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The Nebular Redshift

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The possibility of an effect of the free electrons in a highly ionized gas on the frequency of light traversing it has been investigated. Electrons to a density of about 5×10^{12} per cc were produced in a series of low voltage arcs. Light of wave-length 5461A was passed through the arcs and a frequency shift sought by means of an interferometer in vacuum. A shift of approximately two parts in 10^{10} could have been detected. A very satisfactory null result was obtained. This is interpreted with special reference to the possibility of explaining the nebular redshift by such a mechanism. It is concluded that the shift is not attributable to interstellar electrons.

INTRODUCTION

THE discovery by Hubble and Humason[1] that statistically the wave-lengths of spectral lines of distant nebulae experience a fractional shift toward the red proportional to the distances of the nebulae seems at present best explained in terms of an expanding universe. The form of the observed relationship, however, suggests the possibility that it may depend in some way on intergalactic matter; almost any mechanism of interaction would yield proportionality between the redshift and distance, at least to a first approximation.

A theory of Zwicky,[2] according to which the gravitational interaction occurring between the photon and intergalactic matter gives rise to a loss of momentum and therefore of frequency by the photon, has been shown untenable on the basis of the relativity theory of gravitation by Tolman, Ehrenfest and Podolsky.[3] The hypothesis of the present writers, a test of which is the main subject of this paper, was suggested by the well-established fact that the gas in intergalactic space is practically completely ionized. It merely postulates a frequency shift in the photon in its interaction with a free electron, the mechanism of the interaction and the magnitude of the individual shifts not being assumed in advance. When the test had been about completed an essentially equivalent theory of Abraham[4] appeared. He, however, employed the classical Thomson theory of scattering in combination with the quantum photoelectric equation and was thereby enabled to assign a definite numerical value to the frequency shifts due to individual encounters of photon and electron. Such a procedure must naturally be regarded sceptically, but it does suggest a shift of frequency in the observed direction. The writers have preferred to make no quantitative predictions of an effect. Nevertheless only a slight and plausible modification of the theory of the Compton effect, to permit a slight radiation of energy by the electron during its reaction with the photon, would be required to yield an effect of the kind observed.

THEORY AND PROCEDURE

As basis of the present theory we assume merely that a photon loses energy to electrons in proportion to its frequency and either continuously or discretely, the rate in the latter case depending on the probability of encounters. In either case the mean loss per unit length of its path is evidently proportional to the density of free electrons, and we may therefore write $d\nu=-k\rho\nu dx$, where k is the unknown constant of proportionality, ν is the frequency, ρ the density and dx the length of the element of path. Assuming ρ to be roughly constant, this expression can be integrated to give $\nu=\nu_0e^{-k\rho l}$, where l is distance between source and observer. As a first approximation, then

$$\delta\nu/\nu_0=(\nu_0-\nu)/\nu_0=k\rho l. \quad (1)$$

This expression is of the same form as the Hubble-Humason law.

[1] Hubble and Humason, Astrophys. J. **74**, 43 (1931).
[2] Zwicky, Proc. Nat. Acad. Sci. **15**, 773 (1929).
[3] Tolman, Ehrenfest and Podolsky, Phys. Rev. **37**, 602 (1931).
[4] Abraham, Comptes rendus **15**, April 8 (1935).

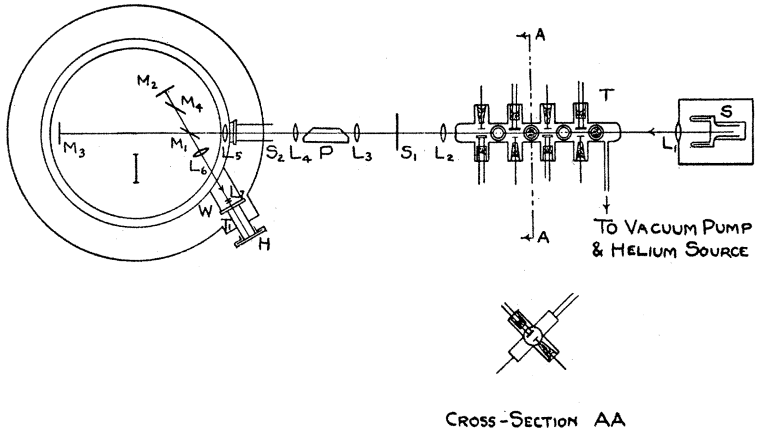

Fig. 1. Schematic diagram of apparatus showing light path.

Now although the value of l for the nebulae is enormous, nevertheless since ρ can be shown to be very small, even with complete ionization of the gas in intergalactic space, it turns out to be feasible to test our hypothesis experimentally. This is so because a very large value of ρ can be produced in the low voltage arc and an extremely small value of the ratio $\delta\nu/\nu_0$ can be detected. The experiment consists of comparing the frequency of a spectral line in a beam passed through a series of arcs, with the frequency of the same line when the path contains no ions.

