dynamics. The atomic heats of simple substances agree as well as can be expected with the theoretical expressions, especially when one remembers the difficulty of working out and weighting all the modes of oscillation of a space-lattice of atoms or even complicated molecules. The atomic frequencies calculated from elastic constants agree with those derived from the atomic heat curves; even the fine structure in the spectral lines due to nuclear spin is mirrored in anomalies in the specific heats at the calculated temperatures. Quantum considerations, as Simon showed, enable one to understand the curious fact that helium remains liquid, in the sense that it has a very low viscosity, down to the lowest temperatures, though there is a point at which a certain order tends to be established. For with liquid helium the zero point energy is so great that at atmospheric pressure the substance can never become solid. If the pressure is raised, it can be reduced to the crystalline state even at temperatures ten times as high as its boiling point.

There is, however, one phenomenon, and that a very striking one, that has so far defied adequate explanation. In 1913 Kamerlingh Onnes announced that when mercury was cooled below 4° its electrical resistance vanished. Supra-conductivity, as this effect is called, was afterwards found to occur in lead, tin and a number of other metals, though not by any means in all, for example, not in copper as low as 0·05°. Even some semi-conductors exhibit the same property, such as niobium carbide—indeed in this substance supra-conduction sets in at the highest temperature so far observed, namely, 12°. All attempts to observe some trace of electrical resistance in the supra-conducting state have failed. A current induced in a ring of supra-conducting material continues to run with undiminished strength for days on end. The phenomenon does not seem susceptible of explanation by any of the ordinary theories of electron conduction.

Much work has been done in Leyden, Berlin, Toronto and Oxford on this strange effect, and the somewhat complicated phenomena are gradually being disentangled. But whether it will be possible to fit it into the general scheme or whether it may not require some new mode of approach it is too early yet to say.

Though more low temperature research has been carried out in the last twenty-five years than in all preceding periods put together, and though temperatures within one hundredth of a degree from the absolute zero have been attained, there is no question of our having reached finality.

Our nearness to the absolute zero is apparent rather than real; if we had chosen to measure the temperature on a geometric rather than an arithmetic scale, it would have been less convenient in many ways; but it would have made it clear that, towards low temperatures, as towards high, there is always an infinite distance ahead of us; and in each such range we may expect new effects and new phenomena.

Fortunately, there are within the Empire laboratories where these effects can be studied. At Oxford, Cambridge and Toronto, work at liquid helium temperatures and below is being done. It may be hoped that the next generation will see the position of pre-eminence enjoyed by England in Dewar's time recaptured, and that advances as valuable and important as those which have signalised the past quarter of a century await us in the next.

Cosmic Rays

By DR. ARTHUR H. COMPTON, University of Chicago, and George Eastman Visiting Professor in the University of Oxford

THE twenty-five year period of King George's reign includes almost the entire history of the study of cosmic rays. The presence of these rays was revealed by a series of experiments carried on between 1909 and 1914. Wulf, on the Eiffel Tower, and Gockel, flying in a balloon to 4,500 metres, found that rays from radioactive sources in the ground could not account for the ionisation observed at high altitudes, and suspected some radioactive material in the upper atmosphere[1]. Hess, in a series of notable balloon flights, found an actual increase of ionisation with increasing altitude, and concluded "that a radiation of very high penetrating power enters our atmosphere from above". These experiments were at first criticised by other investigators, but were quickly confirmed by the more precise observations of Kolhörster, and have since been found correct in all their essentials.

After eleven quiescent years, Millikan made some bold speculations regarding the origin of these penetrating rays, which showed in a striking manner that their study might well give important new information regarding the evolution of the universe. Largely through his experiments and those of Hoffmann, the existence of the radiation was by this time generally recognised, and an intensive series of investigations was started by many physicists throughout the world. It was found that the rays which Hess had discovered are of a far more penetrating kind than any known before, being perceptible to a depth of hundreds of feet below the ground. They bring into the earth a total amount of heat somewhat smaller than that of starlight; but the energy of the individual cosmic ray is thousands of times greater than the most powerful artificial ray that man has produced. The more recent studies have sought to learn the nature of these rays, where they come from, how they are produced, and what effects they have on objects which they strike.

