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

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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 of the infra-red. The theory put forward by Gold in 1909 depended on the investigation of the balance of radiation absorbed and given out by water vapour. The theory remains incomplete, for it is not clearly understood why there should be a sharp transition in the temperature gradient at the tropopause, and the contrast between the conditions over the equator and in higher latitudes has not been explained.

During the last twenty-five years, knowledge of the temperature distribution in the stratosphere has accumulated. The meagre data from tropical regions have been supplemented by excellent series of observations in Batavia and in India, and in the far north the balloons sent up at Abisko in Lapland have yielded valuable information. It is now believed that over the tropics there is a considerable increase of temperature above the tropopause, the average temperature at 24 km. being about 220° A. On the other hand, near the Arctic Circle there is a wide annual range of temperature in the stratosphere. At 10 km. the range is from 212° A. in January to 227° A. in July. At 20 km. the averages in those months are estimated as 207° A. and 240° A.

The relations between pressure and temperature in the upper air were set out by W. H. Dines in 1911 in terms of correlation coefficients. Dines was impressed by the strong correlation between the pressure at a height of 9 kilometres and the other variables, the height of the tropopause, the temperature of the stratosphere and the average temperature of the troposphere. It looked as if the movements of the atmosphere must be dominated by developments taking place at the boundary between the stratosphere and the troposphere. The doctrine was neatly expressed by Gold in 1914 in "The Ballad of the Stratosphere":

"I am the rolling Stratosphere,
I long to perturbate;
So I tickle the top of the Troposphere,
To make him undulate."

Later investigations have concentrated attention on the lower strata of the atmosphere, and nowadays most of the meteorologists who are interested in the day-to-day changes of weather are content to regard the stratosphere as playing a passive rôle. There is, however, a school in Germany which regards 'stratospheric steering' as dominating the movements of cyclones and anticyclones.

The theory of the stratosphere has been developed by Simpson, who has demonstrated that the heat balance of the atmosphere is maintained in such a way that the energy of such solar radiation as is not intercepted and reflected by the clouds eventually escapes as long-wave radiation. According to Simpson, any increase in solar radiation would be followed by an increase in evaporation from the oceans and an increase in cloudiness. This would reduce the fraction of the solar radiation available for heating the ground, the oceans and the atmosphere, so that the rise of temperature would be comparatively small. It appears that the temperature of the stratosphere is governed by the properties of water vapour rather than by the strength of solar radiation. Simpson believes that the temperature would be changed but little if the earth received as much radiation as Venus or as little as Mars.

So early as 1875, Hann discussed the constitution of the atmosphere at great heights on the assumption that Dalton's law could be applied, each of the constituent gases behaving as if the others were not present. He showed, for example, that as oxygen is heavier than nitrogen the proportion of oxygen would fall off with increasing height. After the discovery of the stratosphere it was generally assumed that the same uniform temperature would prevail right through the atmosphere from the tropopause upwards, and that the density of each of the constituent gases could be calculated on that basis. Whilst the proportion of hydrogen in air near the ground was only three parts in 100,000, this gas was found according to the calculations to predominate at 80 km. and at greater heights. Wegener came to the conclusion that even hydrogen was not light enough to extend to the greatest heights at which aurora had been observed, and in 1911 he postulated a still lighter gas, geocoronium.

Faith in these calculations was rudely upset in 1922 when Lindemann and Dobson published their paper on "A Theory of Meteors and the Density and Temperatures of the Outer Atmosphere to which it Leads". Qualitatively there was little new in the theory of meteors. In his "Thermodynamik der Atmosphäre", published in 1911, Wegener says that on account of the great velocity of a meteor the air does not get out of its way but is compressed. The air is heated by compression, and heat from the air raises the superficial temperature of the meteor until it begins to evaporate. Wegener thought that the heated air would become visible, whilst Lindemann and Dobson insist that it is only when volatilisation begins that the meteor is seen. That is a small detail, however: the important step was to calculate how much air must have been encountered before the meteor would be raised to incandescence, how much before it was completely volatilised and therefore disappeared. The result of these calculations was that the air throughout the range of height through which meteors had been observed must be much denser, at 100 km. a hundred times denser, than the speculations based on the hypothesis of uniform temperature had indicated.

