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LETTERS TO THE EDITOR

Red-Shifts in the Spectra of Celestial Bodies*

Stars of high surface temperature, that is B-stars ($T \sim 20\,000^\circ\text{K}$) and O-stars ($T \sim 30\,000^\circ\text{K}$), show a very marked red-shift of their spectral lines. This is especially noticeable in the case of the stars embedded in the Orion Nebula, since in that case it is possible to deduct from the observed red-shifts the red-shift due to the recession of the system as a whole. If one considers these stars, it is found that, relative to the Orion Nebula itself, the B-stars show a systematic red-shift corresponding to a recession velocity of 11.4 km sec^{-1} and a similar discussion of O-stars gives a red-shift corresponding to 17.6 km sec^{-1} .†

In earlier discussions it was suggested that this red-shift might be due to the relativistic gravitational effect. From the known masses and radii of B-stars it follows, however, that the gravitational effect would only lead to red-shifts of the order of 1.2 km sec^{-1} , which are by a factor 10 smaller than the observed red-shifts.

While the observed red-shifts in the case of B- and O-stars are by far larger than the relativistic red shifts, in the case of the sun the situation is just the opposite. In this case most detailed and accurate data are available, but while the theory of relativity predicts a red-shift $\Delta\lambda/\lambda = 2 \times 10^{-6}$, the red-shift in the centre of the solar disc is only 8×10^{-7} , although the relativistic value is reached, and even surpassed, at the limb. A careful analysis of the red-shift in the solar spectrum shows that it follows the law $\Delta\lambda/\lambda = a + b \sec \theta$, where θ is the angle between the line of sight and the solar radius to the point where the line of sight cuts the solar surface.

It is tempting to try to account for all these red-shifts by one process and we suggest the following formula:

$$\Delta\lambda/\lambda = AT^4l, \quad A = 2 \times 10^{-29} \text{ cm}^{-1} \text{ deg}^{-4}. \quad \dots\dots(1)$$

In eqn (1) $\Delta\lambda/\lambda$ is the relative red-shift, T the temperature of the radiation field through which the light has passed and l the length of its path through the radiation field. The constant A is chosen in such a way that $\Delta\lambda/\lambda = 3 \times 10^{-5}$ for $T = 20\,000^\circ\text{K}$, $l = 10^7\text{ cm}$, which are the values for a B-star. Formula (1) implies that the red-shift is due to a loss of energy in the intense radiation field, perhaps due to photon-photon interactions.

It turns out that eqn (1) can well account for most of the observed red-shifts. For the sun we get $\Delta\lambda/\lambda = 2.7 \times 10^{-7} \sec \theta$, while the observed value of b is 3.0×10^{-7} . The constant term a may be due to a gravitational effect, which in that case would be about five times smaller than the theoretically predicted constant red-shift.‡

In the case of A-stars eqn (1) predicts a red-shift of about 0.6 km sec^{-1} , while the observed red-shifts lie between 0.1 and 0.9 km sec^{-1} . In the case of

* A more detailed account of the subject matter of the present note can be found elsewhere (Freundlich 1954 a, b).

† I would like to express my thanks to T. B. Słebarski for critically discussing the available data.

‡ It is of interest to note that the red-shift in Sirius B, which can only be due to a gravitational effect, is also about five times smaller than the theoretical value.

supergiant M-stars T is very small, but their enormous atmospheres—about a thousand times more extensive than the solar atmosphere—lead to expected red-shifts of about 5 km sec^{-1} . It is found that lines formed at the top of the atmosphere are, indeed, displaced by about 5 km sec^{-1} to the violet with respect to lines formed at the bottom of the atmosphere. In the case of Wolf-Rayet stars ($T \gtrsim 40\,000^\circ\text{K}$) eqn (1) leads to red-shifts of the order of 100 km sec^{-1} , which also have been observed (Wilson 1949).

Finally, it seems tempting to apply formula (1) to the case of the cosmological red-shift or Hubble effect. In that case $\Delta\lambda/\lambda$ is about 0.0008 for every million parsec ($= 3 \times 10^{24} \text{ cm}$). Using eqn (1) this leads to an intergalactic temperature of about 1.5°K , which does not seem to be an unreasonable value.

