PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Early Ionosphere Investigations of Appleton and His Colleagues

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Phil. Trans. R. Soc. Lond. A 1975 **280**, 3-9
doi: 10.1098/rsta.1975.0088

Phil. Trans. R. Soc. Lond. A. **280**, 3–9 (1975) [3]
Printed in Great Britain

(1) THE EARLY DAYS OF IONOSPHERIC RESEARCH

The early ionosphere investigations of Appleton and his colleagues

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The pioneering experiments of Appleton and Barnett, which measured the height of reflexion of radio waves, is described, and an account given by Barnett is included. It is shown how the method of wavelength change was used in the late 1920s to investigate several ionospheric phenomena. When Appleton based his magnetionic theory on an earlier theory of Lorentz he decided not to include the 'Lorentz term', whereas in another investigation, Hartree decided to include it. Later Darwin showed that Appleton was right, and Hartree wrong. Attention is drawn to the inconsistency by which the expression derived by Appleton is usually called the 'Appleton–Hartree equation'.

Appleton graduated in Physics in the Cavendish Laboratory just before the First World War and started work on the X-ray analysis of copper. He was an Army Signals Officer during the war and on his return to Cambridge in 1920 he decided to make radio the subject of his future researches. Jointly with Van der Pol, who at that time was working under J. J. Thomson at the Laboratory, he investigated the non-linear properties of triodes, and, inspired by C. T. R. Wilson, he made some investigations of atmospheric wave-forms.

In April 1924 he was joined by Barnett, a young research student from New Zealand. Regular broadcasting had recently started in England, and Appleton suggested that Barnett should study the fluctuations of the signals received at Cambridge from London (distant 50 miles). They thought that after sunset the signal resulted from the simultaneous reception of a groundwave and a wave reflected in the upper atmosphere, and that the fluctuations were caused by changes in the height of reflexion. They saw an optical analogy in Lloyd's single mirror interferometer, in which movements of the mirror cause the interference fringes to sweep past the observing point. With this analogy in mind, they realized that a change in the wavelength of the radio sender would also cause the radio fringes to sweep past the observer, and they decided to make a simple test of their idea.

They chose a broadcasting sender whose wavelength could be altered back and forth over a small range, and a receiver at a distance where they estimated that the sky wave and the ground wave would be roughly equal so that the 'fringes' would be large. The wavelength of the sender was about 400 m and it was changed smoothly through about 10 m soon after the cessation of broadcasting at midnight. There was no doubt that 'fringes' were seen as expected, but the occurrence of natural fading made it difficult to count them accurately and only an approximate estimate of the height of the reflecting layer could be made (Appleton & Barnett 1925). On a tape record that was played at the meeting on 5 December 1974, Barnett has recalled the occasion in the following words:

'The 11th December 1924 is a long time ago but I still remember very clearly many of the events of that evening.

'The object, of course, was to count the number of fades, or interference fringes, produced when the wavelength of the Bournemouth broadcasting station was varied smoothly over a range of about 10 m.

'A four stage tuned-anode high-frequency amplifier had been made up, in bread-board fashion, and I remember that I wound the coils with resistance wire to ensure flat enough tuning to cover the wavelength change. A crystal detector and small Pye moving coil galvanometer were used.

'The equipment was set up during the evening in Professor Townsend's Electrical Laboratory in Oxford and tuned in to the Bournemouth broadcast. We were disappointed to find that there was fairly rapid fading. It had been hoped that, late at night, we would find irregular but much slower variations.

'I was still convinced that we would detect the artificially produced fringes but was now much less sanguine about being able to make a reasonably accurate count. To suit the relatively slow response of our galvanometer we had aimed at having the wavelength change extend over a period of about a minute, but it was now evident that during this interval there would be some 10–12 natural fades.

'The advantage of having a much faster wavelength change was obvious, and Mr Gill kindly made available a small Eindthoven type galvanometer in which the string was observed through an eyepiece. This might have proved ideal had there not been fairly severe interference from atmospherics and ships' morse signals from spark transmitters. These kept the string in fairly continuous movement but were largely damped out on the more sluggish moving coil instrument.

'The preliminary tests were completed sometime before midnight and there was nothing more we could do but wait, rather anxiously, for the broadcast programme to close down. We then had a continuous land-line telephone connexion with Captain West at the Bournemouth station.

'After a preliminary test, in which the original arrangement for a 1 min change was used, a series of readings were made in which the sequence was 1 min steady transmission followed by a 30 s wavelength change from 382 to 392 m; then steady for 1 min and another 30 s change from 392 to 382 m.

