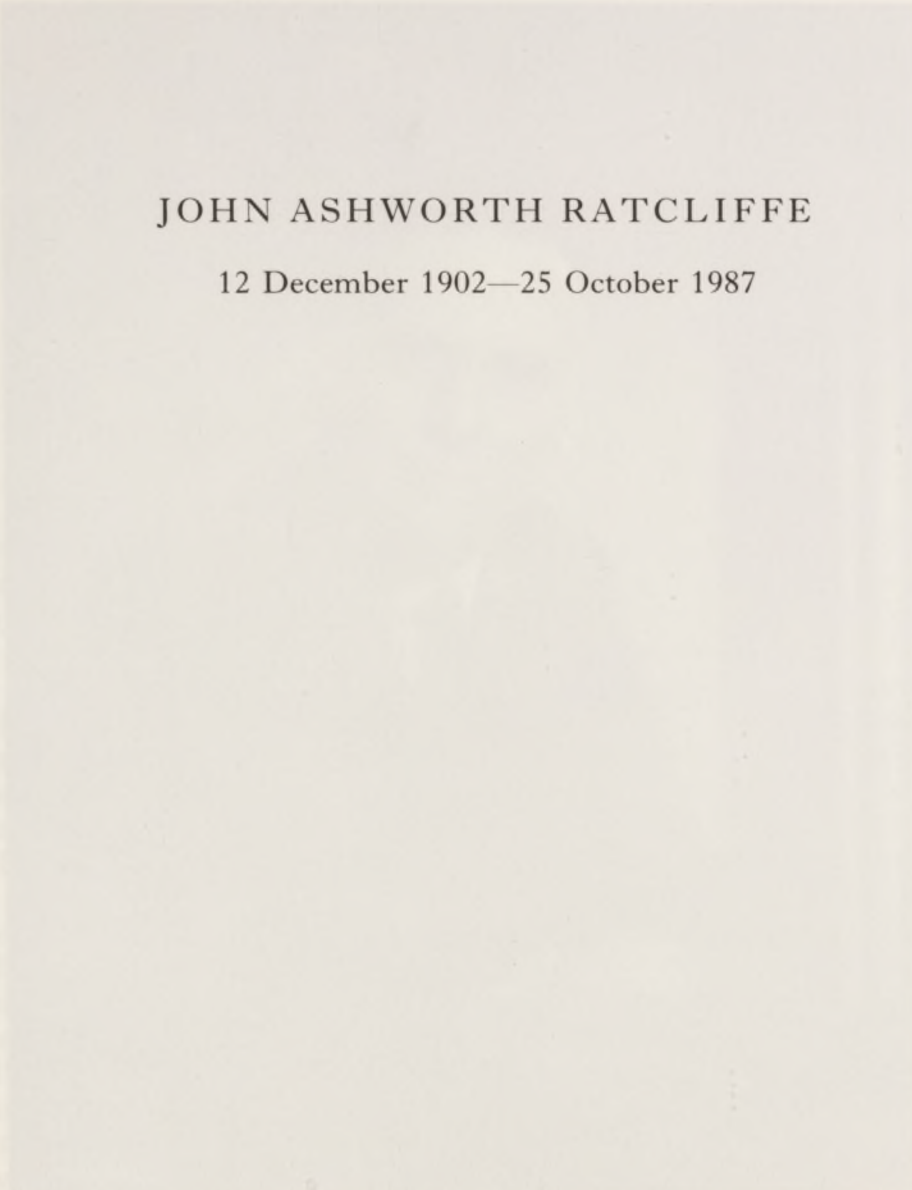
JOHN ASHWORTH RATCLIFFE

12 December 1902—25 October 1987



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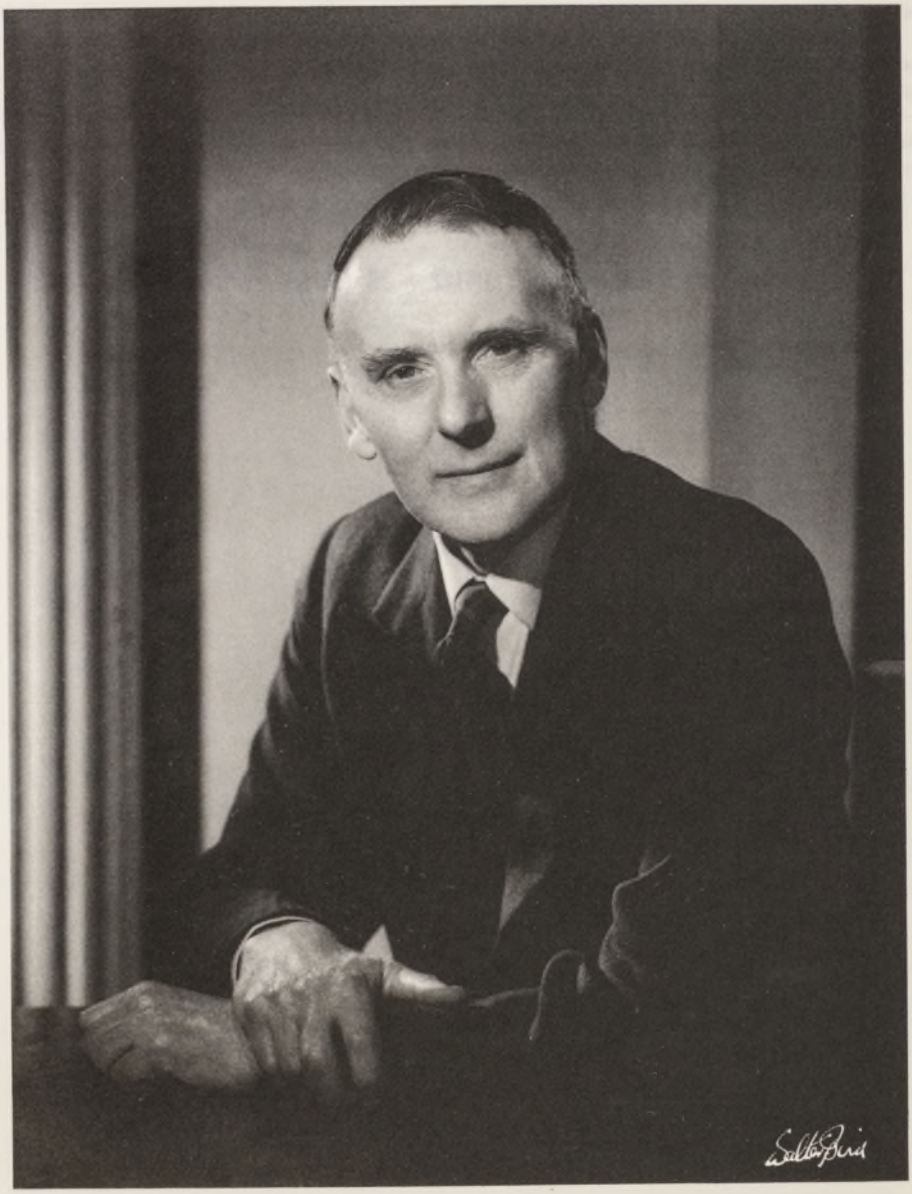

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By K. G. Budden, F.R.S.

When Ratcliffe began research in the Cavendish Laboratory in 1924, 'wireless', as it was then called, had started its rapid advance to become a major science. The thermionic valve had been coming into use in World War I. The BBC had been formed and broadcasting had started in 1922. The large Post Office transmitter at Rugby, call sign GBR, frequency 16 kHz, was being built in 1923–24. The presence of conducting regions in the upper atmosphere had been surmised from the work of Balfour Stewart on terrestrial magnetism, and the idea of elevated conducting surfaces to explain the propagation of wireless waves to great distances had been used in some mathematical papers. It was as a branch of physics that wireless had the greatest appeal for Ratcliffe. In his final undergraduate year he had attended lectures by E. V. Appleton (later Sir Edward Appleton, F.R.S.) and they impressed him with the fact that wireless covered a very large part of physics and depended on phenomena discovered in the pure research of the physics laboratory. His first book (1929) was entitled *The physical principles of wireless*, and when he later organized a Physical Society conference in Cambridge in 1954 he gave it the title 'The physics of the ionosphere'. In this way the subject now known as ionospheric physics was launched.

Ratcliffe was also deeply interested in the applications of electrical science and in the advance of wireless as a part of electrical engineering, and he was to become President of the Institution of Electrical Engineers 1966–67.

His teaching and his research were closely linked. He used to say that teaching was his main job and research was a hobby. But he also said that university scientists are paid to teach and promoted for research. He enjoyed lecturing and had the highest reputation for clarity of presentation. His books and papers are models of clear exposition and many of his students would say that in the use of English for scientific explanations he excelled all others.

Early years: the start of radio research

John Ashworth Ratcliffe was born on 12 December 1902 at Bacup, Lancashire. His father, Harry Heys Ratcliffe, was a partner in the stone-quarrying firm of Henry Heys and Co. His mother was the daughter of Richard Ashworth, who was the founder of the firm of Mitchell, Ashworth, Stansfield and Co., felt manufacturers. There was a younger brother, Geoffrey, who became chairman of this firm and later started his own firm G. Ratcliffe and Sons, Stanley Mill, Burnley.

In 1912–14, J. A. Ratcliffe attended Bacup and Rawtenstall Secondary School. In 1914–19 he went as a boarder to Heversham Grammar School. Here he became interested in chemistry and mathematics and found R. G. Tully a stimulating science master. He then went to Giggleswick School from January 1919 to July 1921. Here he started physics under P. Haswell and calculus under E. D. Clark, and both these men were inspiring teachers. He had a real interest in mathematics and science, but particularly physics. At Giggleswick the scientists spent much extra time on mathematics for which he was later very grateful.

In December 1920 Ratcliffe was elected to a Minor Scholarship at Sidney Sussex College, Cambridge, which he entered in October 1921. P. Haswell at Giggleswick was a former Scholar of Sidney Sussex, and undoubtedly influenced Ratcliffe's choice of College. They kept in touch, and in the preface to Ratcliffe's first book, *The physical principles of Wireless*, there is an acknowledgment of Haswell's help.

For Part I of the Natural Sciences Tripos Ratcliffe studied physics, chemistry and geology. His choice of geology may have been influenced by C. T. R. Wilson, who was then a Fellow of Sidney Sussex and had himself included geology in Part I in 1888. They later became good friends. In 1923 Ratcliffe obtained a first class in Part I and was awarded a Major Scholarship. He took physics in Part II of the Natural Sciences Tripos in 1924 and again obtained a first class.

Ratcliffe had an interest in wave motion and optics, which was strengthened by his twice attending the Part I lectures on optics by Alex Wood. In June 1924 he started research on radio wave propagation. His interest in this subject came through hearing E. V. Appleton's lecture course on 'Electrical oscillations and radio telegraphy'. His research is described in more detail later. Unlike most workers in radio he had no special knowledge of circuits or electronics. He regarded them as the tools with which the problems of the upper atmosphere could be investigated. But he would have had some acquaintance with them through his membership of the Cambridge University O.T.C. and of its Signals Section, which was run by him with weekly meetings.

During his first few years of research, he attended lectures by Sir Joseph Larmor on electric and optical waves. These were intended for mathematicians but physicists could attend. The attendance began to fall off until there were only two physicists and one mathematician in the audience. On one occasion Ratcliffe was prevented from attending and sent a note of apology to Larmor. Shortly afterwards the mathematician ceased to attend and so the rest of the course was cancelled. But through Ratcliffe's unusual courtesy he and Larmor became acquainted. In 1926 Ratcliffe was awarded the first Stokes Studentship at Pembroke College. For this there was an interview and Larmor was one of the interviewers. In later years Ratcliffe would tell this story to illustrate that it pays to be polite.

