E. V. Appleton

EDWARD VICTOR APPLETON

1892-1965

Elected F.R.S. 1927

Early days

Edward Victor Appleton was born in Bradford, Yorkshire, on 6 September 1892. He attended Barkerend Elementary School from 1899-1903, and from there he won a Scholarship to Hanson Secondary School, where he studied from 1903-1911. One of his contemporaries at the school later wrote: 'He was brilliant in every way when he was a schoolboy. He not only learnt with ease and rapidity everything that his teachers put before him, but he also seemed to have anticipated the next lesson. This was due to his remarkable talent, very rare in schoolboys, for grasping the significance of a school subject as a whole. I well remember his gaining 100 per cent. in his first school examination in physics. No amount of success ever led him to rest on his laurels, but his tremendous initiative led him to greater and greater efforts. To his genius he added an almost super-human capacity for sustained hard work, and one of my most vivid memories of him is that he always sought the hard road, the one that taxed his powers most. . . . If he had not been so keenly attracted to science he would have been as successful on the arts side; his reading in English literature was always much wider than was usual at his age, he quickly gained facility in reading, writing, French and German. Called upon to qualify in Latin and Greek for the Cambridge "Previous" examination, he reached the required standard in less than a year.' The letter referred to other things, such as his being a self-taught pianist, a boy soprano, a clever gymnast, a player of football and cricket, with a sturdy figure and ruddy countenance (1).*

It soon became apparent that the young Vic, as his family always called him, had unusual ability. He obtained a First Class in the London Matriculation Examination at the minimum allowable age of sixteen, and he passed the London Intermediate Examination the next year, again at the minimum age. His parents realized the possibilities for Victor and helped him in every way to continue with his work at school until he was eighteen, and in 1910 he was awarded the 'Isaac Holton Scholarship' tenable at Cambridge. He also won an exhibition at St John's College and went up to Cambridge in 1911 to read for the Natural Sciences Tripos.

* The numbers in parentheses refer to the numbered references on p. 17.

Appleton later wrote:

'There was no family reason why I should have been steered to a scientific career. But I was much influenced by my family's interest in music; and I suppose I was rather exceptional, as a boy, in studying Sir John Stainer's book on harmony and so on. Indeed, music in the home, and sport outside—notably cricket—were my main interests beyond school until I reached the age of sixteen. At that age I suddenly became interested in physics and mathematics, though my matriculation subjects in the London University examination included also English, French and German. Only later, when I'd to prepare for the Cambridge "Little-go" examination, did I add Latin and Greek to these.

'But I do remember, when I was fifteen or sixteen, being much influences by reading Gibson's *Introduction to the Calculus* and acquiring what I felt was a new power for dealing with physical problems of all kinds. After this experience I encountered Silvanus Thompson's *Calculus made easy* and, with the arrogance of youth, thought it very poor stuff indeed.

'However, I think it must have been largely the influence of my school Physics master, J. A. Verity, a Liverpool graduate, which made me specially fascinated with Physics. By then, the fame of the Cavendish Laboratory as a centre for modern physical research, under Sir J. J. Thomson, was even reaching the schools and I recall that, in my schoolboy mind, I was firmly determined to go to Cambridge. If I failed in this, King's College, London, was my second choice.

'Actually I had finished my schooldays by the time I was eighteen. But Cambridge would not admit me until I was nineteen. This year was useful, especially as I had an opportunity to work by myself and take the Cambridge entrance examination in Latin and Greek, both of which were then compulsory subjects.

'But the year was also significant in another way. I had ample time for general reading and came across a fascinating book *The scientific study of scenery* by Professor J. E. Marr, who, I learned later, was a member of my own College, St John's. Due to his influence I read Geology in my first year as a Tripos student, adding to it Mineralogy, in my second year. As a result, I was awarded the University Wiltshire Prize in Geology and Mineralogy, a prize I did not know existed until I saw the announcement of the award in "The Yorkshire Post"!' (2).

He gained First Classes in Part I of the Tripos in 1913, and in Part II (Physics) in 1914, when he was also awarded the Hutchinson Research Studentship in Mineralogy and the Hicken Prize in Physics. He immediately began research with W. L. (now Sir Lawrence) Bragg and helped in the unravelling of the structure of one or two metallic crystals. Soon, however, the First World War started, and

'I applied for a commission in the Royal Engineers, through the Cambridge Officers' Training Corps, and was gazetted in December

1914. But I could not put up with the long wait, and so joined an infantry battalion (6th West Yorks) in the preceding August. I suppose I was prouder of the two stripes I then earned, before going to Aldershot for my R.E. training, than I was about any later military promotion I received. . . . I was chosen to specialize in signal duties. I was very fortunate in this, because radio was then just beginning to influence army communications. The thermionic valve, which we now know to be a primary tool in radio, was then a secret device, whose design was little understood, and whose performance had to be discovered experimentally rather than predicted. Then, again, the subject of radio wave propagation was in its infancy, for there were only available the crudest methods of measuring signal strength.

'However, during my R.E. career, I was able to put a few problems "on the shelf" in my mind, to be attacked when the war was over. Two of these occupied my interest when I got back to Cambridge, the theory of the thermionic valve and the theory of long-distance radio propagation" ' (2).

Research worker and professor

When the war was over, Appleton immediately returned to Cambridge, where he was elected a Fellow of St John's College in 1919 and an Assistant Demonstrator in Physics at the Cavendish Laboratory in January 1920. His first researches were directed towards understanding the principles underlying the action of the thermionic valves which he had encountered as new devices during the war. In these activities he was joined by Balth van der Pol, who had come from Holland to work with J. J. Thomson in the Cavendish. Later he also investigated the nature of those radio atmospherics which originate in lightning discharges.

In April 1924 a young research student, Miles Barnett, joined Appleton from New Zealand and between them they started to study the fading of the signals received at Cambridge from the Broadcasting Station in London. As a result of this study, they performed a crucial experiment in December of that year, which proved the starting point of Appleton's main researches on the ionosphere. These are described in detail later.

In fact this important experiment was made just after Appleton had gone to London, in October 1924, to occupy the Wheatstone Chair of Physics at King's College. Soon after it had been performed, he obtained facilities from the Radio Research Board to set up an experimental station at Dogsthorpe, Peterborough, and for several years he continued his work there with the help of Barnett and others. In addition, he started researches at King's College on the radio frequency properties of ionized gases (or 'plasmas' as they would now be called), on radio atmospherics, and on ionospheric problems. The electrical noise at King's College proved troublesome for the reception of the weakly reflected waves from the ionosphere, and in 1932 the work was moved to the Halley Stewart Laboratory at 3 Chesterford

Gardens, Hampstead. In this house, presented to King's College by Sir Halley Stewart, the ground floor and basement contained the laboratories, while the upper floors provided a residence for Appleton and his family. As Rutherford said when he formally opened the laboratory on 4 May 1933 'Even if the experiments require occasionally that night should be turned into day, the work of Professor Appleton and his staff can be carried out under the pleasantest conditions' (3).