'Fortunately the period of the natural fading was fairly uniform, at about 11 or 12 fades per minute, and from the counts made during the wavelength change we deducted the average number of natural fades which were assumed to have taken place. The resultant figures, which represented the number of interference fringes, varied a good deal but were mostly between about 5 and 7. On a number of occasions, however, smaller values were obtained.

'If a fringe was in phase with a natural fade, or if the amplitude became too small, it would probably be missed in the count and I argued that we should give less weight to the small numbers; but Appleton was more cautious and felt that they might be real and that the equivalent height of reflexion might in fact have been varying over a wide range.

'We did try faster wavelength changes observed on the string galvanometer but, although additional fluctuations were noted, the interference effects precluded the possibility of making even a rough count.

'From the number of interference fringes observed and knowing the distance between Bournemouth and Oxford, it was a matter of simple arithmetic to calculate the path difference between the interfering rays and to deduce the corresponding equivalent height to reflexion.

'We stayed that night at Merton College and I still have a vivid recollection of getting into a very cold bed, in the early hours of the morning, with the satisfaction of knowing that the wavelength-change experiment had worked and that, although still somewhat uncertain, the height of the Heaviside layer appeared to lie somewhere in the region of 80–100 km.'

It is interesting to notice Appleton's immediate reaction to this successful experiment. It was his custom to carry a small notebook in which he listed possible research topics: before the experiment there were several relating to non-linear phenomena in electrical circuits, and to atmospherics, and a few to radio waves, but as soon as the experiment proved successful he dropped all except the one on radio propagation, and he devoted the remainder of his scientific career to that subject.

If we are to understand how Appleton and his collaborators conducted their experiments and and theoretical investigations in the period just after 1924, we must first understand the contemporary ideas about the upper atmosphere and the propagation of radio waves. Fortunately for us a monograph by Pedersen, published in 1927, gives a full account of the ideas only a few years later. From the available evidence he concluded that the temperature of the atmosphere was about 210 K at all heights greater than 12 km, although most workers accepted the views of Lindemann & Dobson (1922) (based on the observed disappearance of meteor trails) that the temperature above 100 km was about 300 to 350 K. Turbulent mixing was thought to be effective only below 20 km so that above that height the atmosphere was thought to consist of molecular oxygen, molecular nitrogen and helium in diffusive equilibrium. Helium thus predominated at heights above about 120 km. Hydrogen was not thought to be present in the upper atmosphere because there was no evidence for it in the spectra of the airglow or the aurora.

The early workers had to speculate about what caused the ionization in an atmosphere of that kind; what was the ratio of free electrons to negative ions, and, if the ionization was caused by some kind of solar radiation, how quickly it would disappear at night?

Measurements made by Bailey (1925) showed that free electrons would be lost by attachment to neutral molecules so rapidly that, if the source of ionization were removed, they would disappear in about 5 min. Some investigators supposed, therefore, that ions of molecular mass, and not electrons, were effective in reflecting the waves at night. Others supposed that electrons were the effective charges and that a supply was maintained throughout the night by corpuscular radiation arriving equally by night and by day.

Because of these, and other doubts it was important to decide whether or not the ionizing radiation came from the Sun, whether it consisted of charged particles (corpuscules) or of photons, whether electrons or ions were responsible for the reflexion, and whether the loss process for the ionization followed a linear law, as for attachment of electrons, or a quadratic law, as for recombination of electrons (or equally of ions).

Although the earliest measurements of 'effective height' were made only on one central frequency, they showed that the height decreased near sunrise, and the conclusion was drawn that the ionizing agency travelled in straight lines from the Sun. In 1924 it was believed that there was a stream of corpuscles (ions) repelled from the Sun by radiation pressure, and their speed had been estimated (this was not the solar wind of the present day). It was important to decide whether the ionization of the air was caused by these particles or by photons (u.v. or X-rays). During the eclipse of 1927 (which occurred just after sunrise) the height of the layer was found to increase: this showed that an important part of the ionizing radiation consisted of photons travelling with the same speed as the visible light (Appleton 1928). There was no corresponding effect later, as might have been expected if the slower particles had produced

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ionization. Soon afterwards, however, it was pointed out by Chapman that the particle eclipse would, in fact, be expected *before* the photon eclipse and, indeed, it would have been expected before the Sun had risen, so that no clear answer was available about the possibility of a corpuscular ionizing radiation from the Sun. The matter was not settled until 1932 when an eclipse occurred during the middle of the day; experiments at that time showed that the ionizing radiation was undoubtedly due mainly to photons.