Before about 1924 many people thought that somewhere in the upper atmosphere there were regions where the air is an electrical conductor. In fact for the bending of radio waves it is the dielectric rather than the conducting properties of the ionosphere that are important, and Ratcliffe often used to point out that this was shown by Larmor (1924). In his paper Larmor says that this theory was hammered out in class lectures at Cambridge in February 1924, and had been in fact already expounded in answers in the Mathematical Tripos.

In 1926 Ratcliffe was elected to the Clerk Maxwell Scholarship, which he shared with J. D. Cockcroft. But in 1927 Ratcliffe resigned and Cockcroft held the complete scholarship.

From 1921 to 1927 Ratcliffe lived in lodgings in Cambridge. In 1927 he was elected a Fellow of Sidney Sussex College and moved into College. In 1930 he married Nora Disley, the daughter of Mr and Mrs Walter Disley of Waterfoot, Lancs. A few years later they had a house built for them at 193 Huntingdon Road, Cambridge. They moved to it in 1937 and it remained the Ratcliffe home for the rest of his life, except for the war years and the period 1960–66 when he was at the Radio and Space Research Station, Slough. At this house they entertained many research students and many distinguished visitors. There were two daughters, Margaret and Joan.

Ratcliffe retained his rooms in Sidney Sussex College until 1939. In those days most staff members did not have offices in the Cavendish Laboratory. His College rooms were used for discussions with his research students and for colloquia of the Radio Section, as well as for College teaching. The bedroom would sometimes be used by a research student who was observing late at night and had to avoid disturbing his landlady in the small hours.

Radio and the ionosphere

M. A. F. Barnett came to Cambridge from New Zealand in April 1924 and worked under E. V. Appleton. Ratcliffe joined them in June 1924 immediately after graduating. Appleton left Cambridge in October 1924 to take up a professorship at King's College, London, but he continued to direct the work of Ratcliffe and Barnett. He came to Cambridge on one day each week to give his lectures on 'Electrical oscillations and radio telegraphy'. In late 1925 Ratcliffe gave part of this course and from 1927 onwards he took it over completely.

Appleton and Barnett, and other workers elsewhere, had observed that the signal from a fixed transmitter 'faded' during the dark hours and had concluded that, at night, a wave was returned from the 'Heaviside layer'. An experiment was needed to test this hypothesis, and it was performed first on 11 December 1924 (Appleton & Barnett 1925). It used the Bournemouth transmitter of the BBC, mean wavelength 386.5 m, frequency 776.2 kHz. Its object was to observe the interference of two waves reaching the receiver, one travelling directly over the ground, the ground wave, and the other reflected from the ionosphere, the sky wave or reflected wave. Natural fading was believed to occur because of changes of phase of the sky wave resulting from variations of height of the reflecting layer. It was realized that changes of the relative phase of the two waves would also be caused by changing the frequency of the transmitter. To make the effect most easily observable the receiver should be at a distance where the ground and sky waves have roughly equal amplitudes. For this reason the receiver was at Oxford. It was arranged that the frequency was changed continuously and slowly through about 20 kHz in $\frac{1}{2}$ to 1 min. The resultant received signal amplitude was observed on a table galvanometer connected to the receiver output. The observer's task was to count the number of maxima and minima in the galvanometer deflection while the transmitter frequency was varying. This was made more difficult because natural fading was sometimes occurring at about the same rate as the artificially produced fading. But it proved possible to make counts from which the equivalent height of the reflecting layer could be estimated.

Ratcliffe undoubtedly gave considerable help with this work. At the end of their first paper Appleton and Barnett say that they are '...very much indebted to Mr J. A. Ratcliffe of the Cavendish Laboratory for assisting us in the greater part of the experimental work'. The paper includes a description of some experiments made, on Ratcliffe's suggestion, near his birthplace, at Rawtenstall. This was only 29 km from the BBC transmitter at Manchester, but the ground wave was partly screened by the hills, and at this short range, observations could be made with sky waves whose paths were nearly vertical. It is perhaps surprising that Ratcliffe was not included as a joint author of this paper and the one that followed it (Appleton & Barnett 1926).

A few days after the first experiment on 11 December 1924 the annual Cavendish dinner was held in Cambridge and Lord Rutherford presided. It was customarily an occasion for light hearted entertainment, and more serious matters were forgotten. But Rutherford took the unusual step of announcing, at the dinner, the success of this experiment. In later years Ratcliffe often mentioned this to illustrate the importance that Rutherford attached to it.

The first paper by Appleton & Barnett (1925) also describes a second set of experiments made on 17 February 1925. The second paper (1926) describes some improvements in technique including the use of an Einthoven string galvanometer, which was used to make photographic records of the signal variations. Its rapid response allowed the changes of transmitter frequency to be made more rapidly, in a time short compared with the period of the natural fading. The method became known as the 'frequency change' method. The success of these experiments left no doubt about the existence of reflecting ionospheric layers and further experiments followed in which Ratcliffe continued to participate fully (2, 3, 5).* Appleton arranged for the Radio Research Board to establish a small research hut near Peterborough where the waves emitted from an experimental sender at the National Physical Laboratory, about 120 km distant, could be studied. Ratcliffe and Barnett used to go over from Cambridge to Peterborough on about three nights per week. They had a resident assistant, W. C. Brown, also a New Zealander, who brewed strong tea to keep them awake during the night-time observing hours.

The work was now concerned with possible explanations of the natural fading. It must be caused by variations in the reflected wave and it could be through changes of angle of incidence, or intensity, or phase, or polarization. It was studied by using the property that the signals received from an obliquely downgoing wave, by a vertical wave aerial and by a loop aerial in the plane of incidence depend on the angle of incidence in different ways. Thus a combination of a loop and a vertical wire aerial can be constructed that does not respond to the ground wave. This is called a 'suppressed ground wave' system. It responds only to the component of the downgoing wave whose electric intensity $\boldsymbol{E}$ is in the plane of incidence. This component was called the 'normal component'. The component of $\boldsymbol{E}$ perpendicular to the plane of incidence was called the 'abnormal component' and could be observed with a loop aerial whose plane was perpendicular to the plane of incidence. From these experiments it was established that natural fading is caused mainly by variations of intensity and to a lesser extent of phase of the reflected wave. With these aerial systems (2), and by using loop aerials inclined at various angles to the plane of incidence (3), it was established that the downcoming wave was approximately circularly polarized with a left-handed sense. This result provided the first confirmation of the influence of the Earth's magnetic field on the dispersive properties of the ionosphere and so demonstrated that it contained free electrons.

The use of the frequency change method continued, and soon afterwards Appleton showed that there are two main reflecting layers, which he called E and F.

Magneto-ionic theory is the name given to the study of the dispersive properties of radio waves in the ionosphere plasma in the Earth's

* Numbers or letters in parentheses refer to entries in the bibliography or the list of sources, respectively, at the end of the text.

magnetic field. This medium is now known as a cold electron magnetoplasma. It is doubly refracting so that, for any given direction of the wave normal, two waves are possible, and magneto-ionic theory gives their refractive indices and polarizations. They are called 'ordinary' and 'extraordinary' and these terms are defined in a way similar to that used for light waves in a uniaxial crystal. Ratcliffe's book (1959) on the subject is a standard work that is still widely used.

Lorentz (1909) had shown how a light wave would be modified if it passed through an assembly of molecules that contained bound electrons. In particular he showed how the refractive index and polarization of the wave would behave when it travelled either along, or perpendicular to, an imposed magnetic field. Appleton in 1927 generalized the theory to deal with free electrons and with a wave that travelled in an arbitrary direction. He published a brief version of his result in the proceedings of an U.R.S.I. General Assembly, but not in a well-known journal, perhaps because he did not then appreciate its importance. The same result, in different notation, was later published in a journal by Lassen (1927). Lorentz had concluded that the electric field acting on a single molecule contained a contribution from the electric polarization $\boldsymbol{P}$ of the nearby molecules. In rationalized units (not then used by Ratcliffe or Lorentz or Appleton) the contribution is $\frac{1}{3}\boldsymbol{P}/\epsilon_0$, and is called the 'Lorentz term', where ϵ_0 is the electric permittivity of a vacuum. There was controversy as to whether it should be included in the calculations for free electrons. Darwin published two papers that purported to show that it should be omitted, but they were difficult to understand. Ratcliffe (34) examined the possibility of testing the question by experiment. He showed that, for an ionospheric layer with a parabolic height distribution of electron concentration, the Lorentz term affects the curves of equivalent height of reflection against frequency at vertical incidence, and the curves of range against angle of incidence at oblique incidence. But he concluded that the experimental measurement of these curves could not be expected to be accurate enough to decide the question. We now know that for free electrons the Lorentz term should be omitted, mainly because the phenomenon of whistlers, described later, would not occur if it were present.

Appleton (1932) published the derivation of the refractive indices and polarizations of magneto-ionic theory and gave the results both with and without the Lorentz term. In 1933 Ratcliffe (19) gave a full discussion of the properties of the formulae for a wide range of conditions. He handed a reprint of this paper to each research student who joined his section, and they were expected to become familiar with it. I still have my copy.

Appleton had used the symbols x, y, z, given by

$$x = \omega_N^2/\omega^2,\ y = \omega_H/\omega,\ z = \nu/\omega,$$

where ω is the angular wave frequency, ω_N is the angular plasma frequency, ω_H is the angular electron gyrofrequency and ν is the effective electron collision frequency. Appleton's students, including Ratcliffe, used these symbols. But in later work, x, y, z came to be needed for spatial Cartesian coordinates and it was very inconvenient when they had other meanings. M. V. Wilkes (now Professor M. V. Wilkes, F.R.S.) suggested that x, y, z should be replaced by X, Y, Z, and Ratcliffe accepted this. He used these capital letters in his book (1959) and this is the notation that is now widely used.

The Radio Ionosphere research group

In 1927 Ratcliffe was appointed a University Demonstrator in the Cavendish Laboratory, Cambridge, and was elected to a Fellowship of Sidney Sussex College. From then on he took part in the University teaching, and he began to take on research students for his research group. From 1928 onwards he had, on average, two or three research students working with him. In 1928 he ceased to use the receiving station at Peterborough. A similar station was set up in a wooden hut on the Rifle Range at Cambridge just west of the University Rugby Ground, in an area used by the Cambridge University O.T.C., and Ratcliffe's research became centred there. Another wooden hut was added later about half a mile to the west, on a site where there was less disturbance of the electromagnetic field by telephone wires. About 1933 a brick building was added on the first site. Appleton was now in London and he and Ratcliffe worked independently but they kept in close touch and often exchanged letters.

In the various research projects of the following account Ratcliffe was responsible for the central ideas and plans, and in most cases for the major part of the theories. The research students were mainly responsible for the equipment.