The natural deduction was that the latter hypothesis was wrong. The air at moderate heights must be sufficiently distended to support comparatively heavy air at the greater heights. The case was met by postulating that the air at heights of 60 km. and upwards was at a temperature of at least 300° A., about the average temperature prevailing on the ground. It was pointed out afterwards that better agreement could be obtained by placing the base of this upper region of high temperature a good deal lower, at 40 km.

The Transmission of Sounds to Great Distances

It was a curious coincidence that Lindemann and Dobson discovered the high temperature of the upper atmosphere in 1922. The observational material which they used in their calculations had been available for at least half a century. On the other hand, when they announced their discovery, investigations were in progress which were leading to the same conclusion. That the sounds of explosions could sometimes be heard at very great distances though inaudible at smaller distances had been noticed long ago ; there is a famous instance, recorded in the diaries of Pepys and Evelyn, of firing in the Straits of Dover being heard in London but not at Dover. The first detailed investigation of the phenomenon was made by van den Borne after a dynamite explosion at Förde in Westphalia in 1904. Previously it had been supposed that abnormal audibility could be explained by the effect of wind, but van den Borne came to the conclusion that this explanation was not adequate, and put forward the hypothesis that the sound waves travelled through the atmosphere at a great height. In his calculations he utilised Hann's estimates of the amounts of different gases in the atmosphere. According to these estimates hydrogen preponderated at heights exceeding 70 km. In an atmosphere of hydrogen the velocity of sound is about four times that in ordinary air. Van den Borne saw that waves passing from the lower atmosphere into an atmosphere which was mostly hydrogen would be refracted and would return to the ground. He reckoned that waves starting upwards in a direction inclined at 30° to the vertical would reach the ground about 116 km. from the source after culminating at a height of 75 km.

The theory seemed to fit the observations, though there was a good deal of scepticism as to the possibility of waves being transmitted through such attenuated gas.

Wegener's account of the theory is followed by the remark that systematic investigations of these sound phenomena could probably be carried out at no great cost and were much to be desired. The Great War provided plenty of opportunities for qualitative observations and directed general attention to the subject, but as a test of theory observations of the time of transmission of sound were needed. After the War, experiments were inaugurated by the International Meteorological Organisation.

These experiments and others have demonstrated that van den Borne's theory cannot be valid, for the times taken by the sound of an explosion to reach various distances are much less than the times computed by that theory.

When Lindemann and Dobson announced that the atmosphere at 60 km. was probably at a high temperature, it was seen at once that this provided the explanation of the phenomenon of 'abnormal' audibility of sounds at great distances. The same explanation was in fact propounded by Wiechert shortly afterwards without any reference to the work of Lindemann and Dobson.

The investigation of the waves from explosions has been carried on, mostly by the use of autographic records. Records of the transmission of air waves to great distances were secured within the Arctic Circle in Lapland and in Novaya Zemlya during the Polar Year. Observations which show that the outer zone of audibility is a universal phenomenon have been collected in other parts of the world.

Accordingly it is probable that high temperatures occur in the upper atmosphere in all parts of the world and at about the same height. More definite information can only be obtained by multiplying observations under controlled conditions.

Ozone

The existence of ozone in the earth's atmosphere was revealed by a remarkable feature of the solar spectrum, the absence of ultra-violet rays of short wave-length. The visible spectrum ends at about $0{\cdot}4\mu$, and photographs obtained with the quartz spectroscope show that there is a narrow band of ultra-violet, but this is cut off at $0{\cdot}29\mu$. In 1881 Hartley discovered that ultra-violet light was absorbed by ozone, and attributed to this gas the limitation of the solar spectrum, but Wegener, writing in 1911, passed over this evidence and based his statement that the quantity of ozone in the atmosphere increased with height on chemical analysis. He added, however, the remarks that the ozone was obviously produced by the action of ultra-violet solar radiation on oxygen, and the greatest part of this radiation was already absorbed at great heights. Accordingly, the distribution of ozone in a way which was inconsistent with Dalton's law was comprehensible.