One of Appleton's first acts after arrival at King's College was to double the accommodation in the main teaching laboratory by constructing a mezzanine floor, much as Rutherford had done just after the war with the old 'M.B. Room' in the Cavendish. Most of the research had, however, to be done in underground basement rooms or, in the case of the atmospherics work, in a hut on the roof. The addition of the Halley Stewart Laboratory provided a much needed increase of space.

At King's the students were:

> 'struck by his youthful zest, his kind understanding of the student's problems and his lively appreciation of the good things in life.
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> 'He considered it his fundamental duty to see each honours student at intervals and carried this out by himself sharing in the supervision of practical work of the Final Year Honours Course. This could not have been easy for him considering the time he was giving to re-organizing the department and his heavy assignment of lectures.
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> 'It was at this time that the height of the Heaviside Layer was first measured and the existence of an Appleton Layer beyond it demonstrated. I remember vividly the excitement of the Professor when he came in one morning and informed us that a plane polarized signal was reflected from one of the upper layers as a circularly polarized wave and explained it as analogous to the theoretical treatment of the Zeeman Effect, which we were studying at that time.
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> 'Any distinguished visitors were invited to talk to the Honours group on their line of research. One professor was unable to do this, as the only common language with Professor Appleton and himself was Latin.
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> 'Another interesting development was that of greater use of the physics workshop by the students who were encouraged to make their own apparatus' (4).

The Maxwell Society started its meetings at King's during Appleton's time there. It met regularly to discuss the researches being conducted in the laboratory, and there were frequent visits and papers by outside workers.

In 1934 C. T. R. Wilson retired from the Jacksonian Chair of Natural Philosophy at Cambridge, and in 1936 Appleton was appointed to it and was attached to the Cavendish Laboratory. He brought his Laboratory Assistant and several of his research students with him, and persuaded the University to build a field laboratory for his ionospheric researches. He also started in the Cavendish some work on ionized gases, and in St John's College, where he had been re-elected a Fellow, he held stimulating discussion meetings on topics of ionosphere research. Soon after his appointment Rutherford died suddenly and unexpectedly, so that Appleton became acting-Director of the Laboratory, a duty which, added to all his other activities, he found rather onerous.

Government scientist

Early in 1939 Appleton took the crucial step of leaving active scientific work in universities to become Secretary of the Department of Scientific and Industrial Research. Almost his first task was to switch the activities of D.S.I.R. from civil science to those which would help the war effort. He firmly believed that some of the Department's work, for example on fuel, roads, buildings, engineering and the like, was as necessary in war-time as in peace; he also realized that the skill possessed by D.S.I.R.'s scientists, particularly when they worked as teams, could be turned to war-time problems. He emphasized that it was not in the national interest to drain off all the best staff of the Department to Service Laboratories, and he proved this by turning some of his teams to effective war work; for example in the protection of stored foodstuffs from insect attack, in the design of Civil Defence protection of buildings, and in studies with models for bombing attacks on enemy objectives.

In 1941, D.S.I.R. was given the responsibility of creating and managing the 'Directorate of Tube Alloys'—a title which disguised the U.K.'s first major steps to find ways to use nuclear energy. This involved Appleton in many difficult organizational problems, though fortunately in Mr (later Sir) Wallace Akers he found an experienced scientific administrator to help him.

As soon as the tide of war had begun to turn, Appleton encouraged D.S.I.R. to look forward to the problems of post-war reconstruction. He saw clearly the large part that science would play in the rebuilding of houses and roads, and in bringing the essential services, concerned for example with food, fuel and transport, back to peace-time standards. He was convinced that fruitful collaboration between scientists and industry could be developed more fully than in the past.

Principal and Vice-Chancellor

In 1949 Appleton returned to academic work as Principal and Vice-Chancellor of the University of Edinburgh.

The Secretary to the University wrote:

> 'There were some occasions, few but inevitable, when carping voices called attention to the fact that he was not a Scot by birth. To this parochial criticism, he provided the best answer—by devoting sixteen years of his life to the service of Edinburgh and the University. He was always sympathetic to the real interests of Scotland, but he was always anxious that Scotland should never be allowed to take a merely parochial view.

'In all his discussions and negotiations, and in all the many committees, in which he displayed such magnificent qualities, he never lost sight of the essential purposes of the University—i.e. teaching, and research—and was at the same time keenly alive to the general desire for greater autonomy both of the academic staff and of the students themselves. He was always interested in the young, and was always particularly sympathetic to the new academic at the beginning of his career. With all his speeches, he took the most incredible pains, but no matter how important other speeches might be, he regarded his addresses to the students, e.g. Freshers' Conference, and others, and at graduation ceremonies, as being of the first importance. On none of these occasions did he neglect to say something that was directly addressed to the young aspirant for academic advancement' (5).

In a special minute, after his death, the Court of the University recorded that

'He proved to be an eminently successful Principal of the University, an inspiring guide and an imaginative leader. His enthusiasm, particularly for the doings of the young, seemed to increase as his years advanced and he was both a source of ideas in himself and a ready recipient of ideas and new projects which emanated from others. But it is particularly as a wise chairman of capacious and incredibly retentive memory, of great patience, and of real shrewdness that all those who served on the University Court will best remember him. His sense of justice, of giving his due to every man, was always to the fore, and his ready grasp of the essentials of any situation, however complicated, was tempered by human understanding and by a readiness to make allowance for the foibles, even for the prejudices, of others.

'Many in the University were well aware of this understanding and sympathy, and of the care which he devoted to presiding at councils and committees at every level. Relatively few knew how much he himself contributed in effort, in sacrifices, in restraint and in persuasion to the physical development of the University, to the improvement of its constitution, to the safeguarding and increase of its investments, and above all, to its unending struggle to extend the boundaries of knowledge.

'Throughout his busy life, without in any degree losing that human touch and capacity for enjoyment which so endeared him to all his friends, he maintained a feeling for the importance and dignity of the University rather than of himself, and never for one moment lost sight of the fact that he held a position of the most sacred trust.'

The view held of him by the students was expressed by the President of their Common Room as follows:

'To the students of this University, Sir Edward was not a remote or an august person.

'New students arriving at the annual pre-sessional conference caught through him something of the atmosphere of University life and perhaps learned to share in the evident pride which the Principal felt for this University.

'His willingness to listen to and advise the S.R.C. president at any time did much to remove the frustrations so often felt by students' representatives. He never said no to any student request without making one feel that it was wholly reasonable that he should do so.

'If he was not a remote or an august person, he lost nothing by this, but was thought of by the students with a curious mixture of affection and esteem' (5).