The study of the polarization of the reflected wave was continued in Ratcliffe's group and two main methods were used. In the first (12, 16), he and F. W. G. White (now Sir Frederick White, K.B.E., F.R.S.) used a suppressed ground wave system similar to that already used by Appleton & Ratcliffe (2) and described above. But they did not need to measure equivalent height and so it was not necessary to use the frequency change method. Their measurements were made on ordinary BBC transmissions, with amplitude modulated waves, at frequencies in the range 0.6–1.5 MHz. The Einthoven string galvanometer had by now been replaced by a cathode ray oscillograph. These were now available and coming into increasing use. They were filled with gas at low pressure, which assisted the focusing of the beam. Two receivers were used, one for the normal component and the other for the abnormal component. They used the superheterodyne method with a common local oscillator, so that the phase relations of the two signals were not disturbed. This arrangement of the receivers was later much used for other experiments. The outputs of the two receivers were applied to the two pairs of plates of the cathode ray oscillograph, giving deflections at right angles to each other. This gave an ellipse on the screen from which the polarization of the received downgoing wave could be deduced. It was found that the polarization is almost always left-handed, but variable. Magneto-ionic theory was used to show that, for the frequencies studied, the ordinary wave would be less attenuated and therefore stronger than the extraordinary wave, and its polarization would have a left-handed sense. The paper mentions the problem of what was later called the 'limiting polarization' of a wave emerging downwards from the bottom of the ionosphere.

Before discussion of the second main method of studying polarization, another development must be mentioned. In 1925, the year after the first frequency change experiment, the existence of reflecting ionospheric layers had been shown in another way by Breit & Tuve (1926) in the U.S.A. They used pulses of radio waves launched vertically upwards. The receiver was close to the transmitter and the equivalent height of the reflections was found by measuring the time interval between the pulses received directly and after reflection from the ionosphere. This method was the forerunner of the method of ionospheric sounding that is now widely used, and the apparatus is now known as the ionosonde. From 1931 onwards it was one of the main methods of research of Ratcliffe's group. The first Cambridge pulse transmitter was designed and built by E. L. C. White (1931). It worked at a fixed frequency in the range 3–4 MHz. It was grid modulated and had a power of 40 W. It was at first in Sidney Sussex College, but was later moved to a hut in the grounds of the Cambridge Observatories. From time to time improvements were made, including the use of series modulation and an increase of the power to 400 W (C).

In the second method for studying polarization Ratcliffe and E. L. C. White (18) used the pulse transmitter. There were at least three advantages. First, the use of pulses meant that the ground wave and reflected wave signals were separated in time, so that it was not necessary to use a suppressed ground wave aerial system. Second, the waves travelled with the wave normal vertical so that at all heights the angle between it and the Earth's magnetic field was the same, with a consequent simplification of the theory. Third, and most important, an aerial system was used that responded to circularly polarized waves, so that the ordinary and extraordinary reflected waves could be examined separately. It consisted of two loop aerials whose planes were perpendicular to each other, and the signals from them were combined with a phase difference $\pm\frac{1}{2}\pi$. A change from left-handed to right-handed circular polarization could be made simply by reversing the connections to the terminals of one of the loops. The signals were observed on a cathode ray oscillograph. A linear time base was applied to one pair of deflecting plates. The received signal was applied to the other pair of plates. For automatic recording

(17, 21), it was arranged that the time base, when not deflected, was visible through a long narrow slit and a received pulse then caused a gap. The slit was photographed on moving paper. In later work the signal was applied as a brightness modulation of the cathode ray beam. Thus continuous records were made of equivalent height of reflection against time, now called $h'(t)$ curves. This work was done mainly by E. L. C. White, and Ratcliffe (A) later wrote that the paper (17) should not really have carried his name as an author. 'The method of paper (18) is now "classical"' (A). The frequencies were in the range 2–5 MHz, that is rather greater than had previously been used. These papers report many of the features that later became familiar to users of the ionosonde technique. For example they describe the change over of the reflection from the E layer to the F layer, at different frequencies for the ordinary and extraordinary waves, and the group retardation of a wave that had just penetrated the E layer and was now reflected from F. They discuss the absorption of the two waves and show that it occurs mainly in the E layer or just below it.

The study of absorption was an important subject that was pursued in further papers. Ratcliffe with F. T. Farmer (22) used vertically travelling pulses and a circularly polarized receiving aerial to study absorption for frequencies mostly greater than 1.5 MHz. They found that in the day considerable absorption occurs where the refractive index is nearly unity, at a height below the maximum of the E layer in a region that had previously (5) been called the D region. This effect was later called 'non-deviative absorption'. At night the absorption is smaller and, for the ordinary wave, it occurs in the F layer near the top of the wave trajectory; this was later called 'deviative absorption'.

About this time Chapman (1931) gave the theory of the production of electrons in an isothermal atmosphere by the ionizing effects of monochromatic radiation. From this, by making assumptions about the loss of electrons, it was possible to deduce how the electron concentration $N(z)$ would depend on the height z and on the Sun's zenith angle χ. The assumption made was that electrons rapidly recombine with positive ions. Although this works in the E region, the process is not simple and was not understood at the time. The resulting function $N(z)$ was called a Chapman layer.

Ratcliffe with J. E. Best (30) continued the work on absorption with vertically incident pulses and showed that its diurnal variation could be explained if the D region is the lower part of a Chapman layer. They studied how the reflection coefficient ρ for the ordinary wave depends on χ and found that on undisturbed days $\ln \rho \propto (\cos \chi)^p$, where the power p is close to 1.5. This could be explained if the electrons were removed by a recombination process, and the height dependence of the recombination coefficient could be studied.

Some experiments were done with obliquely incident pulses by

Ratcliffe with F. T. Farmer (27) by using the Cambridge pulse transmitter with receivers at Edinburgh as well as at Cambridge. The total equivalent path of a reflected wave going from transmitter to receiver is denoted by P', and this symbol is used for oblique incidence. For vertical incidence it is usually written $2\,h'$, where h' is called the equivalent height. In this work the frequency to which the transmitter and receivers were tuned could be varied in synchronism so that curves of h' and P' against frequency f could be observed. This was among the first experiments where $h'(f)$ and $P'(f)$ curves were displayed, as is now done by ionosonde equipments. For either of the waves, ordinary or extraordinary, and for frequencies that slightly exceed the penetration frequency, two oblique rays can travel from a transmitter to a distant receiver. The one at the higher angle of incidence is called the Pedersen ray or 'high angle ray', and has the larger equivalent path P'. Pulsed reflections of this ray were observed in these experiments, probably for the first time.

In principle these experiments could be used to decide whether or not the Lorentz term should be included, but no firm conclusion could be reached because of the variable nature of the E layer. The work was not continued for long because of the difficulty of expeditions to Edinburgh, but Ratcliffe later wrote (A) that it was in advance of the general thought at the time, and that he now realized it should have been continued.

Two methods, the frequency change method and the pulse method, have been described for measuring the height of the reflecting layer in the ionosphere. A third method, the Hollingworth ground interference pattern, is mentioned later. Appleton showed that all three methods provide essentially the same information. It is the group time of travel of the wave and depends partly on the height of reflection and partly on the delay in passing through the underlying ionosphere. It is this 'group height' or 'equivalent height', h', that is directly measured. To obtain information about the phase of the reflected wave further measurements are needed. Methods of studying the phase of reflected radio pulses had been suggested by various authors, and some trials were made at Cambridge by S. H. W. H. Falloon. Ratcliffe suggested that a method of this kind should be used by J. W. Findlay, who joined the group in 1937. It had an oscillator on a frequency close to but slightly different from that of the transmitter. It was triggered by the transmitted pulse so that it gave a continuous signal whose phase was coherently related to that of the radio frequency in the pulse. Some of this signal entered the receiver. When the reflected pulse was received it gave beats with the signal from the oscillator, and by measuring the beat frequency, changes of the phase ϕ of the reflected wave could be studied.

There is a relation between the equivalent height and ϕ. Because changes in $d\phi/dt$ could be measured it was possible to observe small changes in the equivalent height with greater accuracy than simply from the travel time of the reflected pulse. It was thus shown that the E layer did not behave exactly as a Chapman layer. This may have been because of a solar tide in the E region. The method was also used for the study of ionospheric disturbances and of moving clouds of ionization in the E region. Findlay continued this work until 1939 and completed it when he rejoined Ratcliffe after the war.

One paper (15) by Ratcliffe and J. L. Pawsey (later Dr J. L. Pawsey, F.R.S.), on horizontal irregularities and time variations in the ionosphere, opened up an important topic in ionospheric physics and foreshadowed much of the later work on this problem in Cambridge by Ratcliffe's group, and elsewhere. They were concerned with explaining natural fading and made experiments of several types. They used BBC broadcast transmissions in the frequency range 0.8–1.5 MHz, at distances less than 200 km. In one series of experiments they used suppressed ground wave aerials and perpendicular loops. There were two receiving sites on a line perpendicular to the direction of the transmitter. They found that if the separation exceeded one wavelength, the fluctuations at the two receivers were largely uncorrelated. This suggested that the downgoing waves were suffering lateral deviation. They confirmed this by further tests with a receiving aerial system similar to an Adcock direction finder. In another experiment they used an aerial system that responded to one or other of the two circularly polarized components of the downgoing wave. They used the suppressed ground wave system, and the perpendicular loop was coupled to it with a phase difference $\pm\frac{1}{2}\pi$. They thus found that the left-handed component is the stronger and they confirmed that fading is caused by fluctuation of the left-handed component, and not by interference between the two circularly polarized components. This paper contains the important idea that the waves emerging downwards from the ionosphere form an irregular diffraction pattern on the ground. In later work the movements and changes of this pattern were to be studied.

In the period 1920–26 a number of large transmitters had been built working on frequencies less than about 25 kHz. Their advantage was that their signals could be received all over the world at most times. They included FT at St Assize near Paris on 20.9 kHz, and GBR at Rugby on 16 kHz. They were keyed with Morse code signals and used for commercial traffic. Some preliminary work on the signals from GBR Rugby was done by J. L. Pawsey and S. H. W. H. Falloon. Hollingworth (1926) measured the signal from St Assize at several places between London and Edinburgh and found that it exhibited maxima and minima. These were attributed to a stationary interference pattern formed by the superposition of a ground wave and a sky wave, and from the positions of the turning points the equivalent height of reflection h' of the waves was deduced.

Ratcliffe with J. E. Best and M. V. Wilkes (26) and later with K. G.

Budden and M. V. Wilkes (33) initiated a long series of measurements of this kind for the waves from GBR, frequency 16 kHz. A mobile receiver was used in a small caravan towed behind Ratcliffe's car. It was found that the stationary interference pattern with these waves was constant enough for observations to be made over several hours. This applied for most summer days and for some winter days. It was thus shown that the equivalent height of reflection was about 70 km by day and 90 km by night.

These waves were then called 'very long waves'. They are now referred to as waves of 'very low frequency' (VLF). At this time most radio experimenters were trying to study waves of shorter wavelength. It was through Ratcliffe's insight that the work on longer waves was started. He realized that they provide a way of studying the lowest parts of the ionosphere, now called the D region. Until the advent of rockets, this work on VLF provided almost the only way of studying the D region. Ratcliffe later (A) described it as 'Probably the most original work which I did before the war'.

Experiments with the signals from GBR Rugby were also started, at a fixed site in Cambridge, aimed at studying the reflected wave and its changes. They used equipment similar to that used on higher frequencies by Ratcliffe and F. W. G. White (12, 16) already described. There were two similar receivers with a frequency change and a common local oscillator. The two outputs were applied to the two pairs of deflecting plates of a cathode ray oscillograph. One receiver used a vertical aerial and gave a signal that was almost the same as the ground wave. In later work after the war this output was supplied by a signal sent from the transmitter by a land line. The other receiver was designed to display either the normal or the abnormal component of the downcoming wave. For the abnormal component a loop aerial perpendicular to the plane of incidence was used. For the normal component a suppressed ground wave system was used. This could not be adjusted in the daytime, as had been done for higher frequencies, because of the presence at this frequency of a downcoming wave even in the day. It had to be adjusted by trials using different settings on successive days.