In an attempt to decide whether the reflexion was caused by electrons, or by ions of greater mass, the polarization of the downcoming wave was measured by an adaptation of the frequency-change technique, and the result favoured electrons, at any rate in the absorbing regions of the ionosphere (Appleton & Ratcliffe 1928).

I was helping Appleton when he was making these measurements and in the first draft of our paper we said that the measurements, and the theory, both showed the downcoming wave to be right-handed circularly polarized. I well remember my dismay when I found that I had made a mistake in interpreting the observations, and that they really indicated left-handed and not right-handed rotation. My letter telling Appleton about this mistake crossed with one from him to me saying that he also had made a mistake concerning a sign in the magnetoionic theory, so that we should expect left-handed polarization: so all was well and experiment agreed with theory. Another worker, who was measuring the polarization at the same time, published a note saying that he had found right-handed rotation; he also had made a mistake, which he had to correct in a later publication. Someone once commented 'All scientists make mistakes, but the best ones make two, and arrange for them to cancel out'.

Appleton and his co-workers appear not to have noticed some earlier work concerning the polarization of the downcoming wave. In 1921, T. L. Eckersley pointed out that night-time errors in radio direction finding showed the downcoming wave to be polarized with an 'abnormal' component: in 1920 Eccles knew of this observation and said that to produce this component 'the Earth's magnetic field (must) introduce obliquity into the motion of ions propelled by the electric force of the wave...On taking the case of an oxygen ion I find that a magnetic field of 1700 c.g.s. units is required, for hydrogen 100 units, for an electron 0.06 units. Now the Earth's magnetic field at the surface has a horizontal component of about 0.18 unit. Therefore ...the observed facts of directive wireless telegraphy could be furnished by the passage of the waves through a space containing free electrons' (Eccles 1921).

After about 1932 the wavelength-change method was used on five or six different central frequencies in succession, the whole experiment occupying about 30 min (Appleton & Naismith 1932). It was then found that the greater frequencies were often reflected from an upper (F) layer and it was possible to deduce the penetration frequency of the lower (E) layer: from this the peak concentration of electrons was deduced. It was then possible to find out how the concentration was related to the zenith angle (χ) of the solar ionizing radiation and to compare the observed relationship with that expected theoretically. In 1931, Chapman emphasized that the peak concentration of charged particles would be proportional to cos χ if the loss was by a linear attachment process, or $(\cos\chi)^{\frac{1}{2}}$ if it was by a quadratic or recombination-like process. It is interesting to notice that Pedersen's monograph, published in 1927, contained similar expressions for the peak concentration and for its dependence on χ (see appendix). Comparison of the experimental results with these theories showed that the square-law loss process was operative in the E layer.

From the start Appleton realized that before he could use the observed penetration frequency to deduce the peak electron concentration in a layer, he must understand three points about the propagation and reflexion of radio waves: the first was concerned with the effect of the Earth's magnetic field, the second with the 'Lorentz term' in the equations, and the third with the 'damping term' that resulted from collisions of the electrons with neutral particles.

In a monograph entitled *The theory of electrons* Lorentz (1909) had shown how a light wave would be modified if it passed through an assembly of molecules that contained bound electrons moving under the influence of a radial attracting force. In particular he showed how the refractive index and the polarization of the wave would behave when it travelled either along, or perpendicular to, an imposed magnetic field. Appleton (1927) generalized the theory to deal with free (and not bound) electrons and with a wave that travelled in an arbitrary direction: he expressed his results in the somewhat inconvenient nomenclature of Lorentz, but later changed his symbols to those that are now accepted as standard in the magnetoionic theory.

When, in the theory of Lorentz, the electron in a molecule is driven into oscillation by the field of the wave, its movement is disturbed every time the molecule makes a collision. Lorentz showed that the resulting motion of the electron can, on the average, be described by supposing it to be acted upon by a 'damping' force equal to $(2\,m\nu)v$ where m is the mass of the electron, v the velocity, and ν the collisional frequency. Appleton investigated this 'damping' term for free (and not bound) electrons and showed that, for them, it was equal to $(m\nu)v$, just half the size of the Lorentz value, and he made laboratory experiments to test his conclusion (Appleton & Chapman 1932). His expression for the term is now used in magnetoionic theory.