Personal Notes and Reminiscences

Appleton married Jessie Longson in 1916, and had two daughters, Marjery and Rosalind. Lady (Jessie) Appleton suffered a severe stroke in 1961 and died in 1964. While she was incapacitated in a nursing home he insisted on continuing with all his public work and the work of the University, and yet, whenever he was in Edinburgh, he found time to visit her regularly every day. In March 1965 he married Mrs Helen Allison who, as his secretary for 13 years, had helped him to keep a little time for his own researches during the pressure of his other work. He died suddenly at his own house on 21 April 1965 exactly one month after his second marriage.

Those who remember Appleton recall in common several outstanding characteristics; his wide humanity, his ability as a public speaker, and his continuing dedication to his scientific researches. His humanity showed itself in all he did. He was invariably considerate to everyone, and especially to those in humble positions. He never failed to pass the time of day with the servitors and the cleaners, discussing with them the latest football match or anything he thought would interest them. In Edinburgh they tell the story of the little cleaning woman who was helped by the taller Vice-Chancellor to dust the top of his cabinet. A fund of amusing stories, well remembered and well told, served to break the ice with those who felt he was too important to talk to. Many a timorous secretary, bringing in the cups of tea to some august gathering at which he was present, has been greeted by his remark 'Here comes Hebe—cup bearer to the Gods'.

He was a skilled public speaker with a happy knack of combining penetrating observations with amusing anecdotes. His ability in this respect was never so well demonstrated as at international conferences where he seemed able to convey the point of his very English stories to a wide variety of people from other countries. Perhaps his custom of repeating the essential point, slowly and with a pause just at the right place, helped him here. But it was his beautifully modulated voice which finally added charm to what would otherwise have been merely clever and competent speeches. His father had been a well-known tenor singer in Bradford, and was choirmaster at a chapel there for thirty-eight years. From an early age, little Victor was surrounded by music. He inherited the tenor voice and sang in his father's choir for some time—surely a good training for any gifted speaker. With his easy manner of delivery he often gave the impression that his speeches were made without effort, but those who knew him best realized what great care he lavished on them. In later years his notebooks contained numerous phrases which might be turned to use on some suitable occasion, and the typescripts of his speeches frequently had the most telling words inserted at the last minute in manuscript. Appleton's gifts as a speaker were equally evident in his lectures to students. In these he was never afraid of showing how simple a matter was and, like all the best lecturers, he never tried to blind the audience with the extent of his knowledge. It was only those who knew the subject well who appreciated how penetrating his account in simple terms could really be.

Most of those who had dealings with Appleton have numbers of letters from him written in his own hand. He was a quick writer and the pen would not leave the paper from one end of the line to the other, but once you were used to it the writing was easy to read. He would often write about quite important matters in this way, where others might wish to type so that they could keep a copy for future reference. But he had no need of copies; he had such a detailed and accurate memory that he could always recall what he had written. When he was actively engaged in a piece of research there would often be a letter every day, sometimes two, and many of these would continue for one or two pages of after-thoughts beyond the formal ending and the signature.

He never lost his deep interest in the ionosphere. He made numerous notes on the subject, interspersed with suggestions for his speeches, in his little notebooks. Until the day of his death, he was discussing the details of his researches through regular correspondence with active workers on these subjects. He never lost the enthusiasm of the young research student. In recent years when an ionosphere worker visited him in his office he would usually produce some of his new results from a drawer and, forgetting the worries of the Principal of a great University, would discuss and argue again, just as he did when he was running his own research team. At international conferences he could often be seen sitting in a corner with his results in front of him, pencil in hand, discussing in the same way with workers from different parts of the world. All he asked was that they should be interested and should know what they were talking about. This usually meant they were young, and that pleased him best. He liked their enthusiasm and he knew he was encouraging them. They liked him too, for he remained young in heart and it never occurred to him to be pompous.

Soon after moving to Edinburgh he started the *Journal of Atmospheric and Terrestrial Physics* and he remained its Editor-in-Chief for the rest of his life. He took a very personal interest in this publication, which became known throughout the world as 'Appleton's Journal'. Through it he kept in touch with workers in many places and he went out of his way to encourage those working under difficult conditions in other parts of the world to publish what they had achieved.

Early radio researches

When Appleton returned to Cambridge in 1919, he brought back with him some thermionic valves 'not I may add lifted from the British Army. Some were gifts from the lamp firms who had been making valves, and one German type was picked up by me from a captured pill box. For quite a while these valves were the only ones available in the Cavendish Laboratory' (2). He was interested in the fact that these differed from ohmic resistances in that they had curved voltage-current characteristics, and he set to work with van der Pol to find out how they behaved as elements in electrical circuits.

They dealt with phenomena which in those days were unusual and unexpected. For example, one in which two separate valve-driven oscillators working on nearly the same frequency both lock on to precisely the same frequency when they are brought near enough together. In their paper on this subject they drew attention to an old paper of Rayleigh's in which he discussed a similar occurrence with mechanical oscillations. He knew that if several pendulum clocks running at nearly the same speed were put on one and the same shelf they would often be found to pull into step so that the pendulums all swung together, and that this was caused by a mechanical non-linear coupling in the movement of the shelf.

Throughout their work they frequently referred in this kind of way to examples of non-linear phenomena in other branches of physics. Indeed the importance of what they did was that in the valve they had found a device which was markedly non-linear and whose non-linearity was controllable. By studying effects which it produced they learnt to understand more clearly the part played by much smaller and uncontrollable non-linear effects which were present in other cases.

The work on thermionic valves led to the writing of Appleton's only text-book, *Thermionic vacuum tubes*, one of the early volumes in Methuen's Mono-graphs on Physical subjects. For many years this little volume provided a most valuable and scholarly introduction to the physical principles under-lying the action of triodes, and the best simple account of many of the non-linear phenomena which occurred in circuits to which they were connected.

Another interest of Appleton's in the days just after the war was the nature of those radio atmospherics which originate in lightning flashes and cause unpleasant noises in radio receivers. This interest was stimulated by his friendship with C. T. R. Wilson who was then doing some of his pioneer work on thunderstorms in Cambridge. Appleton tried to relate what C.T.R. was finding out about the lightning flash to what was known about wireless atmospherics. There followed a few papers on this subject also, mainly in collaboration with Watson-Watt who was investigating the same topics elsewhere.

Early in 1925 Appleton's interest was centred on these two fields of research, and to show how his mind was working we are fortunate in having available a little notebook which he kept at the time. In it there are three lists, one of papers published, one of possible papers, and one of papers projected. In these lists there are 23 papers on valves or non-linear phenomena, three on atmospherics, and in the 'projected' list, three on radio wave propagation.

The ionosphere

In April 1924 Miles Barnett arrived in Cambridge from New Zealand intending to work on wireless with Appleton. It was fortunate that just a little earlier, in 1922, the London B.B.C. station, known in those days as 2LO, had started to transmit and Barnett set to work to record the strength of the signals received from it at Cambridge.