This system had the great advantage that, as well as the amplitude of the downcoming wave components, it could measure their phases relative to that of the ground wave. It was thus found that the downcoming wave was elliptically polarized with a left-handed sense. The apparatus was known as the 'phase apparatus'. It was used to study how the equivalent height of reflection h' varied with time in the sunset period when the Sun's zenith angle, χ, was changing most rapidly. M. V. Wilkes (33) showed that the observed dependence of h' on χ could be explained by using Chapman's theory of electron production in an isothermal atmosphere, mentioned earlier, and that the results indicated a temperature of about 180 K in the D region.

The phase apparatus was later used to study the effect of disturbances, particularly 'sudden ionospheric disturbances' (SIDs) and magnetic storms. The receivers for this VLF work were designed and built by J. E. Best about 1932. They were taken over in 1934 by M. V. Wilkes who made some improvements. I took them over in 1936 after able instruction from Wilkes in their use. Ratcliffe later arranged for this work to be extended by using the mobile receiver on a roughly north–south line from Rugby to Aberdeen, and by the use of a modified form of phase apparatus at Aberdeen with the collaboration of C. H. Westcott.

Ratcliffe attached great importance to the theory underlying his experimental research. His views about mathematics in relation to physics are discussed later. Much of the theory of his early research could be handled by the approximations of geometrical optics, that is 'ray theory', and by comparatively simple algebra and calculus. Geometrical optics can be satisfactory if the ionospheric medium is sufficiently 'slowly varying', which means that it must not change much within one wavelength. But this condition is violated for very low frequencies. To study the reflection of waves in a stratified ionosphere it is then necessary to solve the governing differential equations, and Ratcliffe called the solutions 'full wave solutions'. They are complicated, but by making approximations they can sometimes be reduced to a form that can be solved in terms of the functions of mathematical physics. M. V. Wilkes was one of the main experimentalists in the work on VLF. But he was a mathematics graduate and in addition to his experimental work he devised several solutions of the basic differential wave equations and was able to account for some of the features of the VLF observations.

H. G. Booker (now Professor) joined Ratcliffe's group in 1934. He too was a mathematics graduate. He gave lectures in which he included several of the important full-wave solutions. He was the first of Ratcliffe's students whose research was entirely theoretical, but he also helped with the taking of observations.

In addition to his ionospheric research already described, Ratcliffe was interested in three important topics that are not directly concerned with the ionosphere. He began work on these soon after starting research in 1924. The first was the study of the ground wave. In this he was joined by Barnett (1), and later by W. F. B. Shaw (4) and F. W. G. White (7, 9). The experiments were of two kinds. In the first, the dielectric constant (now called electric permittivity) and electrical conductivity of samples of soil were measured in the laboratory for various frequencies (4, 7). In the second, the amplitude of the ground wave was measured at various distances from the transmitter (1, 9, 25). In the later experiments a mobile receiver was used in a small caravan towed behind Ratcliffe's car. It was the same caravan that was later used for the work on VLF already mentioned.

The second non-ionospheric research topic stemmed from Ratcliffe's interest in the working of valves and valve circuits. One investigation was concerned with a type of automatically interrupted triode oscillations. Perhaps the best known effect of this kind is the 'squegging' oscillator, which depends on the nonlinear grid-cathode characteristics of the oscillating valve. Ratcliffe with L. G. Vedy (6) studied a somewhat different type in which the nonlinearity was not in the oscillating valve itself but in a circuit coupled to it and containing a crystal rectifier.

A more important valve topic was the study of Barkhausen–Kurz type oscillations. These depend on using a valve with its grid at a positive potential so that electrons are attracted to it and oscillate from one side to the other. The frequencies involved are of the order of hundreds of megahertz, and this effect was then regarded as a possible future way of generating these high frequencies. It was important to know how to make the method work and to increase the power output. R. A. Chipman worked on this subject in Ratcliffe's group. These and similar phenomena were known as electron-inertia effects. Ratcliffe's mastery of the subject was shown by his lucid treatment of it in his lectures after the war.

Ratcliffe then had the idea of studying these effects by making a valve in which, instead of electrons, more massive ions were used. Others had shown how to make emitters of lithium ions and of caesium ions. Ratcliffe and S. Kownacki (32) made a valve that used positive caesium ions and showed that the movements of the ions had a resonance at the expected frequency, about 0.5 MHz. Finally Ratcliffe and W. S. Elliott (now F. Eng.) (35) made a valve that gave maintained oscillations of Barkhausen–Kurz type, with positive caesium ions.

The third non-ionospheric topic was the theory of radio aerials. Ratcliffe's first paper on this (10) dealt with a simple straight-wire receiving aerial and showed how reradiation brings about the flow of electromagnetic energy into the wire. The second paper, with L. G. Vedy and A. F. Wilkins (11), was a theoretical and experimental study of the electric and magnetic fields of a Hertzian electric dipole aerial at short distances where the storage fields are of dominating importance.

Before the war most aerials were simple, either straight wires, single or in an array, or loops. During the war some very sophisticated aerials were used for radar equipment. Ratcliffe gave a very thorough and clear account (36) of this subject in the volume of papers describing radar, published after the war by the I.E.E.

Appleton returned to Cambridge in 1936 as Jacksonian Professor of Natural Philosophy. He ran his own research group in the Cavendish Laboratory independently of Ratcliffe, but the two groups had common interests and relations between them were excellent. A brick field laboratory was built on the Madingley Road near the Observatories for Appleton's work. His group included W. R. Piggott who came with him from London, and K. Weekes who joined him after graduating in 1936. Appleton left Cambridge again in 1938 to go to the DSIR, and Ratcliffe briefly took over the supervision of some members of his group.

The pre-war work of the radio group of the Cavendish Laboratory has here been described in some detail because Ratcliffe attached great importance to it, as is shown by some of his later writings (49, 51, 61, 87, 89, 92, 93, 97, 100, 102). It is probable that this was the happiest period of his life. The early experiments were done with simple apparatus. They mainly used transmissions from existing senders, and the BBC, the Post Office, Cable and Wireless and others generously gave their help and time in arranging special transmissions. Ratcliffe believed that good experiments are simple and argued that there is a case for 'style' in research methods (102). After the war there was a drastic change in people's attitude and he later wrote (99): 'Before the war most physicists did their research because they were interested in their subject and they used simple equipment... After the war they had, perforce, to become more professional... The era of "string and sealing wax" was replaced by one of "sophisticated science and secretaries"'.

The war years

In the autumn of 1939 there was a chain of radar stations on the east and part of the south coast of Britain, known as CH (Chain Home) stations. They used a wavelength of about 13 m and the transmitting and receiving aerials were horizontal wire aerials so that the waves were linearly polarized with their electric field horizontal. It was this chain that was to play a leading part in the winning of the Battle of Britain.

In August 1939, when war was imminent, it was arranged that many physicists from Cambridge and other universities would spend a month at one of the CH stations. Ratcliffe went to the station near Dover as the leader of the team there. War started while he was there. He was granted leave of absence from Cambridge and joined the Air Ministry Research Establishment later known as TRE (Telecommunications Research Establishment). It had just moved from Bawdsey Manor in Suffolk to Dundee.

Waves from the radar stations travelled at small angles of elevation. In these conditions the sea and most types of ground are almost perfect reflectors, and the phase of the reflected wave is reversed. Thus at certain angles of elevation there is destructive interference between the signal coming direct from the target and the signal reflected from the sea or ground. One of these angles is at zero elevation so that an aircraft at a low enough height could come in undetected. Radar cover for low-flying aircraft had already been improved by mounting the CH aerials on high towers, but this was not enough. There was an urgent need for cover against low-flying aircraft, especially in the defence of the Thames estuary and the Firth of Forth. A new type of radar was coming into production at the end of 1939. It used the much shorter wavelength of $1\frac{1}{2}$ m so that the angles between the nulls in elevation cover were smaller, and good low-angle cover could be obtained by choosing a site on a high cliff. These new stations were called CHL (Chain Home Low-flying) and many were installed on the east coast in late 1939 and early 1940.

At Dundee Ratcliffe was in charge of a group concerned with the installation and use of CHL. Some of its members worked in the laboratory improving the design of the receivers and the aerials and the aerial feed systems, but, most important of all, there was a team of scientific observers who lived and worked on the stations and helped to keep them running. They had to send in regular reports. Several results of scientific interest emerged from this work and two may be mentioned.

The nulls in elevation cover could sometimes be tiresome. The signal from a target flying near one of the nulls could be lost for some time. It was desirable to find some way of filling these gaps in elevation cover. One way was to choose the site so that the aerials were some distance back from the edge of a cliff. Then two reflected waves, one from the sea and one from the ground of the cliff top, would combine with the direct wave from the target. The object then was to choose the site so that the combination of the two reflected waves could never annul the direct wave. This method of gap filling had already been suggested for CH stations. For the shorter wavelength of the CHL stations it was easier to use. The problem was to choose the best site. There were discussions in Ratcliffe's office reminiscent of the prewar Cambridge days using physical optics with Fresnel zones and Cornu spirals, applied to diffraction at a cliff edge.

Observations were sometimes reported of what was variously called 'superrefraction' or 'anomalous propagation'. The temperature of the atmosphere normally decreases with increasing height and the air undergoes turbulent mixing. But sometimes, in anticyclonic conditions or when a warm air mass from the land moves over the cooler sea, there can be a range of height of a few hundred metres up from the ground where the temperature increases, and the atmosphere is stable. This is called a temperature inversion or duct. In it the refractive index of air decreases with increasing height. An upgoing radio wave is refracted to travel more horizontally and eventually to travel downwards. The atmosphere is then like a downward reflector and this, together with the upward reflection at the sea or ground, means that the waves can be propagated as in a wave-guide. They are trapped in the guide and travel to large distances. A radar within the duct then gives anomalously large ranges on low targets. The effect occurs most readily for short wavelengths. It was often reported by scientific observers at CHL stations. For CH stations, wavelength 13 m, the duct width is usually too small but there were some exceptions. In January 1940 there was an intense anticyclone over Britain. Ratcliffe was visiting the CH station at Dunkirk near Canterbury and reported that radar reflections could be observed from the other radar stations extending up the east coast. The aerial towers at these stations could give radar reflections. But they were in the null at zero elevation and would normally be undetectable.

In May 1940 Ratcliffe moved to Swanage when TRE was transferred there. In September 1940 he moved to Petersham, Surrey, and there organized the A.A. Radio School at the instance of General Sir Frederick Pile, G.O.C.-in-C. Anti-Aircraft Command. Radar equipments of a type known as GL had been in use for directing the fire of anti-aircraft guns, but the army operators had found them difficult to use and their potential was largely lost. There was a need to get trained scientists on to the gun sites, particularly those round London, to keep the GL radars working. To the School at Petersham came scientists of all types, biologists, physicists, mathematicians, chemists and schoolmasters, to be trained in the mysteries of radar.

In August 1941 Ratcliffe moved back to TRE to become head of a new organization, later known as TRE Development Services, that tackled the problem of taking radar equipments that were new and untried, and making them work in the field in the hands of service personnel. Some ground radars with a wavelength of 10 cm were already deployed and were very successful. There was now every hope that airborne centimetric radar would be equally successful, and to make it so was the first objective of the new organization. It involved teaching untrained personnel to install, adjust, maintain and repair the most sophisticated electronic equipment ever to go into an aircraft. It was a tremendous task involving a training school, manual writing, sending scientific officers out to the squadrons and developing new field test gear.

