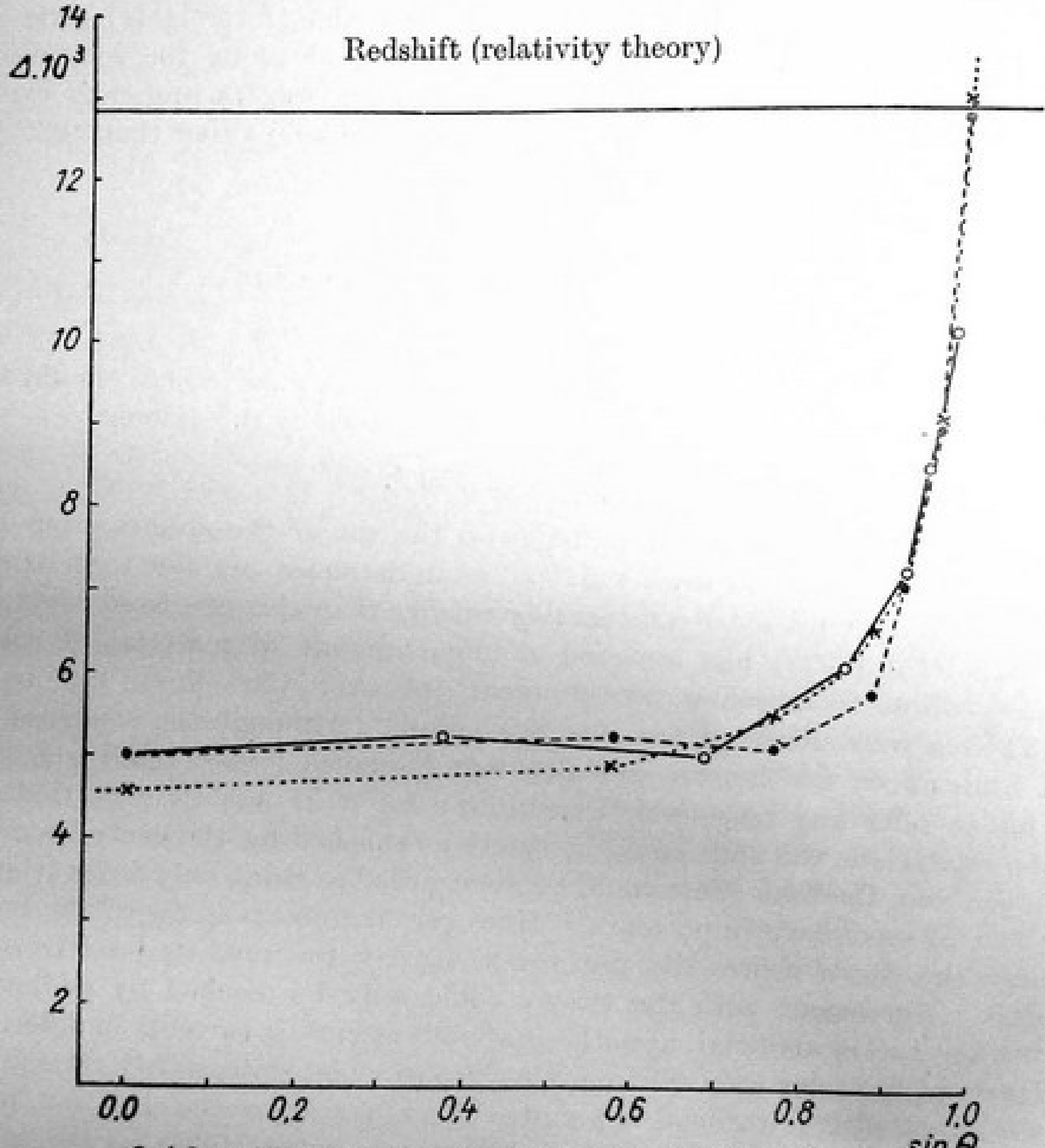
Modern tower telescopes, producing on the slit of the spectrograph an image of the Sun of at least 4 in. to 6 in. in diameter, are able to measure line displacements even considerably smaller than this predicted effect.