Nature of the Cosmic Rays

It was at first natural to suppose that these highly penetrating rays were of the same nature as the γ-rays from radium, the most penetrating rays then known. Though this view has not been entirely abandoned, the large majority of investigators now believe them to be electrically charged particles. This view of their nature was first urged by Bothe and Kolhörster, who found associated with the cosmic rays some electrical particles which were as penetrating as the cosmic rays themselves. They noted further that if such electrical particles approach the earth from all directions, some of those near the equator should be so deflected by the earth's magnetic field that the intensity of the rays should be less there than near the poles. Through the experiments of Clay and many others, the existence of such a 'latitude effect', which depends upon the earth's magnetic field just as the theory predicts, has at last been established. This has proved the existence of an important component of the cosmic rays which is electrically charged.

More recently, using methods developed by Piccard, Regener and others, it has been possible to extend the measurements of cosmic rays high into the stratosphere. Typical data taken at different latitudes are shown in Fig. 1. Here it will be noted that the latitude effect, which is only 15–20 per cent at sea-level, has become a factor of 40 near the top of the atmosphere. That is, nearly all the incoming rays are affected by the earth's magnetic field, and are hence electrically charged. Even of the small percentage which penetrates the magnetic barrier at the equator, supplementary experiments show that a large fraction and perhaps all is electrical in character[2,3].

A method of analysing the various electrical components has recently been developed[2,3], in which the earth is used as a huge natural mass-spectrograph, similar in principle to the laboratory instrument for identifying the isotopes of elements. The earth's magnetic field permits only those particles to reach the earth which have an energy, and hence a range in air, greater than a certain minimum. This minimum range is different for every type of particle. Analysis of such curves as those shown in Fig. 1 has enabled us to distinguish three groups of rays having distinct range minima. Best agreement between these observed minimum ranges and those calculated from the earth's magnetic field is found if the least penetrating group of rays is identified as α-particles, that of medium penetration as electrons (positive or negative), and the most penetrating ones as protons.

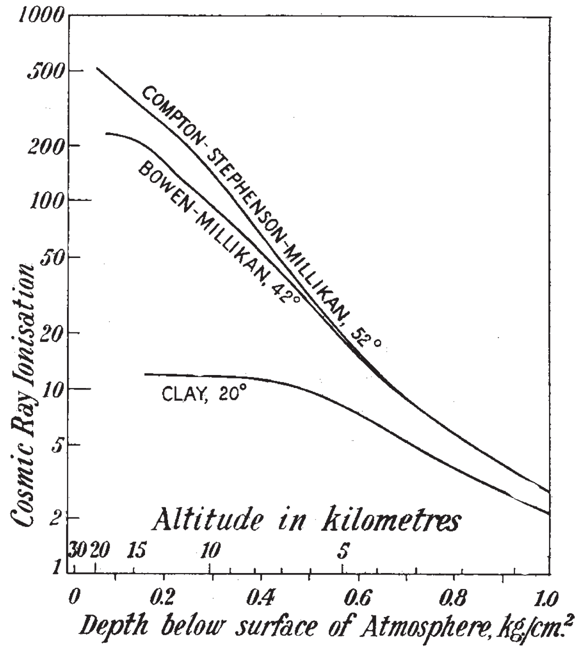

Fig. 1. Cosmic ray ionisation at different altitudes as observed at different geomagnetic latitudes, showing great latitude effect at high altitudes.

It is possible that this analysis may require revision as the result of further measurements; the method, however, seems adequate to supply a definite identification of the components of cosmic rays as soon as sufficiently precise data are available. In the meantime, other observations, especially the directional experiments of Johnson, Alvarez, Rossi, Clay and others, lend support to this tentative analysis[4]. Rapid progress is thus being made toward a complete determination of the composition of cosmic rays.

Whence Come the Cosmic Rays?

One of the most significant aspects of the latitude effect is its implication that the cosmic rays originate far beyond the earth's atmosphere. The earth's magnetic field is not strong enough to bend appreciably any radiation produced within the atmosphere before it is stopped by collisions with molecules. Furthermore, the cosmic ray intensity is found to depend upon the average magnetic effect of the whole earth, and to be almost unaffected by 'local' magnetic idiosyncrasies which may extend even over a whole continent. This must mean that they feel the effect of the earth's magnetism when yet thousands of miles from the earth's surface.