It soon became clear that the signal strength was constant during the day, but that it began to vary as night approached. They explained this variability in terms of a wave returned from a reflecting layer in the high atmosphere during dark hours. It had long been thought that a 'Heaviside layer' of this kind was responsible for guiding radio waves which travelled to long distances round the earth. The new suggestion was that it could also reflect waves steeply to be returned at short distances.

Appleton and Barnett decided to test their hypothesis and, if it proved correct, to measure the height of reflexion. This they did by arranging to make a continuous change of wave-length at the transmitter, and to look for the corresponding oscillations of amplitude produced at the receiver by interference between the reflected wave and the ground wave. To make these oscillations as marked as possible, the two interfering waves should be comparable in strength and to achieve the right conditions the waves were emitted by the B.B.C. sender at Bournemouth and received at Oxford. Fortunately it was possible to alter the wave-length of that particular sender smoothly and continuously back and forth after the cessation of programme transmissions at midnight. E. W. B. Gill gave them facilities for installing the receiving apparatus in Townsend's Electrical Laboratory at Oxford. The expected oscillations in signal strength were duly observed, and from their number it was deduced that the reflexion had been from a height of about 100 km.

This crucial experiment was made on 11 December 1924. Appleton immediately saw that with this technique of the wave-length change he had a powerful method of investigating the details of the ionized upper atmosphere. He almost immediately dropped his other research interests and concentrated all his energies on the new technique, to find out more about how the waves were reflected and about the constitution of the upper atmosphere which reflected them.

Here, I think, lay his real genius. This was his third line of research, non-linear phenomena and atmospherics being the first two, but here was one which held out incomparably greater possibilities for investigating much more fundamental aspects of nature. After the 1924 list of papers almost all his notes and jottings related to the new work. He devoted the rest of his scientific life to following up the implications of what he had done.

He arranged through the Radio Research Board to continue the experiments with a transmitter at the National Physical Laboratory, and a receiving station at Peterborough. The technique was improved by making the wave-length changes much more rapidly so that the artificial oscillations of signal strength could be clearly distinguished from the natural fading. For this purpose he replaced the original slow-moving galvanometer by an Einthoven galvanometer which could follow the rapid changes and which could be recorded photographically. The chief interest was to investigate how the height of reflexion and the strength of the reflected wave changed over the period of dawn. The height came down and the strength decreased as the sun's radiation built up the ionization, and the experiment usually stopped about one hour after sunrise when the reflected wave became too weak to record.

In 1927 an eclipse of the sun provided an opportunity to show that the height of the Heaviside layer changed just at the time of optical eclipse. This observation was important in showing that the agency which produced the ionization travelled from the sun to the earth with the speed of light.

While these early experiments were being made Appleton was busy thinking about how the waves were reflected and what he could deduce about the ionization in the Heaviside layer. He realized that the earth's magnetic field would have an effect on the ions and electrons responsible for reflecting the waves and he knew that Lorentz had considered what is effectively the same problem when light passes through some material substance, such as a gas, or a crystal, in the presence of a magnetic field. The only difference is that the electrons and ions were free from each other in the upper atmosphere but were bound together in atoms in the gas or crystal. Lorentz dealt with two different cases, one where the light travelled along the magnetic field and the other where it travelled at right angles, and he showed that there would be a phenomenon of double refraction in which a single wave was split up into two. Appleton extended this idea to deal with the case where the electrons and ions were completely free and also where the wave could be travelling in any direction at all, not necessarily just parallel or perpendicular to the magnetic field. He named his theory 'The magneto-ionic theory'.

He does not seem at first to have fully realized the importance of what he had done. He probably thought it was an obvious extension of the earlier theory of Lorentz and he mentioned it rather as an aside at an international meeting in 1927. Later he seems to have realized what an important step he had taken and in 1932 he published the details of his theory. Since that time his equation has been of the greatest possible importance, both in ionospheric physics and nowadays also in plasma physics.

While thinking about the theory he found that he had to consider in detail the effects which would be produced when the free electrons collided with heavy particles, particularly when there was a superimposed magnetic field: he therefore investigated this matter both theoretically and in the laboratory. He and his students wrote a series of papers about the radio-frequency properties of ionized gases, and although they found that the 'sheath' effects near the electrodes were difficult to interpret, their work has not, even now, been much improved upon.

At first all the radio propagation experiments were made near the original wavelength (400 m.) of the Bournemouth broadcasting station and in 1929 a new phenomenon began to be noticed. Sometimes the records contained secondary fringes which corresponded to waves reflected up and down twice and naturally these were smaller than the primary fringes because the twice-reflected waves were weaker. But sometimes the 'secondary fringes' were much the stronger, and they frequently became the only observable ones for several minutes on end. It was then realized that on these occasions they did not correspond to twice-reflected waves, but to waves reflected from a layer at a greater height. Appleton called the lower layer the *E*-layer and the upper one the *F*-layer: they have often been called the Heaviside and the Appleton layers.

It was realized that a measurement of the radio-wave frequency which would just penetrate the *E*-layer could lead to a knowledge of the peak electron concentration in that layer. Appleton therefore proceeded to measure that frequency at different times of day and season, and he showed that it varied with the height of the sun in the way which had been calculated theoretically by Sydney Chapman. It also began to be clear that the ionospheric layers, and with them the solar radiations which ionized them, waxed and waned with the solar cycle, although, in contrast, the intensity of solar radiation received at the ground was known not to vary.

It now became clear that for the purpose of determining the critical frequency the wave-length change method was not really very convenient and Appleton began to consider going over to the pulse, or radar, technique which had been used in America. But, as always, he used the simplest apparatus. He knew that he could make an ordinary valve oscillator emit pulses just by giving the grid-leak a large value. That would cause it to oscillate in bursts, or in the jargon of the time, 'make it squegg'. At first he used a squegging oscillator of this kind as his transmitter. It was situated at East London College and he received it at the Halley Stewart Laboratory of King's College. It was only later that his more technically-minded assistants persuaded him to use a separately modulated pulsed oscillator.

In 1932 the Second International Polar Year was organized as an international effort to study scientific phenomena in the polar regions, and Appleton arranged for a team of workers to make ionosphere soundings at Tromsö in Norway, near the zone of maximum occurrence of aurorae. He himself went with the team to set up the observing station and played a considerable part both in the installation of the station and in the early days of observing.

In a personal journal which he sent back to his family he wrote on 6 August 1932: 'I am writing this on Saturday evening at the end of our three weeks' work. We had our first 24-hour run last week when I worked through the night alone from 5 p.m. one night to 8 a.m. the next morning. We had the good fortune to get a magnetic storm in the middle of the test which was very good luck, although at first I was mystified by the fact that the upper atmosphere sent back no echoes at all! On the whole all went well and I am fairly sure we shall find many new points from the year's work out here.'

This observation of Appleton's was the first recorded example of a polar radio blackout, of the kind now known to be caused by charged particles projected into the atmosphere from the sun.