St. John (1928) has amassed a huge amount of material of solar observations comprising measurements of over 1500 lines, but only 133 lines were observed near the Sun's limb. Although the existence of a limb effect was known and although Evershed (1935, 1936) was not able to offer any reasonable explanation for it, it was thought that, if the relativistic red shift could be safely established for the central region of the Sun, the limb effect could be disregarded as being only a disturbing effect of secondary importance. However, the observations of the lines near the Sun's centre did not reveal clearly the predicted relativistic shift. Agreement with the theory could only be reached by adding a further, rather artificial, hypothesis about systematic currents in different layers of the solar atmosphere giving rise to violet shifts partly cancelling the expected gravitational red shifts. To characterize the situation, it is sufficient to quote the summary of Hunter's paper (1934) on the solar limb effect :—

" It seems clear that no hypothesis yet put forward will account for all the facts. Until one is forthcoming, the large deviations from the predictions of Einstein will give reason for doubting even the assignment of the major part of the red displacements to the gravitational effect. Any future explanation retaining the relativity shift as valid must account for the excess shift at the limb and the defect at the centre together with the variations in these quantities with line intensity and with epoch, and also for the observed form of the function representing the change in wavelength of a Fraunhofer line across the solar disc."

This is in full agreement with later observations by Miss Adam (1948), which are a most consistent set of observations of solar lines at about 6100 Å. In fig. 2 (taken from Freundlich 1954), the values of the red

Fig. 2



● Adam (Oxford) 1948 ○ Freundlich *et al.* (Potsdam)

× $\Delta=(2{\cdot}72+1{\cdot}85\sec\theta)\,.\,10^{-3}$

The red-shift Δ of solar lines as a function of the angle θ between the line of sight and the solar radius to the point where the line of sight cuts the solar surface. The horizontal line ($\Delta=0{\cdot}0129$) is the red shift according to the theory of relativity.

shift from the centre of the Sun to the limb (Adam 1948) are shown and compared with observations made by Freundlich, v. Brunn and Brück (1930) in Potsdam. These latter observations gave only relative changes of the red shift when one moved from the centre of the Sun to the limb along 12 radii of the discs. The red shift increases along all radii according to the same law—which, however, at that time could not be explained. The observations of Miss Adam at 6100 Å, which are referred to a terrestrial light source, give absolute values of the red shift. The Potsdam observations which are based on a selected group of solar lines at about 4400 Å have been made to coincide with Miss Adam's observations at 6100 Å at the centre of the disc. The practically complete coincidence of both series demonstrates the accuracy attainable with powerful tower telescopes and emphasizes the general character of the limb effect. We shall base all further discussion on this latest set of observations. Before doing so we wish to quote Miss Adam's summary which is very similar to the one of Hunter's paper (1934) :—" If we assume that the solar lines do suffer an Einstein gravitational displacement, then we must find some mechanism other than radial currents which will effectively neutralise this displacement over 80–90 per cent of the solar disc and yet leave the full Einstein shift near the limb."

(ii) *A New Interpretation*

If what we observe on the Sun is chiefly due to the new effect discussed in the previous section, we would expect to find the following two phenomena.

(1) Taking the Sun's temperature to be 6000°K, we would expect a red shift which is smaller than the one shown by the B2 stars by a factor of the order $(6/20)^4=8\cdot 1\times 10^{-3}$. The shift should thus be of the order of 0·081 km/sec or $\Delta\lambda/\lambda=2\cdot 7\times 10^{-7}$. The group of lines observed by Miss Adam has the mean wavelength 6100 Å, and we get thus $\Delta\lambda=1\cdot 65\times 10^{-3}$ Å which should to a first approximation be the red shift at the centre of the Sun, if produced by the effect studied in the present paper.

(2) Moving from the Sun's centre to the limb, we would expect the red shift to increase proportional to $\sec\theta$, θ being the angle between the line of sight and the solar radius to the point where the line of sight cuts the surface, since the length of path through the atmosphere is equal to $l_0 \sec\theta$, l_0 being the length of path at the centre.

Accordingly we obtained a least square solution for the quantities x and y in the equation $\Delta\lambda_{\text{obs}}=x+y\sec\theta$ using Miss Adam's data. The least square solution gives

$$x=(+2\cdot 72\pm 0\cdot 2)\times 10^{-3}\,\text{Å},\quad y=(+1\cdot 85\pm 0\cdot 1)\times 10^{-3}\,\text{Å}.$$

The dotted curve in fig. 2 shows that the red shift along the whole surface of the Sun is well represented by the formula

$$\Delta\lambda=(2\cdot 72+1\cdot 85\times \sec\theta)\times 10^{-3}\,\text{Å}.$$

The value of $1{\cdot}85\times10^{-3}$ Å for the central red shift is in good agreement with the predicted value $1{\cdot}65\times10^{-3}$ Å. In addition a constant red shift is found, but its value is only about one-fifth of the value predicted by the theory of relativity (see fig. 2). It is of the greatest importance that solar observations are taken up again from this new point of view.