The new organization was at first concerned with the AI Mark 7 radar which was for fighter aircraft and used a wavelength of 10 cm. Its purpose was to enable enemy bombers to be intercepted at night. The organization soon began to deal with other equipments including the radio navigational aids Gee and H2S, with ground radar installations and with many other airborne radars including ASV, used by Coastal Command for detecting surface vessels, especially surfaced submarines. Thus the team rapidly grew. The Chief Superintendent of TRE was A. P. Rowe. Under him Ratcliffe was Superintendent in charge of TRE Development Services, which was made up of about four Divisions, including Post Design Services, Test Gear and Teaching. The detailed organization and the names of its parts were changed from time to time. Eventually Ratcliffe was in charge of about one third of the scientific personnel of TRE, that is over 100 in the scientific officer and scientific assistant grades. The magnitude of the task is well illustrated by some attendance figures for the courses given by the teaching division. In the 3.5 years from August 1941 to March 1945 the total attendance was about 6000, of whom about 4000 were R.A.F. and W.A.A.F., about 1300 were civilians, and the rest were from the Royal Navy, the Army and the U.S. Army. All this work was carried on through the Normandy landings to the end of the war.

From August 1941 to May 1942 Ratcliffe's office was in Forres School near Swanage and his family lived in a house nearby. In May 1942 TRE moved to Malvern, Worcs, and occupied Malvern College. The family then lived in South Lodge, within the College precincts, until the war ended.

Cambridge, 1945–60

After the war there was more space in the Cavendish Laboratory, for the Austin Wing had come into use. There were separate offices for the more senior staff members, and each of the main research groups had its own secretary. Ratcliffe returned to Cambridge and moved into the office that Rutherford had used. He quickly restarted research with a larger group, which now included several staff members, namely K. Weekes and J. W. Findlay, who were University demonstrators in physics and mainly experimentalists, and H. G. Booker, a University lecturer in mathematics, whose work was mainly theoretical. These all came back in 1945. I rejoined the group in 1947 as a University demonstrator. Ratcliffe had recruited several others from TRE and elsewhere, including B. H. Briggs, who later became a staff member in the radio ionosphere section. There were others who were to become distinguished radio astronomers. Among these new recruits was Miss Margaret (Peggy) Watling, who became secretary to the radio group and, with a mixture of charm and firmness, played an important part in getting the group restarted and running smoothly.

In 1945 the radio group divided into two sections, radio ionosphere and radio astronomy, as described later. The radio astronomy section used the old rifle range to the west of Cambridge, and the radio telescopes were on this site until the Mullard Observatory at Lord's Bridge was ready in 1957. The radio ionosphere section used the large brick field laboratory on the Madingley Road that had been built for Appleton. Temporary huts on suitable sites around Cambridge were also used for experiments that required receivers separated by a few miles or less. Both sections were large. In the period 1945–60 the number of research students at any one time was between 20 and 30. At first most were in the radio ionosphere section, but by about 1956 the radio astronomy section was the larger. Many of the research students came from overseas. In one year, about 1950, in the ionosphere section there were at the same time workers from Australia, Canada, Ceylon (now Sri Lanka), India, New Zealand, Norway, South Africa and the U.S.A.

In this postwar period one staff member of the group was concerned with the theoretical aspects of radio propagation. At first it was H. G. Booker, who left to go to the U.S.A. in 1948. He was succeeded for a short time by J. M. C. Scott and then by P. C. Clemmow, who held a special lectureship in theoretical electrodynamics and radio.

Ratcliffe attached great importance to teamwork in research. In several of the projects of the ionosphere section there were groups of research students working together on different aspects of their main problem. In radio astronomy the team spirit was probably even stronger. It was also important for the whole group to work together coherently.

In about 1949 Ratcliffe started holding weekly meetings to review recently published papers. At first they were shared by the two sections, but soon there were separate meetings for the ionosphere and radio astronomy sections. Each member of the group was assigned one or more journals and his task was to report regularly on new papers relevant to the subject and to give a summary of their contents. All members of the group were expected to participate. Sometimes it was demanding and time-consuming work. But it was a tremendous success and compelled us to keep abreast of the literature of our subject. It was known as the 'literature discussion'. Ratcliffe left Cambridge in 1960, but we continued it here until 1982. The custom was started elsewhere by several members of the Cambridge group who later went to other universities. When Ratcliffe became Director of the Radio Research Station in 1960 he introduced two regular 'literature discussion' meetings there, one concerned with the physics of the upper atmosphere, the ionosphere and the Sun–Earth environment, and the other concerned with radio and electronic techniques.

In September 1954 there was a Physical Society Conference in Cambridge on 'The physics of the ionosphere'. It was largely planned by Ratcliffe and under his general control. It was attended by distinguished ionospheric physicists from all over the world, and gave a new impetus to ionospheric research in many countries. The number of papers presented was large and it was necessary to restrict the time allotted to each speaker. Ratcliffe was aware that many speakers would overrun their time and would disregard a bell or buzzer operated by the chairman. He asked S. H. W. H. Falloon if something more compelling could be devised. The result was the 'AUTO COR STRIKE A LIGHT', a device that was placed on the lecture bench and so terrified every speaker that none overran his time. Ratcliffe very sportingly prolonged his concluding speech as chairman, so that the device could be demonstrated. When a button was pressed, a motor started that turned on the gas to a bunsen burner; this was then lit by a very loud spark. It heated the boiler of a model steam engine. As the steam pressure built up it first blew a whistle then started the engine. This pulled back a spring loaded hammer which got released and hit an enormous tuning fork to which was attached a tin can. About ten seconds later a low tension transformer ignited a thunderflash (D).

In April 1951 Ratcliffe left Cambridge for a term's sabbatical leave in the U.S.A. He asked K. Weekes to take charge of the ionosphere section, with the admonition 'Don't mess it up'. He returned in July 1951 and Weekes said to him: 'I've messed it up. I'm going to marry your secretary'. Kenneth and Peggy were married in the following December.

Radio astronomy

In 1939 Ratcliffe met Ryle (later Sir Martin Ryle, F.R.S., Astronomer Royal). In 1972 Ryle wrote to me (B).

> I first met Jack Ratcliffe in 1939 in a gloomy room in the Clarendon in Oxford, and our friendship has never looked back—for he was the external examiner in the Physics Finals, and he somehow persuaded the other examiners that despite an appallingly bad theory paper, there must be something to be said for me because of my practical exam. in which I assembled an impressive array of rudimentary electronics to measure the light variations from a sodium vapour street lamp—newly arrived in the Oxford streets.
>
> He later said that he would have me in his ionosphere group—where John Findlay, Kenneth Weekes and you were already at work—and so saved me from low-temperature research with Lindemann! But then the war started and we were all sent off in various directions in the radar game.

Ryle and others from TRE joined Ratcliffe's group in 1945. It was originally Ratcliffe's intention that they should work on radio problems concerned with the ionosphere, but Ryle and his immediate colleagues decided not to do this, essentially because they thought that all the interesting problems in this field had already been solved. They decided instead to follow up J. S. Hey's (later F.R.S.) discovery of the radio emission from the Sun, using techniques and skills derived from their work on radar and with Ratcliffe's full support. Thus the Radio Group divided into the two sections, Radio Ionosphere under Ratcliffe and Radio Astronomy under Ryle, with Ratcliffe in overall charge. In the letter already quoted, Ryle wrote in 1972 (B): 'It was his [Ratcliffe's] efforts right at the beginning, in the difficult months after the war, when he found a place for Derek Vonberg and me, and then Tony [later Professor A. Hewish, F.R.S.] and Graham [later Sir Francis Graham-Smith, F.R.S., Astronomer Royal] which started us off. But just as important was his continuing help in the years to follow, on the one hand by persuading the D.S.I.R. and then Mullards to provide the funds which allowed us to build each new telescope, but more important, by teaching us about Fourier transforms, and how to write papers.'

Ryle was a member of Ratcliffe's College, Sidney Sussex, and was registered as a research student under Ratcliffe's supervision until 1949, but he then decided that he did not want to take a Ph.D. degree. He was elected to a Fellowship of Trinity College in 1949. In 1947 he was appointed a University Lecturer, and so became a staff member. But he had been treated rather like a staff member in the preceding years 1945–47 except that, as a research student, he had no university teaching duties. Thus Ryle was left comparatively free to pursue his research.

In 1945 a good deal of surplus wartime radar equipment had been acquired, including several German radars. The paperwork for this was done by Ratcliffe, who also relieved Ryle of the other tiresome administrative jobs. Ryle and his group started off with the idea of observing radio noise from the quiet Sun, using the German equipment. Success came quite soon although there were teething troubles at first. Ratcliffe and Ryle had very different methods of conducting research. By persuasion and argument Ratcliffe exerted a tremendous influence and it is largely through him that Cambridge radio astronomy got started as quickly as it did. Ratcliffe retained his interest in radio astronomy. He gave lectures on it (46) and wrote several papers about it (47, 67). From the start Ryle was in charge of the work at Cambridge but he had Ratcliffe's continued support and interest.

Administration and teaching

Ratcliffe always carried a heavy load of administrative duties. Most of his wartime work was administration and he took it easily in his stride and became expert at it. In Cambridge he served on numerous boards and committees. He was on the Faculty Board of Physics and Chemistry from 1933 to 1939 and again from 1946 to 1960, and he was its chairman in 1958–59. He was a member of the Syndics of the Cambridge University Press in 1934–39 and of the Observatories Syndicate in 1954–56. He was a secretary of the Cambridge Philosophical Society in 1937–38. In 1950–52 he served on the General Board of the Faculties, which is one of the main committees that control the running of the University, and Ratcliffe devoted much time and energy to it. His appointments outside Cambridge included membership of the Council of the Royal Society in 1954–55, and he served on several Royal Society Committees, including the National Committee for Scientific Radio, of which he was chairman. In the Institution of Electrical Engineers he was chairman of the newly formed Electronics Board in 1962–63, and served on several other committees. He was Vice-President of the Institution in 1963–66 and President in 1966–67. He served, often as chairman, on several commissions and committees of the International Scientific Radio Union (U.R.S.I.). He was President of the Physical Society in 1959–60 and gave much help in arranging its amalgamation with the Institute of Physics. For some years he served on the Radar and Signals Advisory Board of the Ministry of Supply, and he was chairman in 1955–60. He was also chairman of their committees on propagation, aerials and waveguides. He was President of section A of the British Association for the Advancement of Science in 1964.

About 1956 Ratcliffe attempted to establish courses in Cambridge for introducing science to arts students (59, 62). He made detailed proposals for a 'Principles of Science Tripos', which had strong support from many people in both the arts and the sciences. But others could not support the scheme. Ratcliffe had the superb ability of explaining quite complicated physical ideas in simple terms. Some opponents of the scheme may have felt that this could lead to the erroneous belief that a question was settled, and that further probing by more advanced methods was unnecessary. Thus a competent scholar in the arts or humanities might have been misled into supposing that he understood a physical subject completely. The scheme was in the end rejected. Ratcliffe was, however, active in getting 'History and Philosophy of Science' introduced as a half subject in Part I of the Natural Sciences Tripos.