In 1937 he gave the Bakerian Lecture to the Royal Society, on the subject of 'Regularities and irregularities in the ionosphere'. In summarizing the state of our knowledge at that time, he paid particular attention to two points. First he showed how, by observing the absorption of the waves, it was possible to deduce the frequency with which the electrons collided with the neutral atoms. This frequency depended on the density of the neutral atmosphere and on the temperature of the electrons, and the measurements indicated that at the greater heights the atmospheric density was much greater, and therefore the temperature much greater, than had previously been supposed. A second point to which he gave particular attention in the Lecture was the relation between his measurements of the ionosphere and what was known of the variation of the earth's magnetic field. He used his knowledge of the ionosphere to deduce a value for the conductivity to be inserted in the 'atmospheric dynamo' theory of geomagnetism and he showed that there was an important discrepancy in the results. It was not until after the Second World War that this discrepancy was explained by others, who appreciated the importance of the fact that the conductivity itself is controlled by the geomagnetic field.

While he was considering the relations between geomagnetic and ionospheric phenomena he could not help remembering that the direction of the compass needle underwent two oscillations, which seemed to correspond to two tidal motions in the ionosphere, one caused by the moon and the other caused by the sun. When he returned to Cambridge as Jacksonian Professor he started an experiment to see whether he could detect lunar tidal variations in the height of the reflexions from the *E* region. Because this height varied from day to day in rather an irregular way, and because there was some inaccuracy in the experimental measurements, refined statistical methods had to be used in the search for a small lunar effect. By making a long run of observations, and with the help of these methods of analysis, Appleton and his research student Weekes were able to show quite clearly that there is a lunar tidal variation in the height of reflexion of the *E* region so that it is about two kilometres higher at full moon than at new moon.

After his appointment as Secretary of the Department of Scientific and Industrial Research in 1938 Appleton had no opportunity to work with research teams and had little time to pursue his own research interests. But the remarkable thing is that in spite of all his administrative responsibilities, both in the D.S.I.R. and later in Edinburgh University, he always remained deeply interested in anything to do with the ionosphere. He used to carry little books in his pocket in which he made jottings from time to time and right to the end of his life the large majority of these are concerned with problems in ionospheric physics. It is quite common for scientists who have become administrators to adopt a pose of remaining interested in their science, but Appleton really did remain deeply interested, as all who discussed their researches with him in later years know from their own experience.

Although after leaving Cambridge he had no research students of his own he kept close touch with workers at the Radio Research Station so long as he was in London, and later, when he removed to Edinburgh, he employed assistants to analyse the ionospheric results from observatories all over the world. Of course it would not be expected that the researches he conducted in this way were comparable in importance with his earlier ones, but there was one result, obtained very soon after the war, which certainly represented a major step forward. By examining the records which had been made during the war in several parts of the world he noticed that the ionosphere near the equator is peculiar. The records for the *F* region showed that when the sun is overhead at the equator, and we might expect the ionization there to be greater than anywhere else, it is in fact greatest, not at the equator, but at two points on each side of the equator. Moreover, the dip in the middle is not in fact at the geographical equator but at the geomagnetic equator, where the earth's magnetic field is horizontal. This fact indicated that the structure of the ionospheric *F* region is controlled by the earth's magnetic field, a point which Appleton saw was of major importance for ionospheric theory.

Any account of Appleton as a radio scientist would be incomplete without mention of the International Union of Scientific Radio, usually known as U.R.S.I. after the initial letters of its name in French. Appleton early recognized that since investigations of the ionosphere must ultimately be made all over the world this Union would provide him with a valuable platform for stimulating world-wide interest. At the 1927 meeting in Washington he played a leading part and it was there that he first announced his magneto-ionic theory. He was President of the Union from 1934-1952. For many years he was chairman of a Mixed Commission on the Ionosphere, consisting of representatives from U.R.S.I. and from other International Scientific Unions. This Mixed Commission helped to plan many of the ionospheric investigations all over the world during the period 1947 to 1960. It was they who first adopted and elaborated a proposal that there should be an International Geophysical Year near the sunspot maximum year of 1957 and Appleton played a large part in planning the activities of this international enterprise.

What part did Appleton play in laying the foundations of our knowledge of the ionosphere? He once said that it was a region of the universe which had been both invented and discovered. It was true that when he started work it had been invented as a theoretical idea, but there was no proof that it really existed; it was left to him to discover it experimentally. When he started nothing was really known about it, it was a suggestion and no more. Did it exist even, were the charge carriers ions or electrons, how many were there, how did their number vary over the earth with the day, the season and the solar cycle, how frequently did they collide with neutral molecules, did the solar radiation which produced them consist of photons or of charged particles, how did it vary throughout the solar cycle? He answered these questions, and several others, and found, quite unexpectedly, that there were two layers with quite different behaviour, that the atmospheric density and hence the temperature in the higher one was greater than in the lower and that the upper part was strongly controlled by the earth's magnetic field.

Up to 1939 Appleton was pre-eminently the leader in this work, in practically every single point of importance his was the leading paper and I think it can quite fairly be said that what we knew about the ionosphere up to that time was almost entirely due to him, or at any rate to him and to the research schools which he started and inspired. Since the war able and enthusiastic schools of ionosphere research have grown up in several different parts of the world quite independent of Appleton and they have added very considerably to what was known of the ionosphere in 1939. Some of Appleton's ideas have been revised but on the whole they still remain completely valid.

In compiling these notes I have had considerable help from Lady Appleton, Miss Dorothy Appleton and other members of the family; also from Professor Beynon and, in relation to the D.S.I.R., from Mr Hogg, Mr Joliffe and Mr Wooldridge. To these, and to many others whom I consulted, my best thanks are due.

J. A. Ratcliffe

Honours and decorations

Nobel Prizeman and Medallist.
Fellow of The Royal Society.
Foreign Member, American Academy of Arts and Sciences.
Foreign Member, Royal Norwegian Academy of Sciences.
Foreign Member, Royal Swedish Academy of Science.
Honorary Member, Australian Institution of Radio Engineers.
Honorary Member, Royal Belgian Society of Engineers and Industrialists.
Honorary Member, Institution of Civil Engineers.
Honorary Member, Institution of Mechanical Engineers.
Honorary Member, Institution of Electrical Engineers.
Honorary Member, Royal Irish Academy (in Section of Science).
Honorary Member, Royal Institution of British Architects.
Honorary Member, American Meteorological Society.
Honorary Member, American Academy of Arts and Sciences.
Member, Pontifical Academy of Sciences.
Honorary Fellow, National Institute of Sciences of India.
Honorary Fellow, the Royal Institute of Chemistry.
Corresponding Member, Prussian Academy of Science.
Foreign Member, Deutsche Akademie der Wissenschaften zu Berlin.
Corresponding Member, Mainz Academy of Science and Letters.
Honorary Fellow, St John's College, Cambridge.
Honorary Freeman of Bradford, Yorkshire.
Honorary Fellow, Royal College of Surgeons of Edinburgh.
Honorary Member of Cincinnati Medical Academy.
Honorary Fellow, Royal Society of Edinburgh.
Fellow, King's College, London.
Honorary Member, U.K. and Eire Section of the I.E.E.E.
Life Member of the National Trust for Scotland.