§ 5. Observed Red Shifts of other Stellar Spectra

The red shift effect considered in the present paper decreases so rapidly with decreasing temperature that observable effects are only to be expected for later type stars under very special conditions.

(i) A-*Stars*

The effective temperature for A-stars is about 10 000° K and the red shift should have decreased to about 0·6 km/sec. Various statistical investigations (Gyllenberg 1915) of the K-effect for A-stars give, apart from the dependence on galactic longitude mentioned earlier, a positive mean red shift between 0·1 and 0·9 km/sec. A mean red shift of the right order of magnitude is thus indicated.

(ii) *Super Giant* M-*Stars*

The surface temperature of these stars has decreased to about 3000° K. The characteristic feature of these stars are their very large radii. The mean density of their matter must be extremely low and according to Unsöld (1938) their atmospheres are about two thousand times as extended as the solar atmosphere. The depth at which the stellar lines originate in the stellar body and the depth at which other lines originate in the surface layers of their atmospheres must differ by the great length of path these stellar lines must traverse. It was discovered by Adams and McCormack (1935) that in various of the near and bright supergiants of low temperature (given in table 4) lines which must be

Table 4

1	2	3	4	5
α Orionis	cM2	+3·4	+5·8	460
β Pegasi	M2	+5·3	+8·2	110
α Scorpii	cM2	+5·2	—	160
α′ Herculis	M5	+3·5	—	320

Column 1 gives the name of the star, Col. 2 its spectral type. Col. 3 the red shift in km/sec of the stellar lines with respect to the D_1 and D_2 lines of Na, Col. 4 the red shift in km/sec of the stellar lines relative to the H and K lines of Ca, Col. 5 the stellar radius in solar radii as unit.

produced on the top level of the atmosphere, such as the sodium D_1 and D_2 and Ca^+ H and K lines, show a marked violet shift relative to the stellar lines. They tried to explain these systematic shifts as indicating a general expansion of the atmosphere of such stars, but there is no other evidence to support this hypothesis.

According to the ideas developed here we would interpret the observed line displacements as *red shifts* of the stellar lines, coming from great depths, relative to the high level atmospheric lines. Although the surface temperature of these stars is relatively low (3000°K), the length of path l may be 10^3 times as large as in the case of the Sun. Hence red shifts should be expected of the order of $(3/20)^4 \times 10^3 \times 10$ km/sec$\doteq 5$ km/sec in full agreement with observations.

The list of stars in Adam's and McCormack's paper contains also β Ori, a cB8 star of $T_{\mathrm{eff}} \sim 13\,000$°K and α Cygni ($T_{\mathrm{eff}} \sim 10\,000$°K). In these two cases very much smaller values for l are, of course, sufficient to explain the observed red shift of low level lines relative to the atmospheric lines.