In 1962 Ratcliffe was appointed to the Academic Planning Board of the University of Lancaster. In 1964 the Board was succeeded by the Academic Advisory Committee, on which Ratcliffe served until it was dissolved in October 1970. In January 1969 he opened the new physics building at Lancaster. In this period he was again pressing strongly the view that science could and should make a contribution to a general education (F). This formed part of a restless search at Lancaster for educationally balanced but academically sound degree courses. In October 1970 the search had not ended.

In 1945, when the Cavendish Laboratory returned to normal working, Sir Lawrence Bragg was Cavendish Professor and head of the department of physics. He relied on Ratcliffe for help with administrative work, particularly work on committees, at which Bragg did not excel, whereas Ratcliffe was already experienced and expert. In staff meetings he would be heard to say: 'We think, professor, don't we...'.

Ratcliffe was regarded as second in command and he took the lead in organizing the teaching in the Cavendish Laboratory. The lectures and classes were divided into Part I and Part II, which referred to the two parts of the Natural Sciences Tripos. Part I lectures were for first and second year students who were studying other subjects besides physics. Part II lectures were for students in their final year who were specializing in physics. Ratcliffe believed that all teaching staff in the Cavendish Laboratory ought to be qualified to give any of the Part I courses. His own lectures, at various times before and after the war, covered all the main subjects of the Part I courses.

Part I physics lectures were nearly always scheduled to start at 9 a.m. Ratcliffe was intolerant of those who came in late. He would say sternly that there is no previous lecture and therefore no excuse for lateness. The loss of five minutes in each of the 24 lectures of a course is equivalent to the loss of two whole lectures. Sometimes the doors were locked at 9 o'clock and the latecomers had to miss the lecture. This ultimately had the desired effect, though it was unpopular.

Ratcliffe believed in the value of good lecture experiments and used many himself. For some years either a research student demonstrator or a staff member was assigned the task of designing and constructing lecture experiments, and many of them were based on Ratcliffe's suggestions. Among these were a model servo mechanism, diffraction experiments with centimetric electromagnetic waves and a water-jet model of a reflection klystron.

In 1950–53 Ratcliffe gave a course of Part II lectures on electricity in which many of these experiments were used. The final lecture dealt with nonlinear phenomena in electromagnetism and was illustrated by a whole series of experiments. These included nonlinear effects with valves, which Appleton and van der Pol had worked on, partly in the Cavendish Laboratory. The last topic of all was 'relaxation oscillators'. After showing the main features with valve circuits, Ratcliffe said that he would show one last example, and the class was led to expect a sophisticated final experiment. From beneath the lecture bench he produced a toy model in which a trolley ran down an incline. At the bottom it engaged with a clockwork mechanism that pulled it back to the top. Here it was released to run down again. The final lecture always ended with peals of delighted laughter and much applause from the students.

Another task was examining for entrance scholarships. For a few years from 1945 onwards Ratcliffe was chairman of examiners in Natural Science for the Queens' group of colleges and was the senior physics examiner. He devised a form of question that was so successful that it was used for many years. It began 'Comment on the following statements and amend them if necessary'. There followed a series of statements that often, but not always, contained a fallacy. A typical one was: 'In unpolarized light the direction of vibration is continually changing. Therefore to obtain interference fringes it is necessary to use polarized light.' Many candidates rejected the first sentence and said that in unpolarized light the vibrations occur in all directions at once. Ratcliffe sometimes mentioned this later in his lectures and quoted from Stephen Leacock's Nonsense Novel, *Gertrude the governess*, in which 'Lord Ronald...flung himself upon his horse and rode madly off in all directions.'

Postgraduate lectures were important in the training of research students and each research group in the Cavendish Laboratory organized its own. The radio astronomy and ionosphere sections sometimes shared these lecture courses. Usually each course had one lecture per week and there were two courses running. They extended into the vacations because research students did not keep University terms. In the ionosphere section Ratcliffe expected all staff members to share the lecturing, and all research students and staff members were expected to attend. When not lecturing himself Ratcliffe was nearly always there taking notes. His own postgraduate lectures included a course on Fourier analysis and correlation functions in diffraction and circuit theory, which he gave several times. It is mentioned in more detail later.

The writing of papers

Ratcliffe attached the highest importance to clarity in scientific writing. He attributed this to the influence of both Rutherford and Appleton. He devoted much time to the redrafting of papers written by the radio group, including radio astronomy. He could give excellent advice on the correct use of English and on keeping the style crisp and clear. He was generous in giving credit to others for ideas that he originated or to which he contributed. Consequently many papers published by members of the group contain passages written by him even though he is not included as an author. The list of his own published scientific papers from 1945 to 1960 gives a misleading underestimate of his contribution to the advance of scientific knowledge.

He once visited the field laboratory and was very impressed by the progress that J. W. King had made. A few days later he appeared again and told King how pleased he was with the work: 'I've just drafted a couple of papers that I think you ought to write'.

Sometimes a paper had to be redrafted six or seven times before Ratcliffe considered that it could be submitted for publication. The task of writing papers in the radio group is well illustrated by some verses written by a radio astronomer. They relate how a research student promised to write a paper on sunspots, and how the first few drafts earned the opprobrium of Martin (Ryle). Eventually a version was produced that was considered suitable for submission to Mr Ratcliffe. The next verse runs:

> Said Ratcliffe: 'This paper is now very good,
> And publish at once you most certainly should.
> There are a few points I consider unsound.
> On these ten sheets of foolscap I've written them down.'

(The verses are quoted in full in the forthcoming book *A history of radio astronomy* by Professor W. T. Sullivan III.)

Physics and mathematics

Ratcliffe insisted that his research students should be conversant with the theory of their subject. At least one research student, examined by him for the Ph.D. degree, was required to revise and resubmit his thesis because it did not contain a section on the theory. But he was equally insistent that elaborate mathematics should not be used for its own sake. For example, in the prewar period some authors had studied magneto-ionic theory by deriving what is now called the tensor electric permittivity of a cold magnetoplasma, but this method was not used by Appleton or Ratcliffe. They had derived the formulae of magneto-ionic theory without it, and would have felt that it was unnecessary to study a mathematical method that was unfamiliar to them.

Ratcliffe wrote (A) that he had thought in terms of what the waves or electrons are actually doing and not in terms of equations. Professor H. G. Booker writes: 'Ratcliffe did not hesitate to use mathematics to explain the physics of whatever he was discussing. However, he rarely used complicated mathematics. He did not want the mathematics to obscure the physics; he wanted it to illuminate the physics. Even though I was educated as a mathematician, I adopted the same philosophy. I have taught students to try to understand the physics of every line of mathematics that they write down and never unnecessarily to show off the mathematics that they happen to know.'

One of the most advanced mathematical papers published by the radio section was by Heading & Whipple (1952). It dealt with a full-wave solution for the oblique reflection of radio waves of very low frequency from the ionosphere. Professor J. Heading writes: 'He [Ratcliffe] always claimed not to be a mathematician, yet his intuition seldom failed him.... This intuition was tested to the utmost when [this paper] was being prepared for publication... The circuit relations for the hypergeometric function and the asymptotic forms of generalized hypergeometric functions in the complex plane had to be explained to him from a physical point of view.'

Once when in jocular mood Ratcliffe was heard to say 'Many a physicist can only do silly fool mathematics. He usually gets it wrong, but he knows that it is wrong because the answer isn't right.' This attitude is perhaps better illustrated by an example that he used. He was writing (89, 102) about Marconi's success in sending radio signals a long way round the curvature of the Earth, from England to America. A mathematician had claimed to show that this could be explained by a diffraction process if the Earth is a perfectly conducting sphere. This interested Lord Rayleigh, who objected that nothing of this sort is observed in the case of light. The relation of wavelength to diameter of object is about the same in Marconi's phenomenon as when visible light impinges on a sphere one inch in diameter. No creeping of light into the dark hemisphere through any sensible angle is observed under these conditions. Rayleigh then proceeded to explain in detail why the mathematician was wrong. Ratcliffe's comment (89, 102) was: 'I think the interesting point here is that even a mathematician with the ability of Rayleigh preferred to see the solution of the problem in the light of physical common sense rather than through an elaborate piece of mathematics. We should all do well to follow Rayleigh's example.'

Ratcliffe's postgraduate lectures included a course on Fourier analysis and correlation functions in diffraction and circuit theory, which he gave several times, sometimes with a different title. Although it is a mathematical topic he treated it from a physical viewpoint. Before the war, under Rutherford, the staff and research students in the Cavendish Laboratory were expected to be proficient in physical optics, and this would have had a strong influence on Ratcliffe's thinking. When this course was first given it had the title 'The optics of radio'. Some radio aerials could be treated like a diffraction grating. The angular spectrum from a grating or an aerial is simply derived from the Fourier transform of the field in its aperture. This applied to the Michelson stellar interferometer and to the interferometer aerials used in radio astronomy. Similarly, in the theory of electric circuits, the impulse response of a linear circuit is the Fourier transform of its transfer function. For some applications some statistical theory was needed. One physical illustration used for this was the study of noise in electric circuits. It was from these and other physical problems that Ratcliffe built up the subject, with many illustrative examples. One application much used in the research of the ionosphere section was to the fading of radio signals and the study of movements and irregularities in the ionosphere. When a radio wave is reflected from the ionosphere the signal on the ground varies with time, and when it is observed by two receivers the correlation of the signal fluctuations depends on the distance between them. In this and other ways the study of correlation was introduced.

Two of the research students who attended these lectures later wrote books on Fourier analysis. R. D. Stuart (*Fourier analysis* (1961) London: Methuen) and R. N. B. Bracewell (*The Fourier transform and its applications* (1965) McGraw-Hill) both have acknowledgements to Ratcliffe's lectures in their prefaces.

Radio and the ionosphere, 1945–60

In the postwar years the number of research workers in the ionosphere was so large and the various topics they worked on were so numerous that it is impracticable to describe them all. The following account deals in outline with five main topics, here labelled I to V, that Ratcliffe would have considered important (E). In the years up to about 1950 the electronic digital computer EDSAC 1 was developed in the Cambridge University Mathematical Laboratory by Wilkes and his colleagues; Wilkes had done experimental work with Ratcliffe's group before the war. The possibilities opened up by this computer, and those that followed it, both for solving theoretical problems and for performing elaborate and lengthy computations, were made full use of by the radio group.

I. Work on the propagation of waves of very low frequency was resumed (45), including the continued use of signals from GBR Rugby on 16 kHz. Ground interference patterns were now studied by using a receiver flown in an aircraft, with the help of the Royal Aircraft Establishment at Farnborough. This made it possible to delineate the interference pattern more rapidly and to follow it to greater distances than had been possible with the trailer caravan of the prewar days. Because flights of this kind could be made only occasionally they were not helpful in determining the average state of the ionosphere or how it changed with time. Observations of the phase and amplitude of the reflected wave were therefore recorded at one point, over a long period, by using an improved form of the phase apparatus described earlier. The phase reference was now sent along a telephone line from the transmitter to the receiver. The measurements were made over the short distance of 90 km from Rugby to Cambridge. The measurements over the longer distance of 400 km from Rugby to Aberdeen, which had been started before the war, were continued with the collaboration of workers at the University of Aberdeen. Similar measurements were made on higher frequencies with other commercial Morse code transmitters and also with transmitters of the Decca navigator system.