Honorary degrees

Hon. LL.D. Aberdeen, Birmingham, St Andrews, London, Glasgow, Liverpool and Dalhousie.
Hon. D.Sc. Oxford, Brussels, Leeds, Sydney, Sheffield and Laval.
Hon. Sc.D. Cambridge.
Hon. Litt.D. Cincinnati.
Hon.D.Eng. Hannover Technische Hochschule.
Hon.Doc. Montreal.

Decorations

G.B.E., K.C.B., Medal of Merit (U.S.A.); Legion of Honour (France); Cross of Freedom (Norway); Commander with Star, Order of Saint Olav (Class II); Knight Commander with Star of the Icelandic Order of the Falcon.

Degrees

M.A., D.Sc.

MEDALS

Royal	Royal Society.
Hughes	Royal Society.
Alfred Ewing	Civil Engineers.
Faraday	Institution of Electrical Engineers.
Chree	Physical Society.
Albert	Royal Society of Arts.
Poulsen	Danish Academy of Technical Science.
Transeater	Belgium.
Indian	Calcutta University (the Sir Debaprasad Sarbadhikary Gold Medal).
Medal of Honour	Norwegian Polytechnical Society.
Medal of Honour	Institute of Radio Engineers of America.
Kelvin	Joint Engineering Institutions' award.
Keith	Royal Scottish Society of Arts.

REFERENCES

(1) Minutes of the meeting of Bradford City Council, 9 June 1947, when Appleton was admitted to the roll of Honorary Freeman of the City.

(2) Notes prepared for an autobiographical interview which never took place.

(3) *The Times*, 5 May 1933.

(4) A note supplied by F. Oldham, M.A. (King's College, London, 1922-1925, St John's College, Cambridge, 1925-1927).

(5) *Student*, 29 April 1965 (The Students' newspaper of Edinburgh University).

BIBLIOGRAPHY

The most important papers of Sir Edward Appleton

1918. A thermionic valve slopemeter. *The Wireless World*, **6**, November.

1918. Note on the production of continuous electrical oscillations by the three-electrode valve. *The Electrician*, December.

1919. Note on the effects of grid currents in three-electrode ionic tubes. *Phil. Mag.* **37**, 129.

1921. A method of testing triode vacuum tubes. *Proc. Camb. Phil. Soc.* **20**, 239.

1921. A method of demonstrating the retroactive property of a triode oscillator. *Proc. Phys. Soc. Lond.* **33**, 100.

1921. On the function of the variable anode tap connection in triode generators. *Radio Rev.* **2**, August.

1921. (With BALTH VAN DER POL, JUNR.) On the form of free triode vibrations. *Phil. Mag.* **42**, 201.

1922. (With BALTH VAN DER POL, JUNR.) On a type of oscillation-hysteresis in a simple triode generator. *Phil. Mag.* **43**, 177.

1922. (With A. D. ROBB.) On a graphical solution of a class of differential equations occurring in wireless telegraphy. *Phil. Mag.* **43**, 214.

1922. The automatic synchronization of triode oscillators. *Proc. Camb. Phil. Soc.* **21**, 231.

1923. (With W. M. H. GREAVES.) On the solution of the representative differential equation of the triode oscillator. *Phil. Mag.* **45**, 401.

1923. (With R. A. WATSON-WATT.) On the nature of atmospherics. I. *Proc. Roy. Soc.* A, **103**, 84.

1923. (With A. G. D. WEST.) On ionic oscillations in the straited glow discharge. *Phil. Mag.* **45**, 879.

1924. (With F. S. THOMPSON.) Periodic trigger reception. *J. Instn. Elec. Engrs.* **62**, 181.

1924. (With K. G. Emeleus & M. A. F. Barnett.) Some experiments with an alpha-particle counter. *Proc. Camb. Phil. Soc.* **22**, 434.

1924. On the anomalous behaviour of a vibration galvanometer. *Phil. Mag.* **47**, 609.

1925. A discussion on geophysical influences on the transmission of wireless waves. *Proc. Phys. Soc. Lond.* **37**, 16D.

1925. (With M. A. F. Barnett.) Local reflection of wireless waves from the upper atmosphere. *Nature, Lond.* **115**, 333.

1925. (With M. A. F. Barnett.) Wireless wave propagation, the magnetic-ionic theory: the part played by the atmosphere; the effect of diurnal variations. *Electrician*, **94**, 398.

1925. (With M. A. F. Barnett.) On some direct evidence for downward atmospheric reflection of electric rays. *Proc. Roy. Soc.* A, **109**, 621.

1925. (With M. A. F. Barnett.) A note on wireless signal strength measurements made during the solar eclipse of 24 January 1925. *Proc. Camb. Phil. Soc.* **22**, 674.

1925. Geophysical influences on the transmission of wireless waves. *Proc. Phys. Soc. Lond.* **37**, 16D.

1925. Problemen Bij de Uitbreiding van Electro-magnetische Golven. Overdruk uit het. *Tijdschr. Nederlandsch Radiogenootschap*, November.

1926. (With R. A. Watson-Watt & J. F. Herd.) On the nature of atmospherics—Parts II and III. *Proc. Roy. Soc.* A, **111**, 615, 654.

1926. The Kerr effect in wireless transmission. *Nature, Lond.* **118**, 514.

1926. (With M. A. F. Barnett.) On wireless interference phenomenon between ground waves and waves deviated by the upper atmosphere. *Proc. Roy. Soc.* A, **113**, 450.

1926. On the diurnal variation of ultra-short wave wireless transmission. *Proc. Camb. Phil. Soc.* **23**, 155.

1927. Magnetic storms and wireless transmission. *Electronics*, **98**, 256.

1927. (With J. A. Ratcliffe.) On the nature of wireless signal variations. *Proc. Roy. Soc.* A, **115**, 291.

1927. The existence of more than one ionized layer in the upper atmosphere. *Nature, Lond.* **120**, 330.

1927. Magnetic storms and wireless transmission. *The Electrician*, March.

1927. The influence of the earth's magnetic field on wireless transmission. *U.R.S.I. Papers of the General Assembly, Washington.* Fasc. 1, 2.

1927. Wireless transmission and the upper atmosphere. Royal Institution of Great Britain, Weekly Evening Meeting, April. *Proc. R. Instn Gt. Br.* **25**, 272.

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

1928. (With J. A. Ratcliffe.) On a method of determining the state of polarization of downcoming wireless waves. *Proc. Roy. Soc.* A, **117**, 576.