(iii) *Wolf–Rayet Stars*

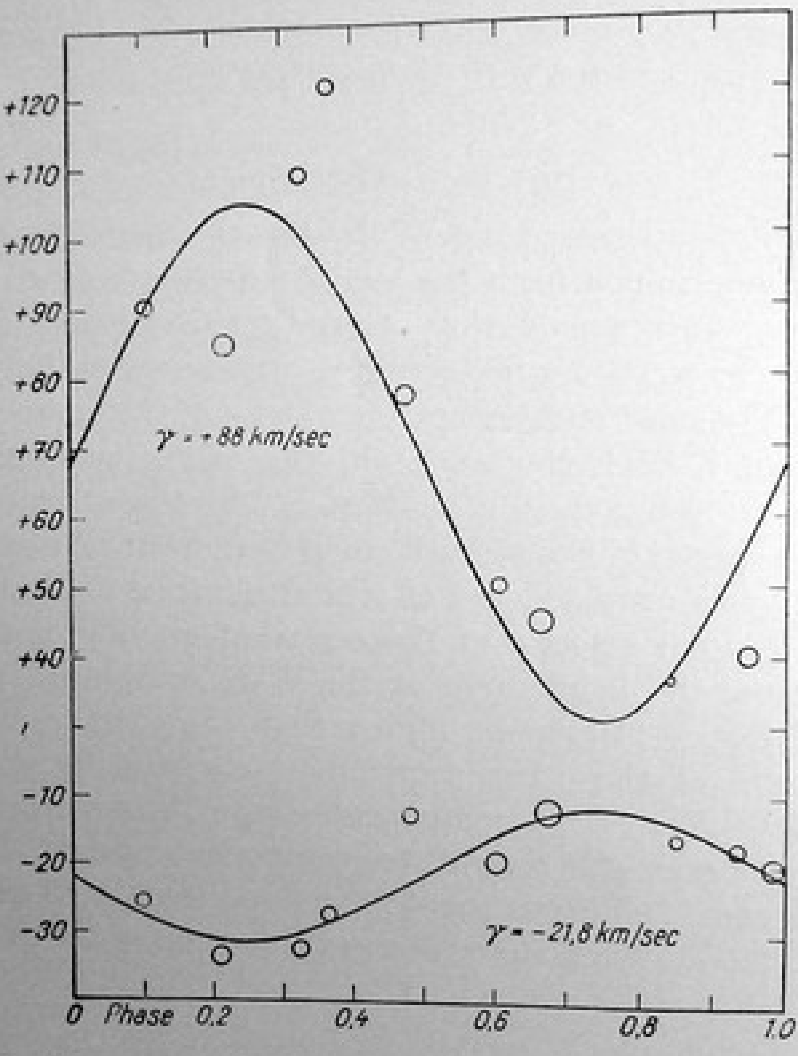
The effective temperatures of W–R-stars lie between 40 000°K and 100 000°K, as determined from the ionization potentials of lines in their spectra. These stars should thus, according to formula (1), show red shifts of the order of 100 km/sec or more. These red shifts have, indeed, been found. The most striking cases are those of the binaries HD 193576 (one component a W–R-star and the other component an O-star) and HD 190918 (one component a W–R-star and the other component a B-star). The spectral lines of both components can be observed in both cases and lead to a consistent set of orbital elements (Wilson 1940, 1949). However, the radial velocity of the centre of gravity of the system as determined from the light curve of the W–R component gives a value $+90$ km/sec resp. $+110$ km/sec higher than the value determined from the light curve of the other component (compare fig. 3, taken from O. C. Wilson). The W–R component shows thus a red shift relative to the other component. Since these components should show red shifts of 10 km/sec resp. 20 km/sec (see § 2), we see that W–R-stars show red shifts of 110–120 km/sec in agreement with formula (1) with $T=40\,000$°K.

(iv) *White Dwarfs*

In connection with the problem under consideration the red shift of Sirius B attains special significance. At the surface of white dwarfs, such as Sirius B, the radiation field is so strongly reduced compared to normal dwarf stars, such as the Sun or Sirius A, that the relativistic red shift should become observable quite unimpaired by the new effect due to the radiation field in the stellar atmosphere. It is highly regrettable that the accuracy attainable in measuring the red shift of the lines in Sirius B is so low and that there is still a great uncertainty concerning the mass and radius of Sirius B, so that final conclusions cannot yet be drawn.

The results in Adam's paper (1925) are mainly based on measurements of H_β and H_γ; the other lines which were measured gave results of only very low weight. The measurements of H_β yield a red shift of $+26$ km/sec, the values scattering between $+17$ km/sec and $+31$ km/sec; H_γ gives a red shift of $+10$ km/sec, values scattering here between $+2$ km/sec and $+17$ km/sec. To make these two sets compatible, the red shift obtained for H_γ is corrected by multiplying the observed mean value by a factor 2·1, the assumption being that the blending of the spectrum of Sirius B by the light of Sirius A makes such a radical correction necessary.

Fig. 3



The radial velocity curves of the two components of the binary HD 190918. The upper curve corresponds to the Wolf–Rayet component, the lower one to the B-component. The velocity γ of the centre of gravity of the system following from the upper curve is $+88$ km/sec and following from the lower curve is -22 km/sec.