The first estimate of the quantity of ozone needed to produce the absorption observed in the solar spectrum was made by Fabry and Buisson, whose work was first published in 1913. They announced that the ozone was localised in the atmosphere at heights above the regions accessible to man. Their method was to compare the intensities of light in different parts of the Hartley band and at different elevations of the sun. In this way they were able to eliminate the effects of absorption by haze and of Rayleigh scattering. The quantity of ozone is very small; it is equivalent to a layer of the gas at normal pressure and temperature only 3 mm. thick. If the ozone is in a layer 10 km. deep at such a height that the average pressure is 1/20 of an atmosphere, then in that layer the number of oxygen atoms united in molecules of O_3 is only $1/(2 \times 10^4)$ of the number constituting O_2.

The variations in the quantity of ozone in the upper atmosphere have been studied by Dobson with the aid of several collaborators. The results are striking. The annual variation in Europe has a range of about 30 per cent, the maximum occurring in the spring, the minimum in the late autumn. Both the mean amount (about 2 mm.) and the annual range are least near the equator. Within the Arctic Circle the mean is about 3 mm. and the range is nearly 50 per cent of the mean. There is symmetry in the northern and southern hemispheres.

No regular diurnal variation has been detected, but the amount of ozone varies with changes of pressure in the lower atmosphere. There is more ozone above places where pressure is low, the maximum amount of ozone occurring a little to the west of the centre of a cyclone. The minimum amount is observed a little to the west of the centre of an anticyclone. These results are consistent with the hypothesis that the ozone is transported by currents from polar or equatorial regions, and indicate that the currents at the levels at which ozone is found are generally in the same direction as the currents nearer the ground.

The earlier estimates of the height of the ozone depended on measurements of the absorption of the ultra-violet light in the direct solar beam at different times of day and especially on measurements made when the sun was very low; but the investigators were never very confident about the estimates which they gave of about 50 km. for the centre of gravity of the ozone.

Recently a new and powerful method of dealing with the problem has been developed by Götz, Meetham and Dobson. This method depends on measurements of the intensity of the ultra-violet light from the sky in the zenith. The essential difference is that, whereas in the older method the height of the ozone is compared with the radius of the earth, in the newer the height is compared with the heights at which the density of the air has assigned values. It is now found that the centre of gravity of the ozone is on the average at a height of about 21 km. The published observations refer to Arosa in Switzerland and to Tromsø within the Arctic Circle in Norway, and the difference in height is insignificant. In both locations the ratio of the densities of ozone and air is greatest at 35 km. or 40 km. It should be noted, however, that the Tromsø observations were made only in summer.

That the ozone is mostly below a height of 30 km. has now been confirmed in a very direct way by Regener. A spectroscope was carried up by a sounding balloon to about that height, and the spectrum of the light reflected upwards from a horizontal white surface was photographed automatically at regular intervals. It was demonstrated that as the maximum height was approached the spectrum extended at the violet end, clear evidence that the balloon had passed beyond the greater part of the gas which absorbs the ultra-violet light.

A "theory of upper-atmospheric ozone" has been developed by Chapman. The theory is too difficult and elaborate to summarise here. It may be mentioned, however, that oxygen is dissociated by the absorption of ultra-violet light of very short wave-length, that ozone is formed by the combination of molecular and atomic oxygen and that the ozone is eventually dissociated by the absorption of the ultra-violet of the Hartley band. Most of the oxygen atoms derived from the dissociation of ozone combine again to form new ozone molecules, so that the ozone is in a sense more persistent than the individual molecules of ozone. One notable success of Chapman's theory is that he declared that the ratio of the densities of ozone and oxygen should pass through a maximum at a moderate height, so anticipating the results of observation.

The theory that high temperature was produced in the upper atmosphere by the absorption of ultra-violet light was sketched by Lindemann and Dobson in 1922 in their paper on meteors. The theory was elaborated by Gowan. In his analysis he used the earlier estimates of the height of the ozone, and was led to the conclusion that, under certain assumptions as to the distribution of ozone and of water vapour, the air at such a height as 50 km. could be maintained at a temperature of 300° A., whilst much higher temperatures were to be expected at greater heights. The results were not in accordance with those derived from observations of the transmission of air-waves, which put the base of the high-temperature region about 10 km. lower down. Gowan's work requires revision in the light of the recent determinations of the height of the ozone layer, but at present it seems unlikely that the absorption of ultra-violet light by ozone and by oxygen can provide enough energy at the right levels to maintain the high temperature postulated to explain the refraction of sound waves. It may be that the hypothesis of high temperature will have to be abandoned in favour of the view that the lightness of the atmosphere is due to the dissociation of oxygen. It may also be that some source of energy has yet to be discovered.