Ratcliffe had started this work before the war because he realized that these experimental results ought to contain information about the structure of the lowest part of the ionosphere where the waves are reflected, but the theory for determining that structure is not simple. The wavelengths, 18.75 km for GBR Rugby, are comparable with the thickness of the E region, and the Earth's magnetic field makes the ionosphere doubly refracting. For an assumed height distribution of electron concentration $N(z)$ in the lower ionosphere, a 2×2 reflection coefficient matrix must be found by using a rather complicated full-wave solution of the governing differential equations. Different functions $N(z)$ must then be tried until one is found that gives results that match the observations. D. R. Hartree had derived the differential equations before the war and he now devised the first computer program for solving them. I had the task of getting the program to work. Because of the rather small storage capacity of the EDSAC 1 computer we were at first restricted to very simple functions $N(z)$. The techniques got better as larger and faster computers became available. This work was continued at the Radio Research Station, Slough, in the period 1960–66 when Ratcliffe was Director, and is described later.

II. Ratcliffe had a close interest in the work on diffraction applied to the fading of radio waves (40, 48, 52, 55, 60) and the irregularities and movements in the ionosphere. This followed on from J. L. Pawsey's prewar work on fading (15) already mentioned. It was realized that when a wave was reflected from the upper atmosphere each point in the ionosphere reradiated towards the ground and it was the combination of these reradiated wavelets that constituted the received wave. If the ionosphere had been quite smooth, the result of this addition could be investigated in the usual way by means of a spiral vector diagram, and it could be seen that the main contribution would come from the first Fresnel zone, which in the case investigated by Pawsey would be a circle of radius about 2 km. The Fresnel zone appropriate to a nearby point on the ground would be another circle, and if the two circles overlapped appreciably the strength of the waves received at the two points could not differ much. But the experiment showed that when the points were only 600 m apart, so that the zones would overlap considerably, the waves faded in quite different ways. How could this possibly come about?

Considerations of this kind showed that the ionosphere was not at all like a smooth uniform reflector, but that important radiation came from regions far removed from the first Fresnel zone. These simple ideas were elaborated into a theory of the diffraction of waves reflected from, or passing through, a medium containing irregularities of its refracting or absorbing properties. Just as in ordinary diffraction theory there is a close link through Fourier transforms with electrical circuit theory, so in the present case there is a close link through correlation functions with the theory of random noise. It was shown (42) that the spatial correlation function of the wave amplitude measured over the ground was the same as that measured just as the wave left the ionosphere, so that measurements on the ground could be used to investigate the statistical properties of the ionosphere.

Once these ideas of diffraction had been appreciated, it was possible to discuss what gave rise to the fading of a single wave reflected from the ionosphere. There might be two different causes. If the ionosphere drifted horizontally as a whole while its structure remained constant, then the irregular diffraction pattern on the ground would drift with it and produce irregular fading as it passed over a fixed receiver. The fact that the fading arose in this way would be obvious if the fading curves recorded at two separated receivers were similar, but displaced in time. It would then be possible to deduce the velocity with which the diffraction pattern moved, so that the time variation recorded at one point could be converted into the space variation of the pattern as a whole. Once the spatial distribution was known, the correlation function could be found and from that the sizes of the ionospheric irregularities could be estimated. These statements are, in fact, correct only if the direction of the ionospheric drift is along the line joining the two receivers. If it is not, it is necessary to use three receivers not in line and the analysis becomes a little more complicated.

The fading could, however, be produced differently. Suppose that, on the whole, the reflecting region were stationary, but that individual parts of it were moving up and down in an irregular way. It could then be shown that the fading would be analogous to the variation in strength of electrical noise that had passed through a band-pass filter. Methods of analysis developed in noise theory could then be applied to give a statistical description of the random velocities of the different points in the ionosphere (40). The methods were worked out and used by B. H. Briggs and his colleagues under Ratcliffe's guidance.

The application of diffraction theory to the experimental results led to a determination of the sizes and movements of the ionospheric irregularities. It was found, for example, that in the E region there was a component of velocity of about 50 m s^{-1} which rotated twice during the day, and the velocity in the F region was predominantly towards the east by day and towards the west by night and was greater at times of ionosphere storm. The methods developed at the Cavendish Laboratory have since been used in many other places to investigate the ionospheric drift movements on a world wide basis.

III. Chapman's theory of layer formation was useful in explaining many of the observations on the E and D layers, but the behaviour of the F layer was different. This interested Ratcliffe and he worked on it during his sabbatical leave in the U.S.A. in 1951 (44). From the early days the F region had been explored with the help of ionograms, that is recorded curves of the equivalent height of reflection, $h'(f)$, against frequency, f. Appleton had pointed out that it should be possible in principle to use these records to deduce the distribution, $N(z)$, of electron concentration, N, with height, z, in the ionosphere but, possibly because he had overemphasized some of the difficulties, no serious attempts had been made to use them for this purpose. Instead, attention had been concentrated almost entirely on measurements of the penetration frequencies, from which only the maximum electron concentrations in the layers could be deduced. Ratcliffe (43) devised a quick but approximate method of deriving $N(z)$ curves from $h'(f)$ curves, but something more accurate was needed. About 1954 workers in the ionosphere section developed a method of using the computer EDSAC 1 for solving this problem. They computed electron distributions appropriate to different parts of the world at different times of day, season and solar cycle. This work was supervised by J. O. Thomas. He was able to build up a most valuable team consisting mainly of wives of research students, to prepare the data for feeding into the computer.

Once the distributions, $N(z)$, had been determined, it was possible to consider in detail the process by which the electrons, produced by the ionizing radiations from the Sun, were finally disposed of (54, 57, 69, 70). It could be by recombination with positive ions, or else by attachment to neutral particles to form negative ions. These processes had previously been discussed in detail, but up to now there were no detailed electron distributions against which the theoretical results could be tested. Arguments based on the new electron distributions soon showed that the electrons in the F region were lost by a process that simulated attachment, and led to the suggestion that the maximum of the region was, in fact, formed not at the place where the ionizing radiation produced its greatest effect, but at a level determined jointly by diffusion and by the loss of electrons. Because the loss rate by attachment depends on the concentration of molecules of nitrogen or oxygen, it decreases rapidly with increasing height. This, by itself, would result in an electron concentration that increased indefinitely with height. It is the process of diffusion that leads, at greater heights, to the occurrence of a maximum in the layer.

Normally, electrons and ions moving under the force of gravity are impeded by collisions with the particles of the neutral air. At great enough heights, however, there is so little air that these collisions are unimportant and the ions and electrons can take up a distribution appropriate to their diffusive equilibrium under gravity. At heights where diffusion is fully operative it causes the electron concentration to decrease with height, so that as a result of all three processes, production, loss and diffusion, a layer is formed with its maximum at a level that can be calculated. It was found that the observed electron distribution could be explained in outline in this way. Although these ideas have been elaborated in detail since the work was done in the Cavendish Laboratory, they are still considered to be the basis of any explanation of the F region.

IV. In 1950–51, at Ratcliffe's suggestion, L. R. O. Storey tried to find out what caused those naturally occurring phenomena known as whistlers. Some preliminary work on this had been done by S. H. W. H. Falloon (D), who prompted Storey to choose this line of research. If a long wire is attached to an audio amplifier and one listens in the telephones, many crashes and bangs are heard corresponding to radiation received from lightning flashes within a few thousand kilometres, but interspersed among these there are sometimes whistling noises of a kind in which the frequency decreases while the whistle lasts. Storey set out to study these naturally occurring whistlers by recording them on magnetic tape and using a simple form of audio frequency analyser to find how the frequency varied during the whistle. Ratcliffe was at first sceptical about this work and never thought there could be much in it until Storey sent him the draft of a paper in 1952. From then on he helped in getting the paper into proper shape and communicated it to the Royal Society (Storey 1953). It is now regarded as one of the most important original papers in the field of radio propagation.

Storey explained his results as follows. A lightning flash emits radio waves of all audio frequencies superimposed upon each other, and when these are received direct in the telephones they produce the bangs and crashes already mentioned. These same waves also pass up into the ionosphere where they are guided along the magnetic lines of force of the Earth so as to come down at the other end. In their passage through the ionosphere the waves do not, however, all travel with the same speed. The high-frequency waves arrive first and those of low frequency later, so that at the far end of the line of force a whistle of decreasing frequency is heard instead of the bang that is heard at the near end.

From measurements made on his records Storey was able to deduce the electron concentration at the highest point on the line of force and concluded that at distances of about four times the Earth's radius the electron concentration was about 6×10^8 m^{-3}. This was very much more than anybody had expected in those days.

Ratcliffe described these results to a large audience for the first time in Australia in 1952 at a General Assembly of U.R.S.I. Soon people in many different parts of the world began to use the method to explore the electron concentration at great heights in the ionosphere and magnetosphere.

V. Wave interaction, also called cross modulation, or the Luxembourg effect, was first observed in 1933. A broadcast signal from Beromünster, Switzerland (652 kHz), was being received in Eindhoven. It was observed that the radio programme from Luxembourg (252 kHz) was heard at the same time. It was established that the modulation of the Luxembourg signal, called the 'disturbing wave', was impressed as amplitude modulation of the Beromünster signal, called the 'wanted wave' and that the process was occurring within the ionosphere. The theory of the effect was given by Bailey & Martyn (1934) and in more detail in a long series of papers by Bailey. Many people considered that this theory was difficult and it was not well understood. In 1948 Ratcliffe with L. G. H. Huxley (41) published a survey of the subject that stressed the basic physical ideas, and which has since been widely used and much cited. Ratcliffe also started to use the effect as a tool for investigating the ionosphere. The disturbing wave heats the electrons. They cool again with a time constant of order 1 ms. If the wave is modulated, the temperature of the electrons is modulated at the same frequency and this in turn modulates the effective electron collision frequency. Thus the absorption rate of the wanted wave is modulated and an amplitude modulation is thereby transferred to the wanted wave. Because of the time constant, there is, between the modulations of the disturbing and wanted waves, a phase difference that depends on the modulation frequency. Ratcliffe with I. J. Shaw (39) used signals from various BBC transmitters to study this effect. They were able to estimate the height where the interaction was mainly occurring, and the electron collision frequency, and the factor determining the transfer of energy from the heated electrons to neutral molecules.

Other aspects of this subject were studied by various members of the radio group. One of these was J. A. Fejer, who later devised a method of using pulses for both the disturbing and the wanted waves. By adjusting the timing of the pulses, the height where the interaction was occurring could be controlled. This method was so successful that it has since been elaborated and used by many other workers.

The five research topics just described are only a small fraction of those in which Ratcliffe was interested. A few more must be mentioned very briefly.

Besides his interest in wave interaction, J. A. Fejer worked on the atmospheric dynamo theory of the variations of the Earth's magnetic field, and on the propagation of waves in irregular media, and he wrote important papers on these subjects. It was Ratcliffe who stimulated his interest in them.

For ray tracing of radio rays in the ionosphere or other plasmas such as the magnetosphere or the solar corona it was required to formulate the differential equations of a ray path. Hamilton's equations for a ray in an anisotropic medium were adapted for this purpose by J. Haselgrove for use on the digital computer. Her equations are now known as the Haselgrove equations and are widely used.

Several members of the radio section worked on problems of the magnetosphere and its interaction with the solar wind. Among them was J. W. Dungey, whose work Ratcliffe regarded as of pioneering importance.

About 1958–60 the technique of using incoherent scatter to probe the ionosphere became of interest and there were many discussions about it in the radio ionosphere section. An important paper on the theory by J. P. Dougherty & D. T. Farley (1960) was communicated to the Royal Society by Ratcliffe. J. A. Fejer also made important contributions to this subject.