The final value of the red shift is $+19$ km/sec, which agrees well with a second independent determination by Moore (1928) which gave $(+21\pm5)$ km/sec. From these observations the conclusion can be drawn that Sirius B reveals a systematic red shift, the value of which *most probably lies between $+10$ km/sec and 30 km/sec, but no more can be said.*

Since then white dwarfs have been the object of intensive study, and evidence is accumulating that the true values for the mass and radius of Sirius B differ considerably from the values on which the first determination of the gravitational red shift had been based. The mass is apparently very nearly equal to the solar mass and the radius smaller than 0·008 $R_{\odot}$. The new values of mass and radius lead to a predicted gravitational red shift much larger than the red shift so far observed.

Kuiper (1941) discusses, for instance, a possible model for Sirius B which would give rise to a gravitational red shift of nearly 80 km/sec, but dismisses this model chiefly because it would contradict the actually observed red shift, taking the agreement of the observed and the theoretically predicted value as absolutely necessary. However, Gamow and Critchfield (1949) are also led to a very similar model for Sirius B :— it has a mass of 0·98 $m_{\odot}$ and a radius of 0·008 $R_{\odot}$. They state, without giving further references, that these values are consistent with recent observations. From these values of mass and radius a gravitational red shift of nearly +80 km/sec follows.

There is obviously also in the case of Sirius B growing evidence that the observed red shift is considerably smaller than the value predicted by the theory of relativity.

§ 6. The Cosmological Red Shift

The fundamental character of the effect under consideration raises, necessarily, the question whether it might not also be the cause of the cosmological red shift which hitherto has been interpreted as a Doppler effect. In this case, the influence of the factor l in formula (1) is given explicitly from observations. The observed red shift $\Delta\lambda/\lambda$ increases for every million parsec ($=3\times10^{24}$ cm) by $0{\cdot}8\times10^{-3}$ which corresponds to a velocity increase of 500 km/sec when interpreted as a Doppler effect. An increase by 10 km/sec—corresponding to the red shift in a B2 star with $T_{\mathrm{B}}=20\,000°\mathrm{K}$—would correspond to a path $l_{\mathrm{S}}=1{\cdot}2\times10^{23}$ cm.

As far as the mean temperature T_{S} of intergalactic space is concerned, apart from the knowledge that it must be near the absolute zero, no reliable information is available. If we may interpret the cosmological red shift in the same way as the stellar red shifts, the following equation should hold :

$$T_{\mathrm{S}}{}^4 l_{\mathrm{S}} = T_{\mathrm{B}}{}^4 l_{\mathrm{B}}, \quad \text{or} \quad T_{\mathrm{S}} = T_{\mathrm{B}}(l_{\mathrm{B}}/l_{\mathrm{S}})^{1/4}. \qquad . \quad . \quad . \quad . \quad (3)$$

Equation (3) shows that the value of T_{S} obtained in this way does not depend strongly on the choice of l_{B}. Taking for l_{B} the two extreme values 10^7 cm and 10^9 cm, we get the following two reasonable values

$$T_{\mathrm{S}}=1{\cdot}9°\mathrm{K} \quad \text{and} \quad T_{\mathrm{S}}=6{\cdot}0°\mathrm{K}.$$

In a recent paper Gamow (1953) derives a value for T_{S} of 7°K from thermodynamical considerations assuming a mean density of matter in space of 10^{-30} g/cm³.

One may have, therefore, to envisage that the cosmological red shift is not due to an expanding universe, but to a loss of energy which light suffers in the immense lengths of space it has to traverse coming from the most distant star systems. That intergalactic space is not completely empty is indicated by Stebbins and Whitford's discovery (1948) that the cosmological red shift is accompanied by a parallel unaccountable excess reddening. Thus the light must be exposed to some kind of interaction with matter and radiation in intergalactic space.

§ 7. Conclusions

It appears that an effect of not yet established nature produces red shifts of the lines in stellar spectra which overshadows the gravitational red shifts predicted by the theory of relativity. This has obviously been the reason for the difficulties which the astronomers encountered in their attempts to test the theory of relativity. There are also indications that where a gravitational red shift occurs (constant term in the solar red shift, Sirius B) this shift is only about one-fifth of the theoretically predicted shift.

The idea suggested here, that light suffers loss of energy in an intense radiation field, perhaps due to photon–photon interactions, must first be incorporated in the theory of the nature and propagation of light before final conclusions can be drawn.

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