1928. Some notes on wireless methods of investigating the electrical structure of the upper atmosphere. *Proc. Phys. Soc. Lond.* **41**, 43.

1929. The equivalent heights of the atmospheric ionized regions in England and America. *Nature, Lond.* **123**, 445.

1930. On some measurements of the equivalent height of the atmospheric ionized layer. *Proc. Roy. Soc.* A, **126**, 542.

1930. Some notes on wireless methods of investigating the electrical structure of the upper atmosphere. II. *Proc. Phys. Soc. Lond.* **42**, 321.

1930. (With J. A. Ratcliffe.) Some simultaneous observations on downcoming wireless waves. *Proc. Roy. Soc.* A, **128**, 133.

1930. (With A. L. Green.) On some short wave equivalent height measurements of the ionized regions of the upper atmosphere. *Proc. Roy. Soc.* A, **128**, 159.

1930. (With E. C. Childs.) On some radio frequency properties of ionized air. *Phil. Mag.* **10**, 969.

1931. A method of measuring upper atmosphere ionization. *Nature, Lond.* **127**, 197.

1931. (With G. Builder.) A simple method of investigating wireless echoes of short delay. *Nature*, **127**, 970.

1931. Polarization of downcoming wireless waves in the southern hemisphere. *Nature, Lond.* **128**, 1037.
1932. (With G. Builder.) Wireless echoes of short delay. *Proc. Phys. Soc. Lond.* **44**, 76.
1932. (With F. W. Chapman.) The collisional friction experienced by vibrating electrons in ionized air. *Proc. Phys. Soc. Lond.* **44**, 246.
1932. (With S. Chapman.) Suggested wireless observations during the solar eclipse of 31 August 1932. *Nature, Lond.* **129**, 757.
1932. (With R. Naismith.) Some measurements of upper atmosphere ionization. *Proc. Roy. Soc.* A, **137**, 36.
1932. (With J. A. Ratcliffe.) Polarization of wireless echoes. *Nature, Lond.* **130**, 472.
1932. Wireless studies of the ionosphere. *Proc. Instn. Elect. Engrs.* **71**, 642.
1933. (With G. Builder.) The ionosphere as a doubly-refracting medium. *Proc. Phys. Soc. Lond.* **45**, 208.
1933. (With R. Naismith.) Weekly measurements of upper atmospheric ionization. *Proc. Phys. Lond.* **45**, 389.
1933. Fine-structure of the ionosphere. *Nature, Lond.* **131**, 872.
1933. (With R. Naismith & G. Builder.) Ionospheric investigations in high latitudes. *Nature, Lond.* **132**, 340.
1933. On two methods of ionospheric investigation. *Proc. Phys. Soc. Lond.* **45**, 673.
1933. (With others.) Meeting for discussion of the ionosphere. *Proc. Roy. Soc.* A, **141**, 697.
1933. (With E. G. Bowen.) Sources of atmospherics and penetrating radiation. *Nature, Lond.* **132**, 965.
1933. Radio observations during the international Polar Year 1932-33. Royal Institution of Great Britain, Weekly Evening Meeting, October. *Proc. R. Instn Gt. Br.* **28,** 1.
1933. Empire communication. The Norman Lockyer Lecture, 1933. The British Science Guild. November.
1934. Radio exploration of the ionosphere. *Nature, Lond.* **133**, 793.
1934. (With F. W. Chapman.) The lightning flash as source of an atmospheric. *Nature, Lond.* **134**, 968.
1935. Recent measurements of upper-atmospheric ionization. *Phys. Rev.* **47**, 89.
1935. A method of measuring the collisional frequency of electrons in the ionosphere. *Nature, Lond.* **135**, 618.
1935. (With S. Chapman.) Report on ionization-changes during a solar eclipse. *Proc. Inst. Radio Engrs.* **23**, 658.
1935. Temperature changes in the higher atmosphere. *Nature, Lond.* **136**, 52.
1935. (With R. Naismith.) Some further measurements of upper atmospheric ionization. *Proc. Roy. Soc.* A, **150**, 685.
1935. (With L. J. Ingram.) Magnetic storms and upper atmospheric ionization. *Nature, Lond.* **136**, 548.
1935. (With D. B. Boohariwalla.) The influence of a magnetic field on the high frequency conductivity of an ionized medium. *Proc. Phys. Soc. Lond.* **47**, 1074.
1935. The seasonal variation of ionization in Region *F*2 of the ionosphere. *Phys. Rev.* **47**, 704.
1935. (With D. B. Boohariwalla.) The influence of a magnetic field on the high-frequency conductivity of an ionized medium. *Proc. Phys. Soc. Lond.* **47**, 1074.
1935. Temperature changes in the higher atmosphere. *Nature, Lond.* **136**, 52.
1936. Interruptions in shortwave communication. *World Radio*, **23**, 9.
1937. (With F. W. Chapman.) On the nature of atmospherics. IV. *Proc. Roy. Soc.* A, **158**, 1.
1937. (With R. Naismith & L. J. Ingram.) British radio observations during the Second International Polar Year 1932-1933. *Phil. Trans.* A, **236**, 191.
1937. Regularities and irregularities in the ionosphere. *Proc. Roy. Soc.* A, **162**, 451.
1938. (With J. H. Piddington.) The reflexion coefficients of ionosphere regions. *Proc. Roy. Soc.* A, **164**, 467.