The experimental arrangement is shown in Fig. 1. Light from the mercury-vapor arc S is collimated by the lens L_1 and passed through a series of helium arcs in the discharge tube T to the lens-and-prism system L_3PL_4 which separates out the green line λ5461. The interferometer I forms an interference pattern focused on a photographic plate in the holder H which automatically shifts the plate between exposures which are made with the helium arcs alternately on and off.

The source is a low voltage discharge in mercury vapor, between a cylindrical anode and an oxide-coated helical hot cathode. The discharge tube is illustrated in Fig. 2 which is self-explanatory. The luminous part of an arc is mainly confined to the jacketed part of the central tube and the light passes out through a window set close to it in order to minimize the amount of reversal of any of the numerous components of the green line which was used. The interference pattern had been found to be sharpest when the arc was kept at a temperature within a very few degrees of 35°C, hence it was jacketed with ether maintained at the boiling point by heat from the arc and condensed in a water-jacketed condenser. With the current in filament and arc kept constant by an automatic regulator, the brightness of this source exhibited no measurable variations as the helium arcs

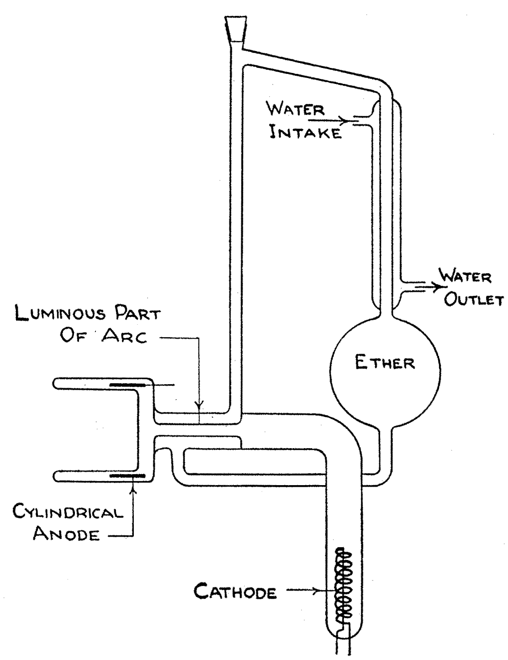

Fig. 2. Low voltage discharge in mercury vapor used as a light source.

(which employ the same source of direct current) were turned on and off; this steadiness was essential because otherwise there might have occurred a spurious shift of the interference pattern correlated with the discharge in the helium tube. This sort of spurious effect is discussed in a paper referred to below.[5]

The interferometer is of the Michelson type, built almost entirely of fused quartz and contained in a vacuum chamber kept at a temperature constant to within about 10^{-3} degrees C. The vacuum is necessary in order to keep the optical path-difference constant. The interferometer is compensated accurately for temperature. The fixed path difference is slightly more than 600,000 wave-lengths of the line $\lambda 5461$. Sections of the interference pattern (a system of concentric rings) were automatically photographed in such a way that exposures taken with the helium arc on were interleaved with those taken with the arc off. By this procedure errors due to differences among individual photographic plates were minimized.

The measurements of the plates were made with a comparator in which the interference rings were compared directly with those on a nearly identical reference plate which was taken as a standard. With this device each exposure could be measured with a probable error corresponding to a variation in path-difference of about 10^{-3} wave-length. That is, the probable error for each exposure corresponds to a variation in frequency of one part in $1000 \times 600{,}000 = 6 \times 10^{8}$.

The interferometer and comparator are discussed in more detail elsewhere.[5]

The ionized gas was contained in a tube 40 cm long provided with plane-parallel windows at the ends. Equally spaced along the tube were eight units, each consisting of an oxide-coated cathode set 1 cm away from a flat nickel anode. The cathode was made of heavy tungsten ribbon folded in zigzag fashion with the edge lying in a plane parallel to that of the anode; the area was sufficient to provide a current of over 1 ampere per unit without saturation. In order to provide uniform ionization on the average over the whole area of the light beam, which traversed a path 1 cm square along the axis of the tube, successive units were rotated 90° with respect to each other about the axis. Each cathode was heated by a separate secondary coil of a transformer, and each unit had its own ballast resistances, so the several units could be operated very stably in parallel.

[5] Kennedy and Thorndike, Phys. Rev. **42**, 400 (1932).

The ionized gas was helium at the pressure (1.5 mm of mercury) which had been found to give maximum ionization. The pressure was measured with a butyl phthallate gauge; a mercury gauge would, of course, have contamined the helium and given rise to objectionable mercury lines in the ionization tube. Helium was used because it has no spectral lines near the mercury green line, and so permitted the use of a low resolving power monochromator and consequently a maximum intensity of light.