Radio and Space Research Station

In 1953 Bragg resigned as Cavendish Professor. There were inevitable changes in the Cavendish Laboratory, and by 1960 Ratcliffe felt the need to do something different until he retired. He wrote (A): 'When I realized that I had once been conducting College Supervision with the fathers of my own undergraduates, and in just the same way, I thought it was time to make a change'. At that time all except one of the other staff members in the radio ionosphere section held non-tenured posts, which had to be renewed every five years. In 1960 they had all run out or were about to do so, and it was difficult to arrange for their renewal because of the need for new posts in the radio astronomy section and for solid state physics, which was then rapidly growing in importance. In October 1960 Ratcliffe therefore took up the posts of Director of Radio Research in the Department of Scientific and Industrial Research, and Director of the Radio Research Station at Slough. The move was a great success and he appreciated to the full the enlarged opportunities that his new post gave him.

The laboratories of the Radio Research Station had been built in 1956. They had been concerned mainly with radio propagation over the Earth, in and below the ionosphere, and including the effect of the troposphere and of various types of ground. There was at the station a World Data Centre, whose task was to receive ionosonde data from observatories spread widely over the Earth, and use it to forecast radio propagation conditions. It issued bulletins that were available to commercial and other users of radio communication.

The first Sputnik had been launched in 1957 and by 1960 plans were already well advanced at Slough for using satellites and rockets for studying radio propagation. When Ratcliffe joined the station in October 1960 a planned reorientation of the work had already started, so that half the effort would be applied to space research problems. Thus the research would be extended above the level of maximum ionization of the F layer into the magnetosphere and beyond. In collaboration with the National Aeronautics and Space Administration of the U.S.A. (NASA) a 'Minitrack' station was installed at Winkfield in 1961. Its dual purpose was to track satellites and to receive telemetry signals. There were already three other outstations controlled by the main station. They were at Singapore, at Port Stanley, Falkland Islands, and at Inverness, and these now took a share in the satellite work. A few years later another outstation was added at Lerwick, Shetlands.

A Pegasus digital computer belonging to the Road Research Laboratory was housed at the Slough station from 1961 onwards. It was used by the station scientists for a good part of its working time.

Ratcliffe's main concern was to consolidate and extend the scientific work of the station. When he arrived there were 28 workers in the scientific officer grades; by 1962 there were 40. Some of those who joined had previously worked in the radio ionosphere section at Cambridge. He wanted the thinking to be on a sound physical basis. In his first year he gave a lecture course on 'Fundamental physics of the ionosphere'. He later gave courses on 'Fourier analysis for physicists and engineers' and on 'Radio wave scattering'.

He very soon became acquainted with all members of the station. At the annual party held each year on 5 November he would speak to everybody present. He ensured close contact with the universities by arranging that university scientists should visit the station for several weeks or months as consultants. He arranged that members of the station made visits to universities and establishments at home and overseas, often on an exchange basis, so that distinguished physicists would spend some time working at Slough.

In 1964 the Department of Scientific and Industrial Research ceased to exist, and the Radio Research Board and Radio Research Station came under the newly formed Science Research Council. There were thus many changes in the people at government headquarters. In April 1965 the name of the station was changed to the Radio and Space Research Station.

It was originally Ratcliffe's intention to stay as Director until 1968. In fact he resigned in February 1966. There were several reasons for this. From 1960 to 1966 the Ratcliffe family lived at a house in Beaconsfield. Early in this period the health of the younger daughter, Joan deteriorated and she died in February 1965. His wife Nora's health was also precarious, and by 1966 Ratcliffe may have felt the need to leave Beaconsfield.

He was to become President of the Institution of Electrical Engineers in October 1966 and he knew that he would devote his fullest efforts to this task. He had been a Vice-President in 1963, and the President is normally selected from the Vice-Presidents. Ratcliffe became senior Vice-President two years earlier than expected because one Vice-President had died and another had resigned. In addition he had been asked to visit Australia in April–May 1966 to deliver the Royal Society's Rutherford Memorial Lecture, and he was to take part in international conferences in August–September 1966.

Research at R.S.R.S., 1960–66

The scientific work of the Research Station covered many topics, too numerous to describe in detail here. They were reviewed each year by Ratcliffe as Director (76, 81). The average number of scientific papers published each year by the station was about 34. The following is a brief account of three of the topics that interested Ratcliffe.

It was now possible to install ionosonde equipment in a satellite so that the pulse method of sounding the ionosphere could be used with the apparatus above the level of maximum electron concentration. This was known as 'topside sounding'. It was used by many of the satellites and was particularly successful with the two Canadian satellites *Alouette* I and II. For the first time it allowed a detailed examination of the electron distribution in the upper part of the ionosphere. It led to some new and interesting problems partly because the equipment was immersed in the plasma of the upper ionosphere. The records of equivalent path against frequency showed resonances, called 'spikes', not seen in ionograms recorded at the ground. The theory of these resonances opened up a new branch of plasma physics. It was now possible to extend to the upper ionosphere the work on the production and loss of electrons, and particularly the diffusion process, in the F layer, that had been started by Ratcliffe's ionosphere section in Cambridge.

Rockets were used to study the lowest parts of the ionosphere, below about 100 km, and the first two firings were made at Woomera, Australia, in 1962. This work was done in collaboration with the University of Sheffield. The principle of the method is as follows. A transmitter on the ground sends a radio wave of frequency about 200 kHz into the ionosphere. During its travel the wave suffers attenuation, has its polarization altered, and at a certain height is reflected. The original upgoing wave and the downcoming reflected wave combine to produce a quasi-stationary wave, in which the form of the wave field depends on the height distribution of electrons and on their collision frequency. All these effects combine to produce a complicated field pattern and the purpose of the experiment is to send a rocket up through this so as to measure its characteristics, and thence to deduce the height distribution of electron concentration, $N(z)$, and collision frequency, $\nu(z)$. For this purpose special receiving aerials were mounted on the rocket. To use the results, possible distributions $N(z)$ and $\nu(z)$ are first postulated and the wave fields to which they would give rise are calculated. If this field is different from that observed, the postulated model is altered until, by a process of trial and error, the calculations agree with the experimental results. For a frequency of 200 kHz or less the ionosphere can change appreciably in a height range of one wavelength. Thus it is necessary to use a 'full-wave' solution of the wave equation, and many solutions must be found. Methods of doing this had been devised at Cambridge in the previous ten years. The process is complicated and therefore slow, and the Pegasus computer at Slough was slower than the Cambridge computers, but the Slough workers were fortunate in having it available for long periods.

A similar process of trial and error was used to determine possible distributions $N(z)$ and $\nu(z)$ that would explain the observations previously made at Cambridge of the reflections of waves of very low frequency. This was done very successfully (Deeks 1966). It represented the final outcome of the work that Ratcliffe started 30 years earlier.

Other researches are described in the Director's reports (76, 81). They include: ionospheric irregularities and movements, propagation through the troposphere, radio meteorology, satellite measurements of energetic particles, solar X-rays, auroral electrons, circuit techniques for space experiments, lasers, laboratory plasma physics, and many other topics.

Retirement

Although Ratcliffe had nominally retired early in 1966 he remained active in many fields for some time. When Appleton died in 1965 Ratcliffe had taken over as Editor-in-Chief of the *Journal of Atmospheric and Terrestrial Physics* and he continued until May 1976. He gave the Royal Society's Rutherford Memorial Lecture in Australia in April 1966, as already mentioned. He attended the 15th General Assembly of U.R.S.I. in Munich in August 1966. Also in 1966 he received the Royal Medal of the Royal Society and he was elected an Honorary President of U.R.S.I. In 1968 he was president of the Cambridge Philosophical Society, but from about 1967 onwards he dropped nearly all professional activities.

His wife Nora's health continued to decline and he cared for her devotedly at their Cambridge home. In October 1975 she was moved to hospital in Northampton, and he visited her there regularly. She died in October 1977.

In this period he wrote two books: *Sun, Earth and radio*, published in 1970 in the World University Library series, and *An introduction to the ionosphere and magnetosphere*, published in 1972 by Cambridge University Press.

He derived great pleasure from his four grandchildren. He corresponded with them regularly, played chess with them, took an interest in their school work and shared their other interests. For many years he gave his voluntary services to 'Meals on Wheels' in Cambridge.

In December 1972 a dinner was held at the Royal Society to celebrate Ratcliffe's 70th birthday. It was attended by his daughter Margaret and her husband, Rev. Noel Pollard, and by many of his colleagues and former research students. Sir Martin Ryle was unable to attend because of illness, but he wrote to me the letter (B) that has been quoted earlier. Ratcliffe was presented with a bound volume of reprints of papers that had been contributed and autographed by about 60 former research students. They had selected papers that they thought were highlights in their work under Ratcliffe's guidance.

Professor W. Dieminger from the Max-Planck-Institut für Aeronomie at Katlenburg–Lindau presided and proposed the toast 'Mr Ratcliffe'. He had been a friend and colleague for many years. Ratcliffe was so pleased that he was present that part of his speech in reply to the toast was in German.

Before the war Ratcliffe had done some cross-country running and had sometimes persuaded F. T. Farmer to join him. He also played fives and squash. He was head of the squash ladder in Sidney Sussex College when he was over 50. He then gracefully accepted deposition by P. C. Clemmow, who was about 19 years younger. At age 70 Ratcliffe was still reasonably fit, and he was then asked to join a group of old school friends for walking in the Lake District. From then onwards walking in the hills became one of his chief interests.

He sometimes suffered from asthma, which became more troublesome and curtailed his activities as the years advanced. He died peacefully at home on 25 October 1987.

It was through Ratcliffe, more than any other, that the new subject of Ionospheric Physics was launched as a major branch of scientific knowledge. His influence has set the pattern of thinking and research in many countries throughout the world.

Honours and awards

Ratcliffe was awarded the O.B.E. in 1946, the C.B.E. in 1959, and was made a Companion of the Order of the Bath in 1965. His other honours and distinctions include:

1951 Fellow of the Royal Society
1966 Royal Medal, the Royal Society

The Physical Society

1953 The Holweck medal and prize (jointly with Société de Physique de France)
1959–60 President

The Institute of Physics

1971 Guthrie Medal and Prize
1972 Honorary Fellow

The Institution of Electrical Engineers

1950 Ambrose Fleming Premium
1952 Duddell Premium
1966–67 President
1966 Faraday Medal
1977 Honorary Fellow

1953 Fellow of the Institute of Radio Engineers (U.S.A.)
1962 Honorary Fellow, Sidney Sussex College, Cambridge
1965 Vice President, Institute of Electrical and Electronics Engineers (U.S.A.)
1966 Honorary President, International Scientific Radio Union (U.R.S.I.)
1973 Fellow, American Geophysical Union
1976 Gold Medal, Royal Astronomical Society
1979 D.Sc. *honoris causa*, University of Kent at Canterbury
1981 Fellow, Indian National Science Academy

Acknowledgments

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The photograph reproduced was taken in 1951 by Walter Bird.

Sources

(A) Biographical notes left by J. A. Ratcliffe.
(B) Letter from the late Sir Martin Ryle, F.R.S., to K.G.B., dated 14 December 1972, on the occasion of Ratcliffe's 70th birthday.
(C) Letter from Dr E. L. C. White.
(D) Letter from Mr S. H. W. H. Falloon.
(E) The Royal Society's Rutherford Memorial Lecture, given by Ratcliffe in 1966 in Sydney (unpublished typescript).
(F) Letter from the Registrar of the University of Lancaster.

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