Except for deflection by the earth's magnetic field, however, the cosmic rays are found to approach the earth nearly uniformly from all directions. Outside the earth's atmosphere, we fail to find any isotropic distribution of matter within our galaxy where such rays might originate. The extra-galactic nebulæ or space itself would, on the other hand, satisfy the condition of spherical symmetry. Calculations by both Eddington and Lemaître have shown that the probable absorption of a cosmic ray traversing the matter in interstellar space with about the speed of light for 10^{10} years would be wholly negligible. If, however, these rays are subject to the same red shift as that which occurs in the light from the distant nebulæ, the rays originating at distances as great as 10^{10} light years would arrive at the earth with only a small fraction of their initial energy. If the rays are being continuously produced, therefore, their isotropic distribution suggests that most of them originate in the remote galaxies or in remote space, at an effective distance of between 10^9 and 10^{10} light years. An alternative would be to suppose with Lemaître that they were formed at the beginning of the expansion of the universe, and have ever since been coursing through space.

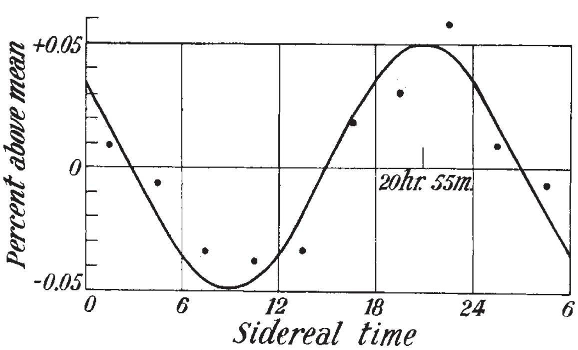

FIG. 2. Apparent effect due to rotation of galaxy. Curve, theory; data, complete year's observations by Hess and Steinmaurer.

Some positive support for this view of the remote origin of cosmic rays is given by the fact that there appears to be an effect on their intensity due to the rotation of the galaxy[5]. According to Stromberg and Hubble, this rotation carries us toward declination 47° N. and right ascension 20 hr. 55 min., at a speed of about 300 km. per second—one thousandth the speed of light. If the source of the cosmic rays is outside our galaxy and at rest relative to its centre of gravity, calculation shows that at our latitude this motion should cause a diurnal variation, following sidereal time, through a range of the order of 0·1 per cent. The best available records of cosmic ray intensity[6] show, as in Fig. 2, a variation with sidereal time of about the predicted magnitude, and with its maximum at precisely the predicted time. Though further experiments are necessary before other possible interpretations of this sidereal time variation are ruled out, the complete agreement with the predictions may justify the presumption that it is really due to the rotation of the galaxy. This would necessarily imply that an important part of the rays originates outside the galaxy, a long-wanted justification of their rather heuristic appellation of 'cosmic'.

How are the Rays Produced ?

Of the many hypotheses regarding the origin of cosmic rays, none has received sufficient experimental support to gain general acceptance. Those which assume the primary cosmic rays to be photons appear to be in definite conflict with the observed latitude effect. Also those which would ascribe their origin to transformations of atomic nuclei with resulting loss of mass are unable to account for the huge energies of from 10^9 to almost 10^{12} electron volts which the more recent studies[7] seem to require for the individual rays. Local or interstellar electric fields have been suggested; but the maintenance of such fields in highly ionised stellar atmospheres seems an insurmountable difficulty. There remain, however, a number of theories which cannot thus be excluded. Prominent among these are Lemaître's hypothesis of 'super-radioactive particles' emitted at the initial explosion of his expanding universe, Swann's theory of the acceleration of electrical particles by electromagnetic induction from the changing magnetic fields of 'sunspots' on giant stars, and Milne's view[8] that the particles owe their energy to the gravitational attraction of the universe. At present we are unable to give these suggestions a definitive experimental test.

Action of Cosmic Rays on Matter

One of the most fruitful lines of cosmic ray research has been the study of their effects on passing through matter. Especially valuable have been the experiments with Wilson chambers in strong magnetic fields, and the use of Geiger-Müller counting tubes. These and other methods have shown that a complex mixture of secondary rays is excited by the primary cosmic particles. In this complex mixture, Anderson made the remarkable discovery of positive electrons, or positrons, which have since been found to play an important rôle in the absorption of high energy photons.