Results and Interpretation

One hundred and ninety-six (196) exposures were made with the helium alternately ionized and unionized. The average difference was $(1.4 \pm 0.9) \times 10^{-4}$ fringe; this is clearly a null result. It corresponds to a frequency shift of one part in $600{,}000/(1.4 \times 10^{-4}) = 4 \times 10^{9}$.

By using this result in formulae (1) we can show that the nebular redshift is not to be attributed to interstellar electrons in a static universe. The value of ρ in similar circumstances has been determined by the Langmuir probe method by Kenty,[6] and Compton and Eckart[7] and Druyvesteyn,[8] and from line absorption measurements by de Groot.[9] Their results enable us to set $\rho = 5 \times 10^{12}$. The length of the ionized path, l, is 40 cm. Therefore from Eq. (1)

$$k = \frac{\delta\nu/\nu_0}{\rho l} = \frac{1.4 \times 10^{-4}}{6 \times 10^{5} \times 5 \times 10^{12} \times 40} = 1.2 \times 10^{-24}.$$

This is to be regarded as an approximate upper limit to the possible magnitude of the mean fractional shift per electron.

Now Hubble's value of $(1/l)(\delta\nu/\nu_0)$ is 6.0×10^{-28} per cm, from which and the above value

[6] Kenty, Phys. Rev. **32**, 625 (1928).
[7] Eckart, Phys. Rev. **25**, 139 (1925).
[8] Druyvesteyn, Zeits. f. Physik **64**, 781 (1930).
[9] De Groot, Zeits. f. Physik **60**, 617 (1930).

of k we find by Eq. (1) the value of the density of intergalactic electrons

$$\rho \geq 5.0 \times 10^{-4} \text{ per cc.}$$

Making the least favorable assumption for the present purpose, i.e., that intergalactic matter consists entirely of doubly-ionized calcium, the number of atoms per cc is one-half of ρ, or 2.5×10^{-4}, and since the mass of the calcium atom is 6.7×10^{-23}, the corresponding density of matter is $\rho_0 = 1.7 \times 10^{-26}$.

It has been shown[10] that there are but three possible types of static universe, i.e., those characterized by the line elements of Einstein, of de Sitter and of the restricted theory of relativity. Of these only the first allows an appreciable density of matter, and for it we have the relation[11] $1/R^2 = 4\pi(\rho_0 + p)$, where R is the radius of curvature of a spatial section of the universe and p the mean pressure exerted by the matter of the universe; both ρ_0 and p are expressed in relativistic units in which the velocity of light and the gravitational constant are made equal to unity. Since p is presumably not negative, evidently $R \leq (1/4\pi\rho_0)^{\frac{1}{2}}$. Translating this expression into c.g.s. units and substituting our computed value of ρ_0 we find $R \leq 7.1 \times 10^{25}$ cm $= 7.6 \times 10^7$ light-years. But this is only about a sixth of the distance to which the 100-inch telescope has penetrated, and so can scarcely be a plausible value for the radius of the universe. Hence we conclude that our hypothetical mechanism of the nebular red-shift is not tenable. Abraham's theory, according to which k turns out to be about one-half our computed value, is likewise contradicted by this conclusion.

Another fairly obvious test of a theory of the kind here proposed is suggested by the existence of the interstellar calcium cloud in our own galaxy. Here as in intergalactic space the calcium is almost entirely doubly ionized, so one might expect the lines of the remoter stars to exhibit a shift proportional to distance. At the time when the experimental test was undertaken, however, the best figures on the electron density in the cloud (those of Gerasimovič and Struve[12]) were too low to provide as sharp a test as the experimental one. But since then Eddington[13] has demonstrated very plausibly that the density is at least 200 times as great as had been computed by the previous writers. Since a value of $\delta\nu/\nu_0$ of a very few parts in a million could probably be detected on averaging out Doppler effects, and Eddington's value of ρ is around 10^{-2} per cc, we should find for $l = 10{,}000$ light-years $\backsimeq 10^{22}$ cm a value of k from Eq. (1)

$$k \backsimeq 10^{-6}/(10^{-2} \times 10^{22}) = 10^{-26};$$

this is too small to yield the *intergalactic* shift. This result provides good confirmation of our conclusion against the general effect, and in addition rules out Abraham's value for k, which is too small to be tested by the experiment.

Finally our hypothesis and Abraham's appear to require an asymmetrical broadening toward the red in the Fraunhofer lines. The electron densities and optical depths of the stellar chromosphere and photosphere are still controversial but apparently are sufficient to yield (on this theory) shifts which could not well have escaped observation.

[10] See for example Tolman, *Relativity, Thermodynamics and Cosmology* (Oxford, 1934), p. 333, et seq.

[11] Tolman, reference 10, p. 340.

[12] Gerasimovič and Struve, Astrophys. J. **69**, 7 (1929).

[13] Eddington, M. N. of Roy. Astronom. Soc. **95**, 2 (1934).