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7th December 1953.

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FREUNDLICH, E. F., 1954 a, *Göttinger Nachr.*, No. 7; 1954 b, *Phil. Mag.*, **45**, in the press.
WILSON, O., 1949, *Astrophys. J.*, **109**, 76.

On the Interpretation of Freundlich's Red-Shift Formula

Freundlich (1954) has suggested that his red-shift formula $\Delta\nu/\nu = -AT^4$ ($A = 2 \times 10^{-29} \text{ cm}^{-1} \text{ deg}^{-4}$) may be interpreted as an effect of photon-photon collisions. I have investigated whether this is possible. The first step is to write the equation in a dimensionless form,

$$\frac{\Delta\nu}{\nu} = -C \frac{l}{l_0} \frac{u}{u_0} \quad \dots\dots(1)$$

where $u = aT^4$ ($a = 7.66 \times 10^{-15} \text{ erg cm}^{-3} \text{ deg}^{-4}$) is the radiation density according to Stefan's law. If one takes for l_0 and u_0 the atomic constants

$$\left. \begin{aligned} l_0 &= \frac{\lambda_0}{2\pi} = \frac{h}{mc} & (\lambda_0 = \text{Compton wavelength}) \\ u_0 &= \frac{mc^2}{l_0^3} = \frac{hc}{l_0^4} & (\text{one electron per cube } l_0^3) \end{aligned} \right\} \quad \dots\dots(2)$$

$$\text{one has} \quad l_0 u_0 = \frac{hc}{l_0^3} = 5.54 \times 10^{14} \text{ erg cm}^{-2} \quad \dots\dots(3)$$

$$\text{and obtains} \quad C = \frac{l_0 u_0}{a} A = 1.45, \quad \dots\dots(4)$$

a value so near to unity that the assumptions (2) seem to be justified.

A simple analysis of (1) then leads to the result that it can be written in the form

$$\Delta\lambda/\lambda = -\Delta\nu/\nu = CN\lambda_0\bar{\lambda}, \quad N = l_0^2 n \quad \dots\dots(5)$$

where n is the number of photons per unit volume and $\bar{\lambda}$ the wavelength corresponding to the mean frequency of the radiation field defined by $u = nh\bar{\omega}$.

Hence the red-shift can be explained as a sequence of N photon-photon collisions with an effective cross section l_0^2 , each of which produces a small change in wavelength or frequency

$$\delta\lambda/\lambda = C\lambda_0/\bar{\lambda}, \quad \delta\nu = -C\nu/\nu_0. \quad \dots\dots(6)$$

If Freundlich's explanation of the Hubble effect is accepted, these frequency (energy) changes should not be accompanied by deflections (changes of momentum).

An effect like this is of course not in agreement with current theory. It has, however, an attractive consequence. A simple application of the conservation laws of energy and momentum shows that a collision of this kind is only possible if a pair of particles with opposite momenta is created. The energy of one of these is $h\nu' = -\frac{1}{2}h\delta\nu$, where $\delta\nu$ is given by (6). If the secondary particles are photons their frequency is of the order of radar waves (for the sun $\nu' \sim 2 \times 10^9 \text{ sec}^{-1}$, $\lambda' \sim 15 \text{ cm}$). Thus the red-shift is linked to radio-astronomy. A simple estimate of the efficiency leads to the result that it is very high; one has to assume that only a small part of the secondary particles are photons or are observed as photons. Thus it seems possible that the strong radar emission of sun spots and flares and of other celestial objects may be explained by this new effect.

The secondary radiation for two colliding primary x-ray beams of $\lambda \sim 10 \text{ \AA}$ would be visible ($\lambda' \sim 6000 \text{ \AA}$). But it seems to be hardly possible to observe this effect because of the smallness of the cross section.

This theory would indicate the appearance of an absolute length in the field equations for the vacuum, and as the laws of general relativity do not contain such a length they ought to be modified. Therefore the predictions of relativity about the red-shift cannot be used as an argument against Freundlich's formula and its interpretation indicated here.

A more detailed account will soon appear in *Göttinger Nachrichten*.

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7th December 1953.

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