1938. (With F. T. Farmer & J. A. Ratcliffe.) Magnetic double refraction of medium radio waves in the ionosphere. *Nature, Lond.* **141**, 409.
1938. (With K. Weekes.) Tides in the upper atmosphere. *Nature, Lond.* **142**, 71.
1938. Radio transmission and solar activity. *Nature, Lond.* **142**, 499.
1938. Note on a method of investigating the interaction of radio waves. *Int. Sci. Radio Un., Proc. Gen. Assembly, 1938*, **5**, 23.
1938. (With K. Weekes.) Tides in the upper atmosphere. *Int. Sci. Radio Un., Proc. Gen. Assembly, 1938*, **5**, 71.
1938. (With J. Sayers.) Recombination in the ionosphere. *Int. Sci. Radio Un., Proc. Gen. Assembly, 1938*, **5**, 272.
1938. (With R. Naismith.) Report of Ionospheric Subcommission of Commission II. *Int. Sci. Radio Un., Proc. Gen. Assembly, 1938*, **5**, 313.
1938. Remarks on Dr Chapman's note on radio fade-outs and the associated magnetic disturbances. *J. Geophys. Res.* **43**, 487.
1939. The ionosphere. *Occ. Notes Res. Astr. Soc.* **3**, 33.
1939. (With R. Naismith & L. J. Ingram.) The critical frequency method of measuring upper atmospheric ionization. *Proc. Phys. Soc. Lond.* **51**, 81.
1939. (With R. Naismith.) Scattering of radio waves in the polar regions. *Nature, Lond.* **143**, 243.
1939. (With R. Naismith.) The variation of solar ultraviolet radiation during the sunspot cycle. *Phil. Mag.* **27**, 144.
1939. (With K. Weekes.) On lunar tides in the upper atmosphere. *Proc. Roy. Soc.* A, **171**, 171.
1939. Characteristic variation of Region *F*2 ionization throughout the year. *Nature, Lond.* **144**, 151.
1939. The upper atmosphere—the structure of the atmosphere as deduced from ionospheric observations. *Q. J. Roy. Met. Soc.* **65**, 324.
1940. (With R. Naismith.) Normal and abnormal region-*E* ionization. *Proc. Phys. Soc. Lond.* **52**, 402.
1940. (With W. J. G. Beynon.) The application of ionospheric data to radio communication problems. Pt. I. *Proc. Phys. Soc. Lond.* **52**, 518.
1943. A simple method of demonstrating the circular polarization of ionospherically reflected radio waves. *Nature, Lond.* **141**, 250.
1945. The scientific principles of radio location. *J. Instn. Elect. Engrs.* **92**, 340.
1945. Departure of long-wave solar radiation from black-body intensity. *Nature, Lond.* **156**, 534.
1946. (With J. S. Hey.) Solar radio noise. I. *Phil. Mag.* **37**, 73.
1946. Extra-tropospheric influences on ultra-short-wave radar operation. *J. Instn. Elect. Engrs.* **93**, 110.
1946. Two anomalies in the ionosphere. *Nature, Lond.* **157**, 691.
1946. (With J. S. Hey.) Circular polarization of radio noise. *Nature, Lond.* **158**, 339.
1946. (With R. Naismith.) Radar detection of meteor trails. *Nature, Lond.* **158**, 936.
1947. (With W. J. G. Beynon.) The application of ionospheric data to radio communication problems. Pt. II. *Proc. Phys. Soc. Lond.* **59**, 58.
1947. (With R. Naismith.) The radio detection of meteor trails and allied phenomena. *Proc. Phys. Soc. Lond.* **59**, 461.
1947. Geomagnetic control of *F*2-layer ionization. *Science*, **106**, 17.
1947. The investigation and forecasting of ionospheric conditions. *J. Instn. Elect. Engrs.* **94**, 186.
1947. The influence of tropospheric conditions on ultra-short-wave propagation. *Physical & Royal Meteorological Societies' Report*, p. 1.
1947. Earth, stars and radio. *Nature, Lond.* **160**, 283.
1948. (With W. J. G. Beynon & W. R. Piggott.) Anomalous effects in ionospheric absorption. *Nature, Lond.* **161**, 967.

1948. (With W. J. G. Beynon.) Lunar tidal oscillations in the ionosphere. *Nature, Lond.* **162**, 486.
1949. (With W. J. G. Beynon.) Lunar oscillations in the *D*-layer of the ionosphere. *Nature, Lond.* **164**, 308.
1949. Discussion on the investigation and forecasting of ionospheric conditions. *Proc. Instn. Elect. Engrs.* **96**-III, 213.
1950. (With W. R. Piggott.) World morphology of ionospheric storms. *Nature,* **165**, 130.
1950. Magnetic and ionospheric storms. *Arch. Met.* (*Wien*), **3**, 113.
1950. Studies of the *F*2 layer in the ionosphere. I. The position of the ionospheric equator in the *F*2 layer. *J. Atmos. Terr. Phys.* **1**, 106.
1952. (With W. R. Piggott.) The morphology of storms in the *F*2-layer of the ionosphere. I. Some statistical relationships. *J. Atmos. Terr. Phys.* **2**, 236.
1953. Storm phenomena in the ionosphere. *Arch. Elektr. Ubertr.* **7**, 271.
1953. (With W. J. G. Beynon.) Radio communication on frequencies exceeding predicted values. *Proc. Instn. Elect. Engrs.* **100**, 192.
1953. Ionospheric storms and the geomagnetic anomaly in the *F*2-layer. *J. Atmos. Terr. Phys.* **3**, 121.
1953. A note on the 'sluggishness' of the ionosphere. *J. Atmos. Terr. Phys.* **3**, 282.
1953. Science for its own sake. Presidential Address to the British Association. *Advancement of Science*, No. 38, 103.
1953. Finding things out with radio and rockets. Junior Presidential Address to the British Association. September.
1954. (With W. R. Piggott.) Storm phenomena and the solar cycle variations of the *F*2-layer ionization at noon. *Physics of the Ionosphere*, p. 219. London: The Physical Society.
1954. (With A. J. Lyon.) Ionospheric layer formation under quasi-stationary conditions. *Physics of the Ionosphere*, p. 20. London: The Physical Society.
1954. (With W. R. Piggott.) Ionosphere absorption measurements during a sunspot cycle. *J. Atmos. Terr. Phys.* **5**, 141.
1954. The anomalous equatorial belt in the *F*2-layer. *J. Atmos. Terr. Phys.* **5**, 348.
1955. Storms in the ionosphere. *Endeavour*, **14**, 24.
1955. (With W. J. G. Beynon.) An ionospheric attenuation equivalence theorem. *J. Atmos. Terr. Phys.* **6**, 141.
1955. (With A. J. Lyon & Mrs A. G. Pritchard.) The detection of the *Sq* current system in ionospheric radio sounding. *J. Atmos. Terr. Phys.* **7**, 292.
1955. (With A. J. Lyon & Mrs A. G. Turnbull.) Distortion of the *E*-layer of the ionosphere by electrical currents flowing in it. *Nature, Lond.* **176**, 897.
1955. Experiments in concert—The International Geophysical Year of 1957-1958. *The Times*, January.
1957. (With A. J. Lyon.) Studies of the *E*-layer of the ionosphere. I. Some relevant theoretical relationships. *J. Atmos. Terr. Phys.* **10**, 1.
1959. The normal *E* region of the ionosphere. *Proc. Inst. Radio Engrs.* **47**, 155.
1959. Global morphology of the *E*- and *F*1-layers of the ionosphere. *J. Atmos. Terr. Phys.* **15**, 9.
1961. (With A. J. Lyon.) Studies of the *E*-layer of the ionosphere. II. Electromagnetic perturbations and other anomalies. *J. Atmos. Terr. Phys.* **21**, 73.
1961. Sir Joseph Larmor and the ionosphere. *Proc. Roy. Irish Acad.* **61**, 55.
1962. Radio and the ionosphere. *Nature, Lond.* **195**, 225.
1963. Ionospheric consequences of the earth's orbital eccentricity. *Nature, Lond.* **197**, 1239.
1963. A seasonal anomaly in the ionospheric *E*-layer. *J. Atmos. Terr. Phys.* **25**, 577.
1964. Sunspot-cycle control of ionospheric and geomagnetic variations. *J. Atmos. Terr. Phys.* **26**, 633.