AURORA

Whilst information as to the condition of the atmosphere at heights from 30 km. to 50 km. can be obtained in indirect ways, there is no method of investigating conditions between 50 km. and 80 km., though something can be gleaned from the occasional observations of meteor trails, which indicate that there are strong currents in this region. 80 km. is approximately the lower limit of the aurora borealis in southern Norway. Farther north there are few rays which come below 90 km. The majority terminate between 95 km. and 115 km., maximum frequencies occurring at 101 km. and 106 km. The upper ends of the rays are rarely above 400 km. during the greater part of the night, but after sunset, aurora can be seen above the earth's shadow extending to a height of 800 km. Krogness has suggested that the radiation pressure of sunlight drives the air forward so that the earth has a tail like a comet's, and that the high aurora is formed by corpuscles from the sun encountering this tail.

The spectrum of the aurora has been closely studied ; the majority of the lines in the spectrum are attributed to nitrogen, but the brightest, in the green, could not be identified with any line obtained in the laboratory until 1925, when McLennan and Shrum found it in an electric discharge through a mixture of helium and oxygen and demonstrated that the line was produced by a transformation of monatomic oxygen.

No lines associated with helium or hydrogen are observed in the auroral spectrum, so that it appears that the atmosphere in the highest levels consists of nitrogen and oxygen. It may be that any helium or hydrogen which diffuses to great heights is driven off in the comet-like tail of the earth.

It has been recognised for a long while that the corpuscles which produce the aurora carry electric charges and are diverted to the neighbourhood of the earth's magnetic poles by the action of the earth's magnetic field. The theory was elaborated by Birkeland about 1901 and has been developed further by Størmer. The height to which the auroral corpuscles penetrate is also the height of the lower of the two levels at which the atmosphere is a good conductor of electricity. These two layers have been discovered in the study of the transmission of wireless waves ; the lower is usually called the Kennelly-Heaviside layer and is at a height of about 100 km., the upper, discovered by Appleton, is at 220 km.

Chapman maintains that the ionisation at 100 km. outside the auroral zone is due to the bombardment of the atmosphere by neutral particles from the sun. These have about the same energy as the charged particles and penetrate to the same depth. The uncharged particles come straight from the sun, and therefore the supply is cut off at night. This theory is, however, open to question ; for the observations made on the occasion of the eclipse of the sun visible in North America in 1932 appear to indicate that the ionising radiation travels with a velocity nearly equal to the velocity of light.

The upper ionised layer at 220 km. is probably the region in which the ultra-violet light of very short wave-length is trapped by oxygen in the atomic state.

The two ionised layers are of importance in theories of terrestrial magnetism. Chapman believes that the upper layer is the seat of the electric currents which affect magnetographs at our observatories and produce the variations of magnetic force in the course of the solar day, and that electric currents in the lower layer are responsible for the variations which are governed by the moon, the latter currents being associated with tidal movements of the atmosphere.

A layer which has not yet been identified is that from which the light of the night sky comes. It has been demonstrated that this light is not much-reflected sunlight and that it is not scattered starlight. The light must be generated in the earth's atmosphere by some slow process like the recombination of atomic oxygen. That atomic oxygen plays a part in the process is shown by the predominance of the green auroral line in the spectrum of the night sky. That the process is slow is proved by the fact demonstrated by Lord Rayleigh, that the intensity of the light varies but little during the night. Rayleigh finds in fact that the maximum intensity occurs about midnight. The layer from which the light comes must be rich in atomic oxygen. Chapman has given reasons for saying that this layer is probably between the Heaviside and Appleton layers.

Whilst the growth of knowledge of the upper atmosphere during the past twenty-five years has been rapid, there are probably more unsolved problems in sight than there were at the beginning of the period. It is safe to forecast that there will be a great consolidation of knowledge in the next twenty-five years, and that at the end of that period there will be still more problems awaiting solution.