Lorentz had concluded that the field acting on a single molecule contained a component arising from the electric polarization of nearby molecules: the term that describes this component of the field is now called the 'Lorentz term'. Because Appleton was concerned with free electrons he thought it proper to omit this term from his calculations. While he was extending the theory of Lorentz, two other English investigators were at work on the same topic. Goldstein (1929) developed a theory that can be shown to be equivalent to Appleton's, but it was expressed in an unsuitable nomenclature and does not appear to have been much used. Hartree (1931) developed equivalent expressions by considering the wavelets that were scattered by the individual electrons, and he had to ask himself what field acted upon each individual electron. In doing so, he came to the conclusion that the Lorentz term must be included for free electrons as for bound ones, and for some time the equation of the magnetoionic theory was quoted with this term included. In particular, Mary Taylor (1933) used it in two widely-read papers and called it the 'Appleton–Hartree equation'. A little later Darwin (1934) showed that Hartree was mistaken and that Appleton had been correct, but, rather surprisingly, Appleton's expression is still usually called the 'Appleton–Hartree equation'.

By 1932, when $P'(f)$ curves (ionograms) were being recorded regularly, the fundamental theory of wave propagation was understood and the simpler questions about the ionosphere had been answered. In the years that followed, it was then possible to concentrate attention on using the radio waves to investigate the detailed behaviour of the ionosphere, with the ultimate objective of understanding the upper atmosphere and the radiations that ionize it.

Appendix. Excerpt from Pedersen (1927, p. 59)

A vertical radiation S penetrates down through the atmosphere which, preliminarily, is supposed to be of the same composition throughout the entire height. The original intensity of radiation is indicated by $S_\infty = S_{h\to\infty}$, where h is the altitude. So far we make no assumptions concerning the nature of the radiation, only that the attenuation dS suffered by the radiation while passing through an air layer of height dh is proportional to the intensity of the radiation, to the thickness of the layer and to the partial pressure p of the absorbing gas. We write consequently

$$\mathrm{d}S = AS\,\mathrm{e}^{h/H}\,\mathrm{d}h, \tag{50}$$

where $A\,\mathrm{d}h$ is that fraction of the radiation which would be absorbed in the layer dh if the latter was situated at the surface of the Earth. H is as usual the height of the 'homogeneous atmosphere', see chapter IV, table 2.

The equation (50) is satisfied by†

$$S = S_\infty\,\mathrm{e}^{-AH\exp(-h/H)} = S_0\,\mathrm{e}^{AH[1-\exp(-h/H)]}, \tag{51}$$

where S_0 is the intensity of radiation at the surface of the Earth.

The absorption at the height h is determined by

$$\mathrm{d}S/\mathrm{d}h = AS\,\mathrm{e}^{-h/H} = AS_\infty\,\mathrm{e}^{-[h/H+AH\exp(-h/H)]}. \tag{52}$$

We assume the number I_h of pairs of ions liberated at the altitude h per cubic cm and per second to be proportional to dS/dh, i.e. proportional to the loss of energy of the radiation:

$$I_h = k\frac{\mathrm{d}S}{\mathrm{d}h} = kAS\,\mathrm{e}^{-h/H} = kAS_\infty\,\mathrm{e}^{-[h/H+AH\exp(-h/H)]} = KA\,\mathrm{e}^{-[h/H+AH\exp(-h/H)]}, \tag{53}$$

where $K = kS_\infty$, is the total number of electrons liberated per second in the atmosphere within a sunbeam column with 1 cm² cross section.

I_h is maximum for

$$\mathrm{e}^{h/H} = AH, \tag{54}$$

and

$$I_{\max} = \frac{kS_\infty}{\mathrm{e}H} = \frac{K}{\mathrm{e}H} = \frac{K}{2.718H}, \tag{55}$$

or

$$K = \mathrm{e}HI_{\max} = 2.718HI_{\max}. \tag{56}$$

The corresponding value of S is determined by:

$$S' = \frac{1}{\mathrm{e}}S_\infty = \frac{1}{\mathrm{e}}S_0\,\mathrm{e}^{AH} = 0.368\,S_0\,\mathrm{e}^{AH}. \tag{57}$$

The value of h determined by equation (54) is the altitude corresponding to the maximum ionization and is indicated in the following by h_m.

The equation (53) may also be written in the form

$$I_h = \mathrm{e}HAI_{\max}\,\mathrm{e}^{-[h/H+AH\exp(-h/H)]} = I_{\max}\,\mathrm{e}^{\{1+(h_m-h)/H-\exp[(h_m-h)/H]\}}. \tag{58}$$

For $h > h_m$ we have approximately

$$I_h = \mathrm{e}HAI_{\max}\,\mathrm{e}^{-h/H} = KA\,\mathrm{e}^{-h/H}. \tag{59}$$

† P. Lenard: *Sber. heidelb. Akad. Wiss.* 12. Abhandlung, Jahrgang 1911.