A prominent feature of the secondary radiation associated with cosmic rays is the occurrence of 'showers' of two to twenty or more high-speed particles emanating apparently from the same point. These particles are about equally divided between positive and negative electrons. Furthermore, these showers themselves frequently occur in groups, all excited by some 'shower producing radiation'. This 'shower producing radiation', according to studies by Rossi, Blackett, Anderson and others, seems to consist of photons, similar to X-rays, produced at the collisions of the primary cosmic ray particles with atomic nuclei. Studies by Johnson[4] of the directional asymmetry of the shower producing radiation suggest that it is excited chiefly by the electron component of the primary cosmic rays, and that this component consists of about equal parts of positive and negative electrons.

Contrary to the situation for rays from radioactive materials, it would seem that, for these very high energies, photons may be more absorbable than electrons of the same energy, and that protons are probably the most penetrating of all. The theories of Oppenheimer and Bethe and Heitler indicate that electrons are stopped chiefly by the excitation of photon radiation (X-rays). This results in an almost exponential type of absorption, similar to that of photons. These unanticipated results account in part for the confusion in our early attempts to identify the nature of the primary rays. The experimental study of these energy losses is beginning to give valuable results[9], while their adequate theoretical treatment seems to require a further extension of quantum-relativity electrodynamics. It seems probable that studies of these energy losses may supply our best means of testing those extensions of the present electrodynamics which are designed to account for the structure of electrons and nuclei.

Our analysis of the composition of cosmic rays is thus well under way, and from present indications should soon give conclusive results. The 'cosmic' origin of the rays, though perhaps not established, appears now more probable than ever. How they originate is still obscure; but increased knowledge of their characteristics has helped to limit the types of hypotheses that are admissible. Of immediate value is the use of these rays as a tool. They have made possible the discovery of the positron, and now afford a means of extending our studies of the properties of matter to energies a thousandfold greater than are available from any other known source.

[1] Detailed reviews of cosmic ray research, with comprehensive bibliographies, have recently been published by A. Corlin (*Annals of the University of Lund*, No. 4; 1934) and E. Steinke (*Ergeb. exakt. Naturwiss.*, **13**, 89; 1934). I shall here give references only to some of the very recent work not discussed by these authors.

[2] A. H. Compton and R. J. Stephenson, *Phys. Rev.*, **45**, 441; 1934.

[3] A. H. Compton, *Proc. Phys. Soc. London*, April 1935.

[4] Compare especially T. H. Johnson, *Phys. Rev.*, in press.

[5] A. H. Compton and I. A. Getting, *Phys. Rev.*, in press.

[6] V. F. Hess and R. Steinmaurer, *Sitzber. Preuss. Ak. Wiss.*, **15**; 1933.

[7] Compare, for example, A. H. Compton, NATURE, **134**, 1006; 1934. Similar estimates have previously been published by W. Kolhörster and E. Steinke.

[8] E. A. Milne, NATURE, **135**, 183; 1934.

[9] For example, C. D. Anderson, Proceedings International Conference on Physics, 1934.

Progress in Knowledge of the Upper Air

By DR. F. J. W. WHIPPLE, Superintendent of the Kew Observatory, Richmond, Surrey

IN considering progress in knowledge of the upper air during the past twenty-five years, the first point to notice is that it is roughly true that in 1910 there was little more to be learned about the condition of the atmosphere below 20 km. and a great deal to be learned about the atmosphere above that level.

THE STRATOSPHERE

The most striking discovery that has ever been made in meteorology, the discovery that the familiar decrease of temperature with increasing height comes to a sudden stop at some 10 km. above sea-level, was already well established by 1910. The discovery was announced in 1899 by Teisserenc de Bort, who afterwards coined the names stratosphere for the isothermal layer and troposphere for the lower part of the atmosphere. A name for the transition, the tropopause, was introduced by Sir Napier Shaw comparatively recently. De Bort reported in 1902 that the tropopause was higher in anticyclones than in cyclones, the variation being from 12·5 km. to 10 km. In 1908 it was discovered by a German expedition to Victoria Nyanza that the tropopause was at a height of nearly 17 km. and that the temperature was about 190° A., much lower than the average temperature, 216° A., recorded in Europe.

It was soon realised that the explanation of the existence of the stratosphere must be based on the study of radiation. The permanent gases of the atmosphere are almost perfectly transparent to radiation both in the visible spectrum and in the part of the infra-red in which objects at atmospheric temperatures radiate. On the other hand, water vapour absorbs and radiates in this part