In case the radiation is not vertical but forms an angle ϕ with the perpendicular, and for distances within which the surface of the Earth and the surfaces of uniform pressure of the air may be considered to be plane, we find exactly the same equations as above, replacing merely the coefficient of absorption A by the coefficient of absorption A' and K by K' determined by

$$A' = A/\cos\phi \quad \text{and} \quad K' = K\cos\phi. \tag{60}$$

If we assume $\cos\phi = 0.1$, thus making the coefficient of absorption ten times as great, then equation (54) shows the height of the maximum ionization to be increased by $2.3H$, while otherwise the shape of the ionization curve remains unchanged, as shown by equation (58).

If the value of I_h is known, the corresponding stationary number n_0 of pairs of ions, corresponding to the various assumptions concerning the dependency of the coefficient of recombination on the pressure, may be found by inserting into formula (4) the values of α given by equations (33)–(36) inclusive.

References (Ratcliffe)

Appleton, E. V. 1927 Proc. URSI Gen. Assembly Fascl, p. 2. (This important note is copied in *J. atmos. terr. Phys.* 1974, **36**, 2135.)

Appleton, E. V. 1928 The study of signal fading. *J. Instn Elec. Engrs* **66**, 872.

Appleton, E. V. 1932 Wireless studies of the ionosphere. *Proc. Inst. Elect. Eng.* **71**, 642.

Appleton, E. V. and Barnett, M. A. F. 1925 On some direct evidence for downward atmospheric reflection of electric rays. *Proc. R. Soc. Lond* A **109**, 621.

(In his 'Larmor Lecture' (*Proc. R. Irish Acad.* 1961, **61**, 55) Appleton explained that this paper was communicated to the Royal Society by Larmor, who altered the title so that it mentioned 'rays', because he wished to emphasize the similarity between radio and optics.)

Appleton, E. V. & Chapman, F. W. 1932 The collisional friction experienced by vibrating electrons in ionized air. *Proc. Phys. Soc. Lond.* **44**, 246.

Appleton, E. V. & Naismith, R. 1932 Some measurements of upper atmosphere ionization. *Proc. R. Soc. Lond.* A **137**, 36.

Appleton, E. V. & Ratcliffe, J. A. 1928 On a method of determining the state of polarization of downcoming wireless waves. *Proc. R. Soc. Lond.* A **117**, 576.

Bailey, V. A. 1925 On the attachment of electrons to gas molecules. SF3–31. *Phil. Mag.* **50**, 825.

Chapman, S. 1931 The absorption and dissociative or ionizing effect of monochromatic radiation in an atmosphere on a rotating earth. *Proc. Phys. Soc.* **43**, 26.

Darwin, C. G. 1934 The refractive index of an ionized medium. *Proc. R. Soc.* A **146**, 17

Darwin, C. G. 1943 The refractive index of an ionized medium. II. *Proc. R. Soc. Lond.* A **182**, 152.

Eccles, W. H. 1921 Inaugural address to the wireless section of the I.E.E. *J. Inst. Elect. Engrs* **59**, 77.

Eckersley, T. L. 1921 The effect of the Heaviside layer on the apparent direction of electromagnetic waves. *Radio Rev.* **2**, 60, 231.

Goldstein, S. 1929 The influence of the Earth's magnetic field on electric transmissions in the upper atmosphere. *Proc. R. Soc. Lond.* A **121**, 260.

Hartree, D. R. 1931 The propagation of electro-magnetic waves in a refracting medium in a magnetic field. *Proc. Camb. Phil. Soc.* **27**, 143.

Lindemann, F. A. & Dobson, G. M. B. 1922 A theory of meteors and the density and temperature of the outer atmosphere to which it leads. *Proc. R. Soc. Lond.* A **102**, 411.

Lorentz, H. A. 1909 *The theory of electrons.* Leipzig: B. G. Teubner.

Pedersen, P. O. 1927 The propagation of radio waves. Copenhagen: Danmarks naturvidenskabelige samfund.

Taylor, M. 1933 The Appleton–Hartree formula and dispersion curves for the propagation of electro-magnetic waves through an ionised medium in the presence of an external magnetic field. Part I. Curves for zero absorption. *Proc. Phys. Soc.* **45**, 245.

Taylor, M. 1934 The Appleton–Hartree formula and dispersion curves for the propagation of electro-magnetic waves through an ionised medium in the presence of an external magnetic field. Part II. Curves with collisional friction. *Proc. Phys. Soc.* **46**, 408.